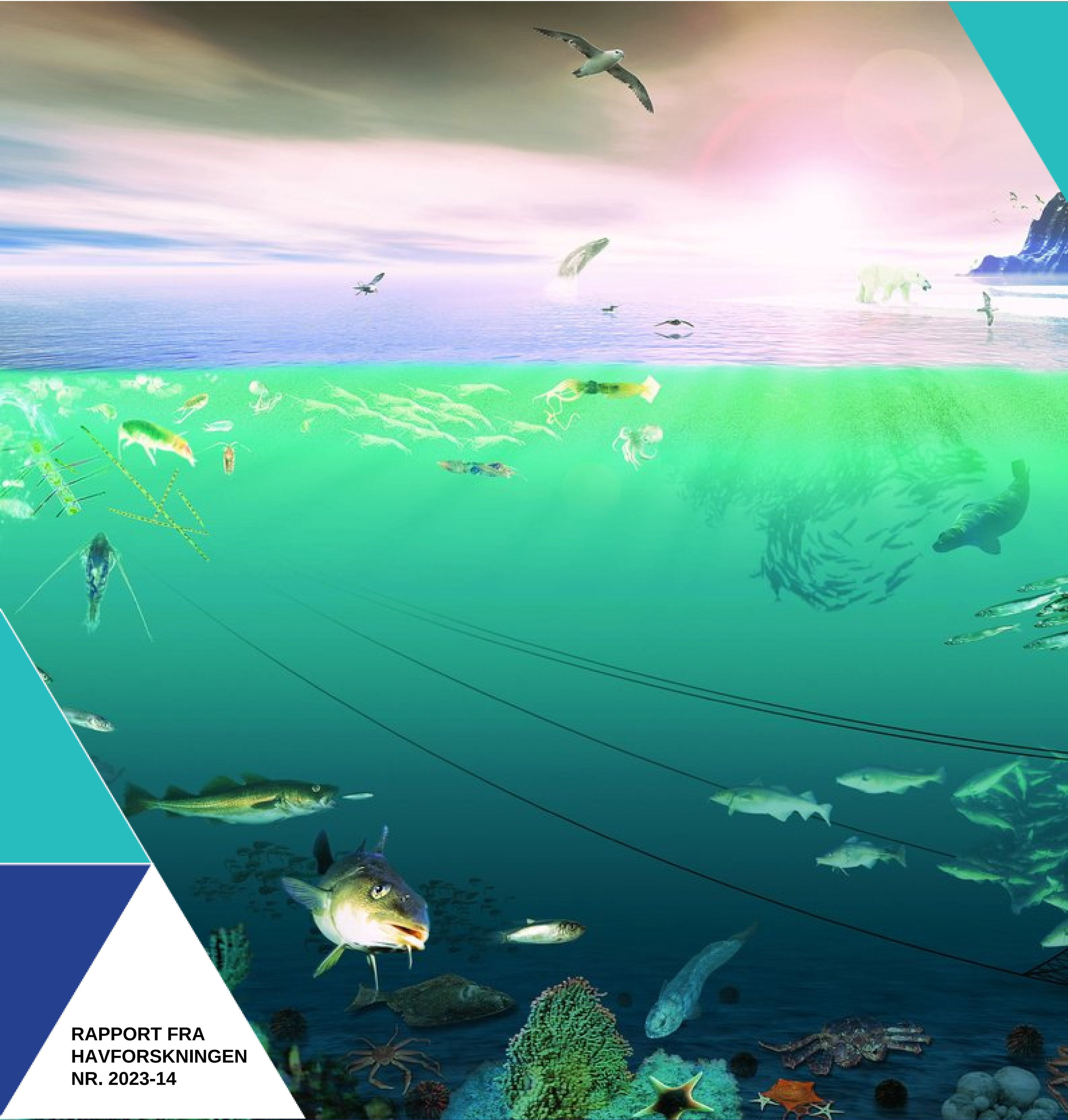
PANEL-BASED ASSESSMENT OF ECOSYSTEM CONDITION OF NORWEGIAN BARENTS SEA SHELF ECOSYSTEMS



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Panel-based Assessment of Ecosystem Condition of Norwegian Barents Sea Shelf Ecosystems

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Author(s):

Anna Siwertsson, Berengere Husson, Per Arneberg, Karen Assmann (IMR), Philipp Assmy (NPI), Magnus Aune (APN), Bjarte Bogstad, Knut Yngve Børsheim, Melissa Chierici (IMR), Sabine Cochrane (APN), Malin Daase (UiT), Per Fauchald (NINA), André Frainer (NINA), Agneta Fransson (NPI), Haakon Hop (NPI), (IMR), Sebastian Gerland (NPI), Randi Ingvaldsen (IMR), Sissel Jentoft (UiO), Kit M. Kovacs (NPI), Deanna Marie Leonard, Sigrid Lind (IMR), Christian Lydersen (NPI), Olga Pavlova (NPI), Laurene Peuchet (UiT), Raul Primicerio (IMR), Paul E. Renaud (APN), Hiroko Kato Solvang, Georg Skaret, Gro van der Meeren (IMR), Paul Wassmann (UiT) and Nils Øien (IMR)

Approved by: Research Director(s): Geir Huse Program leader(s): Maria Fossheim

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NINA Norsk institutt for naturforskning

Norsk Polarinstitutt

UiT Norges arktiske universitet

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Preface:

Mandated by the Ministry of Climate and Environment, the Norwegian Environment Agency is responsible for the development of the “System for assessment of ecological condition” of terrestrial and marine ecosystems in Norway. This report is the first of three from a project funded by the Norwegian Environment Agency on assessing the condition of marine ecosystems. It includes the first assessment of the ecological condition of the Arctic and Sub-Arctic shelf ecosystems in the Norwegian sector of the Barents Sea. The other two reports focus on the assessment of the ecological condition in the North Sea and Skagerrak, and the pelagic ecosystem in the Norwegian Sea, respectively.

For marine ecosystems in Norway, the Panel-based Assessment of Ecosystem Condition (PAEC) has been developed, in cooperation with ecologists working with similar assessments for terrestrial ecosystems, as a methodological framework to assess ecological condition. PAEC was developed to be a structured, consolidated, evidence-based assessment of the ecological condition of an ecosystem. In 2019, a pilot version of the PAEC protocol was tested for Arctic tundra and the Arctic part of the Barents Sea (Jepsen et al., 2019). Based on lessons learned from these two ecosystems, the PAEC protocol has been improved and translated into English (Jepsen et al., 2020), now providing an easily accessible description of the method.

PAEC for the Barents Sea has been led by the Institute of Marine Research (IMR) and been conducted by a panel consisting of 34 scientists from IMR and 5 other institutions: Norwegian Polar Institute (NPI), Norwegian Institute for Nature Research (NINA), UiT The Arctic University of Norway (UiT), Akvaplan-niva (Apl-niva) and the University of Oslo (UiO). The work has been led by Per Arneberg in close cooperation with Anna Siwertsson and Bérengère Husson (all IMR). The work has been conducted in the period from 1 June 2020 to 15 January 2023.

The PAEC framework consists of four phases: 1) A scoping phase where new and existing indicators are evaluated for inclusion; 2) the analysis phase; 3) the assessment phase where the scientific panel meets and discusses the significance and validity of indicator analyses, and 4) the report phase where the scientific background material and conclusions from the scientific panel are written up according to the PAEC protocol.

Covid-19 restrictions influenced the project throughout its duration, and due to these restrictions, there were no physical meetings in the initial phase of the work. Therefore, digital meetings involving mostly smaller sections of the panel were held during the scoping phase. Hybrid meetings with the entire scientific panel for the formal assessment phase were held on 2 December 2021 and 12-13 May 2022.

We thank the Norwegian Environment Agency for valuable contributions to the process, in particular Øystein Leiknes and Hanne-Grete Nilsen, who were contacts for the project.

Tromsø 15 January 2023
Per Arneberg
Project leader

During original publication of this report, Melissa Chierici from the Institute of Marine Research, was erroneously omitted from the author list. Her name was added as an update of the report on 30.10.2024.

Summary (English):

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. The reference condition is defined as “intact ecosystems”, i.e., a condition that is largely unimpacted by modern industrial anthropogenic activities. An ecosystem in good ecological condition is defined as a system that does not deviate substantially from this reference condition in structure, functions or productivity. This means that, in practice, what is assessed here is the extent to which an ecosystem is impacted by anthropogenic drivers. This report describes the first operational assessment of the ecological condition of Norwegian Arctic and Sub-Arctic marine shelf ecosystems in the Barents Sea. The assessment method employed is the Panel-based Assessment of Ecosystem Condition (PAEC[1]), and the current assessment has considered to what extent the Barents Sea shelf ecosystems deviate from the reference condition[2] by evaluating change trajectories.

Key conclusions from the assessment of the Barents Sea Arctic and Sub-Arctic ecosystems

The scientific panel assessed the ecological condition of two ecosystems, the Arctic and sub-Arctic shelf ecosystems in the Norwegian sector of the Barents Sea. The panel concludes that the climate and physical environment are substantially impacted by anthropogenic drivers based on long monitoring time series starting around 1970, in particular through increasing temperatures and declining sea ice area. The panel also identified climate change as a potentially important driver for more than 80% of the indicators in the assessment. However, most of the data on biological components of the ecosystem were available only from 2004, a period with a weaker warming trend than the 1970 to early 2000s part of the climate time series, and the biological indicators showed only moderate changes. Based on these data, the scientific panel concludes that there is **evidence for limited impact of human pressures** on the Arctic ecosystem, and **no evidence** for the Sub-Arctic ecosystem, but point out that there are considerable uncertainties associated with this, due to the short times series for biological indicators. As warming is expected to continue in the future, more substantial changes are expected to be observed also for the biological components of the two ecosystems. In addition to anthropogenic climate impacts, fisheries is another important human pressure in the Barents Sea, and some of its impacts appear to have diminished in recent years.

Assessment method

The assessments of the Arctic and Sub-Arctic Barents Sea ecosystems were done by a scientific panel of 34 experts. To structure the assessment, seven *ecosystem characteristics* had been defined prior to the work. Together these should cover the main aspects of structure and processes in the two ecosystems, and 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 method for the assessment is structured in a hierarchical way. In a first phase of scoping, the experts selected sets of indicators relevant to describe the seven ecosystem characteristics. Second, for each indicator, a description was made on how we expect it to change because of increased anthropogenic impact and the consequences such change can have for the rest of the ecosystem. These descriptions are made based on relevant scientific literature and are evaluated based on how well we understand the links between changes in the indicator, the drivers, and the consequences for the rest of the ecosystem. Third, trend analyses of indicator time series were used to assess the extent to which each indicator has indeed changed because of anthropogenic impact. Information about trends in the anthropogenic drivers were used to support this. Fourth, these results were integrated within an ecosystem characteristic to assess how the characteristic as a whole has changed. In this process, more weight was put on indicators for which we have a better understanding of impact from drivers and ecosystem consequences. Finally, an assessment was made for the ecosystem as a whole, drawing on the conclusions from the seven ecosystem characteristics.

This report will be peer-reviewed to ensure the validity and robustness of its conclusions. As a first implementation of the PAEC framework in a marine ecosystem, this process has been challenging and the panel also reports on suggestions to improve the method (see section 7.3.3).

Datasets and indicators

The assessments of the condition of the Arctic and Sub-Arctic ecosystems in the Norwegian sector of the Barents Sea are based on 32 datasets (ch.3) supporting 42 and 36 indicators respectively, of which 29 are common to both ecosystems. Data used to produce the ecosystem time series for this assessment were collected from stock assessments and population models, satellites, and survey data, in particular from the Barents Sea ecosystem survey operated each autumn since 2004 jointly by the Norwegian Institute of Marine Research (IMR) and the

Knipovichs' Polar Research Institute of Marine Fisheries and Oceanography (PINRO, since 2019 - Polar Branch of Russian Federal Research Institute of Fisheries and Oceanography). Although the ecosystem survey mentioned above was done jointly across the two countries, here we use only data from the Norwegian sector of the Barents Sea. This survey samples many compartments of the ecosystem in a standardized manner along a spatial grid covering the entire domain of the assessment. The main limitations in using these data are that (i) the time series generated may be too short to cover reference conditions or to show relevant dynamics (e.g., seasonality) for some of the ecosystem components, and (ii) the part of the ecosystem in the Russian sector, which can influence dynamics in the Norwegian sector, was not assessed. Data coverage for each indicator is evaluated based on spatial and temporal coverage of used datasets relative to reference conditions and relevant dynamics of the biological compartments and was thus assessed as very good or good for most indicators in both ecosystems. Only eight and five indicators were assessed as having intermediate data coverage in the Arctic and Sub-Arctic ecosystem, respectively.

The indicator coverage was assessed as partially adequate for all ecosystem characteristics except abiotic factors for which it is rated as adequate, in both ecosystems. Thus, the set of indicators used suffer certain shortcomings, although these should not affect the conclusions of the assessment.

The condition of ecosystem characteristics

For the Arctic ecosystem, most ecosystem characteristics show signs of anthropogenic impact and deviate from the reference condition (Table S.1.a). For two ecosystem characteristics (*Landscape-ecological patterns, Abiotic factors*), there is evidence of substantial deviation from the reference condition. For the characteristics *Primary productivity, Biomass distribution among trophic levels,* and *Biological diversity* there is evidence for limited changes away from the reference condition. One characteristic, *Functional groups within trophic levels*, was assessed as showing evidence for no or limited deviation from the reference condition, as the panel could not reach an agreement. Finally, for *Functionally important species and biophysical structures*, it was assessed that there is no evidence for deviation from the reference condition. Main uncertainties for this assessment emerge from the fact that the biological ecosystem characteristics are mainly assessed with data from 2004-2020, a period with strong variation but no overall trend in climate.

Table S.1.a Summary of assessment of the seven ecosystem characteristics for the Arctic part of the Barents Sea.

Ecosystem characteristic	Assessment of the Arctic ecosystem	
Primary productivity	🟨	The ecosystem characteristic is assessed as showing **evidence of limited impact** from human pressures. It is based on 2 indicators with well-known links to the drivers and well understood consequences for the ecosystem. There is some evidence for an increased annual primary production and some signs of earlier spring blooms. The main driver of these indicators is climate change. If the time series had been longer, stronger trends might have been seen. Part of the production (e.g., ice algae and subsurface chlorophyll maxima) is not monitored by satellite. Time series with taxonomic information for primary producers would be useful.
Biomass distribution among trophic levels	🟨	The ecosystem characteristic is assessed as showing **evidence of limited impact** from human pressures. It is based on 11 indicators, most of which have good scientific basis in terms of knowledge about link to the drivers and consequences to the ecosystem. There is some evidence for important changes in the lower trophic levels, suggesting changes in trophic structure. The main driver of this ecosystem characteristic is climate change. The use of primary productivity instead of producers' biomass (not monitored), and short time series for all the intermediate trophic level are the main sources of uncertainty in this assessment.
Functional groups within trophic levels	🟩🟨	The ecosystem characteristic is assessed as showing **no evidence** or **evidence of limited impasct** from human pressures, as the scientific panel could not agree on a single assessment category. It is based on 11 indicators, for most of which the links to the drivers (fisheries, climate change and previous overharvesting) and consequences on the ecosystem are not well understood. There is limited evidence for alteration in functions such as habitat engineering, bioturbation, and habitat use by fish. Evidence for the changes is inconsistent among the indicators, and many important functions of the ecosystem are missing, which leads to large uncertainties in this assessment.

Functionally important species and biophysical structures	🟩	The ecosystem characteristic is assessed as showing **no evidence of impact** from human pressures. It is based on 7 indicators with well-understood linkage to drivers (fisheries and climate change) and consequences for the ecosystem. There is substantial evidence that cod is progressing northwards, but important fish stocks show no clear long-term trends that could be attributed to increased human pressure. Other important species or groups of species (zooplankton, ice algae, shrimps, snow crab) are not included in this assessment and are a major source of uncertainty.
Landscape-ecological patterns	🟧	The ecosystem characteristic is assessed as showing **evidence of substantial impact** from human pressures. It is based on 2 indicators with well-known link to the driver (climate change) and well understood consequences on the ecosystem. There is strong evidence for increase in temperature and sea-ice decline, with subsequent changes in species habitats. Some important geographic features like areas of bottom impact are not included.
Biological diversity	🟨	The ecosystem characteristic is assessed as showing **evidence of limited impact** from human pressures. It is based on 8 indicators, most of them with well-understood linkage to drivers (climate change, fisheries, pollution) and consequences for the ecosystem. There is evidence of decline for the Arctic endemic species populations linked to climate change, while the situation for fisheries sensitive fish species is improving. Uncertainties in this assessment are related to the lack of understanding of the combined impacts of climate change and fisheries on some of the indicators. It should also be noted that this ecosystem characteristic is assessed by looking at indicative species or groups, that we know are sensitive to some pressures and might thus miss unforeseen impacts on other compartments of the ecosystem.
Abiotic factors	🟧	The ecosystem characteristic is assessed as showing **evidence of substantial impact** from human pressures. It is based on 7 indicators with well-known link to the driver (climate change) and well understood consequences on the ecosystem. There is strong evidence for increase in temperature and decrease in stratification in the upper water column, freshwater content and sea-ice extent in winter and summer. There are no major uncertainties linked to this assessment.

For the Sub-Arctic ecosystem, no ecosystem characteristics showed deviation from the reference condition, except the *Abiotic factors* and *Landscape-ecological patterns* (Table S.1.b). Phenomena developed have lower validity as the relative importance of the different drivers and the consequence of change in the indicators are less well understood than in the Arctic.

Table S.1.b Summary of assessment of the seven ecosystem characteristics for the Arctic part of the Barents Sea.

Ecosystem characteristic	**Assessment of the Sub-Arctic ecosystem**	
Primary productivity	🟩	The ecosystem characteristic is assessed as showing **no evidence of impact from human pressures**. It is based on 2 indicators with poorly known links to the main driver (climate change) and unclear consequences on the ecosystem. There is no evidence for a stable and later decreasing annual primary production and an earlier start of the spring bloom. There are no major uncertainties to this assessment, although more detailed information on taxonomic composition of primary producers would be useful.
Biomass distribution among trophic levels	🟩	The ecosystem characteristic is assessed as showing **no evidence of impact from human pressures**. It is based on 10 indicators, most of which have good scientific basis in terms of link to the drivers (climate change and fisheries) and consequences to the ecosystem. There is low or intermediate evidence for changes in parts of the upper (high trophic level seabirds) and lower (suspension feeders) trophic levels. Major uncertainties are linked to the short time series available for most of the biological groups.
Functional groups within trophic levels	🟩	The ecosystem characteristic is assessed as showing **no evidence of impact from human pressures**. It is based on 7 indicators, for most of which the links to the drivers (climate and fisheries) and consequences on the ecosystem are not well understood. There is limited evidence for alteration in habitat use by fish. There are uncertainties in this assessment, partly because more knowledge on cumulative impacts is needed and some important functions were not included.
Functionally important species and biophysical structures	🟩	The ecosystem characteristic is assessed as showing **no evidence of impact from human pressures**. It is based on 7 indicators with well-understood linkage to drivers (mainly fisheries and climate) and consequences for the ecosystem. There is some evidence for changes in haddock stock size and decreasing abundance of Arctic copepod species. The fact that the redfish stock is partially distributed in the Norwegian sea adds some uncertainty in the assessment. Some important groups (shrimp and snow crab) are not included in this assessment which is also a source of uncertainty.

Landscape-ecological patterns	🟧	The ecosystem characteristic is assessed as showing **evidence of substantial impact from human pressures**. It is based on only 1 indicator with well-known links to the drivers and well understood consequences on the ecosystem. There is strong evidence for decreasing area of cold-water above the seafloor. The assessment is uncertain due to only one indicator being included, and some important indicators are missing, such as the area covered by bottom trawling and important spawning and nursery areas.
Biological diversity	🟩	The ecosystem characteristic is assessed as showing **no evidence of impact from human pressures**. It is based on 4 indicators, most of them with well-understood linkage to drivers (fisheries, over-harvesting, climate) and consequences for the ecosystem. There is no evidence of loss of biodiversity for these indicators, which are mainly related to fisheries. Limitations in the time series lengths, in the groups included and in the calculations of some indicators lead to large uncertainties in this assessment. It should also be noted that this ecosystem characteristic is assessed by looking at indicative species or groups, that we know are sensitive to some pressures and might thus miss unforeseen impacts on other compartments of the ecosystem.
Abiotic factors	🟧	The ecosystem characteristic is assessed as showing **evidence of substantial impact from human pressures**. It is based on 5 indicators with well-known links to the drivers and well understood consequences on the ecosystem. There is strong evidence for increase in temperature and area of Atlantic Water. Main uncertainties emerge from the relative weight given to the different indicators.

Future trajectories for ecosystem condition

Continued warming of the Barents Sea and further loss of sea ice is expected in both the near (2050) and distant (2100) future unless global greenhouse gas emissions are cut severely, with large changes in climate expected if emissions remain high. Large ecological changes are expected from this, including northward expansion of species in both systems, resulting in, among other things, changes in the zooplankton community which may set off cascading effects in other parts of the ecosystems. In the Arctic part, increased primary production, increasingly connected food webs and declines or loss of sea-ice dependent and Arctic species, such as polar cod are other clear expectations from warming. In the Sub-Arctic part, northward shifts of important fish stocks in and out of the area are expected towards 2050, which will likely transform the trophic links and functional diversities. Variability in abiotic factors is also expected to increase, with extreme climatic event such as heatwaves occurring more frequently, more intensely, and for longer periods. These are likely to increase the uncertainties around the ecosystems' future conditions.

Research and monitoring recommendations

This assessment relies entirely on long-term monitoring programs that are indispensable and require continuous funding. Some minor adjustments to the current monitoring programs are suggested and concern mainly taxonomic identification of lower trophic levels. Some important knowledge gaps that should be addressed by specific studies and regularly monitored include the microbial loop, ice-associated flora and fauna, and some of the upper trophic level processes (nutrient cycling by marine mammals, aggregation of preys). Finally, more research is needed on the combined impact of multiple drivers in those two specific ecosystems, and on unexpected events, e.g., heatwaves.

Summary (Norwegian):

System for vurdering av økologisk tilstand, koordinert av Miljødirektoratet, skal utgjøre fundamentet for en kunnskapsbasert vurdering av økologisk tilstand for norske terrestre og marine økosystemer som ikke er omfattet av vanndirektivet. Referansetilstanden er definert som «intakt natur», dvs en tilstand som i stor grad er upåvirket av moderne industrielle aktiviteter. Et økosystem som er i god økologisk tilstand avviker ikke betydelig fra denne referansetilstanden i struktur, funksjon eller produktivitet. Denne rapporten beskriver den første operasjonelle vurderingen av økologisk tilstand i arktiske og sub-arktiske marine økosystemer i den norske delen av Barentshavet. Tilstandsvurderingen følger metoden Panelbasert vurdering av økosystemtilstand (Panel-based Assessment of Ecosystem Condition [PAEC][1]) og avvik fra referansetilstanden[2] er vurdert ved å evaluere endringsrater.

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[1] Jepsen, J. U., Arneberg, P., Ims, R. A., Siwertsson, A., and Yoccoz, N. G. 2020. Panel-based Assessment of Ecosystem Condition (PAEC). Technical protocol version 2. NINA Report 1890.

[2] For consistency with the PAEC protocol, it is generally referred to "deviation from the reference condition" rather than "deviation from good ecological condition" in this report.

Hovedkonklusjon fra vurderingen av det arktiske og det subarktiske økosystemet i Barentshavet

Forskerpanelet har vurdert tilstanden til to økosystemer, det arktiske og det subarktiske økosystemet i den norske delen av Barentshavet. Basert på lange overvåkingsserier som startet rundt 1970, konkluderer forskerpanelet med at klimaet og det fysiske miljøet i disse økosystemene er betydelig påvirket av menneskeskapte drivere, særlig gjennom økt temperatur og minkende arealer dekket av sjøis. Panelet har også identifisert klimaendringer som en potensielt viktig påvirkningsfaktor for mer enn 80 % av alle indikatorene i vurderingen. Det meste av data for de biologiske komponentene av økosystemet er imidlertid tilgjengelig kun fra 2004 og fremover. Dette er en periode med svakere oppvarming enn fra 1970 til tidlig 2000-tallet, og de biologiske komponentene viste kun moderate endringer. Basert på disse dataene konkluderte forskerpanelet med at det er belegg for å si at det er begrenset menneskeskapt påvirkning i det arktiske økosystemet som helhet og ingen belegg for å si at det subarktiske systemet som helhet er påvirket. Forskerpanelet understreker imidlertid at det er betydelig usikkerhet knyttet til denne konklusjonen på grunn av de korte tidsseriene for de biologiske indikatorene. Fordi oppvarmingen av Barentshavet er forventet å fortsette i framtiden, er det forventet at betydelige endringer vil bli observert også for de biologiske komponentene i økosystemene. I tillegg til menneskeskapte klimaendringer er fiskerier en annen viktig antropogen påvirkningsfaktor, og noe av denne påvirkningen ser ut til å ha blitt mindre i de senere årene.

Vurderingsmetode

Vurderingene av det arktiske og subarktiske Barentshavet ble gjort av et fagpanel på 34 eksperter. For å strukturere vurderingen hadde syv økosystemegenskaper blitt definert før arbeidet. Til sammen skal disse dekke de viktigste aspektene ved struktur og prosesser i de to økosystemene, og er: Primærproduksjon, Fordeling av biomasse mellom trofiske nivåer, Funksjonelle grupper innen trofiske nivåer, Funksjonelt viktige arter og biofysiske strukturer, Landskapsøkologiske mønstre, Biologisk mangfold og Abiotiske forhold. Vurderingsmetoden er strukturert på en hierarkisk måte. I en første fase valgte ekspertene ut et sett av indikatorer som er relevant for å beskrive de syv økosystemegenskapene. I en andre fase ble det for hver indikator gjort en beskrivelse av hvordan vi forventer den skal endre seg som følge av økt menneskeskapt påvirkning og konsekvensene slike endringer kan ha for resten av økosystemet. Disse beskrivelsene er basert på relevant forskningslitteratur og er evaluert på bakgrunn av hvor godt man forstår forbindelsen mellom endringer i indikatoren, påvirkningsfaktorene og konsekvensene for resten av økosystemet. I en tredje fase ble trendanalyser av tidsserier for indikatorene brukt til å vurdere i hvilken grad hver indikator har endret seg som følge av menneskeskapt påvirkning. Informasjon om trender i menneskeskapte påvirkningsfaktorer blir brukt for å støtte denne vurderingsprosessen. I en fjerde fase ble disse resultatene integrert innen hver økosystemegenskap for å vurdere i hvilken grad egenskapen som helhet har endret seg. I denne prosessen ble mer vekt lagt på indikatorer hvor vi har en bedre forståelse av påvirkning og økosystemkonsekvenser. Til sist ble det gjort en vurdering av hvert av de to økosystemene som helhet basert på konklusjonene for de syv økosystemegenskapene.

Rapporten vil bli underlagt fagfellevurdering for å sikre at konklusjonene er gyldige og robuste. Siden dette er den første operasjonelle anvendelsen av PAEC-rammeverket for et marint økosystem, har prosessen vært utfordrende og fagpanelet gir flere forslag til forbedring av metoden (se kap. 7.3.3).

Datasett og indikatorer

Vurderingen av tilstanden til økosystemene i den arktiske og subarktiske delen av den norske sektoren av Barentshavet er basert på 32 datasett (kap. 3) som støtter henholdsvis 42 og 36 indikatorer, hvorav 29 er felles for begge økosystemene. Dataene som er brukt til å opparbeide tidsserier for denne vurderingen er samlet fra bestandsvurderinger og populasjonsmodeller, satellitter og toktdata, særlig fra økosystemtoktet i Barentshavet som har vært drevet hver høst siden 2004 i fellesskap av Havforskningsinstituttet og Knipovichs' Polar Research Institute of Marine Fisheries and Oceanography (PINRO, siden 2019 - Polar Branch of Russian Federal Research Institute of Fisheries and Oceanography). Selv om dette toktet er utført av to nasjoner er det kun brukt data fra den norske sektoren av Barentshavet her. Dette toktet tar prøver fra mange deler av økosystemet på en standardisert måte i et rutenett som dekker hele vurderingsområdet. De viktigste begrensningene når det gjelder bruk av disse dataene er at: (i) tidsseriene som blir generert kan være for korte til å dekke referansetilstanden eller vise relevant dynamikk (f. eks. sesongvariasjon) for noen økosystemkomponenter, og (ii) de delene av økosystemene som ligger i russisk sektor, og som kan påvirke dynamikken i norsk sektor, er ikke blitt vurdert. Datadekning for hver indikator er vurdert basert på dekningen i rom og tid til hvert datasett der det tas i betraktning sammenfall med periode som kan anses som beskrivende for referansetilstanden samt relevant dynamikk i tid. Datadekning ble vurdert som «svært god» eller «god» for de fleste indikatorene i begge økosystemene. Kun åtte og fire indikatorer ble vurdert å ha intermediær datadekning i henholdsvis det arktiske og subarktiske økosystemet.

I begge økosystemene ble indikatordekning vurdert som delvis adekvat for alle økosystemegenskapene unntatt Abiotiske forhold, hvor den ble vurdert som adekvat. Det er derfor visse mangler i indikatorsettene som er brukt, men dette skal ikke ha betydning for konklusjonene fra vurderingen.

Tilstanden til økosystemegenskapene

For det arktiske økosystemet viser de fleste økosystemegenskapene tegn på menneskeskapt påvirkning og de avviker dermed fra referansetilstanden (Tabell S.2.a). For to økosystemegenskaper (Landskapsøkologiske mønstre og Abiotiske forhold) er det evidens for betydelig avvik fra referansetilstanden. For egenskapene Primærproduksjon, Fordeling av biomasse mellom trofiske nivå og Biologisk mangfold er det evidens for begrensede endringer bort fra referansetilstanden. For egenskapen Funksjonelle grupper innen trofiske nivå greide ikke fagpanelet å bli enig om en konklusjon, og det er derfor vurdert at det er evidens for ingen eller begrenset avvik fra referansetilstanden. For Funksjonelt viktige arter og biofysiske strukturer er det vurdert at det ikke er evidens for avvik fra referansetilstanden. Usikkerheten i vurderingen er i stor grad knyttet til at de biologiske økosystemegenskapene er vurdert med data fra 2004 til 2020, en periode med betydelig variasjon, men ingen klare trender i klima.

Table S.2.a Sammendrag av vurderingen for de syv økosystemegenskapene for den arktiske delen av Barentshavet.

Økosystemegenskap	Vurdering av det arktiske økosystemet	
Primærproduksjon	🟨	Økosystemegenskapen ble vurdert til å vise **evidens for begrenset påvirkning** fra menneskeskapte drivere. Dette er basert på 2 indikatorer, med god kunnskap om forbindelse til påvirkningsfaktorene og konsekvenser for økosystemet. Det er noe evidens for en økning i årlig primærproduksjon og noen tegn på tidligere start av våroppblomstringen. Den viktigste påvirkningsfaktoren for disse indikatorene er klimaendringer. Om tidsseriene hadde vært lenger kunne en sett sterkere trender. Deler av produksjonen (for eksempel isalger og dype klorofyllmaksima) er ikke overvåket med satellitt. Tidsserier med taksonomisk informasjon for primærprodusenter ville vært nyttig.
Fordeling av biomasse mellom trofiske nivå	🟨	Økosystemegenskapen ble vurdert til å vise **evidens for begrenset påvirkning** fra menneskeskapte faktorer. Vurderingen er basert på 11 indikatorer, hvor de fleste har et godt kunnskapsgrunnlag når det gjelder forbindelse til påvirkningsfaktorer og konsekvenser for økosystemet. Det er noe evidens for endringer på lave trofiske nivå, som indikerer endringer i trofisk struktur. Den viktigste påvirkningsfaktoren for denne økosystemegenskapen er klimaendringer. Bruken av primærproduksjon i stedet for produsentenes biomasse (ikke overvåket), og korte tidsserier for alle de midlere trofiske nivåene er de viktigste kildene til usikkerhet i denne vurderingen
Funksjonelle grupper innen trofiske nivå	🟩🟨	Økosystemegenskapen ble vurdert til å vise **ingen evidens** eller **evidens for begrenset påvirkning** fra menneskeskapte drivere. Vurderingen er basert på 5 indikatorer, hvorav en var vurdert til ikke å ha tilstrekkelig data og ble dermed ikke inkludert i vurderingen. For de gjenværende 4 var det noe tegn til nedgang i kroppsstørrelse for hoppekreps og den relative viktigheten til meroplankton sammenlignet med holoplankton. For disse indikatorene er kunnskapen om forbindelse til påvirkningsfaktorene og konsekvenser for økosystemet vurdert som relativt god. De viktigste påvirkningsfaktorene er klimaendringer og fiskeri. Den viktigste kilden til usikkerhet er de korte tidsseriene for de andre indikatorene.
Funksjonelt viktige arter og biofysiske strukturer	🟩	Økosystemegenskapen ble vurdert til å vise **ingen evidens for påvirkning** fra menneskeskapte drivere. Dette er basert på 7 indikatorer med godt forståtte forbindelser til påvirkningsfaktorer (fiskerier og klimaendringer) og konsekvenser for økosystemet. Det er betydelig evidens for at torsk spres nordover, men viktige fiskebestander viser ingen klare tegn på langtidstrender som kan knyttes til menneskeskapt påvirkning. Andre viktige arter eller grupper av arter (dyreplankton, isalger, reke, snøkrabbe) er ikke inkludert i vurderingen, som er en betydelig kilde til usikkerhet.
Landskapsøkologiske mønstre	🟧	Økosystemegenskapen ble vurdert til å vise **evidens for betydelig påvirkning** fra menneskeskapte drivere. Dette er basert på 2 indikatorer med godt forståtte forbindelser til driveren (klimaendringer) og godt forståtte konsekvenser for økosystemet. Det er sterk evidens for økning i temperatur og nedgang i sjøis med påfølgende endringer i habitater for arter. Noen viktige geografiske trekk, som områder med bunnpåvirkning, er ikke inkludert.

Biologisk mangfold	🟨	Økosystemegenskapen ble vurdert til å vise **evidens for begrenset påvirkning** fra menneskeskapte drivere. Dette er basert på 8 indikatorer, de fleste med godt forståtte forbindelser til påvirkningsfaktorer (klimaendringer, fiskeri, forurensning) og konsekvenser for økosystemet. Det er evidens for nedgang for arktiske endemiske arter knyttet til klimaendringer, mens situasjonen for fiskearter som er sensitive for påvirkning fra fiskeri er i bedring. Usikkerheten i denne vurderingen er knyttet til manglende forståelse av samlet påvirkning fra klimaendringer og fiskeri for noen indikatorer. Det er også verd å merke seg at denne økosystemegenskapen er vurdert ved å bruke arter eller grupper av arter en vet er sensitive for visse påvirkningsfaktorer og at det dermed er en mulighet for at man kan ha gått glipp av mindre forutsigbare påvirkninger på andre deler av økosystemet.
Abiotiske forhold	🟧	Økosystemegenskapen ble vurdert til å vise **evidens for betydelig påvirkning** fra menneskeskapte drivere. Vurderingen er basert på 7 indikatorer med godt forståtte forbindelser til påvirkningsfaktoren (klimaendringer) og godt forståtte konsekvenser for økosystemet. Det er sterk evidens for økning i temperatur, nedgang i stratifisering av øvre del av vannsøylen, ferskvannsinnhold og utbredelse av sjøis om vinteren og sommeren. Det er ingen betydelig usikkerhet knyttet til denne vurderingen.

For det subarktiske økosystemet er det ikke vist noen avvik fra referansetilstanden for noen av økosystemegenskapene, unntatt Abiotiske forhold og Landskapsøkologiske mønstre (Tabell S.2.b). Fenomener har lavere gyldighet på grunn av at den relative viktigheten av de ulike påvirkningsfaktorene og konsekvenser av endringer i indikatorene er mindre godt forstått enn i den arktiske delen.

Table S.2.b Sammendrag av vurderingen for de syv økosystemegenskapene for den subarktiske delen av Barentshavet.

Ecosystem characteristic	**Assessment of the Sub-Arctic ecosystem**	
Primærproduksjon	🟩	Økosystemegenskapen ble vurdert til å vise **ingen evidens for påvirkning** fra menneskeskapte drivere. Dette er basert på 2 indikatorer, med dårlig forståtte forbindelser til den viktigste påvirkningsfaktoren (klimaendringer) og uklare konsekvenser for økosystemet. Det er ingen evidens for en stabil og senere minkende årlig primærproduksjon eller tidligere start av våroppblomstringen. Det er ingen betydelig usikkerhet knyttet til denne vurderingen, selv om mer detaljert informasjon om taksonomisk sammensetning av primærprodusenter hadde kommet til nytte.
Fordeling av biomasse mellom trofiske nivå	🟩	Økosystemegenskapen ble vurdert til å vise **ingen evidens for påvirkning** fra menneskeskapte faktorer. Vurderingen er basert på 10 indikatorer, hvor de fleste har et godt kunnskapsgrunnlag når det gjelder forbindelse til påvirkningsfaktorer (klimaendringer og fiskeri) og konsekvenser for økosystemet. Det er lav eller intermediær evidens for endringer i deler av de øvre (sjøfugl på høye trofiske nivå) og lave (grupper av bunndyr) trofiske nivåene. Viktige usikkerheter er knyttet til de korte tidsseriene som er tilgjengelige for de fleste biologiske gruppene.
Funksjonelle grupper innen trofiske nivå	🟩	Økosystemegenskapen ble vurdert til å vise **ingen evidens for påvirkning** fra menneskeskapte drivere. Vurderingen er basert på 7 indikatorer, hvor forbindelsen til påvirkningsfaktorer og konsekvenser for økosystemet ikke er godt forstått. Det er begrenset evidens for endringer i habitatbruk hos fisk. Det er usikkerheter knyttet til denne vurderingen, delvis fordi det er behov for bedre kunnskap om samlede effekter av flere påvirkningsfaktorer, og fordi noen viktige funksjoner ikke var inkludert.
Funksjonelt viktige arter og biofysiske strukturer	🟩	Økosystemegenskapen ble vurdert til å vise**ingen evidens for påvirkning** fra menneskeskapte drivere. Dette er basert på 7 indikatorer med godt forståtte forbindelser til påvirkningsfaktorer (hovedsakelig fiskerier og klimaendringer) og konsekvenser for økosystemet. Det er noe evidens for endringer i hysebestanden og minkende abundans av arktiske hoppekreps. Det at uerbestanden er delvis utbredt i Norskehavet bidrar til noe usikkerhet i vurderingen. Enkelte viktige grupper (reke og snøkrabbe) er ikke inkludert i vurderingen, noe som også er en kilde til usikkerhet.

Landskapsøkologiske mønstre	🟧	Økosystemegenskapen ble vurdert til å vise **evidens for betydelig påvirkning** fra menneskeskapte drivere. Dette er basert på kun 1 indikator med godt forståtte forbindelser til driveren (klimaendringer) og godt forståtte konsekvenser for økosystemet. Det er sterk evidens for reduksjon av områder med kaldt vann over sjøbunnen. Vurderingen er usikker fordi den kun er basert på én indikator, og noen viktige indikatorer mangler, som område dekket av bunntråling og viktige gyte- og oppvekstområder.
Biologisk mangfold	🟩	Økosystemegenskapen ble vurdert til å vise **ingen evidens for påvirkning** fra menneskeskapte drivere. Dette er basert på 4 indikatorer, de fleste med godt forståtte forbindelser til påvirkningsfaktorer (fiskerier, overhøsting og klimaendringer) og konsekvenser for økosystemet. Det er evidens for tap av biologisk mangfold for disse indikatorene, som i hovedsak er relatert til fiskerier. Begrensninger i lengden av tidsserier i gruppene som er inkludert, og utregningene for noen indikatorer, fører til store usikkerheter i denne vurderingen. Det er også verd å merke seg at denne økosystemegenskapen er vurdert ved å bruke arter eller grupper av arter en vet er sensitive for visse påvirkningsfaktorer og at det dermed er en mulighet for at man kan ha gått glipp av mindre forutsigbare påvirkninger på andre deler av økosystemet.
Abiotiske forhold	🟧	Økosystemegenskapen er vurdert til å vise **evidens for betydelig påvirkning** fra menneskeskapte drivere. Vurderingen er basert på 5 indikatorer med godt forståtte forbindelser til påvirkningsfaktoren (klimaendringer) og godt forståtte konsekvenser for økosystemet. Det er sterk evidens for økning i temperatur og område dekket av atlantisk vann. Den viktigste usikkerheten kommer fra den relative vekten gitt til de ulike indikatorene.

Endringer i fremtiden for økosystemet

Fortsatt oppvarming av Barentshavet og fortsatt tap av sjøis er forventet i både nær (2050) og fjern (2100) fremtid med mindre det gjøres omfattende kutt i utslipp av drivhusgasser, der store endringer i klima er forventet dersom utslippene forblir høye. Store økologiske endringer er forventet fra dette, inkludert ekspansjon mot nord av arter i begge økosystemene som blant annet kan resultere i endringer i dyreplanktonsamfunnet som igjen kan sette i gang kaskadeeffekter i andre deler av økosystemene. I den arktiske delen er økt primærproduksjon, et sterkere koblet næringsnett og nedgang for is-avhengige og arktiske arter som polartorsk andre klare forventede konsekvenser av oppvarming. I den subarktiske delen er nordlige utskifting av arter både inn og ut av området forventet frem mot 2050. Dette vil sannsynligvis endre trofiske forbindelser og funksjonell diversitet. Variablitet i abiotiske forhold er også forventet å øke, med økt hyppighet og lengre varighet av ekstreme klimatiske hendelser som varmebølger. Disse fører sannsynligvis til økt usikkerhet om de fremtidige forholdene i økosystemet.

Anbefalinger for forskning og overvåkning

Denne vurderingen avhenger helt av de langvarige overvåkingsprogrammene som er uunnværlige og krever kontinuerlig finansiering. Noen mindre justeringer i det nåværende overvåkingsprogrammet er foreslått. Dette dreier seg hovedsakelig om taksonomisk identifisering av lavere trofiske nivå. Noen viktige kunnskapshull som bør adresseres er spesifikke studier og regulær overvåking av den mikrobielle syklusen, is-tilknyttet flora og fauna og noen av prosessene på høyere trofiske nivå (sirkulering av næringssalter ved hjelp av pattedyr, aggregering av byttedyr). Det er også behov for mer forskning på de samlede effektene av flere drivere og på uventede hendelser, som for eksempel varmebølger.

[1] Jepsen, J. U., Arneberg, P., Ims, R. A., Siwertsson, A., and Yoccoz, N. G. 2020. Panel-based Assessment of Ecosystem Condition (PAEC). Technical protocol version 2. NINA Report 1890.

[2] For consistency with the PAEC protocol, it is generally referred to “deviation from the reference condition” rather than “deviation from good ecological condition” in this report.

Content

Introduction

Based on a mandate from the Norwegian Ministry of Climate and Environment, the *System for Assessment of Ecological condition*[3] was developed with the aim 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). This system will be applied for each of the major terrestrial and marine ecosystems not covered by the EU Water Framework Directive in Norway. The results will be used to follow up the national action plan for biodiversity (Minstry of Climate and Environment, 2015) and holistic ecosystem-based ocean management plans (Ministry of Climate and Environment, 2020). For the latter, results from the assessments will have a central role in the description and evaluation of status of the marine environment, a key part of the scientific advisory work established for the management plans.

Two alternative assessment methods have been developed under the *System for Assessment of Ecological Condition* (Jepsen et al., 2020; Jakobsson et al., 2021). For all assessments of marine ecosystems, the method *Panel-based Ecosystem Assessment of Ecosystem Condition* (PAEC) is used.

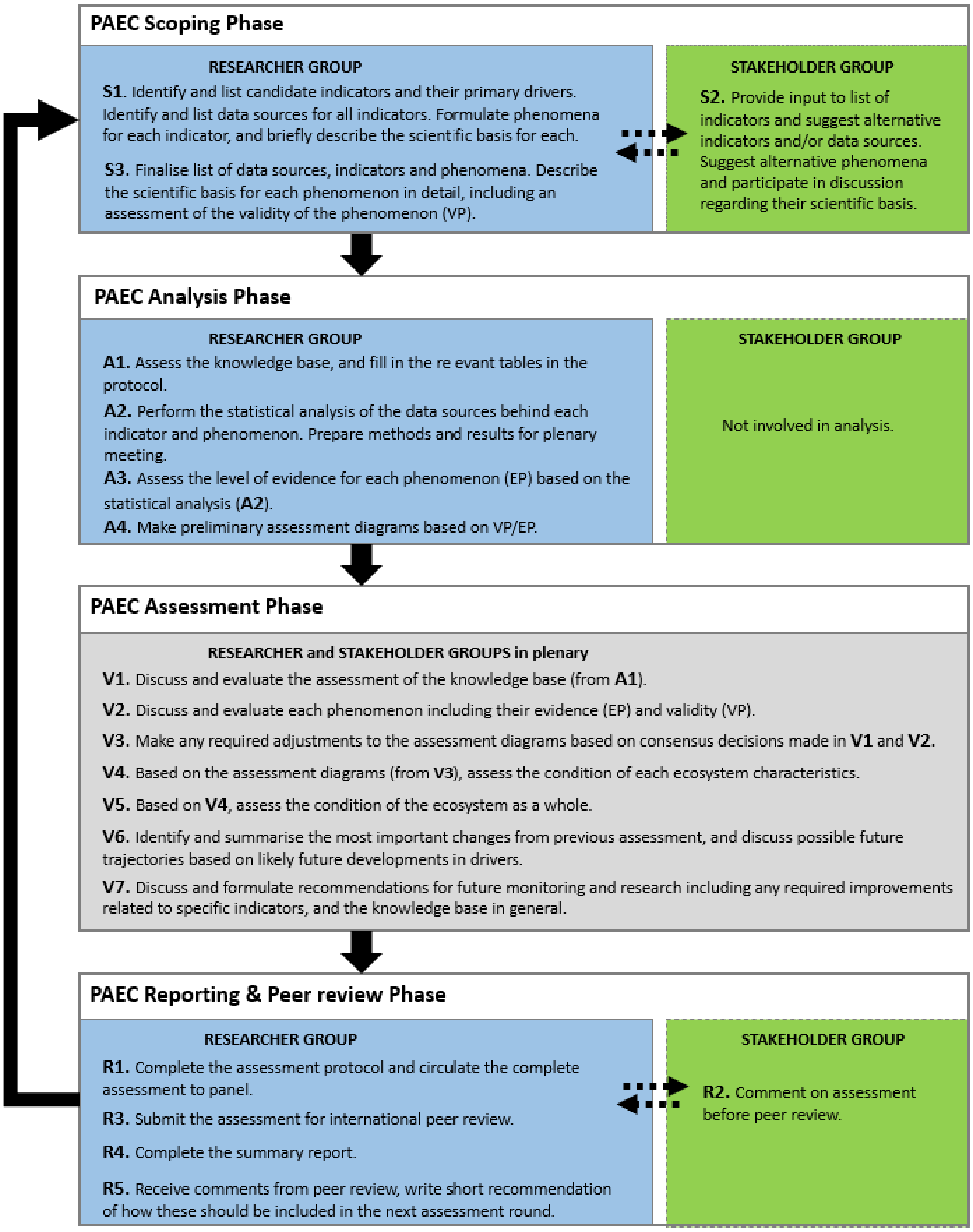
The background for developing PAEC is an increasing demand for integrated assessments of the condition of entire ecosystem units under intensified anthropogenic pressures. PAEC is inspired by approaches used in several national and international bodies, including the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES, 2020), *Intergovernmental Panel on Climate Change* (IPCC, 2020) and the *French national ecosystem assessment* (EFESE, 2020). These bodies share the common belief that the condition or state of complex systems (e.g., climate systems, ecosystems), and the level of evidence for change in the condition of such systems as a result of anthropogenic and natural drivers, is best assessed by broad scientific panels following stringent and structured protocols. PAEC is a structured protocol for a panel-based assessment of the condition of an ecosystem relative to a specific reference condition (Jepsen et al., 2020). A principal goal of PAEC is that it should provide a framework for making reproducible qualitative assessments based on quantitative analyses of the underlying data.

The overall question the current assessment aimed to answer was whether there has been a change away from the defined *reference condition* (“intact nature”, see chapter 2), which can be attributed to anthropogenic impacts. Anthropogenic impact on climate is commonly measured relative to the 1850-1900 period (IPCC AR6), while over-harvesting of marine mammal stocks started even earlier. Observational time series covering these time periods do not exist in the marine realm and, as a consequence, the current assessment did not include quantitative estimates of indicators for periods when the ecosystem was not significantly impacted by humans (reference values). In other assessment frameworks, lack of data for the reference condition has been dealt with by assigning values for the reference condition using expert judgement, observations from least impacted sites or modelling (e.g. (Pedersen et al., 2016; Direktoratsguppen vanndirektivet, 2018; Pedersen et al., 2018). Values for the current state is then compared with these estimates, setting a threshold value for substantial deviation from the reference condition as for example 60% of the reference values (Nybø and Evju, 2017; Nybø et al., 2019; Jakobsson et al., 2021). There are several major shortcomings with this approach, including high uncertainty in expert-based reference values (Morgan, 2014; Pedersen et al., 2018) and low robustness of the threshold values set for deviation from the reference condition (Mupepele et al., 2016; Jepsen et al., 2019). PAEC has therefore been developed as an alternative to the requirement of reference and threshold values, instead focusing on the direction and rate of change (trajectories). The use of expert-based reference and threshold values is replaced by first describing how we expect an indicator to develop as a result of anthropogenic drivers acting on the ecosystem and then use time series data to assess whether this development has indeed taken place. This involves qualitatively describing each indicator under the reference condition (to help describing how we expect indicators to change from anthropogenic impact), but only to the extent that information from published literature allows.

Structurally, PAEC is conducted in a hierarchical manner and consists of four phases: 1) *Scoping*, 2) *Analysis*, 3) *Assessment,* and 4) *Reporting and peer review* (Fig. 1). Key to the *Scoping Phase*, is the selection of relevant indicators within a set of *ecosystem characteristics* covering structural and functional components (biotic and abiotic) of the ecosystem as well as the formulation of specific formalised expectations (termed *Phenomena*) describing expected directional changes in a given indicator or state variable as a result of relevant drivers acting on the system. Phenomena are thus the equivalent of a scientific hypothesis formulated prior to a scientific study. The *Analysis Phase* consists of a statistical analysis of the underlying data to permit an assessment of the level of evidence for each phenomenon. This is based on evaluating whether rates of change seen in indicator time-series can, as described above, be attributed to anthropogenic impact as described in the phenomena. The *Assessment Phase* consists of a plenary session where the assessment panel scrutinises and assesses the knowledge base underlying the assessment, assesses the condition of each ecosystem characteristic, and finally assesses the condition of the entire ecosystem. An independent *Peer review* of the final assessment report will be undertaken, with the aim of continuous improvements, and is seen to be a fundamental step in PAEC. An assessment according to PAEC is primarily a scientific exercise, and the scientific assessment panel should consist of a group of scientists with in-depth knowledge of the focal ecosystem characteristics, as well as relevant quantitative methodologies (study design and statistical modelling). However, PAEC is also envisioned to be a tool for adaptive management of ecosystems, or specific ecosystem components. For this purpose, stakeholder groups may be involved in parts of the work (Fig. 1). For the assessments of marine ecosystems, the Advisory Group on Monitoring ("Overvåkingsgruppen" in Norwegian), which is established to support the ocean management plans (Ministry of Climate and Environment, 2005), has been informed about the work regularly (4 times yearly), throughout all phases of the work, with possibilities to provide feedbacks.

This report is the first operational application of the Panel-based Assessment of Ecosystem Condition (PAEC, Jepsen et al. (2020)) to marine ecosystems. Consequently, conceptual struggles and sources of uncertainties related to the method were noted by the expert panel along the process, of which we describe below the three most important ones (more details in 7.3.2). The first one concerns the lack of knowledge about the reference condition for most indicators. Even with qualitative descriptions, there were sometimes uncertainties if the observed trend was in the direction of *towards* or *away* from what would be considered a reference condition. The second source of uncertainty is the sensitivity of trend analyses to differences in time series lengths, and that the method combines indictors covering different time periods. Related to this is the focus only on long-term trends, without looking into variation within the time-series. The third point is related to the weighting of phenomena in the assessment of ecosystem characteristics, which would be less prone to subjectivity if discussed before the actual results were presented.

As the reference condition used here is a state which is little impacted by modern industrial activities ("intact nature", see chapter 2), deviation from the reference condition is the result of anthropogenic impact. In other words, what is assessed is the extent of anthropogenic impact. As parts of this report (for example main conclusions in chapter 7.3) will be read by persons that are unfamiliar with details of the PAEC framework, deviations from the reference conditions have therefore in some places been described as results of anthropogenic impact, which are more easily understood.



PAEC Scoping Phase

RESEARCHER GROUP

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.

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).

STAKEHOLDER GROUP

S2. Provide input to list of indicators and suggest alternative indicators and/or data sources. Suggest alternative phenomena and participate in discussion regarding their scientific basis.

PAEC Analysis Phase

RESEARCHER GROUP

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.

STAKEHOLDER GROUP

Not involved in analysis.

PAEC Assessment Phase

RESEARCHER and STAKEHOLDER GROUPS in plenary

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

RESEARCHER GROUP

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

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.

STAKEHOLDER GROUP

R2. Comment on assessment before peer review.

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

3 1 In Nybø and Evju (2017) termed *“Technical system for determining good ecological condition”.*

Definition of terms

Table 1. Definition of key terms used in PAEC (Jepsen et al., 2020).

Term	Definition
Ecosystem characteristics	Characteristics of an ecosystem underlying how abiotic factors, ecosystem structure and functions interact. In the current assessment framework, seven characteristics are considered: primary productivity, biomass distribution among trophic levels, diversity of functional groups, functionally important species and biophysical structures, landscape ecological patterns, biological diversity, and abiotic factors.
State variable	Ecosystem feature describing an ecosystem characteristic. A state variable measures directly the functions and processes of its corresponding ecosystem characteristic(s). State variables can be used to build models for estimating causal relations between ecosystem characteristics and external drivers and to make quantitative predictions across space and time. One state variable can be associated with several ecosystem characteristics.
Ecosystem condition	The current state of the ecosystem across all ecosystem characteristics, summarizing the state variables, often in terms of their dynamical regime. We consider here the term ecosystem condition synonymous with ‘ecosystem state’. State is often used in the context of alternative states, when the ecosystem can shift between regimes that persist at a particular spatial extent and temporal scale, but state changes may also be gradual.
Reference condition	A reference condition describes the state of the ecosystem at a pre-defined time period (e.g., “a climatic reference period”), or according to specific criteria such as in the absence of local and global human influences (“a pristine state”), or the maintenance of important functional or structural components (e.g., population cycles, “a functional ecosystem”). The reference condition is characterized by the range of variation and covariation among state variables, due to ecosystem dynamics over a period that is long enough to obtain statistically reliable estimates, but with persistent (stable) environmental conditions.
Indicator	A preferably simple and easily interpreted surrogate for a state variable or a driver/pressure (the “canary in the mine”). Because indicators are required to have many properties (e.g., sensitive to changes, applicable over a large area, valid over a wide range of stress, cost-effective), a set of complementary indicators is often required. In this document, the term *indicator* denotes all metrics that are used to describe the focal ecosystem characteristics. Accordingly, it is important to note that indicators may range from *state variables* that directly denote ecological functions and structures, to *surrogate indices* that have more or less validated indirect relations to such functions and structures.
Ecosystem significance	A change in an indicator is of ecosystem significance if it implies ecologically large changes, either in the ecosystem characteristic the indicator is associated with, in other ecosystem characteristics, or generally in ecosystem condition. This is not related to statistical significance.
Phenomenon	An expected directional change in an indicator which is of ecosystem significance, and which can be attributed to one or more relevant drivers. Phenomena are thus the equivalent of scientific hypotheses formulated prior to a scientific study.
Quantitative phenomenon	A phenomenon is quantitative if one can identify and estimate a threshold value for the change in the indicator which, if exceeded, results in a change away from the reference condition which is of ecosystem significance.
Qualitative phenomenon	A phenomenon is qualitative if one cannot identify and estimate such a threshold value, but rather focuses on the type and direction of changes away from the reference condition linked to drivers that can lead to changes of ecosystem significance.
Validity of Phenomenon (VP)	Addresses the links between drivers and ecosystem significance by assessing 1) how well we understand the mechanisms by which drivers affect an indicator, and 2) how well we understand how the change in an indicator leads to changes that are of ecosystem significance.
Evidence for Phenomenon (EP)	Assessment of the quality of empirical evidence that 1) the expected change in an indicator has occurred (incl. statistical significance) and 2) the change is of ecosystem significance. The assessment hence considers both the relationship between state variables and indicators, and between indicators and ecosystem condition. The assessment relies upon the consistency in observed changes (over space and time), and the uncertainty of the estimated changes. In particular, a distinction is made between the absence of evidence for a phenomenon due to large uncertainties, and evidence that no change of ecosystem significance has occurred.
Design-based sampling and estimation	Given that one can define a target population with a list of units, design-based sampling uses either probability sampling where the probability that each unit is sampled is known *a priori* (e.g., stratified sampling with more variable strata being sampled more intensively) or some form of systematic sampling (e.g., grid). In the former case, one can use the design to estimate parameters of interest (e.g., averages) with known uncertainty without relying on statistical models.
Model-based sampling and estimation	Aims at maximizing the accuracy of estimates of relationships between predictors (e.g., drivers) and responses (e.g., ecosystem state variables). Designs combine two things: 1) precision of estimates by having large contrasts in predictor values, and 2) accuracy of the functional response by allowing for non-linear responses and by sampling intermediate values of predictors. Model-based estimation uses the model to extrapolate to non-sampled units and is sensitive to the model used, and therefore robustness needs to be evaluated.

1. Composition of the scientific panel

For the panel-based assessment of the Arctic and Sub-Arctic ecosystems of the Barents Sea, the panel was composed of 34 researchers with expertise in oceanography, ecology, fisheries, climate change, ocean acidification and monitoring. Below we list participants in the scientific panel, as well as their respective roles and expertise (Table 1.1).

Table 1.1. The composition of the scientific panel with definitions of roles and expertise. The list is sorted alphabetically on last name, except for panel leader, who is listed first and in bold font. TL: trophic level

Name, institution, email	Role	Expertise	Expert on single indicators
Per Arneberg, IMR [1], per.arneberg@hi.no	Project manager, leader of scientific panel, expert	Ecosystem overview/ understanding	
Karen Assmann, IMR [1] Karen.Assmann@hi.no	Expert, participant in scientific panel	Oceanography	*Bottom thermal niches, Sea-ice area, Temperature, Area of water masses, Freshwater content, Stratification*
Philipp Assmy, NPI [2], Philipp.Assmy@npolar.no	Expert, participant in scientific panel	Phytoplankton, primary production	*Annual primary productivity, Timing of spring bloom*
Magnus Aune, APN [3], magnus.aune@akvaplan.niva.no	Expert, participant in scientific panel	Fish	*Fish habitat use, and other fish community indicators*
Bjarte Bogstad, IMR [1], Bjarte.bogstad@hi.no	Expert, participant in scientific panel	Fish, food web ecology	*Cod, Cod distribution, Cod size structure, Haddock*
Knut Yngve Børsheim, IMR [1], yngve.borsheim@hi.no	Expert, participant in scientific panel	Primary production	*Annual primary productivity, Timing of spring bloom*
Melissa Chierici, IMR [1], melissa.chierici@hi.no	Expert, participant in scientific panel	Ocean acidification	*pH, Aragonite saturation*
Sabine Cochrane, APN [3], Sabine.Cochrane@akvaplan.niva.no	Expert, participant in scientific panel	Infauna benthos	*Benthic suspensivores, Benthic habitat engineers, Cold-water benthos, Benthos sensitive to bottom trawling*
Malin Daase, UiT [4], malin.daase@uit.no	Expert, participant in scientific panel	Zooplankton, copepods, food web ecology	*Zooplankton TL < 2.5, Zooplankton TL > 2.5, High TL zooplankton functional groups, Arctic Calanus, Atlantic Calanus, Pelagic amphipods, Krill, Arctic amphipod*
Padmini Dalpadado, IMR [1], padmini.dalpadado@hi.no	Expert, participant in scientific panel	Zooplankton, krill, amphipods	*Zooplankton TL < 2.5, Zooplankton TL > 2.5, High TL zooplankton functional groups, Arctic Calanus, Atlantic Calanus, Pelagic amphipods, Krill, Arctic amphipod*
Per Fauchald, NINA [5], per.fauchald@nina.no	Expert, participant in scientific panel	Seabirds, Ecosystem overview/understanding	*Low trophic level seabirds, high trophic level seabirds, Seabird feeding types, Seabirds sensitive to pollution, Arctic seabirds*
André Frainer, NINA [5], Andre.Frainer@nina.no	Expert, participant in scientific panel	Fish, functional trait analyses, food web ecology	*Arctic fish, and other fish community indicators*

Name, institution, email	Role	Expertise	Expert on single indicators
Agneta Fransson, NPI [2], Agneta.Fransson@npolar.no	Expert, participant in scientific panel	Ocean acidification	*pH, Aragonite saturation*
Sebastian Gerland, NPI [2], sebastian.gerland@npolar.no	Expert, participant in scientific panel	Sea ice	*Sea-ice area*
Hannes Höffle, IMR [1] hannes.hoffle@hi.no	Expert, participant in scientific panel	Redfish	*Redfish*
Haakon Hop, NPI [2], haakon.hop@npolar.no	Expert, participant in scientific panel	Zooplankton, food web ecology	*Zooplankton TL < 2.5, Zooplankton TL > 2.5, High TL zooplankton functional groups, Arctic Calanus, Atlantic Calanus, Pelagic amphipods, Krill, Arctic amphipod*
Bérengère Husson, IMR [1], Berengere.Husson@hi.no	Expert, participant in scientific panel, data management	Ecosystem data and models	
Randi B. Ingvaldsen, IMR [1], randi.ingvaldsen@hi.no	Expert, participant in scientific panel	Oceanography	*Bottom thermal niches, Sea-ice area, Temperature, Area of water masses, Freshwater content, Stratification*
Sissel Jentoft, UiO [6], sissel.jentoft@ibv.uio.no	Expert, participant in scientific panel	Fish, genetics	*Fish community indicators*
Lis L. Jørgensen, IMR [1], lis.lindal.joergensen@hi.no	Expert, participant in scientific panel	Megabenthos	*Benthic suspensivores, Benthic habitat engineers, Cold-water benthos, Benthos sensitive to bottom trawling*
Kit M. Kovacs, NPI [2], Kit.kovacs@npolar.no	Expert, participant in scientific panel	Marine mammals	*Arctic marine mammals' indicators: Low trophic level mammals, Generalist mammals, High trophic level mammals, Mammal bioturbation, Mammals sensitive to pollution, Arctic mammals*
Deanna Marie Leonard, IMR [1] deanna.leonard@hi.no	Expert, participant in scientific panel	Marine mammals	*Sub-Arctic marine mammals' indicators: Low trophic level mammals, Generalist mammals, High trophic level mammals, Mammal top-down control, Mammals sensitive to pollution, Mammal diversity*
Sigrid Lind, NPI [2], Sigrid.Lind@npolar.no	Expert, participant in scientific panel	Oceanography	*Bottom thermal niches, Sea-ice area, Temperature, Area of water masses, Freshwater content, Stratification*
Christian Lydersen, NPI [2], christian.lydersen@npolar.no	Expert, participant in scientific panel	Marine mammals	*Arctic marine mammals' indicators: Low trophic level mammals, Generalist mammals, High trophic level mammals, Mammal bioturbation, Mammals sensitive to pollution, Arctic mammals*
Olga Pavlova, NPI [2], olga.pavlova@npolar.no	Expert, participant in scientific panel	Sea ice	*Sea-ice area*
Laurene Pecuchet, UiT [4], laurene.pecuchet@uit.no	Expert, participant in scientific panel	Fish, fish life history, food web ecology	*Fish size, Fish life history, Fish sensitive to fisheries, and other fish community indicators*
Raul Primicerio, UiT [4], IMR [1], raul.primicerio@uit.no	Expert, participant in scientific panel	Fish, food web ecology	*Fish community indicators*

Name, institution, email	**Role**	**Expertise**	**Expert on single indicators**
Paul E. Renaud, APN [3], paul.renaud@akvaplan.niva.no	Expert, participant in scientific panel	Benthos	*Benthic suspensivores, Benthic habitat engineers, Cold-water benthos, Benthos sensitive to bottom trawling*
Anna Siwertsson, IMR [1], anna.siwertsson@hi.no	Expert, participant in scientific panel, data management	Ecosystem data and analysis, biodiversity	
Hiroko Solvang, IMR [1], hiroko.solvang@hi.no	Expert, participant in scientific panel	Statistical analyses	
Georg Skaret, IMR [1], georg.skaret@hi.no	Expert, participant in scientific panel	Pelagic fish	*Capelin, Polar cod, Pelagic planktivorous fish*
Gro I. van der Meeren, IMR [1], groM@hi.no	Expert, participant in scientific panel	OSPAR indicators	
Paul Wassmann, UiT [4], paul.wassmann@uit.no	Expert, participant in scientific panel	Phytoplankton, Primary production	*Annual primary productivity, Timing of spring bloom*
Nils Øien, IMR [1], nils.oien@hi.no	Expert, participant in scientific panel	Marine mammals	*Sub-Arctic marine mammal indicators: Low trophic level mammals, Generalist mammals, High trophic level mammals, Mammal top-down control, Mammals sensitive to pollution, Mammal diversity*

[1] IMR – Institute for Marine Research, [2] NPI - The Norwegian Polar Institute, [3] APN – Akvaplan-niva, [4] UiT — The Arctic University of Norway, [5] NINA — Norwegian Institute of Nature Research, [6] UiO- University of Oslo

2. Definition of the reference condition

The reference condition is here defined as “intact ecosystems” (Nybø and Evju, 2017), and the assessment should consider the extent to which the current condition of the ecosystem deviates from this reference condition. The term “good ecological condition” is used herein to characterise a condition in which the structure, functions and productivity of an ecosystem do not deviate substantially from the reference condition.

Below, the complete definitions from the framework described in the *System for Assessment of Ecological Condition* (Nybø and Evju, 2017) of what constitutes “intact ecosystems” are given first. This includes the climatic reference on which the assessment should be based (Box 1). We further reiterate their normative description of the condition of each ecosystem characteristic under the reference condition (Box 2) before going on to describe how these definitions have been incorporated into the current assessment.

Box 1. Definitions from (Nybø and Evju, 2017). Translation from Norwegian from (Pedersen et al., 2021). Note that the choice of time period as descriptive for the reference period for climate is discussed in the main text below.

Intact ecosystems

Intact, natural, and semi-natural, ecosystems are characterised by the maintenance of fundamental structures, functions and productivity. Intact ecosystems are further characterised by having complete food webs, and element cycles. The majority of the food web consists of native species which dominate at all trophic levels and in all functional groups. The species composition, population structure and genetic diversity of native species is a result of natural processes occurring through the ecological and evolutionary history of the ecosystem. Intact ecosystems possess characteristics which are not changing systematically over time but vary within the boundaries of the natural dynamics of the system. Human influences can be present, but should not be pervasive or dominating, or be a factor which changes the structure, function or productivity of the ecosystem. This means that human influences should not be at a scale which exceeds the impacts of natural pressures (e.g. disturbance) or dominating species (e.g. top predators) in the ecosystem. Further, human influences should not lead to changes which are more rapid or more pervasive than natural pressures in the ecosystem. In semi-natural ecosystems, the human activities which define the system (e.g. grazing, hay cutting) are considered an integral part of the ecosystem.

Reference climate

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

Box 2 The normative description from Nybø and Evju (2017) of “good ecological condition” for each of the seven ecosystem characteristics, i.e., when there are no substantial deviations from the reference condition (Translation from Norwegian from (Pedersen et al., 2021).)

Primary productivity:
The primary productivity does not deviate substantially from the productivity in an intact ecosystem. Reason: Elevated or decreased primary productivity indicates a system impacted for instance by eutrophication, overgrazing or drought.
Biomass distribution among trophic levels:
The distribution of biomass among trophic levels does not deviate substantially from the distribution in an intact ecosystem. Reason: Substantial shifts in biomass distribution between trophic levels indicate a system impacted for instance by removal of top predators.
Functional groups within trophic levels:
The functional composition within trophic levels does not deviate substantially from the composition in an intact ecosystem. Reason: Substantial changes in the functional composition within trophic levels indicate a system impacted for instance by to loss of functional groups (e.g., pollinators), loss of open habitat species due to encroachment, or super-dominance of certain functional groups or species (e.g., jellyfish in marine habitats).
Functionally important species and biophysical structures:
The functions of functionally important species, habitat building species and biophysical structures do not deviate substantially from the functions in an intact ecosystem. Reason: Functionally important species (e.g., small rodents), habitat building species (e.g., coral reefs, kelp forest), and biophysical structures (e.g., dead wood) have vital importance for the population size of a number of species, and changes in their occurrence will hence have functional implications for the ecosystem.
Landscape-ecological patterns:
Landscape-ecological patterns are compatible with the persistence of species over time, and do not deviate substantially from an intact ecosystem. Reason: Human influences can lead to changes in landscape-ecological patterns which have implications for the population size and population structure of native species, for instance through habitat fragmentation. Fragmented habitats may not be sufficiently large or connected to permit long-term survival of native species. Climate change, altered area use, pollution and invasive or introduced species may also influence landscape-ecological patterns with implications for population size and composition of native species.
Biological diversity:
The genetic diversity, species composition and species turnover do not deviate substantially from an intact ecosystem. Reason: Loss of biological diversity can cause the ecosystem to be less resilient towards pressures and disturbances, and influence the structure, functions and productivity of the ecosystem. Changes in rates of species turnover, due to extinction or colonisation can indicate a modified system.
Abiotic factors:
Abiotic condition (physical and chemical) does not deviate substantially from an intact ecosystem. Reason: Human influences (e.g., environmental toxins, fertilization, changed hydrology or acidification) can lead to substantial changes in the physical/chemical structure and function of the ecosystem, which in turn will impact the species composition, function and dynamics of the ecosystem.

The main implications of the definitions provided above (Box 1 and 2) for the assessment of the Arctic and Sub-Arctic shelf ecosystems in the Barents Sea are as follows:

- The current assessment focuses on the extent to which an ecosystem deviates from the reference condition (i.e., whether there is deviation from a situation with little or no influence from anthropogenic pressures).
- When operationalising this, an obvious question is how human pressures have historically changed the Barents Sea ecosystem. Industrial over-harvesting of marine mammals, commencing in the late 16th century and continuing up until the 20th century, has led to large changes in the structure of the marine mammal community that persist today. Considerable impact from industrial fisheries date back to the 1930s. Because the onset of significant human impacts differs between components of the ecosystem, a single period has not been defined as an ecological reference period. Rather, different periods or conceptual descriptions have been considered representative for the reference condition for different components of the ecosystem.
- For climate indicators, this has been pre-set to 1961-1990 for all assessments of ecological condition in Norway (Box 1). Note that this period is already part of the strong increase in global temperatures after 1950 (IPCC AR6) and therefore is not pre-industrial, i.e., it is already and increasingly impacted anthropogenically (IPCC, 2021). IPCC AR6 uses 1850-1900 as their reference period as a compromise between a climate state that can still be considered pre-industrial, but that has a reasonable coverage of reliable climate records. 1961-1990 represents the earliest period with reasonable geographical coverage in the Barents Sea with regular hydrographic surveys commencing in 1970.
- Monitoring of biological components of ecosystems generally started after the onset of anthropogenic impact, meaning that we have little data for periods with low human impact (Arneberg et al., 2018; Jepsen et al., 2019). Therefore, the reference condition is generally described, if possible, qualitatively for each indicator,

and the assessment is based on the *phenomena*. In short and as described in the introduction, this is done by describing the direction we expect an indicator to change away from the (qualitatively described) reference condition as a result of increasing pressure from the most important anthropogenic drivers (i.e. describe a phenomenon), and then assessing whether this development has indeed occurred using analyses of time series data (i.e. assess the evidence that a phenomenon has occurred, see the protocol Jepsen et al. (2020) for details). In some instances where there were large uncertainties in the direction of expected change, the phenomena have been defined as “Change in …”. Descriptions of the reference condition for each indicator are found in the phenomena descriptions (chapter 5).

- For some of the over-harvested marine mammals, estimates of pre-harvesting population levels are available, and these are included when describing the reference condition for these species. It should be noted that protection of over-harvested marine mammal species has initiated recoveries, and that the course of these can have significant impacts on the overall condition of the ecosystem, meaning that the pre-harvesting population estimates are relevant to consider in the assessment.
- For several of the abiotic factor indicators, which include the climate, monitoring was initiated in the predefined climate reference period (1961-1990). Thus, where data is available, climate indicators are analysed relative to values and variability from the predefined reference period. Phenomena are used to assess deviation from the reference condition also for these indicators, in the manner described above. Additionally, an additional assessment of abiotic factors over a shorter time period were done to match with the assessments period of most of the biotic phenomena.
- Evidence for deviation from the reference condition is classified into one of four categories: (1) no evidence for deviation, (2) evidence for limited deviation, (3) evidence for substantial deviation, or (4) insufficient data to assess deviation from the reference condition.

PAEC requires that the assessment of temporal representativity (Ch. 7.1, Table 7.1a and b) includes an evaluation of the extent to which data underlying the indicators are overlapping with any” temporally defined reference period” used. Following the arguments above about different time periods being representative for the reference condition for different components of the ecosystem, this period has been set differently across indicators. For example, for indicators that are expected to be primarily affected by climate change, temporal representativity has been assessed relative to the climate reference period, while for cod stock biomass, where massive impacts from fisheries commenced in the 1930s, temporal representativity is assessed for the period preceding this.

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

3.1 Delineation of the ecosystem

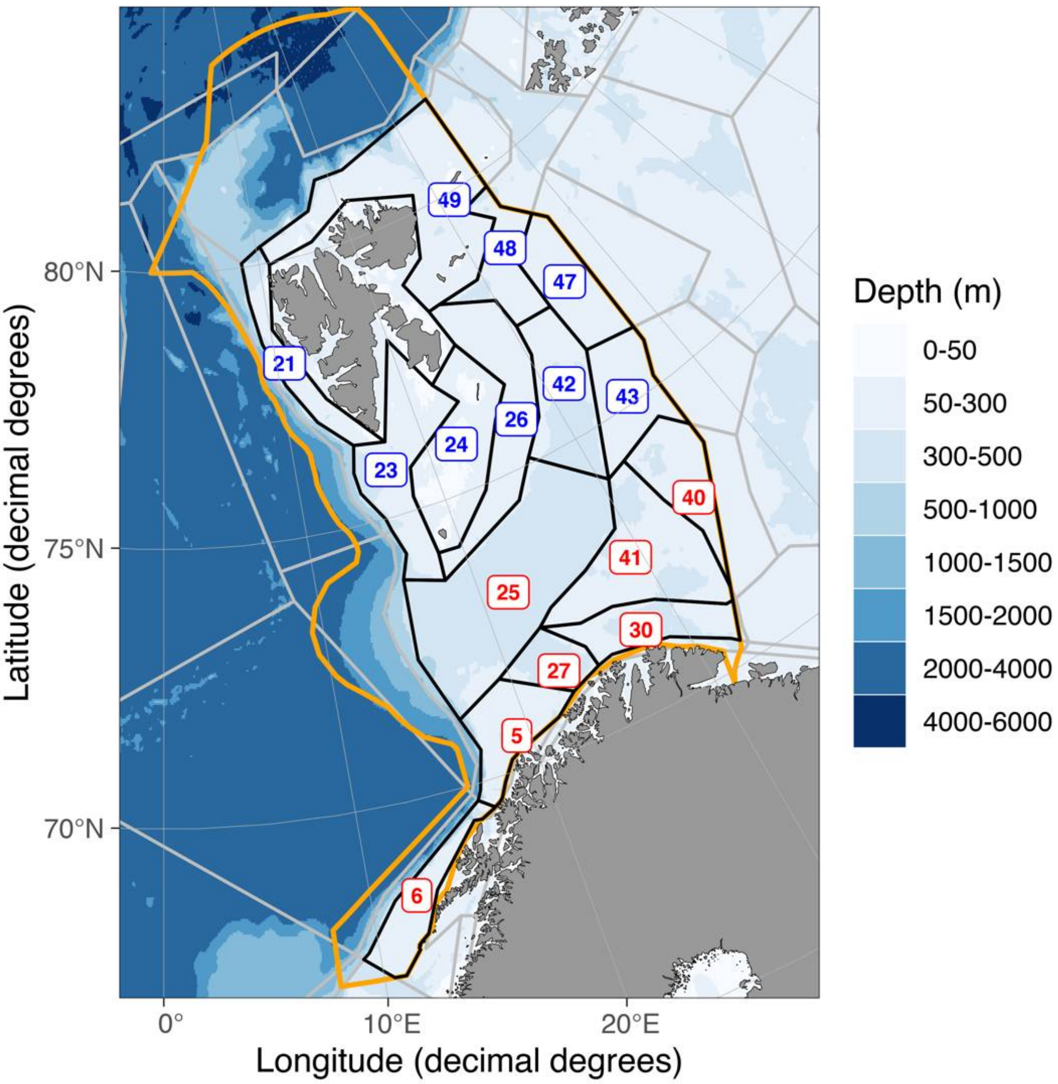


Figure 3.1: Map of the spatial extent of the panel-based assessment of ecosystem condition of the Arctic and Sub-Arctic Barents Sea. Black lines delimit the Atlantis polygons (Hansen et al., 2016). The Arctic part is defined by the blue polygons. The Sub-Arctic part is defined by the red polygons.

The assessment of the Arctic and Sub-Arctic ecosystems of the Barents Sea are limited to the Norwegian Management Plan area and to the shelf areas, thus excluding the continental slope, which is characterised by different species and ecological processes than the shelf and therefore considered a different ecosystem type in this work (Nybø and Evju, 2017). The two shelf ecosystems (Arctic in the north, sub-Arctic in the south) are separated according to how the dominant water masses were distributed during the early observational period

1970-1990 (Fig. 3.1). The delineation follows the assumed position of the Polar Front in this period, which runs north of the Bear Island Trough. An important difference between the two ecosystems is the presence of seasonal ice cover in the Arctic system under the reference condition, which has massive implications for structure and processes in the ecosystem (Jakobsen and Ozhigin, 2011). Each of the two ecosystems is further subdivided into polygons of relatively homogenous bathymetry, bottom conditions and hydrology (Hansen et al., 2016) in order to be able to identify spatial variations in indicators and ecosystem status. For most of the indicators, values have been calculated at the polygon scale (Fig. 3.1), while the assessment has been carried out on the scale of the two ecosystem areas.

3.2 General considerations regarding data source

The Barents Sea is a data rich system. In this assessment, most datasets are sourced from extensive monitoring programs. In particular, the joint Norwegian-Russian (Norwegian Institute of Marine Research (IMR) and the Knipovichs' Polar Research Institute of Marine Fisheries and Oceanography (PINRO, since 2019 - Polar Branch of Russian Federal Research Institute of Fisheries and Oceanography) ecosystem survey of the Barents Sea (Eriksen et al. (2018), hereafter termed BESS) provided abundance indices and data on species recruitment and diet for most ecosystem compartments used in the report. This survey is a long-term collaboration between the two institutions that commenced in the 1960s. The original objectives of the surveys were to monitor important commercial fish and shellfish stocks to support their management. The different surveys have included more species and environmental variables since the 1980s. Since 2004, it has been a multi-ship, multi-purpose survey operating over a large sampling grid with a 35x35 nm grid in most areas and nearly 400 stations. A demersal (Campelen 1800) and a pelagic ("Harstad") trawl haul are done at each ecosystem station, as well as at least one phyto- and zooplankton net set (WP2). Additionally, Conductivity-temperature-density (CTD) probes for physical characterisation of the water column are conducted at each station. Between stations, underway measurements like e.g., echo sounders are operated, trawling is conducted on high registrations and seabirds and marine mammals are observed. Thus e.g., data on acoustic estimates of capelin and polar cod abundance as well as sea bird and marine mammal abundance are not related only to ecosystem station positions.

The BESS has been conducted each year since 2004 in August-September, when the sea ice is at its lowest extent in the Barents Sea, thus allowing for sampling of the maximum number of stations. Although survey data are sampled for the whole Barents Sea, for this assessment, only the Norwegian part of the survey (around 180 stations) is used. Technical issues, weather conditions or sea-ice extent can prevent the ships from visiting some stations, resulting in an average of 121 stations visited yearly between 2004 and 2020. Variability in the position and number of stations visited in the Arctic part of the ecosystem (Fig. 3.1) is greater than in the Sub-Arctic part, resulting in the Arctic time series being generally of poorer quality than the Sub-Arctic ones. For both ecosystems, the short time series of this survey prevent most of the chosen indicators from overlapping with periods that can be characterised as descriptive for the reference condition (see chapter 2), and from robustly applying time series analyses, but the data does include enough years to observe change in the indicators.
In addition to data from BESS and the precursor surveys, the assessment used data on sea-ice extent and primary production, estimated based on satellite remote sensing. Net primary production is estimated from satellite data on chlorophyll *a* concentration (Behrenfeld and Falkowski, 1997) and sea-ice coverage from satellite data on sea-ice extent and concentration (Fetterer et al., 2017). Long-term monitoring of the Fugløya/Bjørnøya transect provided taxonomically resolved estimates of zooplankton inflows into the Barents Sea. ICES stock assessments of the main commercial species, which are based on BESS and other cruises, were used to evaluate the status of functionally important species. Data from SEAPOP on counts from seabird

colonies were included. Finally, Arctic marine mammals' populations statuses are provided by official assessments, based on dedicated monitoring of these species. Some of these data are publicly available on the website of the system *Monitoring of Svalbard and Jan Mayen* (https://www.mosj.no/no/fauna/hav/) and all are published in the scientific literature (see references in relevant sections of this report).

Indicator time series across ecosystem characteristics are covering various time ranges. We believe this adds substantial uncertainty in our assessment for both ecosystems' conditions. First, many of the time series might be too short to capture relevant trends. Second, various lengths of indicator time series make them harder to relate to each other, which hampers the integrative assessment of certain ecosystem characteristics. To partially address this issue, when considering climate forcings in the Barents Sea, we assessed a supplementary set of abiotic factors, at the time scale of other biological indicators. Abiotic factors, including climate, are key parts of ecosystems, and in the current assessment represented by a separate ecosystem characteristic (chapter 2). In the Barents Sea, a major part of the anthropogenic impact is caused by human alterations of the climate. Thus, change in climate is causing change in the biological parts of the ecosystem (see description of phenomena in chapter 5). While change in climate is assessed using long time series (starting in 1970), biological change is assessed with shorter time series (most starting in 2004). To be able to evaluate whether change in the biological parts of the Barents Sea can be attributed to climate change, a separate assessment of climate for the period starting in 2004 is done to be used as supporting information for biological indicators. This separate climate assessment is presented in Appendix 8.6.

3.3 Choice and utility of indicators

To assess the status of the ecosystem through its seven ecosystem characteristics, we have grounded our choice of indicators in the panel's knowledge on each ecosystem's key components and functions. Researchers, grouped by area of expertise (often in link with ecosystem main functional groups), have based their selection of indicators on a compromise between parsimony in the number of indicators and their relevance and importance in the ecosystem. This was evaluated with regard to the ecosystem characteristics, their sensitivity to human pressures, and the existing knowledge about their linkage to the ecosystem structure and function. Some selected indicators described different properties of the ecosystem but were strongly correlated as they might respond to the same drivers (e.g., fish size and fish life history). This was accounted for during the discussion when assessing the ecosystem characteristics' condition.

We also attempted to identify important parameters of the ecosystem that are currently missing from the monitoring programs. Thus, issues of data availability, responsiveness to anthropogenic pressure (with the exception of biological diversity indicators) were not considered in the first part of the scoping exercise. A list of additional indicators to consider are presented in Table 4.2 and Appendix 8.4. Phenomena have been developed for some of these indicators (Table 4.2, Appendix 8.4). The indicators that were finally used were those for which direct measurements or proper proxies were available. A few of the indicators for which data are available were not included because phenomena were not developed due to capacity constraints or unforeseen difficulties linked to the choice of indicators and data to use. These are listed in Table 4.2 and time series with analyses are given in Appendix 8.5.

Three of the seven ecosystem characteristics– *Biomass distribution among trophic levels*, *Functional groups within trophic levels* and *Biological diversity* - are more complex than the other characteristics and require integrating data over ecosystem compartments. This is challenging in the marine environment as the different components of the ecosystem are observed and sampled following different strategies and methods. Therefore, resulting biomass estimates are not comparable. For *Biomass distribution among trophic levels*, we thus decided to select indicators to describe biomass distribution of different trophic level *within* each ecosystem component (phytoplankton, zooplankton, benthos, fish, seabirds, and marine mammals). The assessment of if and how the biomass distribution has changed among trophic levels was done by integrating all this information when doing the ecosystem characteristic assessment. Future reiterations of the assessment, however, should try to find a way to combine different indicators to describe the overall variation in biomass across trophic levels. For *Functional groups within trophic levels*, groups of experts have prioritised important functions that were performed by each ecosystem component. Finally, for *Biological diversity*, classical biodiversity indices were difficult to link to anthropogenic drivers. Instead, we focused on species which may be at risk of population declines and possibly extinction due to human activities, and the selected indicators represented species or groups of species that are known to be sensitive to certain anthropogenic pressures. They are used as indicator species that allows us to track the impact of specific pressures. This approach allows us to detect possible declines in some typically Arctic and other threatened species. It should be noted that the literature reports increasing species richness and functional diversity in the Arctic associated with poleward shifts of many southern species, meaning that standard biodiversity indices may not be informative for changes in biodiversity caused by climate change (Fossheim et al., 2015; Frainer et al., 2021).

Table 3.1 Description of data sources for assessment of ecological condition in Arctic and Sub-Arctic Barents Sea. 1 IMR – Institute for Marine Research.

Dataset name	**ID**	**Dataset DOI/URL/storage**	**Owner institution**	**Contact person for data**	**Content and methods**	**Temporal coverage**
Temperatures and salinities	D01	Norsk Marint Datasenter (NMD)	IMR [1]		CTD profiles from BESS and precursor surveys. For temperature, stratification, freshwater content and water masses area. See Appendix 8.1 for details.	1970-2019
Sea-ice area	D02	https://nsidc.org/data/nsidc-0051	National Snow & Ice Data Centre (NSIDC)		Monthly averages of sea-ice concentration from satellite sensors with 25x25 km resolution. The product is designed to provide a consistent time series from a set of passive microwave instruments: the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), the Defense Meteorological Satellite Program (DMSP) -F8, -F11 and -F13 Special Sensor Microwave/Imagers (SSM/I), and the DMSP-F17 Special Sensor Microwave Imager/Sounder (SSMIS). For more details see (Cavalieri et al., 1996, updated yearly) and Appendix 8.1.	1979 - 2020
Aragonite saturation and pH	D03	https://DOI:10.21335/NMDC-1738969988	Norwegian Environmental Agency	Melissa Chierici, IMR [1]	Mean values for Arctic water mass (T<0 °C) were calculated in the area between 77-80 °N, 20°E to 34°E and mean values for Sub-Arctic water mass (T>3 °C, S>34.98) in the area between 72.5 to 73.5 °N, 20°E to 34°E. Mean values were calculated from observations of total alkalinity and total dissolved inorganic carbon. See appendix 8.1 and 8.2 for details.	1999 and 2012/2013-2020
Chlorophyll, MODIS	D04	Moderate-resolution Imaging Spectroradiometer data (MODIS) Aqua 10.5067/AQUA/MODIS/L3M/CHL/2018 NASA https://lpdaac.usgs.gov/	NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group.	Knut Yngve Børsheim, IMR [1]	Chlorophyll per m ^{2} from satellite. Eight days average with 4x4 km resolution. Primary production is estimated as described in Behrenfeld and Falkowski (1997).	2003–2020
WP2 Fugløya-Bjørnøya	D05	Norsk Marint Datasenter (NMD)	IMR [1]	Padmini Dalpadado, IMR [1]	WP2 net with taxonomic identification and abundance. Main focus on *Calanus* species entering the Barents Sea. Only for the Sub-Arctic ecosystem	1995-2019
WP2 BESS	D06	Norsk Marint Datasenter (NMD)	IMR [1]	Padmini Dalpadado, IMR [1]	WP2 nets from the Barents Sea Ecosystem Survey. For mesozooplankton. Only biomass of size fractions is considered, not taxonomy (Meeren and Prozorkevich, 2021).	1990-2020
Bottom trawl BESS	D07	Norsk Marint Datasenter (NMD)	IMR [1]	Edda Johannesen and L. L. Jørgensen, IMR [1]	Abundance and biomass per species or taxonomic group. From the Barents Sea Ecosystem Survey bottom trawl (Campelen 1800). For abundance and biomass of fish and benthos (Meeren and Prozorkevich, 2021).	2004 – 2020; 2009-2020 for benthos

Pelagic trawl BESS	D08	Norsk Marint Datasenter (NMD)	IMR [1]	Elena Eriksen, IMR [1]	Abundance and biomass per species or taxonomic group. From the Barents Sea Ecosystem Survey pelagic trawl (Harstad). For 0-group fish, krill, amphipod, and jellyfish (Meeren and Prozorkevich, 2021).	2004 - 2020
Polar cod	D09	Available in report	IMR [1] and PINRO	Georg Skaret, IMR [1]	Estimate of total biomass in the Barents Sea in autumn. From the Barents Sea Ecosystem Survey (Meeren and Prozorkevich, 2021)	1986 - 2020
Capelin	D10	https://doi.org/10.17895/ICES.pub.6050	ICES	Georg Skaret, IMR [1]	Total stock biomass estimate from AFWG in ICES (ICES, 2020)	1972 – 2020
Herring	D11	Available in report	IMR [1] and PINRO	Georg Skaret, IMR [1]	Estimate of total biomass in the Barents Sea in autumn. From the Barents Sea Ecosystem Survey (Meeren and Prozorkevich, 2021).	1999 - 2020
Blue Whiting	D12	Available in report	IMR [1] and PINRO	Georg Skaret, IMR [1]	Estimate of total biomass in the Barents Sea in autumn. From the Barents Sea Ecosystem Survey (Meeren and Prozorkevich, 2021).	2004 - 2020
NEA cod	D13	https://doi.org/10.17895/ICES.pub.6050	ICES	Bjarte Bogstad, IMR [1]	Total stock biomass estimates from AFWG in ICES (ICES, 2020).	1946 – 2021
Haddock	D14	https://doi.org/10.17895/ICES.pub.6050	ICES	Bjarte Bogstad, IMR [1]	Total stock biomass estimates from AFWG in ICES (ICES, 2020).	1950 - 2021
Redfish	D15	https://doi.org/10.17895/ICES.pub.6050	ICES	Hannes Höffle, IMR [1]	Total stock biomass estimates from AFWG in ICES (ICES, 2020).	1992 - 2019
NEA cod size	D16	https://doi.org/10.17895/ICES.pub.6050	ICES	Bjarte Bogstad, IMR [1]	Biomass estimates for different age-classes of NEA cod from AFWG in ICES (ICES, 2020).	1946 - 2020
Seabirds BESS	D17	Counts of seabirds per 5 km strip transect. Comma separated text file available upon request.	NINA	Per Fauchald, NINA	From BESS, seabirds counted in transects between trawling stations and within 300 m distance from the ship (Meeren and Prozorkevich, 2021).	2004 - 2020
Seabird colonies	D18	www.seapop.no and www.mosj.no	NP and NINA	Sebastien Descamps (Svalbard), Hallvard Strøm (Bjørnøya), Tone K. Reiertsen (Hornøya), Geir H. Systad (Hjelmsøya)	Counts of active nests or breeding adults in breeding colonies.	Varying between species, earliest from 1980 – 2021
Walrus recent population estimate	D19	https://www.mosj.no/en/fauna/marine/walrus-population.html	NP	Kit Kovacs, NPI	Total population estimates based on aerial counts.	2006-2018

Walrus pre-harvest population estimate	D20	Data from Weslawski et al. (2000)		See publication	Extrapolation of population size based on Franz Josef Land estimates	Around 1600
Bowhead whales' recent population estimate	D21	Data from Vacquié-Garcia et al. (2017a)		See publication	Sightings from aerial and ship-based survey in august	2005
Bowhead whales pre-whaling population estimate	D22	Data from Allen and Keay (2006)		See publication	Back-calculations based on whaling records and delayed-difference recruitment model.	1611
Hooded seals	D23	https://www.mosj.no/en/fauna/marine/hooded-seal.html	NP	Martin Buiw, IMR	Modelled population based on aerial counts of pups.	1946-2019
Harp seals West and East Ice	D24	https://www.mosj.no/en/fauna/marine/harp-seal.html	NP	Martin Buiw, IMR	Modelled population based on aerial counts of pups.	1946-2019
Ringed seals recent population estimates	D25	Data from Krafft et al. (2006)		See publication	Aerial sightings of seals corrected by behavioural model	2003
Harbour seals recent population estimates	D26	Data from Merkel et al. (2013)		See publication	Aerial sightings of seals corrected by behavioural model	2009-2010
White whales' recent population estimates	D27	Data from Vacquié-Garcia et al. (2020)		See publication	Aerial sightings of white whales corrected by behavioural model	2018
White whales catch statistics	D28	Data from Lønø and Øynes (1961)		See publication	Catch numbers from records	1871-1960

Narwhals' recent population estimates	D29	Data from Vacquié-Garcia et al. (2017b)		See publication	Sightings from aerial survey in August	2015
Polar bears' recent estimates	D30	Data from Aars et al. (2009); Aars et al. (2017)		See publications	Sightings from line transect distance sampling in August	2004-2015
Polar bears' catch statistics	D31	https://www.mosj.no/no/pavirkning/jakt-fangst/uttak-isbjorn.html	NP	Jon Aars, NPI	Hunting statistics from records.	1871-1973
Whales' sightings	D32		IMR	Nils Øien	From BESS, marine mammals counted in transects between trawling stations (Meeren and Prozorkevich, 2021).	2004-2020

4. Estimation of indicators and rates of change

This chapter describes the methods for calculation of indicator values based on the datasets described in chapter 3 and the analytical framework for estimating rates of change in the resulting time series. First, we give a general description on how the datasets from the Barents Sea ecosystem cruise, the main data source for the assessment, have been treated (chapter 4.1). This is followed by a description of the framework for estimating rates of change (chapter 4.2). Brief description of the specific methods for each indicator is given in Table 4.1a (for the Arctic part of the Barents Sea) and Table 4.1b (for the Sub-Arctic part of the Barents Sea). Additional descriptions of the methods are given in appendices in chapter 8, which also includes graphical representation of all indicator values and results from statistical analyses. Statistical analyses were conducted in R (R Core Team, 2019) and MATLAB (MATLAB, 2018). Indicators identified by the panel in the initial scoping phase, but that could not be included in the assessment due to data deficiencies and/or that phenomena could not been developed (due to capacity constraints), are given in Table 4.2. A more exhaustive list of potential supplementary indicators made after the assessment (i.e., based on the insights generated through the assessment process) are given in Tables 7.3.4a and 7.3.4b.

4.1 General considerations/treatment of the BESS datasets

As pre-treatment of data from BESS (D06, D07, D08, D17, Table 3.1), supplementary opportunistic sampling occasionally conducted during the survey were removed from the dataset prior to indicator calculations. The biotic indicators are calculated at the station level, then summarised at the polygon level. The summarizing function is the mean (and standard deviation), unless data were strongly skewed, in which case we took the median (and median absolute deviation). For indicator values at the scale of the whole ecosystem, the mean and standard deviation were calculated.

Sub-Arctic marine mammal observations are georeferenced but not associated to a grid cell. Their indicators are expressed as absolute number of individuals observed during the transect. In the Arctic ecosystem, endemic species time series are extracted from the Monitoring of Svalbard and Jan Mayen (https://www.mosj.no/no/) or from the most recent estimates from the literature.

For the physical oceanography indicators extracted from CTD profiles, in addition to the quality control performed by NMDC, the station data was de-spiked and significant instabilities were removed. For the time series of temperature, freshwater content, and water-mass area, we used data fields that were gridded onto a 25 km polar stereographic grid covering the Barents Sea using objective mapping to remove biases due to clustered sampling in small areas. Years when less than 75% of the area of a particular polygon was covered by observations were removed. The mask for this criterium was computed using mean 50 – 200 m temperatures and used for all other variables for consistency. The buoyancy frequency maximum used as an indicator for stratification was computed from station data, averaged for each polygon, and masked for insufficient data coverage as described above

4.2 Framework for estimating rates of change

The framework for estimating deviation from the reference conditions was initially built around an approach aimed at identifying the trend that best fits the available data according to the AIC criteria, termed the “best fitted trend” approach here, and to compare the results to the phenomena written by the experts (see chapters 5.1 and 5.2). The ”best fitted trend” approach follows the first steps of trend estimation from (Solvang and Planque, 2020). This is based on first fitting polynomials of degree 1 (linear trend) 2 (quadratic) and 3 (cubic) to the mean or median values of each indicator and then selecting the best model based on AIC criteria (Solvang and Planque, 2020). Through the work with the assessment, it became evident that this was not always sufficient as non-linear trends can be highly sensitive to values at the start and end of the time series. Simple linear analyses were therefore computed as background information. For some indicators, results from both types of analyses have been used when assessing deviation from the reference condition, whereas for some only results from the linear analyses have been used.

For short time series with poor data quality (e.g., megabenthos data, which form a short time series with high interannual variability likely linked to occasional large catches of sponges), linear trends were fitted by default, rather than the best fitted trend, as higher degree polynomial trends would be more influenced by sudden peaks in data. The linear analyses were based on simple linear regressions, but those are not suited for short time series (<50 data points, Hardison et al. (2019)), so their interpretation was considered carefully. Autoregressive models taking into account effects of autocorrelation in time series data were not fitted (see Pedersen et al. (2021) for an example of application of such models in PAEC), as these are not robust for time series below 30 years length.

For hydrographic data (Abiotic factors and Landscape ecological patterns characteristics), a mean for 1970-1990 was calculated as a baseline for the reference condition and a 2004-2019 mean to cover the period of the full BESS surveys to establish changes from the reference condition. In addition, we calculated linear trends over the whole observational period for the hydrographic variables, 1970-2019, and for the 2004-2019 period to match some of the ecosystem variables. It should of course also be noted that trend estimation depends on the period covered by the available data, with longer time series expected to allow more robust estimation of trends than shorter ones.

The uncertainty around the yearly estimates were not taken into account in the “best fitted trend” and linear trend analyses. Future assessments will have to adapt the method to assess the influence of uncertainty in estimates on the analysis results. For the current assessment, raw mean or median time series of each indicator were plotted with standard deviation or median absolute deviation, respectively, to allow for critical assessment of the fitted trend.

Table 4.1 a. Methods for estimating indicator values from datasets for Arctic Barents Sea. TL: trophic level

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Primary productivity	Annual net primary productivity [AI01]	D04	The indicator is represented by a time series on annual net primary production (g C m $^{-2}$ y $^{-1}$) based on satellite data on chlorophyll concentration and estimated from a vertically generalized production model (Behrenfeld and Falkowski, 1997).
Primary productivity	Timing of spring bloom [AI02]	D04	The bloom start days were calculated using the threshold method (Brody et al., 2013), with start day at 0.68 mg chlorophyll m $^{-3}$ calculated as suggested by Siegel et al. (2002).
Biomass distribution among trophic levels	Annual net primary productivity [AI01]	D04	See above
Biomass distribution among trophic levels	Zooplankton TL < 2.5 [AI03]	D06 and D08	This indicator is represented by two time series: 1) biomass of mesozooplankton (g m- ^{2}, sampled with WP2); 2) biomass of krill (kg km $^{-2}$, sampled with pelagic trawl). *Indicator values are mean* (± sd) of station values within each polygon or the Arctic area.
Biomass distribution among trophic levels	Zooplankton TL > 2.5 [AI04]	D08	This indicator is represented by the sum of biomass of pelagic amphipods and gelatinous zooplankton (kg km $^{-2}$, sampled with pelagic trawl). *Indicator values are mean* (± sd) of station values within each polygon or the Arctic area.
Biomass distribution among trophic levels	Benthic suspensivores [AI05]	D07	The indicator is represented by the sum of biomass (kg/km²) of megabenthic species (sampled with bottom trawl), weighed by a fuzzy coding (i.e., a type of expert assessment, see Wiedmann et al. (2014) and Frainer et al. (2017) for applications) of their degree of suspension feeding as defined by the experts. Indicator values are the mean (± sd) of station values within each polygon or the total Arctic area.
Biomass distribution among trophic levels	0-group fish [AI06]	D08	The indicator is represented by the summed biomass km $^{-2}$ of all 0-group fish species caught. Indicator values are the mean of station values within each polygon or the Arctic area.
Biomass distribution among trophic levels	Pelagic planktivorous fish [AI07]	D09 and D10	The indicator is represented by the sum of total stock biomass estimates of the dominant pelagic species: capelin and polar cod.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Biomass distribution among trophic levels	Low TL seabirds [AI08]	D17	Data are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is represented by time series of density of little auk (*Alle alle*) adjusted for body mass, i.e., biomass km^{-}2. Indicator values are the mean (± sd) of station values.
Biomass distribution among trophic levels	High TL seabirds [AI09]	D17, D18	The first dataset are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is represented by time series of densities of the two most common Arctic seabird species feeding on higher trophic levels: Brünnich's guillemot (*Uria lomvia*) and black-legged kittiwake (*Rissa tridactyla*). The indicator values are the mean (± sd) of station values for each species. The second dataset is from population monitoring of a sample of breeding colonies of Brünnich's guillemot (*Uria lomvia*) and black-legged kittiwake (*Rissa tridactyla*) in Svalbard, incl. Bjørnøya. Methods are described in (Walsh et al., 1995). Indicators are given as number of birds as percentage of the average number of birds in the time series
Biomass distribution among trophic levels	Low TL mammals [AI10]	D19, D20, D21, D22	The data are comprised of a time-series for walrus abundance (population estimates - three timeframes (MOSJ) compared to historical abundance (based on harvests) and a recent population estimate for bowhead whales compared to back-calculated pre-whaling population size for the Spitsbergen stock
Biomass distribution among trophic levels	Generalist mammals [AI11]	D23, D24, D25, D26	The indicator is represented by several data sources. Harp and hooded seals West Ice p opulation estimates are modelled based on time series of aerial surveys (and population parameters) extending over many decades. There are no time-series available for the abundance of Arctic **endemic** generalist feeding marine mammals (ringed, harbour and bearded seals), but there are some data relevant to their current and likely future status.
Biomass distribution among trophic levels	High TL mammals [AI12]	D27 to D31	For polar bears, historical catch data and a two-point time series are available for the Svalbard resident component of the Barents Sea population. Harvest statistics vs a recent population estimate for white whales permit an initial assessment of this population's status. For narwhal there are some data relevant to their current and likely future status
Functional groups within trophic levels	High TL zooplankton functional groups [AI13]	D08	The indicator is represented by the ratio of biomass of pelagic amphipods to the biomass of gelatinous zooplankton (sampled with pelagic trawl). *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Functional groups within trophic levels	Benthic habitat engineers [AI14]	D07	The indicator is represented by the sum of biomass (kg km $^{-2}$) of megabenthic habitat engineers (sampled with bottom trawl), as identified by the experts. Indicator values are the mean (± sd) of station values within each polygon or the total Arctic area.
Functional groups within trophic levels	Fish size [AI15]	D07	The indicator is represented by the biomass weighted community mean body length at maturity. Species-specific lengths at maturity were from Wiedmann et al. (2014). Indicator values are the mean of station values within each polygon or the total Arctic area.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Functional groups within trophic levels	Fish life history [AI16]	D07	Two complimentary approaches for indicator values were included. 1) biomass proportion of each of three life history strategies: equilibrium, periodic, opportunistic (Winemiller and Rose, 1992), and 2) biomass weighted rating along the fast-slow life histories continuum (Wiedmann et al., 2014). For more details on the calculations see Appendix 8.1. For both 1 and 2 indicator values are the mean of station values within each polygon or the total Arctic area.
Functional groups within trophic levels	Fish habitat use [AI17]	D07	The indicator is represented by the biomass proportion of fish classified as utilizing a benthic habitat. Habitat information is taken from the literature (Wiedmann et al., 2014; Frainer et al., 2021). Indicator values are the mean of station values within each polygon or the total Arctic area.
Functional groups within trophic levels	Seabird feeding types [AI18]	D17	Data are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is represented by the ratio of the density of diving vs. surface-feeding seabirds. The proportion of diving seabirds is used as indicator values, and the median (± mad) or mean (± sd) of station values within each polygon or the total Arctic area, respectively.
Functional groups within trophic levels	Mammal bioturbation [AI19]	D19, D20, D27, D28	The data are comprised of a time-series for walrus abundance (population estimates - three timeframes (MOSJ) compared to historical abundance (based on harvests). Harvest statistics vs a recent population estimate for white whales permit an initial assessment of this population’s status.
Functionally important species and biophysical structures	Pelagic amphipods [AI20]	D08	The indicator is represented as biomass (kg km $^{-2}$) of pelagic amphipods (sampled with pelagic trawl). *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Functionally important species and biophysical structures	Krill [AI21]	D08	The indicator is represented as biomass (kg km $^{-2}$) of krill (sampled with pelagic trawl). *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Functionally important species and biophysical structures	Polar cod [AI22]	D09	The indicator is represented by the estimated total biomass of polar cod in the Barents Sea in autumn. There are no calculated uncertainties around these values.
Functionally important species and biophysical structures	Capelin [AI23]	D10	The indicator is represented by the annual total stock biomass estimated from ICES AFWG (ICES, 2020). Indicator values are the running average using a 3-year window. There are no calculated uncertainties around these values.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Functionally important species and biophysical structures	Cod [AI24]	D13	The indicator is represented by the annual total stock biomass estimated from ICES AFWG (ICES, 2020) Indicator values are the running average using an 8-year window, based on generation time. There are no calculated uncertainties around these values.
Functionally important species and biophysical structures	Cod size structure [AI25]	D16	The indicator is represented by the biomass proportion of 7-year-old cod and older. There are no calculated uncertainties around these values.
Functionally important species and biophysical structures	Cod distribution [AI26]	D07	The indicator is based on the biomass km^{-2} of cod in bottom trawls. Indicator values are the median (± mad) or mean (± sd) of station values within each polygon or the total Arctic area, respectively.
Landscape-ecological patterns	Bottom thermal niches [AI27]	D01	The indicator is represented by estimates of area (1000 km^{3}) covered by Atlantic Water ($T > 3°C$), Arctic Water ($T < 0°C$) and or mixed water masses ($0°C < T < 3°C$) from gridded temperature fields covering the lowermost 30 m of the water column. Indicator values are mean (± sd) of station values within each polygon or the total Arctic area.
Landscape-ecological patterns	Sea-ice area [AI28]	D02	The indicator is represented by time series on the average area covered by sea ice (1000 km^{3}) in April (sea-ice maximum) and September (sea-ice minimum), respectively. Indicator values are estimates within boxes covering 1-3 polygons or the total Arctic area.
Biological diversity	Arctic amphipod [AI29]	D08	The indicator is represented as biomass (kg km^{-2}) of pelagic amphipods (sampled with pelagic trawl). *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Biological diversity	Cold-water benthos [AI30]	D07	The indicator is represented by the proportion of biomass (kg km^{-2}) of megabenthic species sensitive to climate change (sampled with bottom trawl), as defined by the experts. Indicator values are the mean (± sd) of station values within each polygon or the total Arctic area.
Biological diversity	Arctic fish [AI31]	D07	The indicator is represented by the sum of normalized log counts km^{-2} of Arctic fish species. Biogeographic classifications were taken from the literature (Andriyashev and Chernova, 1995; Wiedmann et al., 2014; Fossheim et al., 2015; Mecklenburg et al., 2018). Indicator values are the mean of station values.
Biological diversity	Fish sensitive to fisheries [AI32]	D07	The indicator is represented by the summed abundance (counts km^{-2}) of fish species with life history traits that makes them vulnerable to increased mortality from fisheries. For more details on the indicator calculation see Appendix 8.1. Indicator values are the mean of station values within each polygon or the total Arctic area.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Biological diversity	Seabirds sensitive to pollution [AI33]	D17, D18	The first dataset are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is density of glaucous gull (*Larus hyperboreus*). Indicator values are the mean (± sd) count km^{-2} of station values for each polygon and for the whole Arctic area The second dataset is from population monitoring of breeding colonies of glaucous gull (*Larus hyperboreus*) in Kongsfjorden and Bjørnøya. Methods are described in Walsh et al. (1995). Indicators are given as number of birds as percentage of the average number of birds in the time series.
Biological diversity	Arctic seabirds [AI34]	D17, D18	The first dataset are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is represented by Brünnich's guillemot (*Uria lomvia*), little auk *(Alle alle)* and glaucous gull *(Larus hyperboreus)*. The sum of normalized log counts / km^2 was calculated, and indicator values are the median (± mad) or mean (± sd) of station values within each polygon or the total Arctic area, respectively. The second dataset is from population monitoring of breeding colonies Brünnich's guillemot (*Uria lomvia*) and glaucous gull (*Larus hyperboreus*) in Svalbard and Bjørnøya. Methods are described in Walsh et al. (1995). Indicators are given as number of birds as percentage of the average number of birds in the time series.
Biological diversity	Mammals sensitive to pollution [AI35]	D25, D27 to D31	Trends in contaminants are monitored in several key Arctic species – including ringed seals and polar bears in the MOSJ programme. Time-series data have also been collected for white whales because contaminant levels are high, and these animals are particularly sensitive because toothed whales lack the capacity to metabolize many toxins. Individual pollutant levels in those species cannot be used as indicators. This indicator is thus represented by the population estimates and available catch statistics of polar bears, white whales, narwhals and ringed seals.
Biological diversity	Arctic mammals [AI36]	D19 to D31	This indicator is represented by all the time series used for marine mammals in the Arctic ecosystem: walruses, bowhead whales, hooded, harp, harbour and ringed seals, white whales, narwhals and polar bears. It should also include bearded seals but estimates for this population are not currently available; it is expected that they will be for the next assessment.
Abiotic factors	Temperature [AI37]	D01	The indicator is represented by four time series for mean temperature (°C) at 0-30 m, 30-100 m, 100-200 m and the bottom 30 m, respectively. *Indicator values are mean* (± sd) of station values within each polygon or the Arctic area.
Abiotic factors	Area of water masses [AI38]	D01	The indicator is represented by estimates of area (1000 km^3) covered by Atlantic Water ($T > 3°C$), Arctic Water ($T < 0°C$) and or mixed water masses ($0°C < T < 3°C$) from bottom mean temperature from gridded temperature fields. Indicator values are mean (± sd) of station values within each polygon or the total Arctic area.
Abiotic factors	Freshwater content [AI39]	D01	The indicator is represented by estimates [m] c alculated for the top 100 m from gridded practical salinity fields with a reference practical salinity of 35. *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Abiotic factors	Stratification [AI40]	D01	The indicator is represented by estimates based on the maximum of the Brunt–Väisälä frequency, or buoyancy frequency, in the top 100 m of the water column calculated from stations data to preserve the vertical density structure. *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Abiotic factors	Sea-ice area [AI28]	D02	The indicator is represented by time series on the average area covered by sea ice (1000 km^3) in April (sea-ice maximum) and September (sea-ice minimum), respectively. Indicator values are estimates within boxes covering 1-3 polygons or the total Arctic area.
Abiotic factors	pH [AI41]	D03	The indicator is represented by estimates from the core of Arctic Water at a single station. Indicator values are mean of observation (± sd).
Abiotic factors	Aragonite saturation [AI42]	D03	The indicator is represented by estimates (Ω_{Ar}) from the core of Arctic Water at a single station. Indicator values are mean of observations (± sd).

Table 4.1 b. Methods for estimating indicator values from datasets for Sub-Arctic Barents Sea. TL: trophic level

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Primary productivity	Annual net primary productivity [SI01]	D04	The indicator is represented by a time series on annual net primary production (g C m^{-2} y^{-1}) based on satellite data on chlorophyll concentration and estimated from a vertically generalized production model (Behrenfeld and Falkowski, 1997).
Primary productivity	Timing of spring bloom [SI02]	D04	The bloom start days were calculated using the threshold method (Brody et al., 2013), with start day at 0.68 mg chlorophyll m^{-3} calculated as suggested by (Siegel et al., 2002).
Biomass distribution among trophic levels	Annual net primary productivity [SI01]	D04	See above
Biomass distribution among trophic levels	Zooplankton TL < 2.5 [SI03]	D06 and D08	This indicator is represented by two time series, one on biomass of mesozooplankton (g m^{-2}) (sampled with WP2) and one on biomass of krill (kg km^{-2}) (sampled with pelagic trawl)*. Only 70% of krill biomass was used, assuming a ratio of herbivorous/carnivorous to total krill of 70/30. Indicator values are mean* (± sd) of station values within each polygon or the total Sub- Arctic area.
Biomass distribution among trophic levels	Zooplankton TL > 2.5 [SI04]	D08	This indicator is represented by the sum of biomass of pelagic high trophic level krill and gelatinous zooplankton kg km^{-2}) (sampled with pelagic trawl). *Only 30% of krill biomass was used, assuming a ratio of herbivorous/carnivorous to total krill of 70/30. Indicator values are mean* (± sd) of station values within each polygon or the total Sub- Arctic area.
Biomass distribution among trophic levels	Benthic suspensivores [AI05]	D07	The indicator is represented by the sum of biomass (kg km^{-2}) of megabenthic species (sampled with bottom trawl), weighed by a fuzzy coding (i.e., a type of expert assessment, see Wiedmann et al. (2014) and Frainer et al. (2017) for applications) of their degree of suspension feeding. Indicator values are the mean (± sd) of station values within each polygon or the total Sub- Arctic area.
Biomass distribution among trophic levels	0-group fish [SI06]	D08	The indicator is represented by the summed biomass km^{-2} of all 0-group fish species caught. Indicator values are the mean of station values within each polygon or the total Sub-Arctic area.
Biomass distribution among trophic levels	Pelagic planktivorous fish [SI07]	D10, D11, D12	The indicator is represented by the sum of total stock biomass estimates of the dominant pelagic species: capelin, herring and blue whiting.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Biomass distribution among trophic levels	High TL seabirds [SI08]	D17, D18	The first dataset are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is represented by time-series of the densities of common murre (*Uria aalge*) and Atlantic puffin (*Fratercula arctica*). The indicator values are the mean of station values for each species The second dataset is from population monitoring of breeding colonies of common murre (*Uria aalge*) and Atlantic puffin (*Fratercula arctica*) on Hornøya and Hjelmsøya in Finnmark, Norway. Methods are described in Walsh et al. (1995). Indicators are given as number of birds as percentage of the average number of birds in the time series
Biomass distribution among trophic levels	Low TL mammals [SI09]	D32	The indicator is represented by the sighting rate of individuals (number km $^{-1}$) observed during the BESS. Low trophic level marine mammals are fin whales and blue whales. However, only fin whales were observed during the period we have data.
Biomass distribution among trophic levels	Generalist mammals [SI10]	D32	The indicator is represented by sighting rates (number of individuals /km) during the BESS. Generalist marine mammals are humpback whales and minke whales.
Biomass distribution among trophic levels	High TL mammals [SI11]	D32	The indicator is represented by the sighting rates (number of individuals /km) observed during the BESS. High trophic level marine mammals are sperm whales, killer whales, bottlenose whale, white-beaked dolphins, harbour porpoise, harp seals, harbour seals, and grey seals.
Functional groups within trophic levels	High TL zooplankton functional groups [SI12]	D06	The indicator is represented by the ratio of biomass of pelagic high trophic level krill to the biomass of gelatinous zooplankton. *Only 30% of krill biomass was used, assuming a ratio of herbivorous/carnivorous to total krill of 70/30. Indicator values are mean* (± sd) of station values within each polygon or the total Sub-Arctic area.
Biomass distribution among trophic levels	Benthic habitat engineers [SI13]	D07	The indicator is represented by the sum of biomass (kg km $^{-2}$) of megabenthic habitat engineers (sampled with bottom trawl), as defined by the experts. Indicator values are the mean (± sd) of station values within each polygon or the total Sub-Arctic area.
Biomass distribution among trophic levels	Fish size [SI14]	D07	The indicator is represented by the biomass weighted community mean body length at maturity. Species-specific lengths at maturity was taken from Wiedmann et al. (2014). Indicator values are the mean of station values within each polygon or the total Sub-Arctic area.
Biomass distribution among trophic levels	Fish life history [SI15]	D07	Two complimentary approaches for indicator values were included. 1) biomass proportion of each of three life history strategies: equilibrium, periodic, opportunistic (Winemiller and Rose, 1992), and 2) biomass weighted rating along the fast-slow life histories continuum (Wiedmann et al., 2014). For more details on the calculations see Appendix 8.2. For both 1 and 2 indicator values are the mean of station values within each polygon or the total Sub-Arctic area.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Biomass distribution among trophic levels	Fish habitat use [SI16]	D07	The indicator is represented by the biomass proportion of fish classified as utilizing a benthic habitat. Habitat information is taken from the literature (Wiedmann et al., 2014; Frainer et al., 2021). Indicator values are the mean of station values within each polygon or the total Sub-Arctic area.
Biomass distribution among trophic levels	Seabird feeding types [SI17]	D17	Data are counts of seabirds along strip transects sampled on Norwegian vessels during the Barents Sea ecosystem survey (Fauchald, 2011). Observations are aggregated to the nearest sampling station. The indicator is represented by the ratio of the density of diving vs. surface-feeding seabirds. Proportion of diving seabirds is used as indicator values, and the median (± mad) or mean (± sd) of station values within each polygon or the total Sub-Arctic area, respectively
Biomass distribution among trophic levels	Mammals top-down control [SI18]	D32	This indicator is represented by the ratio of high to low trophic level whales.
Functionally important species and biophysical structures	Arctic *Calanus* [SI19]	D05	The indicator is represented by biomass m $^{-2}$ of the biomasses of mesozooplankton species *Calanus glacialis* and *Calanus hyperboreus* (identified in WP2 transects at the Fugløya-Bjørnøya section). *Indicator values are mean* (± sd) of station values within each polygon or the total Sub-Arctic area.
Functionally important species and biophysical structures	Atlantic *Calanus* [SI20]	D05	The indicator is represented by biomass m $^{-2}$ of the biomasses of mesozooplankton species *Calanus finmarchicus* (identified in WP2 transects at the Fugløya-Bjørnøya section). *Indicator values are mean* (± sd) of station values within each polygon or the total Sub-Arctic area.
Functionally important species and biophysical structures	Krill [SI21]	D08	The indicator is represented as biomass (kg km $^{-2}$) of krill. *Indicator values are mean* (± sd) of station values within each polygon or the total Arctic area.
Functionally important species and biophysical structures	Capelin [SI22]	D10	The indicator is represented by the annual total stock biomass estimated from ICES AFWG (ICES, 2020). Indicator values are the running average using a 3-year window. There are no calculated uncertainties around these values.

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Functionally important species and biophysical structures	Cod [SI23]	D13	The indicator is represented by the annual total stock biomass estimated from ICES AFWG (ICES, 2020). Indicator values are the running average using a 8-year window, based on generation time. There are no calculated uncertainties around these values.
Functionally important species and biophysical structures	Cod size structure [SI24]	D16	The indicator is represented by the biomass proportion of 7-year-old cod and older. There are no calculated uncertainties around these values.
Functionally important species and biophysical structures	Haddock [SI25]	D14	The indicator is represented by the annual total stock biomass estimated from ICES AFWG (ICES, 2020). Indicator values are the running average using a 7-year window, based on generation time. There are no calculated uncertainties around these values.
Functionally important species and biophysical structures	Redfish [SI26]	D15	The indicator is represented by the annual total stock biomass of beaked redfish (*Sebastes mentella*) estimated from ICES AFWG (ICES, 2020). There are no calculated uncertainties around these values.
Landscape-ecological patterns	Bottom thermal niches [SI27]	D01	The indicator is represented by estimates of area (1000 km^3) covered by Atlantic Water ($T > 3°C$), Arctic Water ($T < 0°C$) and or mixed water masses ($0°C < T < 3°C$) from bottom mean temperature from gridded temperature fields. Indicator values are mean (± sd) of station values within each polygon or the total Sub-Arctic area.
Biological diversity	Benthos sensitive to bottom trawling [SI28]	D07	The indicator is represented by the proportion of biomass (kg km^{-2}, sampled with bottom trawl) of megabenthic species sensitive to bottom trawl, as defined by the experts. Indicator values are the mean (± sd) of station values within each polygon or the total Sub- Arctic area.
Biological diversity	Fish sensitive to fisheries [SI29]	D17	The indicator is represented by the summed abundance (counts km^{-2}) of fish species with life history traits that make them vulnerable to increased mortality from fisheries. For more details on the indicator calculation, see Appendix 8.2. Indicator values are the mean of station values within each polygon or the total Sub-Arctic area.
Biological diversity	Mammals sensitive to pollution [SI30]	D32	The indicator is represented by the sighting rates (number of individuals km^{-1}) observed during the BESS. Species sensitive to pollution are toothed whales, which are also high trophic level marine mammals: sperm whales, killer whales, bottlenose whale, white-beaked dolphins, and harbour porpoise,

Ecosystem characteristic	Indicator [ID]	Dataset ID	Methods
Biological diversity	Mammal diversity [SI31]	D32	Trends in number of species of whales and dolphins monitored through BESS. Occurrence of coastal Sub-Arctic seal species (harbour, grey) are available only on very short time series and could be included in future assessments.
Abiotic factors	Temperature [SI32]	D01	The indicator is represented by four time series for mean temperature (°C) at 0-30 m, 30-100 m, 100-200 m and the bottom 30 m, respectively. *Indicator values are mean* (± sd) of station values within each polygon or the total Sub-Arctic area.
Abiotic factors	Area of water masses [SI33]	D01	The indicator is represented by estimates of area (1000 km ^{3}) covered by Atlantic Water ($T > 3°C$), Arctic Water ($T < 0°C$) and or mixed water masses ($0°C < T < 3°C$) from bottom mean temperature from gridded temperature fields. Indicator values are mean (± sd) of station values within each polygon or the total Sub-Arctic area.
Abiotic factors	Stratification [SI34]	D01	The indicator is represented by estimates based on the maximum of the Brunt–Väisälä frequency, or buoyancy frequency, in the top 100 m of the water column calculated from stations data to preserve the vertical density structure. *Indicator values are mean* (± sd) of station values within each polygon or the total Sub-Arctic area.
Abiotic factors	pH [SI35]	D03	The indicator is represented by estimates from the core of Sub-Arctic Water at a single station. Indicator values are mean of observation (± sd)
Abiotic factors	Aragonite saturation [SI36]	D03	The indicator is represented by estimates (ΩAr) from the core of Sub-Arctic Water at a single station. Indicator values are mean of observations (± sd).

Table 4.2 Indicators identified during the initial scoping phase that were not included in the assessment due to data deficiencies and/or that phenomena could not be developed due to capacity constraints. TL: trophic level

Ecosystem characteristic	**Indicator**	**Ecosystem**	**Reason for not including and possibilities for future inclusion**	**If data is available, dataset ID and method for estimating indicator values**	**Information in Appendix 8.4 or 8.5**
Biomass distribution among trophic levels	Low TL benthic fish	Arctic and Sub-Arctic	Phenomenon not developed. The indicator was identified based on importance for the ecosystem and approach for the characteristic. However, identifying important drivers and predicting possible directions of change were not straightforward for this indicator which includes a mix of Arctic and Boreal species. It will be added, if possible, in the next assessment.	Dataset D07. The indicator is represented by the biomass km $^{-2}$ of planktivorous and benthivorous feeding strategies in fish, using a fuzzy coding approach (Wiedmann et al., 2014; Frainer et al., 2017). Indicator values are the mean of station values within each polygon or the total Arctic or Sub-Arctic area.	Data and trend analyses (Appendix 8.5)
Biomass distribution among trophic levels	High TL benthic fish	Arctic and Sub-Arctic	Phenomenon not developed. The indicator was identified based on importance for the ecosystem and approach for the characteristic. However, identifying important drivers and predicting possible directions of change were not straightforward for this indicator which includes a mix of Arctic and Boreal species. It will be added, if possible, in the next assessment.	Dataset D07. The indicator is represented by the biomass km $^{-2}$ of the ichthyvorous feeding strategy in fish, using a fuzzy coding approach (Wiedmann et al., 2014; Frainer et al., 2017). Indicator values are the mean of station values within each polygon or the total Arctic or Sub-Arctic area.	Data and trend analyses (Appendix 8.5)
Functional groups within trophic levels	Low TL zooplankton body size	Arctic and Sub-Arctic	Data not available		Phenomenon (Appendix 8.4)
Functional groups within trophic levels	Benthos seafloor stabilisation	Arctic and Sub-Arctic	Data not available, but will be available for the next assessment		Phenomenon (Appendix 8.4)
Functional groups within trophic levels	Fish feeding guilds	Arctic and Sub-Arctic	Phenomenon not developed The indicator was identified based on importance for the ecosystem and approach for the characteristic. However, identifying important drivers and predicting possible directions of change were not straightforward for this indicator where feeding guilds includes a mix of Arctic and Boreal species. It will be added, if possible, in the next assessment.	Dataset D07. The indicator is represented by the biomass weighted proportions of planktivorous, benthivorous and ichthyvorous feeding strategies in benthic fish communities, using a fuzzy coding approach (Wiedmann et al., 2014; Frainer et al., 2021). Indicator values are the mean of station values within each polygon or the total area.	Data and trend analyses (Appendix 8.5)
Functional groups within trophic levels	Mammal nutrient cycling	Arctic and Sub-Arctic	Marine mammals feed at depth, but regularly return to the surface to breathe, where they defecate -thus bringing nutrients back into the photic zone stimulating primary production. However, insufficient water chemistry data in the context of changing abundances and distributions of whales prevent good assessment of this indicator.		Phenomenon (Appendix 8.4)
Functional groups within trophic levels	Mammal carcasses	Arctic	Mammal carcasses can act as biodiversity hotspots on the seafloor. Data not available		Phenomenon (Appendix 8.4)

Functional groups within trophic levels	Pelagic prey aggregation by mammals	Sub-Arctic	Feeding activities of whales on aggregate preys in local spots of the open sea and create feeding opportunities for other species, such as seabirds. The role of this indicator is to track the impact of marine mammal occurrence in the Sub-Arctic Barents Sea on the frequency of these feeding events. This indicator needs specific monitoring		Phenomenon (Appendix 8.4)
Functional groups within trophic levels	Mammal top-down control	Arctic	Marine mammals are large animals that consume significant amounts of prey (Skern-Mauritzen et al., 2022). It is thought that many likely exert significant control over prey populations. However, data are lacking for most prey populations and insufficient modelling effort prevents accurate assessment of this indicator		Phenomenon (Appendix 8.4)
Functionally important species and biophysical structures; Biodiversity	Arctic *Calanus*	Arctic	Data not available		Phenomenon (Appendix 8.4)
Functionally important species and biophysical structures; Biodiversity	Atlantic *Calanus*	Arctic	Data not available		Phenomenon (Appendix 8.4)

5. Methods used to assess deviation from the reference condition

Deviation from the reference condition was assessed by comparing the *expected* variation in an indicator's value with increasing human pressure (phenomenon, see short titles in Tables 5.1a and b and full descriptions in sections 5.1 and 5.2) to *observed* trend in the indicator's data (see 4.2). If the fitted trend on the observed data was similar to what is expected given the observed variation in the relevant anthropogenic drivers, then there is evidence for deviation from the reference condition.

Table 5.1a. *List of phenomena including overall approach used to determine the extent to which each phenomenon has occurred in the Arctic part of the Barents Sea. Approach refers to methods used to determine the extent to which the phenomenon has occurred. (1) For quantitative phenomena: The values of the indicator relative to an estimated quantitative threshold value (2) For qualitative phenomena: The value of the indicator relative to variation estimated from the indicator time series or other qualitative or quantitative information about a reference state (3) For all phenomena: Observed and expected effects of changes in the indicator on other components of the ecosystem (i.e., ecosystem significance). TL: trophic level.*

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
Annual net primary productivity [AI01]	Increasing annual net primary productivity [AP01]	Climate change	2) and 3)
Timing of spring bloom [AI02]	Earlier start of the spring bloom [AP02]	Climate change	2) and 3)
Zooplankton TL < 2.5 [AI03]	Increasing biomass of zooplankton that is predominantly herbivorous [AP03]	Climate change	2) and 3)
Zooplankton TL > 2.5 [AI04]	Change in biomass of zooplankton that is predominantly carnivorous [AP04]	Climate change	2) and 3)
Benthic suspensivores [AI05]	Change in biomass of suspension feeding species [AP05]	Climate change	2) and 3)
0-group fish [AI06]	Increasing biomass of 0-group fish (except for polar cod) [AP06]	Climate change	2) and 3)
Pelagic planktivorous fish [AI07]	Decreasing biomass of pelagic planktivorous fish [AP07]	Climate change	2) and 3)
Low TL seabirds [AI08]	Decreasing biomass of low TL seabirds [AP08]	Climate change	2) and 3)
High TL seabirds [AI09]	Decreasing biomass of high TL seabirds [AP09]	Climate change, fisheries	2) and 3)
Low TL mammals [AI10]	Decreasing abundance of low TL mammals [AP10]	Overharvesting and climate change	2) and 3)
Generalist mammals [AI11]	Decreasing abundance of generalist mammals [AP11]	Overharvesting and climate change	2) and 3)
High TL mammals [AI12]	Decreasing abundance of high TL mammals [AP12]	Overhunting of bears and climate change	2) and 3)
High TL zooplankton functional groups [AI13]	Decreasing biomass of pelagic amphipods relative to gelatinous zooplankton [AP13]	Climate change	2) and 3)
Benthic habitat engineers [AI14]	Decreasing biomass of benthic habitat engineers [AP14]	Bottom trawling	2) and 3)
Fish size [AI15]	Increasing body length at maturity across species in a fish community [AP15]	Climate change	2) and 3)
Fish life history [AI16]	Increasing slow-life, periodic fish species [AP16]	Climate change	2) and 3)
Fish habitat use [AI17]	Change in proportion of benthic fish [AP17]	Climate change	2) and 3)
Seabird feeding types [AI18]	Decreasing proportion of diving to surface-feeding seabirds [AP18]	Fisheries	2) and 3)
Mammal bioturbation [AI19]	Decreasing abundance of mammals involved in bioturbation [AP19]	Climate change	2) and 3)

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
Pelagic amphipods [AI20]	Decreasing biomass of Arctic pelagic amphipod species [AP20]	Climate change	2) and 3)
Krill [AI21]	Increasing biomass of krill [AP21]	Climate change	2) and 3)
Polar cod [AI22]	Decreasing biomass of the polar cod stock [AP22]	Climate change	2) and 3)
Capelin [AI23]	Decreasing biomass of the capelin stock [AP23]	Climate change, fisheries	2) and 3)
Cod [AI24]	Change in cod total stock size [AP24]	Climate change (increase), fisheries (decrease)	2) and 3)
Cod size structure [AI25]	Decreasing biomass of large cod [AP25]	Fisheries	2) and 3)
Cod distribution [AI26]	Increasing biomass of cod in the Arctic Barents Sea [AP26]	Climate change	2) and 3)
Bottom thermal niches [AI27]	Decreasing area of bottom cold-water temperature niches	Climate change	2) and 3)
Sea-ice area [AI28]	Decreasing sea-ice area in winter and summer [AP28]	Climate change	2) and 3)
Arctic amphipod [AI29]	Decreasing biomass of the Arctic amphipod *Themisto libellula* [AP29]	Climate change	2) and 3)
Cold-water benthos [AI30]	Decreasing proportion of Arctic benthos species [AP30]	Climate change	2) and 3)
Arctic fish [AI31]	Decreasing abundance of Arctic fish species [AP31]	Climate change	2) and 3)
Fish sensitive to fisheries [AI32]	Decreasing abundance of fish species sensitive to fisheries [AP32]	Fisheries	2) and 3)
Seabirds sensitive to pollution [AI33]	Decreasing abundance of Glaucous gull [AP33]	Pollution	2) and 3)
Arctic seabirds [AI34]	Decreasing abundance of Arctic seabird species [AP34]	Climate change	2) and 3)
Mammals sensitive to pollution [AI35]	Decreasing abundance of mammal species sensitive to pollution [AP35]	Pollution	2) and 3)
Arctic mammals [AI36]	Decreasing abundance of Arctic mammal species [AP36]	Climate change	2) and 3)
Temperature [AI37]	Increasing temperature of the water column [AP37]	Climate change	2) and 3)
Area of water masses [AI38]	Decreasing area covered by Arctic Water [AP38]	Climate change	2) and 3)
Freshwater content [AI39]	Decreasing freshwater content [AP39]	Climate change	2) and 3)
Stratification [AI40]	Decreasing stratification of the upper water column [AP40]	Climate change	2) and 3)
pH [AI41]	Decreasing pH [AP41]	Global increase in CO_2	2) and 3)
Aragonite saturation [AI42]	Decreasing aragonite saturation [AP42]	Global increase in CO_2	2) and 3)

Table 5.1b. *List of phenomena including overall approach used to determine the extent to which each phenomenon has occurred in the Sub-Arctic part of the Barents Sea. Approach refers to methods used to determine the extent to which the phenomenon has occurred. (1) For quantitative phenomena: The values of the indicator relative to an estimated quantitative threshold value (2) For qualitative phenomena: The value of the indicator relative to variation estimated from the indicator time series or other qualitative or quantitative information about a reference state (3) For all phenomena: Observed and expected effects of changes in the indicator on other components of the eco-system (i.e., ecosystem significance). TL: trophic level*

Indicator [ID]	**Phenomenon [ID]**	**Anthropogenic drivers**	**Approach**
Annual net primary productivity [SI01]	Stable and later decreasing annual net primary productivity [SP01]	Climate change	2) and 3)
Timing of spring bloom [SI02]	Earlier start of the spring bloom [SP02]	Climate change	2) and 3)
Zooplankton TL < 2.5 [SI03]	Decreasing biomass of zooplankton that is predominantly herbivorous [SP03]	Climate change	2) and 3)
Zooplankton TL > 2.5 [SI04]	Increasing biomass of zooplankton that is predominantly carnivorous [SP04]	Climate change	2) and 3)
Benthic suspensivores [SI05]	Change in biomass of suspension feeding species [SP05]	Climate change	2) and 3)
0-group fish [SI06]	Increasing biomass of 0-group fish [SP06]	Climate change	2) and 3)
Pelagic planktivorous fish [SI07]	Change in biomass of pelagic planktivorous fish [SP07]	Climate change, fisheries	2) and 3)
High TL seabirds [SI08]	Change in biomass of high TL seabirds [SP08]	Climate change, fisheries	2) and 3)
Low TL mammals [SI09]	Change in abundance of low TL mammals [SP09]	Climate change, past over-harvesting	2) and 3)
Generalist mammals [SI10]	Change in abundance of generalist mammals [SP10]	Climate change, harvesting	2) and 3)
High TL mammals [SI11]	Change in abundance of high TL mammals [SP11]	Climate change, fisheries, pollution	2) and 3)
High TL zooplankton functional groups [SI12]	Change in biomass of carnivorous krill relative to gelatinous zooplankton [SP12]	Climate change	2) and 3)
Benthic habitat engineers [SI13]	Decreasing biomass of benthic habitat engineers [SP13]	Climate change, physical impact on seabed, and bottom trawling	2) and 3)
Fish size [SI14]	Decreasing body length at maturity across species in a fish community [SP14]	Climate change, fisheries	2) and 3)
Fish life history [SI15]	Decreasing slow-life, equilibrium fish species [SP15]	Fisheries	2) and 3)
Fish habitat use [SI16]	Change in proportion of benthic fish [SP16]	Climate change (decrease), fisheries (increase)	2) and 3)
Seabird feeding types [SI17]	Decreasing proportion of diving to surface-feeding seabirds [SP17]	Fisheries	2) and 3)
Mammals top-down control [SI18]	Change in ratio of high vs low trophic level mammals [SP18]	Climate change	2) and 3)
Arctic *Calanus* [SI19]	Decreasing abundance of Arctic *Calanus* species [SP19]	Climate change	2) and 3)
Atlantic *Calanus* [SI20]	Increasing abundance of Atlantic *Calanus* species [SP20]	Climate change	2) and 3)
Krill [SI21]	Increasing biomass of krill [SP21]	Climate change	2) and 3)

Indicator [ID]	Phenomenon [ID]	Anthropogenic drivers	Approach
Capelin [SI22]	Decreasing biomass of the capelin stock [SP22]	Climate change, fisheries	2) and 3)
Cod [SI23]	Change in cod total stock size [SP23]	Climate change (increase), fisheries (decrease)	2) and 3)
Cod size structure [SI24]	Decreasing biomass of large cod [SP24]	Fisheries	2) and 3)
Haddock [SI25]	Change in haddock stock size [SP25]	Climate change (increase), fisheries (decrease)	2) and 3)
Redfish [SI26]	Decreasing biomass of the beaked redfish stock [SP26]	Climate change, fisheries, oil extraction	2) and 3)
Bottom thermal niches [SI27]	Decreasing area of bottom cold-water temperature niches[SP27]	Climate change	2) and 3)
Benthos sensitive to bottom trawling [SI28]	Decreasing biomass of benthos species sensitive to trawling [SP28]	Bottom trawling	2) and 3)
Fish sensitive to fisheries [SI29]	Decreasing abundance of fish species sensitive to fisheries [SP29]	Fisheries	2) and 3)
Mammals sensitive to pollution [SI30]	Decreasing abundance of mammal species sensitive to pollution [SP30]	Pollution	2) and 3)
Mammal diversity [SI31]	Change in mammal species diversity [SP31]	Climate change	2) and 3)
Temperature [SI32]	Increase in temperature of the water column [SP32]	Climate change	2) and 3)
Area of water masses [SI33]	Increasing area covered by Atlantic Water [SP33]	Climate change	2) and 3)
Stratification [SI34]	Increasing stratification of the upper water column [SI34]	Climate change	2) and 3)
pH [SI35]	Decreasing pH [SP35]	Global increase in CO_2	2) and 3)
Aragonite saturation [SI36]	Decreasing aragonite saturation [SP36]	Global increase in CO_2	2) and 3)

5.1. Scientific evidence basis for the phenomena in the Arctic Barents Sea

Annual net primary productivity [AI01]

Phenomenon: Increasing annual net primary productivity [AP01]

Ecosystem characteristics: Primary productivity, Biomass distribution among trophic levels

Under the reference condition, primary production in the Arctic part of the Barents Sea is contributed by single-celled algae growing in the water column (phytoplankton) and in sea ice (ice algae). Strong seasonality in incoming light limits the time window during which primary production is possible. Consequently, there is a high seasonality in the availability of photosynthetically fixed carbon in the Arctic marine environment and the amplitude of the primary production cycle becomes increasingly shorter toward higher latitudes (Daase et al., 2021). In addition, sea ice limits the penetration of light into the water column. The freeze/melt cycle of sea ice also affects water mass stratification and mixing processes. These physical processes control the replenishment of essential nutrients to the euphotic zone, and thereby constrain primary production.

The most important anthropogenic driver of change in this indicator is climate change. The main climate change-induced effects on primary production in the Arctic part of the Barents Sea are mediated through decreased sea-ice cover, increased temperature of advected water and altered storm tracks and ocean- mixing regimes (Wassmann et al., 2010; Doney et al., 2012; Dalpadado et al., 2014, 2020; Arrigo and van Dijken, 2015; Yool et al., 2015; Lind et al., 2018). Loss of sea-ice habitat and earlier melt and later freeze-up will likely have a negative impact on annual ice algal primary production and the ice-associated food web (Barber et al., 2015; Selz et al., 2018). Field experiments also suggest that ice-algal production may decrease due to their sensitivity to elevated irradiance caused by loss of snow cover and thinning of ice (Lund-Hansen et al., 2020). As the sea ice declines, models and satellite observations (applied to the whole Barents Sea and for observations up to 2017 or earlier) have shown an increase in annual primary production for the Arctic part of the Barents Sea as a result of greater open-water area and longer growing season (Dalpadado et al., 2014, 2020; Arrigo and van Dijken, 2015; Yool et al., 2015; Mueter et al., 2021) as well as increased intensity of primary production per unit area (Lewis et al., 2020). Open-water fraction and length of growing season had the strongest positive impact on primary production during the late 1990’s and early 2000’s while increases in primary production after 2009 were largely driven by increased phytoplankton biomass. This suggests that light was the primary driver during the early observational period while increased nutrient flux was likely the main driver for the latter period (Lewis et al., 2020). This is consistent with weakened ocean stratification, enhanced vertical mixing and increased upward fluxes of heat and salt for the northern Barents Sea since the mid-2000s (Lind et al., 2018). It should be noted that light availability and hence primary production may be dampened by increases in cloud cover (Bélanger et al., 2013), and total annual production is eventually limited by nutrient availability (Randelhoff et al., 2015; Tremblay et al., 2015). Warming and increased advection of Atlantic water masses have also led to a poleward expansion of temperate phytoplankton in the Arctic part of the Barents Sea (Neukermans et al., 2018; Oziel et al., 2020) and satellite data indicate an increased dominance of *Phaeocystis*, an algal species presumably less palatable than diatoms in the Barents Sea (Orkney et al. 2020). Given the strong links between climate change and primary production, the current understanding of the link between drivers and changes in the indicator is rated as certain (see also Table 1 in (Mueter et al., 2021)).

Both models and observations show that primary production is generally positively related to fisheries yield (Iverson, 1990; Ware and Thomson, 2005; Chassot et al., 2007, 2010), thus providing strong evidence that changes in primary production have substantial impacts on other parts of marine ecosystems. Concurrent with increasing primary production in the Barents Sea, substantial increase in pelagic production has been observed (Eriksen et al., 2017), as well as increase in the stock of Atlantic cod, one of the most important predators in the system (Kjesbu et al., 2014). The understanding of the importance of changes in the indicator for other parts of the ecosystem is thus rated as good.

Although it is difficult to relate specific levels of increase in primary production to specific ecosystem changes, it seems likely that the level of change in primary production observed up to 2017 for the entire Arctic part of the Barents Sea (i.e., both Norwegian and Russian sector) is sufficient to trigger changes of **ecosystem significance**.

Knowledge gaps include a need for better *in situ* and autonomous measurements and estimates of the ratio of new to regenerated production, better insight into changes in phytoplankton/ice algal bloom phenology and the impact of changes in algal community composition on annual primary production and trophic transfer, and a need for better high spatial resolution models with high-quality atmospheric and sea-ice forcing.

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Timing of spring bloom [AI02]

Phenomenon: Earlier start of the spring bloom [AP02]

Ecosystem characteristic: Primary productivity

The description of the indicator under the reference condition is as given for the phenomenon for annual primary productivity [AP01].

The most important anthropogenic driver of change in this indicator is climate change. As light availability influences the start of the spring bloom, climate change acting through decreased sea-ice cover is a key driver. In addition to availability of light, retreat of the sea ice also affects the near-surface stratification by the release of freshwater at the surface, which positively influences the bloom (Hunt et al., 2011; Wassmann and Reigstad, 2011; Chierici et al., 2019). Satellite observations have shown an earlier spring bloom timing for the Arctic part of the Barents Sea of nearly one month (looking across both the Norwegian and the Russian sector, Dalpadado et al., 2020). Extensive under-ice phytoplankton blooms have been attributed to improved light conditions below sea ice as a result of thinner sea ice and increased melt pond and lead fractions (Arrigo et al., 2012; Assmy et al., 2017; Ardyna et al., 2020). Although direct evidence is currently lacking (Mueter et al., 2021), both observational (Ardyna and Arrigo, 2020) and modelling evidence (Horvat et al., 2017) point towards increased under-ice production. Given the evidence, the understanding of the link between driver (climate change) and the indicator is rated as certain.

Altered timing of the spring bloom may result in mismatches between phytoplankton and zooplankton grazers, which may affect zooplankton production and other parts of the ecosystem (Mueter et al., 2021). Examples of this include a mismatch between *Calanus hyperboreus* reproduction and the diatom bloom in the Beaufort Sea with consequences for *Calanus hyperboreus* production (Dezutter et al., 2019) as well as a mismatch between the ice algal bloom and *Calanus glacialis* reproduction in a high-Arctic fjord (Søreide et al., 2010). The current understanding of the importance of changes in the indicator for other parts of the ecosystem can be rated as good.

Too little is known about how a given change in spring bloom timing would affect the rest of the ecosystem to evaluate how large changes should be for effects with **ecosystem significance** to occur.

Knowledge gaps include a need for better and more seasonal *in situ* measurements, development of high spatial resolution models and sufficient time/space resolving of remote sensing and autonomous platform data.

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Zooplankton TL < 2.5 [AI03]

Phenomenon: Increasing biomass of zooplankton that is predominantly herbivorous [AP03]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the biomass and turnover of herbivorous zooplankton are large enough to support the community of Arctic predators that depend on lipid rich food sources, such as polar cod (*Boreogadus saida*), little auk (*Alle alle*) and bowhead whale (*Balaena mysticetus*) (Steen et al., 2007; Rogachev et al., 2008; Planque et al., 2014; Eriksen et al., 2020). Lipid-rich copepods such as *Calanus glacialis* and *Calanus hyperboreus* dominate the herbivorous mesozooplankton community in terms of biomass (Søreide et al., 2010; Eriksen et al., 2017; Aarflot et al., 2018; Hop et al., 2019; Dalpadado et al., 2020; Daase et al., 2021; Mueter et al., 2021), while several smaller herbivorous and omnivorous copepods dominate the Arctic mesozooplankton community in terms of numbers but contribute less to the biomass. Other larger herbivorous macrozooplankton such as euphausiids (krill) of the genus *Thysanoessa* are more dominant in the Sub-Arctic region and not an important component in the Arctic part under the reference condition (Dalpadado and Skjoldal, 1991; Søreide et al., 2003; Dalpadado et al., 2020). The pteropods *Limacina helicina* and *Clione limacina*, chaetognaths *Parasagitta elegans* and *Eukrohnia hamata,* ctenophores *Mertensia ovum* and *Beroe cucumis*, and cnidarians *Aglantha digitale* and *Sarsia* sp. are also important components of Arctic zooplankton communities (Søreide et al., 2003), as are pelagic hyperiid amphipod *Themisto libellula* (Koszteyn et al., 1995; Dalpadado et al., 2012, 2020), but most of these species are primarily omnivorous or carnivorous.

The most important anthropogenic driver of change in this indicator is climate change, causing increased water temperature and increased influx of Atlantic water masses (i.e., Atlantification) in the central and northern parts of the Barents Sea (Årthun et al., 2012, 2019; Ingvaldsen et al., 2021). This leads to changes in sea-ice cover and bloom phenology, expanding the productive season for resident species and making the region more habitable for boreal species from the south. The abundance of krill and small mesozooplankton have increased, whereas the abundance of large Arctic mesozooplankton have decreased during the last three decades (looking across both the Norwegian and the Russian sector, Eriksen and Dalpadado, 2011; Eriksen, 2017; Dalpadado et al., 2020). Effects of climate change on many aspects of the zooplankton community are known, in particular a tendency for biomass of large Arctic mesozooplankton to decrease and biomass of smaller Sub-Arctic mesozooplankton e.g., *C. finmarchicus* and euphausiids (in particular *T. inermis*) to increase (Eriksen et al., 2017; Hop et al., 2019; Stige et al., 2019; Dalpadado et al., 2020; Daase et al., 2021; Mueter et al., 2021). The indicator includes biomass of both mesozooplankton and krill, and although the opposing trends described above are likely to result in increased total biomass of herbivorous zooplankton, considerable uncertainties are associated with this. The understanding of the link to drivers should therefore be rated as less certain.

A large increase in the biomass of krill and small mesozooplankton (which is not offset by a decrease in large Arctic mesozooplankton) can have large effects on the predator community, possibly benefitting Sub-Arctic/boreal species, such as capelin (*Mallotus villosus*) (Dalpadado and Mowbray, 2013). This can have (indirect) effects on Arctic species that function as prey for these boreal predators (Stige et al., 2018). Even though we know much about trophic interactions and the importance of euphausiids, there are still many unknowns, for example how Arctic species may be affected indirectly from increased abundance of boreal predators (Johannesen et al., 2020), and indeed also the importance of increased biomass of krill for the boreal predators (Eriksen et al., 2017). The understanding of the importance of changes in the indicator for other parts of the ecosystem is thus rated as less good.

Knowledge gaps include lack of long-term data to assess changes in community structure with climate change and limited understanding of northwards extension of krill.

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Zooplankton TL > 2.5 [AI04]

Phenomenon: Change in biomass of zooplankton that is predominantly carnivorous [AP04]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the zooplankton community is dominated by large and lipid-rich species that occur in biomasses large enough to sustain the community of Arctic predators, including polar cod, little auk and bowhead whales (Steen et al., 2007; Rogachev et al., 2008; Planque et al., 2014; Eriksen et al., 2020). Examples of carnivorous zooplankton that would be important under the reference condition include Arctic pelagic amphipods, particularly *Themisto libellula* (Zhukova et al., 2009; Stige et al., 2019; Dalpadado et al., 2020), which functions as an important link between the herbivorous zooplankton prey and predators such as polar cod, black legged kittiwake (*Rissa tridactyla*), little auk, and seals (Auel et al., 2002; Falk-Petersen et al., 2004; Marion et al., 2008; Renaud et al., 2012; Nahrgang et al., 2014; Vihtakari et al., 2018). Chaetognaths also contribute significantly to the biomass of carnivorous zooplankton under the reference condition (Søreide et al., 2003; Grigor et al., 2017). Three chaetognath species are frequently reported in Arctic plankton surveys. *Parasagitta elegans* is a neritic species, abundant in epipelagic waters. *Eukrohnia hamata* is abundant in meso-pelagic and deep waters. The largest species, *Pseudosagitta maxima* (up to 90 mm) is typically bathy-pelagic but may also occur near the surface in the Arctic. Carnivorous krill do not contribute to the zooplankton community under the reference condition, as the predominantly carnivorous krill species in the Barents Sea, *Meganyctiphanes norvegica*, is mainly associated with advected Atlantic water masses in the southwest of the area under the reference condition (Dalpadado et al., 1998). The reference condition is also characterized by occurrences of gelatinous zooplankton (Falk-Petersen et al., 2002; Lundberg et al., 2006). It has been estimated that *Mertensia ovum* can consume up to 9% of the standing biomass of copepods in the Barents Sea per day when ctenophores were present (Swanberg and Bamstedt, 1991). However, much is unknown about this group and, consequently, uncertainties exist in our understanding of their role in the ecosystem under the reference condition (Eriksen et al., 2012; Eriksen et al., 2018).

The most important anthropogenic driver of change in the indicator is climate change. Climate change will lead to a northward expansion of Sub-Arctic and boreal species, including krill species, and a decline of Arctic species, such as pelagic amphipods (Eriksen, 2017; Hop et al., 2019; Stige et al., 2019; Dalpadado et al., 2020). Climate change may also favor gelatinous zooplankton, but there are large uncertainties associated with this (Eriksen et al., 2012, 2018). The indicator is made up of biomass of amphipods and gelatinous zooplankton, and it is difficult to predict the outcome of the opposing and partly uncertain trends for these two groups. The phenomenon is therefore stated as any change and not a directional one. The understanding of the link between the drivers and changes in the indicator is consequently rated as less certain.

Substantial changes in biomass of the carnivorous zooplankton community will likely have significant effects on the dynamics of at least parts of the ecosystem. For example, if the change is brought about by a decrease in biomass of pelagic amphipods, this can have negative effects on the lipid-dependent predator communities in the Arctic (Dalpadado et al., 2001, 2016; Descamps et al., 2017; Hop and Wiencke, 2019; ICES, 2020). As changes in other groups, such as gelatinous zooplankton (Eriksen et al., 2012, 2018) can have other effects, the overall effects of change in the indictor are hard to predict, and the understating of the importance of changes in the indicator for other parts of the ecosystem is thus rated as less good.

Knowledge gaps include lack of long-term data to assess changes in community composition and poor understanding of life history adaptations and vulnerabilities in gelatinous taxa. It should be noted that only the larger gelatinous zooplankton are currently monitored.

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Benthic suspensivores [AI05]

Phenomenon: Change in biomass of suspension feeding species [AP05]

Ecosystem characteristic: Biomass distribution among trophic levels

A description of the state of the indicator under reference conditions can be done but need more work (see e.g., Jørgensen et al., 2022).

The most important anthropogenic driver of change in this indicator may be climate change, which can directly and indirectly affect the phenology, quality, and quantity of phytodetritus reaching the seafloor. This is expected to occur due to changes in light climate due to altered ice cover (extent, thickness, seasonality). It has been shown, for example, that coastal Arctic benthic compartment production is tightly linked to surface primary production and ice cover (Tremblay et al., 2011). Trawling will likely also lead to this phenomenon (Jørgensen et al., 2015, 2019) as it would tend to reduce the biomass of those generally tall animals, more easily captured by the bottom trawls. In addition, potentially increased importance of advection/establishment of more southern phytoplankton taxa and/or elevated grazing by zooplankton may result in possibly lower likelihood of phytodetritus reaching the seafloor. The link to trawling needs to be verified through testing of existing data and for now is moderately certain. The role of climatic change for biomass distribution for benthic suspensivores is less certain. Thus, the knowledge about overall link of the indicator to the drivers is rated as less certain.

Suspension-feeding benthos such as sponges, bryozoans, hydroids, some sea cucumbers, and other species make up local large biomass of the seabed fauna (Kędra et al., 2013). Epibenthos plays a major role in the carbon cycling of the Arctic ecosystems (Grebmeier et al., 1995; Klages et al., 2004), thus suspension feeders may be central for the functioning in the ecosystem. Such local biomass accumulations with complex, large-bodied species may be refuge and feeding areas for fish and other benthic invertebrates (Kędra et al., 2015). The understanding of the importance for other parts of the ecosystem of decreasing proportion of suspension feeding biomass is moderately good.

The ecosystem significance of decreasing proportion of suspension feeding biomass has not been verified for the Barents Sea, but the effect of structure-forming corals and sponges and their use as fish habitat have been described for the Bering Sea submarine canyons (Miller et al., 2012), and effects on fish habitat and general support of higher biodiversity are expected to be similar for Norwegian cold-water coral habitats.

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0 group fish [AI06]

Phenomenon: Increasing biomass of 0-group fish (except for polar cod) [AP06]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the biomass of 0-group fish is large enough to support predator populations dependent on these fish larvae as prey, and also large enough to ensure sufficiently high recruitment to sustain the fish stocks themselves.

The most important anthropogenic driver of change in this indicator in the Arctic Barents Sea is climate change, through direct effects on their distribution and abundance. Larger areas of Atlantic water masses will lead to larger occupation area of 0-group cod, haddock and capelin (Eriksen et al., 2017). In the Arctic, the 2016 heatwave with the largest area of Atlantic and Mixed water masses was associated with high abundances of herring, haddock and capelin (ICES, 2020). However, it is suspected that higher temperature and lack of sea ice during the egg stage could be critical for polar cod (*Boreogadus saida*) and lead to less successful recruitment at later stages (Eriksen et al., 2012, 2015; Huserbråten et al., 2019). Most species of 0-group fish are expected to increase in abundance with climate change, except for polar cod. The understanding of this link to climate change is assessed as certain.

The four most abundant 0-group fish species are capelin, cod, haddock and herring. Strong year classes of those species lead to increased growth in the stock of adults in the following years. Those species are key to the Barents Sea and have huge impacts on the ecosystem as prey (capelin and younger stage of cod, haddock and cod), plankton consumers (capelin and herring) and predators (herring, cod and haddock). In addition, the 0-group fish have a wide distribution in the entire Barents Sea and is an important part of the pelagic stock in the summer and early autumn (Eriksen et al., 2011). Because of their large consumption/biomass ratio, 0-group fish have a central role in the energy transfer across trophic levels and between regions. They are preyed upon by many piscivorous fish, birds and marine mammals (Barrett and Krasnov, 1996; Skaug et al., 1997; Dalpadado and Bogstad, 2004). The understanding of the importance of changes in the biomass of 0-group fish for other parts of the ecosystem is assessed as good.

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Pelagic planktivorous fish [AI07]

Phenomenon: Decreasing biomass of pelagic planktivorous fish [AP07]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, pelagic planktivorous fish stocks of capelin and polar cod are large enough to support viable populations of endemic Arctic predators (fish, seabirds and mammals) dependent on these species as prey.

The most important anthropogenic driver of change in biomass of pelagic planktivorous fish is climate change. Less sea ice will lead to a shift where less primary productivity will sink to the benthic habitat, and more is consumed by zooplankton in the pelagic water masses (Kedra et al., 2015). This will increase the productivity in the otherwise typically low-productive pelagic habitat in Arctic areas (Hobson et al., 1995; Wassmann and Reigstad, 2011). However, despite this possible increase in pelagic productivity and food availability for planktivorous species, polar cod and capelin are expected to be negatively affected by climate change. Polar cod is the only endemic planktivorous fish species in the Arctic Barents Sea and is expected to be negatively affected by climate change due to its close association and dependence on sea ice (Mueter et al., 2016; Huserbråten et al., 2019; Gjøsæter et al., 2020) (more details in the phenomenon for Capelin [AP23]). Corresponding direct effects from climate change on the capelin stock biomass are more uncertain, however it is expected and observed that capelin feeding grounds have expanded northwards (Carscadden et al., 2013). The biomass of these pelagic planktivorous species is also strongly affected by predation from young NSS herring (Gjøsæter and Bogstad, 1998; Huse and Toresen, 2000; Gjøsæter et al., 2016) and NEA cod (Bogstad et al., 2000; Johannesen et al., 2012; Fall et al., 2018). Predatory interactions with these species are expected to increase with climate change in the Arctic part of the Barents Sea due to northward changes in distribution and increased overlap (Gjøsæter and Bogstad, 1998; Fall et al., 2018). In addition to effects of climate change, the distribution of these predatory fish stocks is affected by fisheries and population size; cod typically spread more into the northern regions when populations are large (Johannesen et al., 2020). Thus, the overall effect from climate change on polar cod and capelin is expected to be negative, and the knowledge about link between driver and indicator is assessed as less certain.

Planktivorous fishes have a key role in top-down regulation of pelagic consumers (zooplankton), and are important for energy transfer to top predators, such as marine mammals, seabirds, and fish (Dolgov, 2002; Orlova et al., 2009; Sakshaug et al., 2009; Jakobsen and Ozhigin, 2011; Hop and Gjøsæter, 2013; Mueter et al., 2016). In particular, the polar cod is essential food for ice-associated mammals including ringed seals, narwhal and white whale as well as fish-eating Arctic seabirds such as Brünnich’s guillemot, black guillemot and Arctic fulmar (Hop and Gjøsæter, 2013). In addition, polar cod is important food for many Arctic fishes, including Arctic skate (*Amblyraja hyperborea),* NEA cod *(Gadus morhua),* Greenland halibut *(Reinhardtius hippoglossoides),* and striped seasnail *(Liparis bathyarcticus*) (Eriksen et al., 2020). The NEA cod is dependent upon capelin for sustaining its high abundance. The capelin is also a key diet item for whales, several seabird species, harp seals and other fish species (Dolgov, 2002). There is also evidence that capelin can inflict top-down effects on its zooplankton prey (Hassel et al., 1991; Dalpadado and Skjoldal, 1996). The understanding of the importance of changes in biomass of pelagic planktivores for other parts of the ecosystem is assessed as good.

Decreasing biomass of pelagic planktivores can be considered of **ecosystem significance** if, for example it has i) direct effects on zooplankton, such as increase in biomass proportion of larger species and size-classes, ii) positive indirect effects on other planktivores through decreased competition, e.g. mammals, seabirds (e.g., little auk) iii) direct negative effects on piscivorous seabirds (e.g., Brünnich´s guillemot), fish, mammals (e.g., narwhals, ringed seals).

Knowledge gaps:

There are uncertainties about energy channeling of increased primary production, related to, for example, how much of the production goes into zooplankton and then higher trophic levels like planktivorous fish.

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Low trophic level seabirds [AI08]

Phenomenon: Decreasing biomass of low trophic level seabirds [AP08]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, little auk (*Alle alle*) is a numerous and important zooplanktivorous seabird species in the Arctic Barents Sea ecosystem (ICES, 2020). Historical changes in the abundance of natural competitors due to industrial whaling and fishing have probably influenced the current abundance of the species (Hacquebord, 2001).

The most important current anthropogenic driver of change for little auks is climate change (Hovinen et al., 2014a, b; Jakubas et al., 2017; Descamps and Strøm, 2021). As an ice-associated species depending on Arctic lipid-rich sympagic zooplankton (Isaksen and Gavrilo, 2000), it has been hypothesized that diminishing sea ice associated with climate warming will have detrimental impact on the populations of little auks (Karnovsky et al., 2010). Moreover, it has been suggested that little auks will be displaced northwards as their habitat in the marginal ice-zone is moving north under climate warming (Karnovsky et al., 2010). Thus, a decline in abundance and a northward shift in little auks are expected in the Barents Sea as a response to climate warming. The indicator is based on data from the ecosystem survey in the Barents Sea, which is conducted in September, representing the post-breeding period when the species is molting and before they start their southwest migration out of the Barents Sea. There is good theoretical and empirical knowledge underpinning the mechanisms of the proposed phenomenon and the understanding of the link to climate change is assessed as certain.

Little auks are considered to be the most abundant seabird species in the Arctic (Stempniewicz, 2001) and an important part of Arctic ecosystems (Karnovsky and Hunt, 2002; González-Bergonzoni et al., 2017). Little auks are a part of the ice-associated Arctic ecosystem which includes sympagic algae and zooplankton, polar cod, ice seals, and bowhead whales. A reduced abundance and a northward displacement of little auks in the Barents Sea could reflect bottom-up changes in this ecosystem. Specifically, it would indicate reduced availability and/or changed distribution of lipid-rich Arctic zooplankton which are central links between primary production and upper trophic levels in the system. A reduction in the abundance of little auks is likely to be accompanied by an increase in boreal planktivorous species such as capelin, mackerel and herring that are better adapted to utilize the smaller boreal zooplankton species (Stempniewicz et al., 2007), and an increase in boreal fish-eating seabirds (Descamps and Strøm, 2021).

Little auks provide an important link to terrestrial ecosystems. The large high-Arctic breeding colonies provide significant amounts of nutrients (nitrogen) to the tundra vegetation (Skrzypek et al., 2015) and the terrestrial landscapes engineered by little auks are important habitats for geese and reindeer (*Rangifer tarandus*) (González-Bergonzoni et al., 2017; Mosbech et al., 2018). A reduction in the breeding population will therefore also have consequences for high-arctic terrestrial ecosystems. Little auks are also important prey for glaucous gulls (*Larus hyperboreus*), gyrfalcons (*Falco rusticolus*), and Arctic foxes (*Alopex lagopus*) (Mosbech et al., 2018). The understanding of the importance of changes in the biomass of little auks for other parts of the ecosystem is assessed as good.

Decreasing biomass of little auks can be considered of **ecosystem significance** if there is a significant gradual long-term (> 10 years) change in the biomass associated with climate warming and a borealization of the Arctic ecosystem.

Knowledge gaps:

Foraging behavior, migration, reproduction and demography are monitored in selected breeding colonies at Bear Island and Spitsbergen. There is, however, little data on the overall population dynamics of little auks. There is little information on the interactions between little auks and prey and between little auks and competitors at sea. The time series from the ecosystem survey in the Barents Sea is relatively short (2004-2020).

The indicator is sensitive to natural fluctuations in, for example, the Barents Sea climate and the abundance and distribution of key species such as capelin. Within limits, little auks are likely to adapt to reduced sea-ice concentration and availability of lipid-rich zooplankton (Grémillet et al., 2012; Jakubas et al., 2017). Lagged responses could therefore be expected.

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High trophic level seabirds [AI09]

Phenomenon: Decreasing biomass of high trophic level seabirds [AP09]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, Brünnich’s guillemot (*Uria lomvia*) and kittiwake (*Rissa tridactyla*) are important piscivorous predators in the Barents Sea ecosystem and a dominant part of the avifauna in the central to Arctic part of the Barents Sea (ICES, 2020). Historical hunting and industrial fishing of important prey items had large impacts on the population dynamics of these species during the 20 th century (Krashnov and Barrett, 1995).

Climate change is considered to be a dominant anthropogenic driver affecting the populations of Brünnich’s guillemots and black-legged kittiwakes on Svalbard (Descamps et al., 2013; Descamps and Ramírez, 2021; Descamps and Strøm, 2021). However, the links to climate change are often complex including changes in sea-ice cover and changes in the pelagic food web affecting the availability of small pelagic fish as prey (Descamps et al., 2013; Descamps and Ramírez, 2021). Although both species are considered to be Arctic, they could, as piscivorous predators, temporarily profit from a borealization of the ecosystem when the change involves a higher abundance of small pelagic fish, such as capelin (Vihtakari et al., 2018).

An unprecedented mass die-off of seabirds, most notably murres, was recently observed in the North Pacific following a marine heat wave, causing widespread changes at lower trophic levels and subsequent starvation among seabirds (Piatt et al., 2020). Such climate extremes, which are expected to increase in frequency due to climate change, could have pervasive impacts on the Arctic marine ecosystems and seabird populations in particular.

Competition with industrial fisheries targeting small pelagic fish has been argued to be an important factor affecting seabird populations worldwide (Cury et al., 2011; Grémillet et al., 2018). In September, black-legged kittiwakes and Brünnich´s guillemots are found in large number in the central part of the Barents Sea, closely associated with capelin. Both species depend on capelin as a prey item during autumn when capelin are on a feeding migration north in the Barents Sea and during pre-breeding, in February – April, when capelin are on a spawning migration towards the coasts of Norway and Murmansk (Fauchald and Erikstad, 2002; Reiertsen et al., 2014). The commercial capelin fishery could accordingly be an anthropogenic factor that indirectly affects the abundance of the two seabird species in the Barents Sea. However, the current prudent regulation of the fishery suggests that the fluctuations in the abundance of capelin might be caused by other factors.

The understanding of the links between the indicator and climate change and fishery are assessed as certain. Fisheries are expected to affect the populations negatively. Climate change is expected to affect the populations negatively through increased frequency of extreme events and through a borealization of the ecosystem. The mechanisms are well understood and there is good empirical evidence for anthropogenic impacts caused by over-fishing and climate change.

Black-legged kittiwakes and Brünnich’s guillemots are, together with marine mammals and cod, important predators on pelagic fish in the Barents Sea and constitute a significant part of the top-predator guild in the ecosystem (ICES, 2020). A large relative drop in the abundance of these species could impact their role as top predators in the ecosystem and would signal negative changes at lower trophic levels (Krashnov and Barrett, 1995; Reiertsen et al., 2014; Vihtakari et al., 2018; Descamps and Strøm, 2021). The understanding of the importance of changes in the biomass of Brünnich’s guillemots and black-legged kittiwakes for other parts of the ecosystem is assessed as good.

Decreasing biomass of Arctic high trophic level seabirds can be considered of **ecosystem significance** if, for example i) there is a sudden drop in the biomass caused by a mass die-off of birds following a collapse in the availability of prey due to climate extremes or over-fishing, ii) there is a significant gradual long-term (> 10 years) decrease in the biomass associated with climate warming and a borealization of the ecosystem.

Knowledge gaps:

Foraging behavior, diet, migration, reproduction and demography are monitored in selected breeding colonies on Bear Island and Spitsbergen. The time series from the ecosystem survey in the Barents Sea is relatively short (2004-2020). The indicator is sensitive to natural fluctuations in the Barents Sea climate and the abundance and distribution of key species such as capelin. Lagged responses could be expected with respect to the effects of borealization. The impacts from fishing and climate change are mediated through multiple direct and indirect pathways, and the relative importance of these drivers is therefore often difficult to separate. More knowledge is needed to understand the mechanisms and dynamics related to these drivers.

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Low trophic level mammals [AI10]

Phenomenon: Decreasing abundance of low trophic level mammals [AP10]

Ecosystem characteristic: Biomass distribution among trophic levels

The two Arctic lower-trophic feeding marine mammal species in the Barents Sea, bowhead whales and walruses were hunted to near extirpation before being protected. Original pre-whaling stock size has been estimated for bowheads (Allen and Keay, 2006) and also for walruses from Svalbard based on records of catches and products reaching markets (Gjertz and Wiig, 1998; Weslawski et al., 2000).

Historically harvest was unquestionable the major driver to population size (biomass) of both species. However, the major driver for these species now is climate change (Kaschner et al., 2011; Kovacs et al., 2021). The status for the Barents Sea bowhead population has just been reclassified as Endangered (RL 2021), downlisted from Critically Endangered, because these whales have recently been found in larger numbers than expected (100s vs 10s), within the marginal sea-ice zone of the northern Barents Sea in summer and even deeper into the ice in winter (Ahonen et al., 2017; Vacquié-Garcia et al., 2017a; Kovacs et al. 2020). The current trend in this population is unknown, but the future trend in this region is expected to be negative because of the strong affiliation that this population displays for sea ice (Stafford et al., 2012; Kovacs et al., 2020). Their dietary specialization on Arctic calanoid copepods also puts them at risk in an Arctic with decreasing sea ice. It is unknown what will happen to Arctic copepods when the summer sea ice retreats beyond the coastal shelves into the deep Arctic Ocean. Increasing ship traffic and ocean noise in general are also perceived to be potential drivers for Barents Sea bowhead whales because this very small population communicates over vast distances (Reeves et al., 2014; Blackwell and Thode, 2021). Bowhead whales remain severely depressed in numbers compared to pre-whaling stock size.

In recent decades, walruses are showing an increasing trend in the Svalbard Archipelago (Lydersen et al., 2008; Kovacs et al., 2014; https://www.mosj.no), despite the likelihood that climate change is already having negative impacts on benthic productivity due to reduced ice cover (Kovacs et al., 2015). The current positive trend is due to the fact that walruses were hunted down to such low numbers that carrying capacity continues to exceed their current abundance (Kovacs et al., 2014). However, the population is very small compared to pre-hunting levels and it is expected that this species will decline in the future because of reduced benthic productivity as a result of sympagic nutrient declines with reduced sea ice (see Ershova et al., 2019; Bluhm et al., 2020). Increased tourism over recent decades has not had negative impacts on walruses in the Svalbard area; they appear to be quite resilient to this potential disturbance factor (Øren et al., 2018). Walruses in Norwegian waters are classified as vulnerable (VU) because of on-going deterioration of their sea-ice habitat.

Knowledge about the link to anthropogenic drivers is assessed as certain. Both of these populations remain dramatically reduced compared to preharvest levels.

These two lower-trophic feeding species have considerable impacts on the ecosystems they occupy, similar to other marine mammals, largely because their large body size(s) resulting in likely top-down control of prey species. However, they also perform unique ecological roles that include vertical circulation of nutrients by bowhead whales and bioturbation of benthic environments by walruses (Oliver et al., 1985). Dead whale carcasses also represent large nutrient supplies for scavengers both on the sea floor and when they wash ashore. This food source is particularly important to polar bears during summer in the Svalbard Archipelago (see below for details regarding these ecosystem interactions). Although common wisdom suggests that these animals have considerable influence on the structuring of the ecosystems that they occupy, the understanding of the results of changes in their standing biomass is complex and not well documented. Alteration of numbers/biomass in the indicators can alter the abundance of other species as well as altering the structure and functioning of the ecosystems they occupy i.e., declines in walruses is thought to have resulted in dramatically increased numbers of bearded seals in the Svalbard area (Weslawski et al., 2000). High densities of walruses would almost certainly influence *Mya truncata*, and perhaps also other benthic invertebrate, densities - although little is known about the prey base for walruses in Svalbard. Effects of reduced numbers of bowhead whales are more uncertain, because their current biomass is low and also given that this species has displayed some capacity to prey-switch in other Arctic areas (Lowry et al., 2004).

Knowledge about importance of changes in the indicator for other parts of the ecosystem is thus assessed as less good.

Current monitoring of abundance of bowhead whales is insufficient to accurately detect trends in this species. Walruses in Svalbard have been surveyed regularly in the past two decades, though numbers of the whole population are uncertain because Russian parts of their distribution in the Barents Sea have never been surveyed. Increased monitoring effort is needed for both species.

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Generalist mammals [AI11]

Phenomenon: *Decreasing abundance of generalist mammals [AP11]*

Ecosystem characteristic: Biomass distribution among trophic levels

Some of the generalist feeding marine mammal species occupying Arctic areas in the Barents Sea are known to have been reduced via commercial overharvesting in some periods, e.g., harp seals and hooded seals, while the others (e.g., harbour, ringed, and bearded seals) have received less concerted hunting pressure (and these harvests have been more poorly documented). Although original stock size is not known with certainty for any of these species, back-calculations are available for the two commercially harvested seals (see https://www.mosj.no).

Harp seals numbers are somewhat reduced from Post WWII levels, but they are still the most numerous pinnipeds in the Arctic regions of the Barents Sea, at least seasonally. Population size is estimated to be in excess of 425,000 animals for the West Ice breeding area and approximately 1.5 M animals from the White Sea breeding area (ICES, 2019). Many of the White Sea breeding harp seals feed seasonally at marginal ice-edge in the northern Barents Sea, sympatrically with West Ice animals, during summer and autumn (Folkow et al., 2004; Nordøy et al., 2008; Lindstrøm et al., 2013; Haug et al., 2021). Although the current population trend for both stocks is increasing, declines in body condition and reproductive rates are a concern (Øigård et al., 2013; Stenson et al., 2016, 2020). Low levels of reproduction for some recent periods in the White Sea/Barents Sea are thought to be due to increased pup mortality because of poor ice conditions in combination with competition for food with the large Atlantic cod stock (Stenson et al., 2020).

Hooded seals have declined precipitously since the 1950s in the Barents Sea. The most recent survey of Greenland Sea hooded seals was conducted in 2018 (ICES, 2019a). Pup production (12,977 CI= 9867–17067) estimated from this survey was lower than the surveys in 2005 and 2007, but similar to the survey conducted in 2012 (Øigård et al., 2014). Population models suggest that the population is either stable (at a new low level - circa 80,000) or is continuing to decline slowly, despite a ban on commercial hunting that was put in place in 2007 (ICES, 2019a). Some of the hooded seal harvest in Southeast Greenland is very likely from this Endangered stock (RL, 2021). Climate change is a serious conservation concern for this ice-breeding species (Kovacs et al., 2011, 2012). Sea-ice losses have occurred throughout the species' range over the last few decades (e.g., Stenson and Hamill, 2014; Spreen et al., 2020) and in the Greenland Sea floes are smaller and less stable, which likely impacts survivorship of pups. Additionally, pupping areas have shifted closer to the Greenland coast where hooded seals of all ages are more vulnerable to polar bear predation (Øigård et al., 2014). The occurrence of hooded seals has increased in the diet of both polar bears and killer whales in east Greenland (Foote et al., 2013; McKinney et al., 2013). Hooded seals from the West Ice disperse broadly outside the breeding season, covering much of the North Atlantic Arctic (Vacquiè-Garcia et al., 2017b). Prey abundance and distribution in the Greenland Sea are undergoing significant change that is very likely to impact hooded seals (e.g., Christiansen, 2017; ICES, 2019b; Pedersen et al., 2020). A recent dietary study on Greenland Sea hooded seals found that their diet is dominated by polar cod *(Boreogadus saida*), which is undergoing decline throughout the Barents region (Enoksen et al., 2017). Hooded seals also consumed krill and squid (*Gonatus fabricii*), but at lower levels than in the past. Despite some evidence of prey shifting, Enoksen et al. (2017) concluded that Greenland Sea hooded seals show narrow niche breadth and specialization on Arctic fishes that makes them particularly vulnerable to negative impacts of climate change.

Ringed seals and bearded seals have been harvested by explorers and whalers in the Norwegian Arctic, with significant numbers of bearded seals in particular being taken by some expeditions that did "plukk-fangst" – taking all of the marine mammals they came upon. Hundreds of animals were taken by individual boats in some years from this relatively low-density species. Data are insufficient to determine whether these harvests had population-level impacts, though it is likely that they did. Current population sizes and trends are unknown although some baseline data are available (e.g., Krafft et al., 2006). Ringed seals are a species of special concern with respect to climate change because of their unique breeding ecology – giving birth and nursing their young in snow caves on top of sea ice (see Kovacs et al., 2011). In Svalbard, where sea-ice conditions have changed dramatically in recent decades, ringed seals appear to be retracting into small Arctic refugia areas and are not showing signs of flexibility with regard to habitat choices (although see Lydersen et al., 2017) or dietary change (Hamilton et al., 2016; Bengtsson et al., 2020). They are diving more and resting less in both offshore and coastal habitats, suggesting that they are working harder to find food; offshore they are doing less sympagic diving and less area-restricted search as well (Hamilton et al., 2015; 2016; 2018a). Summer foraging migrations are now a lot longer compared to a decade ago, to reach preferred sea-ice concentrations (Lone et al., 2019).

Less is known regarding how bearded seals are responding to changing ice conditions, although they transitioned readily from annual ice to glacier ice pieces for pupping and nursing when sea ice collapsed in Svalbard fjords in 2006 (Kovacs et al., 2020), but this alternate habitat is not likely to be a long-term solution in this region given that tide-water glaciers are melting and retracting onto shore. Bearded seal diets show variance with different ice concentrations in some areas (Hindell et al., 2012 ; Wang et al., 2016), with shifts between proportions of invertebrate vs fish occurring either through time or in direct association with sea-ice concentration variation as well as varying with age class (Young et al., 2010). Increased risk of health-related problems with reduced sea ice is a serious concern for Arctic endemic seals, including bearded seals, that are unlikely to have immunity to many viruses, bacteria, parasites etc. that have not been part of their evolutionary history, but which are likely to become more prevalent in a warmer Arctic (e.g., VanWormer et al., 2019). Both ringed and bearded seals are Red Listed in Norwegian waters because of habitat deterioration (RL, 2021).

Among the generalist feeding marine mammal species occupying Arctic areas of the Barents Sea, the major driver of abundance/biomass has historically been harvesting. Commercial harvests are currently conducted within sustainable limits for harp seals, and hooded seals are totally protected. However, despite the harvest being stopped in 2008, hooded seals are not showing any signs of recovery. In Arctic areas, ringed seals and bearded seals are hunted at low levels in a sport-hunt and small quotas are assigned for these species in mainland Norway; sustainability of these harvest has not been evaluated but for ringed seals in some fjords, hunting might be a threat. The most important driver for all of the generalist feeding ice-dependent marine mammal species in the Barents Sea region is now climate change. Negative abundance trends are expected in the future due to both direct (habitat reductions) and indirect (food web changes, disease increases, increased toxicity of contaminants etc) effects of climate change (Laidre et al., 2015; Kovacs et al., 2021).

The small Arctic harbour seal population in in the Svalbard Archipelago is currently extending its distribution northward along the coast of Spitsbergen, where they now occupy fjords that are undergoing Atlantification (Storrie et al., 2018 ; Bengtsson et al., 2020). They are expected to continue to be “climate winners” (Blanchet et al., 2014) and will likely exacerbate negative impacts of climate change on ringed and bearded seals via interspecific competition; unlike the endemic species, that seem to have evolved into somewhat separate feeding niches (Wathne et al., 2000; Hamilton et al., 2019) This population should be monitored in this context.

Knowledge about the link to anthropogenic drivers is assessed as certain.

Similar to the other marine mammals, generalist feeding marine mammals exert considerable influences on the ecosystems they occupy. These include - top-down control, and bioturbation of benthos (bearded seals). Although common wisdom suggests that these animals have considerable influence on the structuring of the ecosystems that they occupy, the understanding of the results of changes in their standing biomass is complex and not well documented. The knowledge about the importance of changes in the indicator for other parts of the ecosystem is thus assessed as less good.

Harp seals are monitoring within the ICES system (e.g., ICES, 2019) with updated population abundance information every five years. The Arctic generalists (ringed, bearded and harbour seals) currently represent gaps in knowledge (data insufficient) although some base-line information is available for ringed and harbour seals (Krafft et al., 2006; Merkel et al., 2013).

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High trophic level mammals [AI12]

Phenomenon: Decreasing abundance of high trophic level mammals [AP12]

Ecosystem characteristic: Biomass distribution among trophic levels

Important mammal top predators in the Arctic Barents Sea are polar bears, white whales and narwhals. Polar bears and white whales were hunted to near extinction in the Norwegian sectors of the Barents Sea (Lønø, 1970; Lydersen and Kovacs, 2021). Polar bear harvests in Svalbard exceeded the currently estimated total stock in many 5-year periods leading up to protection in 1973 (Lønø, 1970) and in some periods were two times the current estimate for the total resident stock. Polar bears are part of the MOSJ monitoring programme (https://MOSJ.no), but the species has only been surveyed twice and the second survey did not include the entire range, so the trend is only available for bears resident in the Svalbard Archipelago (Aars et al., 2009, 2017). Narwhal were taken whenever they were accessible, but historically this harvest did not comprise large numbers of animals. Narwhals and white whales have recently been surveyed for the first time in the Barents Region (Vacquie-Garcia et al. 2017, 2020), providing status information and a base for future trend assessments. White whale harvests have been reviewed (Lønø and Øynes, 1961), so minimal estimates of the takes in Svalbard are known; it is likely that the population was reduced by 95% when it was declared commercially extinct in the early 1960s, and subsequently protected (Lydersen and Kovacs 2021, RL 2021).

Historically harvest was unquestionably the most important driver for polar bear and white whale abundance. Presently climate change and pollutants are the most likely anthropogenic drivers for these two species. Polar bears have undergone some recovery in the period that they have been protected (since 1973) and the population that is resident in Svalbard is estimated to be either stable (some 250 animals) or increasing slightly. However, as ice- affiliated seals whales decline with climate change, polar bear numbers are expected to also decline (Aars et al., 2017; Stern and Laidre, 2016; Kovacs et al. 2021); reproductive values are already showing slight downward tendencies. Climate change is likely going to be the most important driver for future narwhal abundance in the Barents Sea as well. Hunting is currently also a serious issue for narwhal in East Greenland (Heide-Jørgensen et al. 2020), but connectivity among Greenlandic and Norwegian stocks is unknown. Narwhals in the northern Barents region appear to be tightly ice-affiliated (Vacquié Garcia et al., 2017; Ahonen et al., 2019) and are thus likely to be particularly sensitive to ongoing declines in sea ice compared to populations that spend some seasons in coastal ice-free areas. This species is also thought to be particularly sensitive to anthropogenic noise (Laidre et al., 2015). Currently the number of white whales in Svalbard is low (Vacquié-Garcia et al., 2020) and habitat deterioration is expected to result in further decline. High levels of pollutants are also of concern for this species and the narwhal in the Norwegian Arctic (Andersen et al., 2001, 2006; Wolkers et al., 2004, 2006; Villanger et al., 2020). Knowledge about the link to anthropogenic drivers is assessed as certain.

Top-trophic feeding marine mammals likely exert considerable influences on the ecosystems they occupy. These include - top-down control, vertical circulation of nutrients (e.g., Lavery et al., 2014; Devred et al., 2021), bioturbation of benthos for benthic feeders (white whales), and dead whales represent nutrients for scavengers (including polar bears) (see below for details regarding these ecosystem interactions). Polar bears as pinnacle predators have particularly high capacities to influence prey populations. Although common wisdom suggests that these animals have considerable influence on the structuring of the ecosystems that they occupy, the understanding of the results of changes in their standing biomass is complex and not well documented. Knowledge about the importance of change in the indicator for other parts of the ecosystem is thus assessed as less good.

Alteration of numbers/biomass in the indicators can alter the abundance of other species as well as altering the structure and functioning of the ecosystems they occupy i.e., increases in killer whales in the Canadian Arctic have resulted in increased predation pressure on the ice-associated Artic endemic whales (Mathews et al., 2020).

Even though polar bears are a selected monitoring species in MOSJ, surveys are only conducted intermittently (Aars et al., 2009, 2017) and recent information from Russian areas is lacking completely. There is no established monitoring of white whales or narwhal, creating a serious knowledge gap for these species.

It is certain that polar bear and white whale populations remain significantly reduced from historical population sizes. Polar bears are listed as Vulnerable on the Norwegian Red List due to habitat deterioration (RL, 2021). White whales have recently been designated as Endangered due to the massive reduction in population size due to harvesting, the small number remaining and future predictions for declines in core habitat areas (sea ice and glacier fronts) (RL, 2021). Increased monitoring effort is needed to document trends in the high-trophic feeding marine mammal populations in the Barents Sea.

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High TL zooplankton functional groups [AI13]

Phenomenon: Decreasing biomass of pelagic amphipods relative to gelatinous zooplankton [AP13]

Ecosystem characteristic: Functional groups within trophic levels

The indicator is estimated using biomass data based on pelagic trawl catches for pelagic amphipods and gelatinous zooplankton. Under the reference condition, pelagic amphipods, and in particular the hyperiid *Themisto libellula*, are a significant component of the zooplankton community in the Arctic part of the Barents Sea (Zhukova et al., 2009; Stige et al., 2019; Dalpadado et al., 2020) and important for sustaining lipid-dependent Arctic predators, such as the polar cod (Dalpadado et al., 2001, 2016; Hop and Wiencke, 2019; ICES, 2020). There are larger uncertainties associated with our understanding of the ecosystem role of gelatinous zooplankton in general (e.g., Hays et al., 2018; Stoltenberg et al., 2021), and thus also for the Arctic part of the Barents Sea in particular (Swanberg and Bamstedt, 1991) under the reference condition.

The most important anthropogenic driver of change in the indicator is climate change, particularly rising temperatures and increased darkening of the water column in coastal areas. Large pelagic amphipods are negatively affected by increasing temperatures and declining sea-ice cover (Stige et al., 2019; Dalpadado et al., 2020). There are indications that climate change may have a positive effect on jellyfish, but the evidence is weak and limited to ctenophoran and scyphozoan species (Eriksen et al., 2012, 2018). Darkening of the water column because of higher levels of suspended matter from run off in coastal areas may enhance tactile predators, such as gelatinous zooplankton, over visual predators (Aksnes et al., 2009; Szeligowska et al., 2021). The understanding of the link between driver and indicator is therefore rated as less certain.

Amphipods and jellyfish have widely different functions as predators and prey, and a substantial change in the ratio of biomass of these two groups is likely to have ecosystem effects. However, while much is known about the role of amphipods as prey and predator, considerably less is known about gelatinous species (see above). The overall uncertainties are substantial, and the understanding of the importance of changes in the indicator for other parts of the ecosystem is thus rated as less good.

Important knowledge gaps include abundance estimates of gelatinous zooplankton and the importance of jellyfish as predators and prey (i.e. their importance in the food web), including differentiating the roles of smaller jellyfish and larger ones.

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Benthic habitat engineers [AI14]

Phenomenon: Decreasing biomass of benthic habitat engineers [AP14]

Ecosystem characteristic: Functional groups within trophic levels

Under reference conditions, biomass of benthic habitat engineers should be sufficient to host local biodiversity hot spots and provide the ecosystem with habitat complexity promoting nursing and feeding.

The most important anthropogenic driver of change in this indicator is bottom-trawling. Local, large, erected, and immobile species will have a high likelihood of being hit by a bottom trawl compared to small, cryptic infaunal species. Arguably, much of the trawling effect in the southern Barents Sea has already been realized, so effects in the northern regions (AI307) are more likely to be observed when trawling moratoria in the northern Barents Sea are lifted. Some effects are likely already being felt north of Svalbard where shrimp and cod trawling is underway (Sswat et al., 2015). Several studies (Jørgensen et al., 2016, 2019; Øseth et al., 2016) have indicated the threat of bottom trawling to habitat engineers in the northern Barents Sea and rate these areas highly vulnerable to trawling effects (and combined effects with climate warming). The understanding of the link between the driver and the indicator is thus rated as “ certain ”.

Removal of existing benthic species constitutes a development away from intact nature (i.e., without human pressures). Habitat engineers provide substrate and food for a large number of species, and it can be expected that reduction in these habitat-forming species will reduce biodiversity levels. This may be particularly important in areas thus far not experiencing bottom trawling and other seafloor disturbances.

The ecosystem significance of decreasing benthic habitat engineers has not been verified for the Barents Sea, but the effect of structure-forming corals and sponges and their use as fish habitat has been described for the Bering Sea Submarine Canyons (Miller et al., 2018). The understanding of the importance for the rest of the ecosystem of decreasing Benthic habitat engineers is thus rated as good.

The term 'habitat engineer' specifically indicates how the species modifies the environment. Changes in seafloor/habitat heterogeneity, altered bottom-currents, and changes in resuspension and particle loads are just a few changes in the seafloor environment that will likely lead to changes in other components of the system. Indeed, some of the species forming habitat are highlighted as specifically important or vulnerable (sponges, corals, sea pens). Few specific studies have addressed this specifically in the northern or southern Barents Sea, but these patterns of impact have been observed elsewhere and can be expected to occur in the Barents Sea as well.

Knowledge gaps: A risk-analysis of having bottom-trawling in areas with large, upraised, immobile species needs to be made.

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Fish size [AI15]

Phenomenon: Increasing body length at maturity across species in a fish community [AP15]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, community mean body length of demersal fish in the Arctic is comparatively smaller than in the Sub-Arctic region, since Arctic fish species are typically smaller and mature earlier compared to boreal species (Wiedmann et al., 2014).

The most important anthropogenic driver of change in this indicator is climate change. Arctic species are characterized by smaller body length at maturation compared to Sub-Arctic and boreal species (Wiedmann et al., 2014). Due to climate change, southern species are redistributing northwards (Fossheim et al., 2015). The ongoing species redistribution is reflected in an increase of the abundance of larger Sub-Arctic and boreal demersal fish species at the expense of smaller Arctic species, resulting in an increase in the community mean body length of demersal fish species (Frainer et al., 2017). The understanding of the link between climate change and the indicator is assessed as certain in the Barents Sea.

Body size is considered a master trait in the ocean, as an organism´s body size is related to many other traits such as metabolism and feeding ecology (Brown et al., 2004; Andersen et al., 2016). Marine food webs are largely structured by species body size (Brose et al., 2006; Andersen, 2019), with the Barents Sea not being an exception (Pecuchet et al., 2020). As the abundance of the comparatively large Sub-Arctic species increases in the Arctic, the structure of the Arctic food web will change as large species can, in general, eat a wider size range of prey. Notably in the Barents Sea, large boreal species are generally piscivorous species with a higher trophic level (Frainer et al., 2017). These large generalist species have the capacity to feed on both demersal and pelagic compartments and might thus impact the bentho-pelagic coupling. Changes in the size structure of fish communities can have implications for top-down and bottom-up control in the ecosystem (Brose et al., 2012) and affect the energy flow across trophic levels. Changes in the body size composition in the community will thus impact the structure of the Arctic food web, and ultimately its functioning. The understanding of the importance of changes in the indicator for other parts of the ecosystem is assessed as good.

Increasing trend in community level body length at maturation can be considered of **ecosystem significance** if, for example, i) the structure of the food web changes, e.g., from top-down to bottom-up control in the ecosystem, ii) it affects energy flow across trophic levels and ii) changes the coupling between benthic, demersal and pelagic compartments.

Knowledge gaps:

The extent to which ecosystem functions, such as carbon fluxes and bentho-pelagic coupling, are affected by changes in body size structure is uncertain. In addition, it is uncertain how other trophic levels might compensate for changes in fish community size structure.

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Fish life history [AI16]

Phenomenon: Increasing slow-life, periodic fish species [AP16]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the demersal fish communities in the Arctic are likely characterized by a relatively high proportion of small sized species with a fast-life, opportunistic life history strategy, compared to the Sub-Arctic demersal fish communities (Wiedmann et al., 2014).

The most important anthropogenic driver of change in this indicator is climate change. Climate-driven reduction of sea ice, increased sea temperature and pelagic primary productivity facilitate a movement of boreal fish species (mainly pelagic and bentho-pelagic species) northwards into water masses traditionally considered Arctic (e.g. Fossheim et al., 2015). These species include the north-east Arctic cod (*Gadus morhua*), northeast Arctic haddock (*Melanogrammus aeglefinus*), beaked redfish (*Sebastes mentella*) and golden redfish (*Sebastes norvegicus*) (Fossheim et al., 2015). These boreal species are characterized by a generalist diet, large body size, high fecundity, and high age at maturity in comparison to the Arctic fish species (Wiedmann et al., 2014; Frainer et al., 2017). The traits of the most abundant Arctic fish species are characteristic of fast-life, opportunistic species, whereas several of the incoming boreal species are characteristic of Periodic species with slower-life history strategy (Winemiller and Rose, 1992; Pecuchet et al., 2017). Due to climate change, the abundance of mostly opportunistic/fast-life Arctic species is expected to decline whereas the abundance of periodic/slow-life boreal species is expected to increase in the Arctic. Therefore, the fish community composition in the Arctic is expected to be increasingly composed of slow-life, periodic species for the demersal compartment. Although the specific expectation for effects of climate change on life history strategies is quite certain for the Arctic part of the Barents Sea, the mechanistic link between climate change and life history strategies in general is not well understood. Therefore, the link between fish life history strategies and climate change is assessed as less certain.

Life-history strategies are the result of correlations and trades-offs among life-history traits (Winemiller et al., 2015). For fish, the equilibrium–periodic–opportunistic framework (Winemiller and Rose, 1992) links three strategies characterized by trade-offs between fecundity, juvenile survival and generation time to environmental stability and predictability. The ‘equilibrium species’ have a large body size, produce few but large offspring with high survival rate, this strategy is typically followed by sharks and rays (Pecuchet et al., 2017). The ‘periodic species’ have also a large body size but produce many small eggs with low survival rate, this strategy is typically followed by gadoid species such as cod. The ‘opportunistic species’ have a small body size, short lifespan, and short generation time, this strategy is typically followed by small demersal species such as snailfishes (Liparidae) and lumpsuckers (*Eumicrotremus* spp.) or small pelagic species such as capelin (*Mallotus villosus*). The equilibrium strategy is hypothesized to prevail in stable and predictable environments, while the opportunistic strategy in unstable and unpredictable environments. The periodic strategy is hypothesized to occur in seasonal but predictable environments. A resilient ecosystem is composed of species displaying a variety of life-history strategies, because the different life-history strategies respond differently to ecosystem change and variability. Profound changes in the dominance of these strategies could thus affect ecosystem resilience. In addition, these changes can impact food web structure and function, as species’ trophic level is correlated to the life-history strategy (i.e., fast/opportunistic species which are characterized by a small body size have low trophic level (Pecuchet et al., 2017). The understanding of the importance for other parts of the ecosystem of increasing slow life, periodic life history strategies in the demersal fish community is assessed as less good.

Increasing trend in the relative biomass of slow life, periodic life histories in the Arctic Barents Sea can be considered of **ecosystem significance** if i) the diversity in life-history strategies in the communities is eroded, due for example to a decrease in the abundance of fast-life, opportunistic species in the Arctic.

Knowledge gaps:

There are still knowledge gaps on the response of life-history strategies to climate change, and on the impact of changes in the life-history strategy distribution of the community on the ecosystem functions.

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Fish habitat use [AI17]

Phenomenon: Change in proportion of benthic fish [AP17]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the benthic fish community is an important part of the ecosystem, receiving considerable amounts of carbon from pelagic primary production. Arctic benthic fish species constitute a considerable proportion of the bottom fish community biomass in the ecosystem, as the polar cod (*Boreogadus saida*) is the only abundant fish species present in the Arctic throughout the year that has a strong affiliation to the pelagic habitat (Christiansen and Reist, 2013).

The most important anthropogenic driver of change in this indicator is climate change. In areas with extensive sea ice, much of the primary production sinks to the bottom (especially ice algae that are released when the ice melts), but the productivity in the pelagic is low during large parts of the year (Hobson et al., 1995; Wassmann and Reigstad, 2011). Indeed, the proportion of carbon being exported towards the bottom is higher in Arctic than in Atlantic water masses (Reigstad et al., 2011). Less sea ice will lead to a shift where less of the primary production becomes available for benthic organisms, and more is consumed by zooplankton in the pelagic water masses (Kedra et al., 2015). This in turn facilitates a movement of boreal fish species (mainly pelagic and bentho-pelagic species, but also some benthic ones) northwards into water masses traditionally considered Arctic (e.g. Fossheim et al., 2015). These species include the Atlantic cod (*Gadus morhua*), northeast Arctic haddock (*Melanogrammus aeglefinus*), beaked redfish (*Sebastes mentella*), long rough dab (*Hippoglossoides platessoides*) and golden redfish (*Sebastes norvegicus*) (Fossheim et al., 2015). Similar shifts have been observed in the northern Bering Sea (Overland and Stabeno, 2004; Grebmeier et al., 2006). Thus, climate change is expected to lead to an increase in pelagic and bentho-pelagic fish species at the expense of benthic species (Wassmann and Reigstad, 2011; Jones et al., 2014; Kedra et al., 2015). The above-mentioned boreal species are efficient predators that are shown to feed on small, demersal fish species (e.g. Eriksen et al., 2020), and they may therefore have a negative effect on the typically small demersal arctic fish species. Thus, climate change is expected to lead to a decrease in the proportion of the typically arctic benthic fish species due to both lower food resources and increased predation pressure from boreal species. However, benthic boreal species, such as the long-rough dab, will likely increase in the Arctic areas following climate change. Even though the different mechanisms linking the indicator with climate change is well understood, the outcome of different effects on the indicator in unknown, since “benthic fish” includes both typically Arctic and boreal species and the expected decline in Arctic species may be compensated for by increasing boreal species. Therefore, the link between climate change and the indicator is assessed as less certain. In addition, fisheries may be affecting some of the boreal fish stocks (e.g., the Northeast Atlantic cod stock) entering the northern Barents Sea, which could also affect the changes in this indicator.

The indicator reflects the biomass allocation in pelagic (bentho-pelagic) and benthic ecosystem compartments, respectively, and thus changes in the pelagic-benthic coupling (Griffiths et al., 2017). This is a key feature of ecosystem structure in aquatic ecosystems, providing a simple measure of the status of a fish community (e.g. Pennino and Bellido, 2012). Changes in the ratio likely reflect community-wide alterations in community structure and biomass allocation, and the indicator may therefore be indicative of regime shifts (Aschan et al., 2013). When interpreting changes in the ratio, many factors will need to be accounted for simultaneously, and the understanding of the importance of changes in this indicator for other parts of the ecosystem is thus assessed as less good.

Change in proportion of benthic fish biomass can be considered of **ecosystem significance** if, for example, i) benthic fish are replaced by benthic invertebrates (e.g., crabs).

Knowledge gaps and uncertainties:

Although a larger part of the primary production is expected to be consumed in the pelagic compartment, there is uncertainty as to how the primary and secondary production will develop in different, previously ice-covered areas under climate change (e.g., Wassmann and Reigstad, 2011). This will in turn influence the amount and allocation of energy available to bentho-pelagic species during different seasons. Although many of the boreal species moving northwards in response to warming can be defined as bentho-pelagic (e.g., cod, haddock), others are benthic (including the highly abundant and widely distributed long rough dab), which makes interpretation of this indicator challenging. Furthermore, the definition of whether a species is "benthic" or "bentho-pelagic" clearly affects the temporal development of the indicator, although changes may be expected.

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Seabird feeding types [AI18]

Phenomenon: Decreasing proportion of diving to surface-feeding seabirds [AP18]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the diving seabirds are important piscivorous predators in the Barents Sea ecosystem and a dominant part of the avifauna (ICES, 2020). Surface-feeding seabirds are, to a large degree, dependent on diving seabirds and other top predators for food accessibility (Harrison et al., 1991; Camphuysen and Webb, 1999). Extensive industrial fisheries and historical extirpation of cetaceans by the whaling industry during the 19th and 20th centuries did probably alter the ratio between diving and surface-feeding seabirds to an unknown extent.

Fisheries are the most important anthropogenic driver of change affecting the proportion of diving to surface-feeding seabirds. Surface-feeding seabirds typically forage in the upper meter of the ocean and are largely dependent on other top predators (predatory fish, diving seabirds and marine mammals) for driving fish and krill to the surface and making the food accessible (Harrison et al., 1991; Camphuysen and Webb, 1999). In contrast, diving seabirds hunt in a larger portion of the water column and are less dependent on other top predators to access food (Fauchald, 2009; Veit and Harrison, 2017). During the last 50 years, surface-feeding seabirds have profited from large amounts of discards from the fishing industry (Garthe et al., 1996; Votier et al., 2004). At the same time, the same pelagic fisheries are competing with diving piscivorous seabirds, such as auks (Cury et al., 2011; Grémillet et al., 2018). It is therefore expected that increased industrial fisheries could change the functional composition of the seabird community, implying reduced abundance of diving piscivorous seabirds and increased abundance of surface-feeding and scavenging seabirds. In the Barents Sea, dominant surface-feeding birds include gulls (*Rissa tridactyla, Larus argentaus, L. marinus, L. hyperboreus*) and northern fulmar (*Fulmarus glacialis*); and dominant diving piscivorous seabirds include the large auks (*Fratercula arctica, Uria aalge, U. lomvia*) (ICES, 2020). While increased fisheries and discards are expected to result in a decreased proportion of diving to surface-feeding birds, regulatory measures aimed at reducing the discards (i.e., the “discard ban”, Gullestad et al. 2015) and sustainable harvesting could reverse this trend.

The link between fisheries and the indicator is assessed as certain. The mechanisms relating seabird abundance to fishery discards and competition with pelagic fisheries are well understood and have been documented extensively. A decreasing ratio of diving relative to surface-feeding seabirds is expected to be related to unsustainable pelagic fishing practices (i.e., high discard rates and poor regulation of catches). An increased ratio can be expected for reduced discards and sustainable catch regulations.

Seabirds are important top predators in the Barents Sea ecosystem. Facilitation (i.e., positive interactions) between top predators with different functions is considered to be important for top predators in the pelagic ecosystem (Fauchald et al., 2011; Veit and Harrison, 2017), and the function of the top predator guild is accordingly sensitive to changes in functional diversity. There is however still a relatively weak understanding of the importance of these mechanisms. The understanding of the importance of changes in the indicator is assessed as less good.

A decreasing trend in the indicator can be considered of **ecosystem significance** if there is a persistent and relatively large reduction in the ratio related to unsustainable pelagic fishing practices (i.e., high discard rates and poor regulation of catches). An increased ratio can be expected for reduced discards and sustainable catch regulations.

Knowledge gaps:

How functional diversity and facilitation affect top predators and their role in the pelagic ecosystem is poorly known. The time series from the ecosystem survey in the Barents Sea is relatively short (2004-2020) and the relative abundance of surface-feeding seabirds is biased by their attraction to the survey vessel. How climate change could affect the ratio is unknown.

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Mammal bioturbation [AI19]

Phenomenon: Decreasing abundance of mammals involved in bioturbation [AP19]

Ecosystem characteristic: Functional groups within trophic levels

It is not possible to provide information on the original state of the benthic ecosystem prior to near extirpation of benthic foraging walruses and white whales in the Norwegian Arctic, nor its changing status upon the recovery of walruses.

Overharvesting was the major driver of change in both walrus and white whale populations in the Norwegian Arctic (e.g., Kovacs et al., 2014; Lydersen and Kovacs, 2021) and bearded seals were likely also reduced late in the whaling “plukk-fangst” period. Currently, climate change is the major driver that will result in changes in the abundance/biomass of these species (Kovacs et al., 2015; Kovacs et al., 2021).

The understanding of the link between drivers and changes in the indicator is rated as certain.

Benthic feeding marine mammals in the Arctic are important ecosystems engineers, modifying the seafloor as they search for near-bottom swarming crustaceans or infaunal prey - including benthic shrimp, amphipods, crabs, bivalves, octopus, and polychaete worms (Johnson et al., 1983; Quakenbush et al., 2015; Lacher et al., 2019). Via their suction, jetting, rooting and digging activities, benthic feeding marine mammals resuspend many billions of tons of sediments each year in Arctic waters (Nelson et al., 1994; Marshal et al., 2008). The disturbed bottom is also more prone to erosion by bottom currents adding to the nutrient release, recycling and resultant boosting of primary production (Johnson et al., 1983). The pits and furrows created by benthic feeding whales and pinnipeds result in enhanced benthic species biodiversity and recolonization phenomena, similar to edge effects in terrestrial environments enhancing community species richness (Oliver et al., 1983, 1985; Klaus et al., 1990).

Little research has been directed to the issue of benthic bioturbation by marine mammals in Norwegian Arctic waters, but this thematic research area has had modestly extensive investigation in the Pacific Arctic (see above). The indicator should be developed and incorporated in MAREANO efforts, with direct attention the identifying key benthic foraging areas for marine mammals (via tracking studies, many of which are available e.g., Freitas et al., 2009; Lydersen and Kovacs, 2013; Hamilton et al., 2015; Vacquie Garcia et al., 2018).

Changes in the abundance/biomass of benthic foraging marine mammals will have impacts on benthic biodiversity and nutrient release/transfer, which impacts primary production especially in Arctic coastal shelf areas. The understanding of the importance of change in the indicator for other parts of the ecosystem is still rated as less good.

Marine mammal foraging areas should be incorporated into studies and monitoring conducted in the MAREANO programme to get a better understanding of the role marine mammals play in bioturbation in the Norwegian Arctic.

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Pelagic amphipods [AI20]

Phenomenon: Decreasing biomass of Arctic pelagic amphipod species [AP20]

Ecosystem characteristic: Functionally important species and biophysical structures

Amphipods of the genus *Themisto* are the dominant pelagic amphipod species in the Barents Sea. *Themisto libellula* is regarded as an Arctic species and *T. abyssorum,* and particularly, *T. compressa* as Sub-Arctic (Dalpadado et al., 2001; Kraft et al., 2012; Havermans et al., 2019). Under the reference condition, Arctic amphipods are important prey for fish, seabirds, and marine mammals in the Arctic part of the Barents Sea and considered important for sustaining the lipid-dependent Arctic predator community, including polar cod (Dalpadado et al., 2001, 2016; Descamps et al., 2017; Hop and Wiencke, 2019; ICES, 2020). Under the reference condition they are also important predators of *Calanus* species (Auel et al., 2002; Kraft et al., 2013). Other Arctic amphipods are ice-associated species, such as *Apherusa glacialis*, *Gammarus wilkitzkii* and *Onisimus* spp. These amphipods have typically been considered permanent residents of sea ice (sympagic), with their entire life cycle to occur within the sea-ice habitat (Gulliksen and Lønne, 1991; Lønne and Gulliksen, 1991; Macnaughton et al., 2007), although recent observations indicate that *Apherusa glacialis* is more pelagic than previously assumed (Kunisch et al., 2020). In the Barents Sea, they can be found in ice-covered waters, both associated with sea ice and the open water close to the ice edge. They are considered key species in the ice-associated food web (Poltermann, 1998), especially as prey item for juvenile polar cod (Lønne and Gulliksen, 1989) and seabirds feeding in the marginal ice zone (Lønne and Gabrielsen, 1992). Thus, under the reference condition, ice-associated species may also contribute to the pelagic amphipod community.

The most important anthropogenic driver of change in the indicator is climate change. Time series analyses (1980-2015) on pelagic Arctic amphipods (*T. libellula*) covering both the Norwegian and Russian parts of the Barents Sea show that increasing temperatures and subsequent reduced ice cover had a corresponding direct effect with likely decrease in their biomass (Stige et al., 2019). Another study from the west and north of Svalbard (Kongsfjorden, Isfjorden and Rijpfjorden) also indicate that if the warming trend persists, these conditions will favor the smaller Atlantic/boreal amphipods (*T. abyssorum*) over the larger Arctic species *T. libellula* (Dalpadado, 2006). The decline in Arctic species could be due to loss of habitat (less Arctic water masses) during warming periods (Dalpadado et al., 2020; ICES, 2020). In addition, the loss of sea ice, particularly multiyear ice, has had negative consequences on abundance of sympagic organisms like ice amphipods e.g., *Gammarus wilkitzkii* and *Onisimus* species, impacting the biodiversity of the Arctic region (Hop et al., 2021). Given the extensive knowledge on the influence of climate change on pelagic amphipods in the Arctic part of the Barents Sea, the understanding of the link between driver and indicator is rated as certain.

Given the importance of pelagic amphipods in the diet of many species (Dalpadado et al., 2001, 2016; Descamps et al., 2017; Hop and Wiencke, 2019; ICES, 2020), a decline in the biomass of the group is expected to have significant effects on Arctic predator communities. The understanding of the importance of changes in the indicator for other parts of the ecosystem is thus rated as good.

Examples of changes that would be of **ecosystem significance** include declines in pelagic biomass that would affect polar cod recruitment, growth and survival and reproduction of seabirds.

An important knowledge gap is that systematic monitoring of species composition is lacking.

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Krill [AI21]

Phenomenon: Increasing biomass of krill [AP21]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, krill is not an important component of the zooplankton community of the Arctic part of the Barents Sea, as the main krill species in the Barents Sea, *Thysanoessa inermis T. raschii*, *T. longicaudata* and *Meganyctiphanes norvegica*, are all either Atlantic or Sub-Arctic (Dalpadado and Skjoldal, 1991). *Nematoscelis megalops* is another species observed in the Barents Sea, although this species is mainly associated with warmer water masses.

The most important anthropogenic driver of change in the indicator is climate change. Time series analyses (1980-2015) of boreal krill covering both the Norwegian and Russian parts of the Barents Sea have shown that warming and reduced ice cover have had a direct positive effect on krill biomass (Stige et al., 2019). Other studies have shown that the Atlantic *M. norvegica*, which was almost absent during cooler periods in the 1970-1990s, has reentered the Barents Sea during the warmer last two decades (Zhukova et al., 2009; Eriksen et al., 2017; ICES, 2019). After nearly a 30-year long absence, the sub-tropical *Nematoscelis megalops* was again observed in the Barents Sea in the early 2000s (Zhukova et al., 2009). The robust evidence for the effects of climate change implies that the understanding of the link between driver and indicator is rated as certain.

Krill is an important part of the diet of many ecological and commercially important fish species in the Barents Sea (Eriksen et al., 2020; ICES, 2020) and for other groups such as seabirds and seals (Planque et al., 2014). Krill has been shown to be important for growth of capelin and krill stock size may be controlled by predator stock size, especially capelin (Dalpadado and Skjoldal, 1996; Gjøsæter et al., 2002). Krill lipids are important for adult capelin growth (Orlova et al., 2010). Different krill species are likely to function differently as prey. For example, the largest species, *M. norvegica*, is twice the size of the *Thysanoessa* species, implying that a single individual of the former will contribute significantly more biomass and lipids than individuals of the smaller species. Given the substantial knowledge about predator-prey dynamics and the importance of krill as prey, the understanding of the importance of changes in the indicator for other parts of the ecosystem is rated as good.

An increase in krill biomass in the Arctic part of the Barents Sea will provide higher availability of food for predators that are not abundant or dominant in the area under the reference condition, such as cod. This can change the predation pressure on Arctic species and alter their abundance, and even the structure of entire food webs (Kortsch et al., 2015).

An important knowledge gap is the lack of quantitative systematic monitoring of species composition.

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Polar cod [AI22]

Phenomenon: Decreasing biomass of the polar cod stock [AP22]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the polar cod population is large enough to support endemic Arctic predators (fish, seabirds and mammals) dependent on polar cod as prey.

The most important anthropogenic driver of change in this indicator is climate change (Mueter et al., 2016; Huserbråten et al., 2019; Gjøsæter et al., 2020). In particular, the early life stages of polar cod seem vulnerable to increased temperature and reduced ice cover; spawning of eggs happens under the ice and the eggs and larvae have high survival rates in sub-zero temperatures under the ice and larvae feed on zooplankton specific to the seasonal ice-melt-water blooms (Huserbråten et al., 2019). With the warming Barents Sea, the main spawning area of polar cod in the Pechora Sea south of Novaya Zemlya is believed to become less favorable (Huserbråten et al., 2019), with the expectancy of a decreasing population trend in the Barents Sea. Climate change may also increase predation pressure and competition in polar cod, due to the expanding feeding area of predators, in particular NEA cod, and increased competition with other secondary consumers, in particular capelin following a borealization of the Barents Sea (Mueter et al., 2016). Fisheries are not considered an important anthropogenic pressure, as polar cod has never been heavily harvested, and there has been no polar cod fishery at all in recent times (Gjøsæter et al., 2020). There is a good theoretical understanding of mechanisms and empirical evidence to support that the reduced ice coverage as a result of warming of the Barents Sea is likely to result in sub-optimal conditions for early life stages of polar cod and consequently a reduced population of polar cod in the Barents Sea. The link between climate change and the indicator is thus assessed as certain.

Polar cod is by far the most abundant secondary consumer in the Arctic Barents Sea, and therefore important for efficiently making energy from macroplankton available to predators at higher trophic levels (Hop and Gjøsæter, 2013; Mueter et al., 2016). In particular, polar cod is essential food for ice-associated mammals including ringed seals, narwhal and white whale as well as fish-eating Arctic seabirds such as Brünnich’s guillemot, black guillemot and Northern fulmar (Hop and Gjøsæter, 2013). In addition, polar cod is important food for many Arctic fishes including Arctic skate (*Amblyraja hyperborea),* NEA cod *(Gadus morhua),* Greenland halibut *(Reinhardtius hippoglossoides),* and striped seasnail *(Liparis bathyarcticus)* (Eriksen et al., 2020). The importance of polar cod as essential secondary consumer in the Arctic part of the Barents Sea food web is well established. The understanding of the importance of changes in the biomass of polar cod for other parts of the ecosystem is thus assessed as good.

Decreasing trends in the indicator is a sign of borealization of the Barents Sea and less favorable habitat for species adapted to Arctic conditions. Decreasing polar cod population can be considered of **ecosystem significance** if, for example, i) small population size of polar cod over time has negative impact on endemic Arctic predators such as narwhals, ringed seals or Brünnich’s guillemot.

Knowledge gaps:

It is still poorly known how a change in the predator distribution will affect the population of polar cod. An expected change is increased predation pressure due to expanded distribution of main predators, but evidence to support this is still lacking (Mueter et al., 2016).

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Capelin [AI23]

Phenomenon: Decreasing biomass of the capelin stock [AP23]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, long-term population size of capelin is high enough to support viable populations of predators dependent on capelin (e.g., NEA cod, humpback whales, harp seals, black-legged kittiwake, and Brünnich's guillemot). However, based on the life history of capelin being short-lived and semelparous, it is likely that the capelin population size undergoes large fluctuations also under the reference condition (Gjøsæter, 1998). The capelin population in the Barents Sea has been heavily exploited since the mid-60s, while regular monitoring started in 1972. In addition, the population is heavily affected by Atlantic cod, Norwegian spring spawning (NSS) herring and marine mammals, which have been exploited by humans long before that.

The most important anthropogenic driver of change in this indicator today is climate change. Climate change may significantly alter distribution of capelin (Rose, 2005), affect recruitment, and also the strength of the impact of key predators on capelin. Direct effect of warming that can be expected include a northward expansion during feeding, which has already been observed (Carscadden et al., 2013), and possibly the use of spawning grounds further north as temperatures increase (Rose, 2005). Climate change is expected to lead to increased productivity in the pelagic zone in Arctic seas (see phenomenon for indicator AI01), and changes in the zooplankton community composition (see phenomena for indicators AI03, AI20 and AI21) which can have both positive and negative effects on the capelin population (Dalpadado and Mowbray, 2013; Renaud et al., 2018; Duffy-Anderson et al., 2019). The capelin biomass is also strongly and directly affected by other ecosystem components such as Norwegian spring spawning herring, negatively affecting recruitment by feeding on capelin larvae (Gjøsæter and Bogstad, 1998; Huse and Toresen, 2000), and the Northeast stock of Atlantic cod, feeding on adult capelin (Johannesen et al., 2012; Fall et al., 2018; Holt et al., 2019). Climate change is expected to lead to a northward expansion of spawning of NSS herring, which possibly will increase the overlap with capelin larvae thereby reducing recruitment success (Gjøsæter and Bogstad, 1998). Similarly, the climate-change related increased distribution of cod may enhance predation pressure on capelin (Fall et al., 2018). These indirect effects of climate change on capelin may be more important drivers of capelin biomass than direct effects, and the net consequences of a warmer ocean for capelin are uncertain. The link between climate change and the indicator is therefore assessed as less certain.

Fisheries have been an important anthropogenic driver of change in the past for capelin with particularly high harvest level in the 1970s and 1980s (Gjøsæter, 1998). A precautionary management regime is currently in place for capelin where the fishery is only allowed to target a surplus of mature capelin after a proportion is allowed to spawn and after predator consumption (Gjøsæter et al., 2015). With this management regime, the fishery is not expected to be a strong driver of change in capelin biomass. The link between fisheries and changes in the indicator is assessed as certain.

Capelin plays a key role in the Arctic part of the Barents Sea as the most important mid-trophic level species efficiently making energy from plankton available to top-predators (Dolgov, 2002; Orlova et al., 2009). In particular Northeast Atlantic cod is dependent on capelin for sustaining its high abundance. Capelin is also a key diet items for whales, several seabird species, harp seals and other fish species (Dolgov, 2002). There is also evidence that capelin can inflict top-down effects on its zooplankton prey (Hassel et al., 1991; Dalpadado and Skjoldal, 1996). The capelin population in the Barents Sea has undergone strong fluctuations including collapse periods during the period of monitoring from 1973 to present (Gjøsæter et al., 2009). The two collapse periods in the mid-80s and 90s were particularly severe, and in particular the first of these likely lead to a range of cascade effects in the Barents Sea ecosystem, including recruitment failures in seabirds and harp seals and cannibalism and hampered growth in cod (Gjøsæter et al., 2009). The later collapses did not have equally severe impacts on the ecosystem (Johannesen et al., 2012). The reason for this is likely the higher abundance of alternative prey in these periods (Gjøsæter et al., 2009). The understanding of the role of changes in the biomass of capelin for other parts of the ecosystem is assessed as good.

Decreasing capelin stock biomass can be considered to be of **ecosystem significance** if, for example, i) lack of food affects breeding success in seabirds, distribution of marine mammals or growth and cannibalism in cod (Gjøsæter et al., 2009).

Knowledge gaps:

Capelin has large natural variation in recruitment, which is important for the stock development. It is known that predation by young herring may strongly influence the capelin recruitment, but not much is known about how change in the population of other predators such as whales may influence recruitment. There is also a lack of knowledge about potential change in predation pressure and survival at other life stages.

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Cod [AI24]

Phenomenon: Change in cod total stock size [AP24]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, long-term population size of Northeast Atlantic cod is high enough to help supporting top predators on adult fish such as minke whales and harp seals, and also to produce large quantities of larvae and 0-group cod, which are important as food for other organisms in the ecosystem (Eriksen et al., 2011). It is difficult to know how the state of the Northeast Atlantic cod stock was under reference conditions, as it has been exploited by humans for many centuries. However, the impact of the relatively limited fisheries before ca 1900 on this stock was probably moderate.

The most important anthropogenic drivers of change in this indicator are fisheries and climate change (Kjesbu et al., 2014). The Northeast Atlantic cod stock has been exploited by humans for many centuries and was considered to be overharvested from the 1950s and onwards (except for a few years in the early 1990s). However, since 2007 the fisheries have been regulated by a more precautionary management regime, and the NE Atlantic cod stock has recovered to a high level. The pressure from fisheries on the NE Atlantic cod stock is currently regulated through fishing quotas set in cooperation with Russia.

Climate change with higher oceanic temperatures will increase the available feeding area for cod in the Barents Sea. This is suggested as one of the reasons for the increasing density of cod in the northern Barents Sea reported for the period up to the early 2010s (Johansen et al., 2013; Kjesbu et al., 2014; Fossheim et al., 2015). In addition, cod recruitment is positively related to temperature (e.g. Bogstad et al., 2013). The maximal distribution area was observed in 2013, and expansion possibilities outside the area occupied that year are fairly limited as cod is not likely to migrate further northwards as deep waters outside the shelf are not suitable for cod. However, some further expansion to the northeast into the northern Kara Sea is possible if the warming continues. The links between these drivers and cod stock size are assessed as certain.

Cod is a central species in the Barents Sea ecosystem, with many interactions to other organisms in the ecosystem (Kortsch et al., 2015). Cod is an important predator on many fish and shellfish species such as capelin, herring, haddock, shrimp, snow crab, polar cod etc. (see e.g. Dolgov et al., 2011; Holt et al., 2019) and thus changes in the abundance of cod affect the status of these prey species. It is also a competitor with marine mammals as top predators in the ecosystem (Bogstad et al., 2015). Cod is also important as food for other predators, both as larvae and 0-group cod and adults (e.g. Bogstad et al., 2000; Eriksen et al., 2011). It should also be noted that Barents Sea cod is cannibalistic (Yaragina et al., 2009) and thus to some extent regulates itself. Cod is the dominant piscivorous fish species in the Barents Sea, and there is no other fish species which can fill that role if cod abundance becomes very low.

The understanding of the importance of changes in this indicator for other parts of the ecosystem is assessed as good. However, effects of changes in the cod abundance on their prey are more studied than effects on their predators. Weak density-dependence in growth of older (mature) cod was observed in the 2010s when cod abundance was high (ICES, 2020).

Changes in the cod stock biomass can be considered of **ecosystem significance** if, for example, i) Increasing predation from a larger cod population causes declines in typically Arctic species, e.g., polar cod. This can also have cascading effects on mammals dependent on these Arctic species, such as reduced condition in minke whales and harp seals (Bogstad et al., 2015). ii) Declining cod population has a negative effect on predators on cod eggs and larvae.

Knowledge gaps:

Effects on predators of changes in cod abundance are an important knowledge gap. Also, cod abundance has fortunately never been so low that we have any clues about how a ‘cod-less’ ecosystem in the Barents Sea would function.

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Cod size structure [AI25]

Phenomenon: Decreasing biomass of large cod [AP25]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, large cod is present in the population to such extent that they represent an important predator in the ecosystem. In addition, the presence of cannibalistic large cod contributes to self-regulation of the cod population. It is likely that the proportion of old, large fish in the stock would be even larger under reference conditions than in the periods with low fishing pressure from which we have data (1940s, 2010s, see Kjesbu et al., 2014). From West Greenland there are observations of age distributions in a previously unfished cod stock (Hansen, 1949), but whether these observations are relevant for a situation where the Barents Sea cod stock is unfished, we do not know.

The most important anthropogenic driver of change in this indicator is fisheries, which typically target the largest cod individuals. The minimum size in the fisheries is 44 cm, but fishing mortality increases with size/age, both because of gear selectivity and because a considerable part of the catch is taken during the spawning season. Heavy exploitation over many generations may also have affected the genetic composition of the stock, as maturation now occurs at lower age and size than before (see Rørvik et al., 2021 for the most recent discussion and literature review on this). In the Barents Sea, cod have been heavily exploited, but following the strong reduction in fishing mortality around 2007 the age structure in the stock has now been rebuilt and resembles the situation in the late 1940s following a period of low fishing mortality during WWII. The link between fisheries and the indicator is assessed as certain.

Large and old cod are important predators on smaller fish, including being cannibalistic (Holt et al., 2019). There are no other abundant fish stocks with large fish (> 70 cm) in the Barents Sea, so that niche in the ecosystem cannot be filled by other species. Also, the age/size structure in the spawning stock is important for the recruitment to the stock (see references in Kjesbu et al., 2014). The understanding of the importance of changes in the indicator for other parts of the ecosystem is assessed as less good.

Decreasing or stable low biomass of large cod can be considered of **ecosystem significance** if, for example i) the genetic composition of cod is changed due to selective removal of large individuals, ii) it leads to bad recruitment and reduced population size.

Knowledge gaps:

Effects on genetic composition.

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Cod distribution [AI26]

Phenomenon: Increasing biomass of cod in the Arctic Barents Sea [AP26]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, Northeast Atlantic cod is present in the Arctic part of the Barents Sea, but the “center of distribution” is further south. The northern distribution limit is typically determined by water temperature and population size. We know that cod have been distributed in the Arctic in previous periods, e.g., in the 1930s, but a reference condition is hard to determine, and historic records are sparse.

The most important anthropogenic driver of change in this indicator is climate change, but stock size also has an impact. Cod abundance is low in waters colder than 0° C (Yaragina et al., 2011), so the location of this isotherm for bottom temperatures is a good indication of the distribution range. Cod distribution in the Barents Sea is also density dependent, and more cod are found in northern areas when stock sizes are large (Johansen et al., 2013; Kjesbu et al., 2014; Fossheim et al., 2015; Johannesen et al., 2020). Although temperature has a positive effect on recruitment of cod, stock size is affected by a multitude of natural and anthropogenic factors. The link between climate change and the indicator is assessed as certain (but we need to separate natural fluctuations from anthropogenic influence in this context).

There are few other piscivorous fish species in the Arctic part of the Barents Sea, so the occurrence of cod in the Arctic part of the Barents Sea may affect the fish community in this area significantly, as a part of the ‘borealization’ of the Barents Sea (Fossheim et al., 2015). The understanding of the importance of changes in the indicator for other parts of the ecosystem is rated as good.

Increasing trend NEA cod biomass in the Arctic Barents Sea can be considered of **ecosystem significance** if, for example i) typically Arctic fish species are affected negatively by NEA cod.

Knowledge gaps:

Sensitivity of various prey species to cod abundance is not well known.

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Bottom thermal niches [AI27]

Phenomenon: Decreasing area of bottom cold-water temperature niches [AP27]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, which for abiotic factors is predefined as the climate in the period 1961-1990, the Arctic part of the Barents Sea was characterised by an Arctic climate. That is, large areas with cold-water temperatures were dominating, and seasonal or whole-year ice cover were common. Regions dominated by Arctic climate provides permanent habitat for Arctic species and seasonal feeding habitat for migrating boreal species. Data on temperature exist from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in this indicator is climate change (IPCC, 2019). Waters characterized by sub-zero temperatures, are common near bottom in the northern Barents Sea (Loeng, 1991; Lind and Ingvaldsen, 2012). This contrasts with the southern Barents Sea which is dominated by warmer waters (Loeng, 1991). Anthropogenic global warming leads to northward expansion of the warmer waters thereby reducing the area of the colder waters in the Barents Sea (Smedsrud et al., 2010; Smedsrud et al., 2013; Oziel et al., 2016). Given the massive evidence of anthropogenic influence on the climate in general (Masson-Delmotte et al., 2021) and for the Barents Sea locally described above, the understanding of the link between driver and change in the indicator is rated as certain.

The decreasing extent of cold-water temperature niches at bottom has profound impacts on the local and regional Arctic climate and ecosystems. Examples of changes which can be considered of ecosystem significance as a result of decline in waters with sub-zero temperatures include reductions in habitat for Arctic demersal fish and benthic species (Johannesen et al., 2012; Fossheim et al., 2015; Jørgensen et al., 2015; Johannesen et al., 2017; Jørgensen et al., 2019). The understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as good.

The extent of cold-water temperature niches near bottom depends on sea-ice formation and inflow, cooling during winter and the inflow of Atlantic and Arctic Water. Improved understanding is needed to address the relative contribution from these sources on the formation and distribution of cold-water temperature niches.

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Sea-ice area [AI28]

Phenomenon: Decreasing sea-ice area in winter and summer [AP28]

Ecosystem characteristic: Landscape-ecological patterns, Abiotic factors

Under the reference condition, which for abiotic factors is predefined as the climate in the period 1961-1990, the Arctic part of the Barents Sea is characterised by an Arctic climate. Arctic water masses are dominating (Loeng, 1991; Lind and Ingvaldsen, 2012), and seasonal or whole-year ice cover can generally be expected. The climate provides habitat for Arctic species. Data on sea-ice extent from satellite monitoring is available from 1979, thus covering only a small part of the 1961-1990 period.

The most important anthropogenic drivers of change in the indicator are related to climate change. Several forcings and processes lead to later ice formation, less ice extent and earlier seasonal melt in the Arctic (IPCC, 2019). Other drivers, which may be linked to climate change, can come in addition, such as advection of sea ice due to wind and currents (Onarheim et al., 2018; Stroeve and Notz, 2018; Årthun et al., 2019). The understanding of the link between drivers and change in the indicator is rated as certain.

Sea ice makes up the habitat for large numbers of species and affects physical and ecological processes beyond the ice itself. A large number of studies have shown that decreasing sea-ice extent can have significant effects on Arctic ecosystems (Grebmeier et al., 2006; Wassmann and Reigstad, 2011; Hamilton et al., 2015; Descamps et al., 2017; Eriksen et al., 2017, 2019; Frainer et al., 2017; Renaud et al., 2018; Huserbråten et al., 2019; Stige et al., 2019; Dalpadado et al., 2020; Gjøsæter et al., 2020; Daase et al., 2021; Mueter et al., 2021). The understanding of the importance of change in the indicator for other parts of the ecosystem is thus rated as good.

Examples of changes resulting from declines in sea ice which can be of ecosystem significance include i) declines in ice dependent marine mammals, such as ringed seals, white whales, narwhales, and polar bears (Hamilton et al., 2015; Stern and Laidre, 2016; Descamps et al., 2017) ii) declines in pelagic amphipods, such as *Themisto libelulla* (Stige et al., 2019) iii) declines in sea-ice associated mesozooplankton, such as *Calanus glacialis* (Stige et al., 2019; Dalpadado et al., 2020) iv) reduced recruitment of polar cod (Huserbråten et al., 2019).

There are different knowledge gaps associated with sea ice in summer and winter. Among knowledge gaps connected to summer sea-ice extent are details about surface features such as melt-pond development, as well as ice thickness changes. For winter conditions, there is in general less observational *in situ* data available. Among knowledge gaps are needs for more information about snow and ice thickness changes (e.g. (Gerland et al., 2019)).

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Arctic amphipod [AI29]

Phenomenon: Decreasing biomass of the Arctic amphipod Themisto libellula [AP29]

Ecosystem characteristic: Biological diversity

Amphipods of the genus *Themisto* are the dominant pelagic amphipod species in the Barents Sea. *Themisto libellula* is regarded as an Arctic species and *T. abyssorum* and, particularly, *T. compressa* as sub-Arctic (Dalpadado et al., 2001; Kraft et al., 2012; Havermans et al., 2019). Under the reference condition, Arctic amphipods are important prey for fish, seabirds and marine mammals in the Arctic part of the Barents Sea and considered important for sustaining the lipid-dependent Arctic predator community, including polar cod (Dalpadado et al., 2001, 2016; Descamps et al., 2017; Hop and Wiencke, 2019; ICES, 2020). Under the reference conditions they are also important predators of *Calanus* species (Auel et al., 2002; Kraft et al., 2013). In the Barents Sea, they can be found in ice-covered waters, both associated with sea ice and the open water close to the ice edge. They are considered key species in the ice-associated food web (Poltermann, 1998), especially as prey item for juvenile polar cod (Lønne and Gulliksen, 1989) and seabirds feeding in the marginal ice zone (Lønne and Gabrielsen, 1992). Thus, under the reference condition, ice-associated species may also contribute to the pelagic amphipod community.

The most important anthropogenic driver of change in the indicator is climate change. Time series analyses (1980-2015) on pelagic Arctic amphipods covering both the Norwegian and Russian part of the Barents Sea show that increasing temperatures and subsequent reduced ice cover had a corresponding direct effect with likely decrease in their biomass (Stige et al., 2019). Another study from the west and north of Svalbard (Kongsfjorden, Isfjorden and Rijpfjorden) also indicates that if the warming trend persists, these conditions will favour the smaller Atlantic/boreal amphipods (*T. abyssorum*), over the larger Arctic species *T. libellula* (Dalpadado, 2006). The decline in Arctic species could be due to loss of habitat (less Arctic water masses) during warming periods (Dalpadado et al., 2020; ICES, 2020). Given the extensive knowledge on the influence of climate change on *T. libellula*, the understanding of the link between driver and indicator is rated as certain.

Given the importance of Arctic pelagic amphipods in the diet of many species (Dalpadado et al., 2001, 2016; Descamps et al., 2017; Hop and Wiencke, 2019; ICES, 2020), a decline in the biomass of *T. libellula* is expected to have significant effects on Arctic predator communities. The understanding of the importance of changes in the indicator for other parts of the ecosystem is thus rated as good.

Examples of changes that would be of **ecosystem significance** include declines in pelagic biomass that would affect polar cod recruitment, growth and survival and reproduction of seabirds.

An important knowledge gap is that systematic monitoring of species composition is lacking.

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Cold-water benthos [AI30]

Phenomenon: Decrease of proportion of Arctic benthos species [AP30]

Ecosystem characteristic: Biological diversity

Under reference conditions, megabenthos species sensitive to climate change are unaffected. They are adapted to cool areas with at least seasonal ice cover, which is not the case of more boreal species. Thus, they contribute to the biodiversity in the Barents Sea.

The most important anthropogenic driver of change in this indicator is climate change. The area containing communities with a calculated lower temperature preference was reduced in the central Barents Sea in later years, whereas the transition zone expanded north and east, and communities with higher temperature preference covered the entire shelf area west of Svalbard (analyses using data up to 2015, Jørgensen et al. 2019). Early Russian studies have reported biomass fluctuations in macrofauna due to climate variability in the Barents Sea (Anisimova et al. 2011), suggesting that a northward displacement of subarctic and temperate species is a response to climate warming in the Arctic (see review by Wassmann et al. 2011). There is considerable agreement that climate change will result in significant alteration of benthic community structure throughout the Arctic, and within the Barents Sea (Renaud et al., 2008, 2015, 2019; Matishov et al., 2012). Species distributions are both directly and indirectly linked to climate parameters (temperature, ice cover), and these parameters are changing more rapidly in the Arctic than elsewhere on the planet (AMAP 2017). Thus, the understanding of the link between climate change and the indicator is rated as certain.

Removal or arrival of individual species represent a development away from 'intact nature' and will significantly affect regional biodiversity if it is/can become a dominant species or is a habitat-forming species which will have cascading effects on presence/absence of other taxa. Biodiversity is known to affect ecosystem functioning by both optimizing energy flow and resource use (Duffy et al., 2007; Barnes et al., 2018), and by providing functional redundancy, which may make a system more resilient to future changes in species composition (Oliver et al., 2015). Displacement of Arctic species may have no appreciable effects if the taxa play similar ecological roles (Węsławski et al., 2018).

Whereas we are quite certain about the link to the driver, the impact on the ecosystem is less well understood since this is very much dependent on which taxa (and thus which ecosystem roles) that will be impacted. Available information already suggests some taxa that have been or are likely to be changing in the Arctic (Berge et al., 2005; Renaud et al., 2019), and at least some of these play important roles. Thus, the understanding of the importance of change in the indicator for other parts of the ecosystem impact is rated as good.

Even modest changes diversity may have large effects if the changes relate to community dominants, habitat-forming taxa, or species playing key roles in diets of other organisms. Changing benthic species composition associated with measured differences in secondary production, energy flows through food webs, etc. will indicate **ecosystem-significant effects**.

Species compositions among different habitats, and how these values vary temporally, are not well known such that climate-driven changes may not be noticed until there is already a significant ecosystem effect.

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Arctic fish [AI31]

Phenomenon: Decreasing abundance of Arctic fish species [AP31]

Ecosystem characteristic: Biological diversity

Under the reference condition, *Arctic fish species* dominate the Arctic waters found north and east of the polar front (Fossheim et al., 2015).

The most important anthropogenic driver of change in this indicator is climate change. Reduction in sea-ice cover and increase in sea water temperature are related to a decrease in the abundance of Arctic fish species in Arctic communities (Fossheim et al., 2015; Frainer et al., 2017). Arctic fish species are often ice-associated or are tightly coupled with the demersal habitat, where biomass production is dependent on the sinking of organic matter originated in the surface ice or in the pelagic zone (Degen et al., 2016). Arctic fish species have small body sizes, which makes them particularly vulnerable to the larger body sizes and more generalist diet of the boreal species (Frainer et al., 2017). The link to climate change is assessed as certain.

A decrease in the total abundance of Arctic fish species indicates a shift in the functioning of Arctic ecosystems. The boreal and Sub-Arctic species that replace the Arctic ones have different characteristics and life histories that will lead to changes in the ecosystem function and structure of the Arctic. Whereas Arctic fish species are year-round residents of the Arctic region, the boreal fish species are most likely residing in the Arctic during a short season. The effect of the boreal species over the Arctic ones, with the boreal species consuming or out-competing the Arctic ones due to larger body sizes and more generalist diet of the former, will likely have strong effects on the recruitment of Arctic fish species. This will also reduce resource cycling in the Arctic during the months when boreal species are not present. This will likely also reduce the diversity of functional traits present in the Arctic (Frainer et al., 2021), affecting the niche space occupied by the Arctic species in the Arctic. The understanding of the importance of decreasing abundance of Arctic fish species for other parts of the ecosystem is assessed as good.

Decreasing trend in the abundance of Arctic fish species can be considered of **ecosystem significance** if, for example, the Arctic ecosystem becomes dominated by boreal-like species. This would significantly change the character of the Arctic, from ice- or benthic-associated small fish to demersal-pelagic large fish dominating communities.

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Fish sensitive to fisheries [AI32]

Phenomenon: Decreasing abundance of fish species sensitive to fisheries [AP32]

Ecosystem characteristic: Biological diversity

Note: This text is similar to the indicator "Fish life history" in the Sub-Arctic Barents Sea which is focusing on Equilibrium species decline. However, the life history indicator focuses on the life history strategy biomass changes, while this indicator focuses on abundance of species with typical Equilibrium life history strategy.

Under the reference condition, fish species sensitive to increased mortality from fisheries are well represented in the demersal fish community. These species can be identified by their typically "slow-type" life-history traits, having a large body size, long life-span, late maturation and low fecundity. They typically have stable population dynamics and very low rate of intrinsic population increase, making them vulnerable to additional sources of mortality (Jennings et al., 1998; Hutchings et al., 2012; Le Quesne and Jennings, 2012). In addition, these species are often top predators in the system, and have an important structuring role in the ecosystem.

The most important anthropogenic driver of change in this indicator is fisheries. Fisheries preferentially harvest large bodied species and individuals. In addition, species life-history traits are known to be related to their vulnerability to increase in mortality from fisheries (Jennings et al., 1998; Le Quesne and Jennings, 2012). Species with a slow-type, Equilibrium life history have a large body size, produce few but large offspring with high survival rate; this strategy is typically followed by sharks and rays (Pecuchet et al., 2017). Some typical Equilibrium species in the Barents Sea are sharks and rays such Greenland shark (*Somniosus microcephalus*), Velvet belly lanternshark (*Etmopterus spinax*), Rabbit fish (*Chimaera monstrosa*), Spinytail skate (*Bathyraja spinicauda*), and Thorny skate (*Amblyraja radiata*. These large, slow growing, and low fecundity species are characterized by a low intrinsic productivity, which make them especially vulnerable to fishing pressure (Stevens et al., 2000; King and McFarlane, 2003; Winemiller, 2005; Quetglas et al., 2016; Mérillet et al., 2021). Even though fisheries activities are rarely targeting these species, they are often suffering from high by-catch fishing mortality. In addition to the sharks and rays, also Redfishes (*Sebastes* spp.) are vulnerable to additional mortality from fisheries due to slow growth and late maturation, even though they have higher fecundity compared to the elasmobranchs. The understanding of the link between fisheries and the indicator is assessed as certain.

Slow-type, Equilibrium life-history species are often top predators in the marine environment. The removal of these top predators can impact the size structure of the communities and as a result impact the structure of the food web. A decline in top predators can also lead to trophic cascades (Myers and Worm, 2003; Myers et al., 2007), it can have implications for top-down and bottom-up control in the ecosystem (Brose et al., 2012) and affect the energy flow across trophic levels. The understanding of the importance of changes in the abundance of fisheries sensitive species for other parts of the ecosystem is assessed as good.

Decreasing trend in the abundance of fish species sensitive to increased mortality from fisheries can be considered of **ecosystem significance** if, for example, i) some of the species goes extinct, ii) reduced abundance of these species triggers a trophic cascade through reduced predation pressure on its prey.

Knowledge gaps:

Climate change effects on these species may interact with fisheries impacts.

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Seabirds sensitive to pollution [AI33]

Phenomenon: Decreasing abundance of Glaucous gull [AP33]

Ecosystem characteristic: Biological diversity

Under the reference condition, glaucous gull (*Larus hyperboreus*) is an important top predator in the Arctic and Sub-Arctic parts of the Barents Sea (ICES, 2020).

The most important anthropogenic driver of change in this indicator is long-transported pollution (Erikstad and Strøm, 2012). High levels of long-transported organochlorine pollutants (OC) in adults have reduced adult survival and reproduction on Bjørnøya (Bustnes et al., 2003) and this factor has contributed strongly to the observed decline in the population (Erikstad and Strøm, 2012). However, other environmental factors have probably also had an impact (Erikstad and Strøm, 2012), such as OC, which show intensified effects under poor environmental conditions (Bustnes et al., 2006). The links between pollution and the indicator are well described and the understanding about this thus assessed as certain.

The Glaucous gull is an Arctic generalist top predator and scavenger who exploits a variety of prey, including fish, molluscs, echinoderms, crustaceans, eggs, young and adult seabirds, carcasses of whales and marine mammals, fish discards and garbage. Birds nesting in or near seabird colonies often specialize on eggs, chicks or adults of other seabird species (Strøm, 2007). The species is listed as near threatened on the red list for Svalbard (Henriksen and Hilmo, 2015). The understanding of the importance of changes in the indicator for other parts of the ecosystem is assessed as good.

A decreasing trend in abundance of glaucous gulls can be considered **of ecosystem significance** when there is a significant and long-term (>10 years) decrease in the abundance of the species associated with elevated concentrations of organic pollutants.

Knowledge gaps:

The abundance of glaucous gull is monitored on Bear Island and Spitsbergen. Several other factors could contribute to declining abundance, such as shortage of food including reduced availability of fishery discards, predation by a growing arctic fox population and increased competition with great skuas.

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Arctic seabirds [AI34]

Phenomenon: Decreasing abundance of Arctic seabird species [AP34]

Ecosystem characteristic: Biological diversity

Under the reference condition, Arctic seabird species are abundant in the Arctic part of the Barents Sea (ICES, 2020). Historical hunting and industrial fishing of important prey items had large impacts on the population dynamics of these species during the 20th century (Krashnov and Barrett, 1995). In addition, the historical extirpation of cetaceans around Spitsbergen did probably also influence the abundance of Arctic seabirds (Hacquebord, 2001).

The most important anthropogenic driver of change in this indicator is climate change (Descamps and Strøm, 2021). Under climate warming, a borealization of the ecosystem is expected. This mechanism involves a shift in species composition from Arctic to boreal species (Fossheim et al., 2015; Descamps and Strøm, 2021). The most abundant Arctic species observed during the ecosystem survey are Brünnich's guillemot (*Uria lomvia*), little auk (*Alle alle*) and black-legged kittiwake (*Rissa tridactyla*) (ICES, 2020). In addition, black guillemot (*Cephus grylle*) and ivory gull (*Pagophila eburnea*) are frequently observed close to sea ice. These species are expected to decrease in abundance under climate warming (Descamps and Strøm, 2021). The understanding of the link between climate change and the indicator is assessed as certain.

Arctic seabirds are an important and conspicuous part of the sympagic fauna. They forage on polar cod and ice-associated amphipods, krill and copepods (Mehlum and Gabrielsen, 1993; Mehlum, 1997). Arctic species that are unable to adapt to a changing environment and are expected to decrease in abundance under climate warming. As a consequence, several of the characteristic Arctic species are listed on national and international red lists. Brünnich's guillemot and Black-legged kittiwake are listed as near threatened and Ivory gull is listed as vulnerable on the red list for Svalbard (Henriksen and Hilmo, 2015). The understanding of the importance of changes in the indicator for other parts of the ecosystem is assessed as good

A decreasing trend in the indicator can be considered of **ecosystem significance** if there is a significant gradual long-term (> 10 years) decrease in the biomass associated with climate warming and a borealization of the ecosystem.

Knowledge gaps:

The time series from the ecosystem survey in the Barents Sea is relatively short (2004-2020). The indicator is sensitive to natural fluctuations in the Barents Sea climate and the abundance and distribution of key species such as capelin. Lagged responses could be expected with respect to the effects of borealization.

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Mammals sensitive to pollution [AI35]

Phenomenon: Decreasing abundance of mammal species sensitive to pollution [AP35]

Ecosystem characteristic: Biological diversity

All marine mammals are exposed to anthropogenic pollutants, thus there are no places on earth with “intact nature” in this respect.

The drivers are dumping of waste, industrial production of various substances that are released into the environment (often used in agriculture as pesticides or treatment of plant diseases), emissions during industrial processes that in addition to local pollution are transported around the globe with ocean currents and via atmospheric transport – thus reaching the entire planet. Many of the substances bioaccumulate in food webs and are therefore found in higher concentrations in upper trophic level animals such as many marine mammal species. In addition, many contaminants are lipophilic and thus accumulate in lipid tissues, which all marine mammals have in large quantities as an adaptation by homeothermic mammals living in the world’s oceans; Arctic marine mammals are highly dependent on their blubber layer to get them through periods of low production/feeding. Polar bears, which are pinnacle predators, have high concentrations of many pollutants (e.g., Desforges et al. 2018, Routti et al. 2019), reaching levels in the Norwegian Arctic that are thought to disrupt hormone systems, lipid metabolism and neurochemistry (Routti et al. 2019). All toothed whales have poor capacity to metabolize toxic substances and hence white whales are particularly vulnerable to the toxins to which they are exposed in the Barents Sea (e.g., Wolkers et al. 2006, Desforges et al. 2018, Lydersen and Kovacs 2021). Some Arctic seal species also have high concentrations of various pollutants (e.g., Wolkers et al. 2000, Scotter et al. 2019). However, some of the most problematic, lipophilic compounds such as PCBs and DDEs that have been banned from production, are declining rapidly as a result of substance bans (e.g., Wolkers et al. 2008, Routti et al. 2014).

The MOSJ programme monitors selected pollutants in polar bears and ringed seals. Most of the parameters measured in polar bears (HCB, BetaHCH an dDDE, BDE-47, PCB.153 and oxychlordane and PFOS) have declined through the monitoring period. PFNA and PFUnDA show no significant trends. Mercury might be increasing over the monitoring period. The patterns in ringed seals are similar (See MOSJ https://www.mosj.no/no/pavirkning/forurensning) although data appear more variable because sampling is less frequent.

The understanding of the links between the driver and indicators is assessed are less certain, as most effect studies are correlative not causal.

High levels of various pollutants have the potential to impact mammalian functions related to metabolism, reproduction and other vital processes. This can lead to decreased numbers of marine mammals via increased mortality and reduced reproductive rates, which then will alter the structure of the whole ecosystem. The greatest concern is that pollutants are part of a multi-stressor system, where animals weakened by one stressor are more vulnerable to other threats. Thus, top predators are believed to be at risk of being impacted by contaminants and reduction in top predators might have cascading effects on the whole ecosystem (see above-top-down control).

The understanding of the importance of change in the indicator for other parts of the ecosystem is thus assessed as less good.

Understanding of the indicator is less good, because most studies on effects are still based on correlations and not causality, and reduction of reproductive capacity has not been demonstrated to be due to pollution in Arctic marine mammal population in the Barents Sea.

Knowledge gaps: More studies of the effects of pollutants on animal physiology and endocrinology are needed.

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Arctic mammals [AI36]

Phenomenon: Decreasing abundance of Arctic mammal species [AP36]

Ecosystem characteristic: Biological diversity

Historical stock sizes for most Arctic endemic marine mammals were much higher than they are currently for most species (see above). Overharvesting took some species to the brink of extinction. Under such circumstances, most mammalian populations exhibit reduced genetic diversity. Additionally, small populations are at increasingly risk of genetic drift, and disease events which can result in further reduction of diversity and resilience.

Remarkably, despite the extreme harvest levels for bowhead whales in the Barents Sea, the population seems to have maintained a high level of genetic diversity (Bachmann et al., 2021). Similarly, current evidence does not support large genetic losses for walruses in Svalbard (Lindqvist et al., 2016). However, polar bears in the Barents Sea population appear to be undergoing loss of genetic diversity on a decadal scale currently, which is thought to be linked to declining sea-ice conditions inducing habitat fragmentation (Maduna et al., 2021).

There are considerable knowledge gaps in our understanding of genetic diversity of many Arctic marine mammal populations in the Barents Sea that prevents a holistic assessment of potential diversity losses due to overharvesting in the past and current environmental change. For the species for which there are some data, the signals are mixed. The understanding of the linkage between drivers and the indicator is thus ranked as less certain.

The understanding of the importance of change in the indicator for other parts of the ecosystem is ranked as less good.

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Temperature [AI37]

Phenomenon: Warming of the water column [AP37]

Ecosystem characteristic: Abiotic factors

Under the reference condition, which for abiotic factors are predefined as the climate in the period 1961-1990, the Arctic part of the Barents Sea was characterised by an Arctic climate dominated by low ocean temperatures (Loeng, 1991; Lind and Ingvaldsen, 2012). Regions with Arctic climate provide permanent habitat for Arctic species and seasonal feeding habitat for migrating boreal species. Data on temperature exist from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in the indicator is climate change, causing the water column to warm (IPCC, 2019). More open water during summer increases the seasonal warming of the surface layers with subsequent heating of the Arctic Water below at the end of summer (Perovich et al., 2008; Lind et al., 2016; Lind et al., 2018) also beyond the melt season (Timmermans, 2015; Ivanov et al., 2016). Anthropogenic global warming leads to increasing ocean temperature in the inflowing Atlantic Water (Sandø et al., 2014; Årthun et al., 2019). Given the massive evidence of anthropogenic influence on the climate in general (Masson-Delmotte et al., 2021) and for the Barents Sea locally described above, the understanding of the link between drivers and change in the indicator is rated as certain.

Change in temperature has large implications for the ecosystem in the Arctic part of the Barents Sea, either directly or through an influence on other aspects of the abiotic environment, such as sea-ice extent. Impact of increasing temperature and decreasing sea ice has been documented through a large number of studies (Søreide et al., 2010; Dalpadado et al., 2012; Kortsch et al., 2012; Fossheim et al., 2015; Hamilton et al., 2015; Kortsch et al., 2015; Hamilton et al., 2016; Descamps et al., 2017a; Descamps et al., 2017b; Eriksen et al., 2017; Frainer et al., 2017; Hamilton et al., 2017; Lind et al., 2018; Hop and Wiencke, 2019; Dalpadado et al., 2020; Gjøsæter et al., 2020; Mueter et al., 2021), and the understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as good.

Examples of changes which can be considered of ecosystem significance as a result of warming of the water include increases in total primary and secondary production (Dalpadado et al., 2012, 2020), and increases in production and growth further up in the food chain, with contrasting responses between boreal and Arctic species (Dalpadado et al., 2012; Kjesbu et al., 2014; Aarflot et al., 2018; Stige et al., 2019).

A knowledge gap concerns the link between surface fluxes and intermediate water layers. More open water during summer increases the solar input and results in higher temperatures at the end of summer (Perovich et al., 2008; Timmermans, 2015; Ivanov et al., 2016; Lind et al., 2016; Lind et al., 2018). However, sea-ice reduction in winter increases the winter ventilation and thus the heat loss from the water column during the cold season (Asbjørnsen et al., 2020; Polyakov et al., 2020). The understanding of how altered surface fluxes through the year affect the intermediate water layers in the Arctic Barents Sea is not fully understood.

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Area of water masses [AI38]

Phenomenon: Decreasing area covered by Arctic Water [AP38]

Ecosystem characteristic: Abiotic factors

Under the reference condition, which for abiotic factors are predefined as the climate in the period 1961-1990, the Arctic part of the Barents Sea is characterised by an Arctic climate. Arctic water masses are dominating (Loeng, 1991; Lind and Ingvaldsen, 2012), and seasonal whole-year ice cover can generally be expected. The climate provides permanent habitat for Arctic species and seasonal feeding habitat for migrating boreal species. Data on temperature exist from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in this indicator is climate change (IPCC, 2019). Arctic Water, characterized by sub-zero temperatures and low salinity, dominates in the northern Barents Sea (Loeng, 1991; Lind and Ingvaldsen, 2012). This contrasts with the southern Barents Sea which is dominated by warmer Atlantic Water. Anthropogenic global warming leads to northward expansion of Atlantic Water thereby reducing the area of Arctic Water (Smedsrud et al., 2010; Smedsrud et al., 2013; Oziel et al., 2016). The associated reductions in regional sea ice (Årthun et al., 2012; Onarheim et al., 2018) and sea-ice import (Lind et al., 2018) accelerate the loss of the Arctic Water area. Given the massive evidence of anthropogenic influence on the climate in general (Masson-Delmotte et al., 2021) and for the Barents Sea locally described above, the understanding of the link between driver and change in the indicator is rated as certain.

The decreasing extent of Arctic Water has profound impacts on the local and regional Arctic climate (Smedsrud et al., 2010; Smedsrud et al., 2013) and ecosystems (Dalpadado et al., 2012, 2014, 2020; Huserbråten et al., 2019; Stige et al., 2019; Gjøsæter et al., 2020). Northward expansion of Atlantic Water has decreased the area of Arctic Water and promoted invasion by boreal species, as documented for plankton (Wassmann and Reigstad, 2011; Orlova et al., 2015; Wassmann et al., 2015; Neukermans et al., 2018; Oziel et al., 2020; Vernet et al., 2020), pelagic and demersal fish (Berge et al., 2015; Fossheim et al., 2015), marine mammals (Hamilton et al., 2019; Moore et al., 2019) and seabirds (Descamps et al., 2017; Vihtakari et al., 2018). The biogeographic process of borealization modifies Arctic biodiversity, community structure, food web organization and ecosystem functioning (Kortsch et al., 2015; Frainer et al., 2017; Pécuchet et al., 2020; Ingvaldsen et al., 2021). The understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as good.

Examples of changes which can be considered of ecosystem significance as a result of decline in Arctic Water includes reductions in habitat for Arctic species like e.g., the copepod *Calanus glacialis*, the amphipod *Themisto libellula* and polar cod (Dalpadado et al., 2012, 2020; Aarflot et al., 2018; Huserbråten et al., 2019; Stige et al., 2019).

Arctic Water extent decline depend on sea-ice inflow and formation, inflow of Atlantic Water and inflow of Arctic Water formed elsewhere in the Arctic. Improved understanding is needed to address the relative contribution from the three sources on the formation and distribution of Arctic Water.

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Freshwater content [AI39]

Phenomenon: Decreasing freshwater content [AP39]

Ecosystem characteristic: Abiotic factors

Under the reference condition, the Arctic part of the Barents Sea is characterised by its freshwater content in the upper part of the water column, approximately in the upper 100 m (Lind et al., 2018). The freshwater content is sustained over several years, but eroded slowly (over years) from vertical mixing with the more saline Atlantic layer below 100 m. The primary source of freshwater input to it comes from import of sea ice to the Barents Sea that melts in summer (Ellingsen et al., 2009; Koenigk et al., 2009; Lind et al., 2018). The freshwater content of the upper 100 m is a key indicator of vertical and temporal stability for the Arctic part because it sets up the stratification between the Arctic layer and the Atlantic layer. The stratification limits vertical mixing, which constitutes a heat flux up to the upper 100 m, as well a salt and nutrient flux (Lind et al., 2016; Randelhoff et al., 2016; Lind et al., 2018). Thus, a high freshwater content contributes to keeping the upper 100 m cool and fresh, thus acting positively to local sea-ice formation in winter (Lind et al., 2018). Quantitative estimates of freshwater content under the reference condition are 2–3.5 m of freshwater mixed into the upper 100 m when using 35.0 (in psu) as reference salinity (Lind et al., 2018; Aaboe et al., 2021).

The most important anthropogenic driver of change in the indicator is climate change from Arctic warming and sea-ice loss in response to global warming, leading to reduced sea-ice import to the Barents Sea due to sea-ice reductions in the Arctic Ocean. I.e., Arctic sea ice is becoming thinner, less concentrated and has reduced extents in summer (Carmack et al., 2015), and sea-ice imports to the Barents Sea has been declining after 2005 (Lind et al., 2018). It is likely that the reductions of sea ice in the areas nearby the Barents Sea have greatest impact on sea-ice inflows to the Barents Sea, and the Eurasian Basin has suffered the largest loss of thicker multiyear ice since the 2000s (Carmack et al., 2015). This very likely largely stems from Arctic amplification of global warming due to anthropogenic CO_2 emissions (IPCC, 2019; Masson-Delmotte et al., 2021) and is also likely a part of the Atlantification process occurring in the Barents Sea and further eastwards into the Eurasian Basin (Polyakov et al., 2017; Lind et al., 2018). The understanding of the link between drivers and indicator is rated as certain.

The freshwater content of the upper 100 m signifies how resilient the Arctic-type water column is towards 1) continued vertical mixing with the Atlantic layer and 2) longer time periods (several years) without significant sea-ice import and thus low or absent freshwater input. This impacts the ecosystem directly due to increased vertical mixing giving higher nutrient and heat fluxes upward to the halocline. In the longer run, it means that the whole ecosystem is prone to being changed from an Arctic to an Atlantic climate regime unless the sea-ice import and thus freshwater input recover in time, before the stratification breaks down (Lind et al., 2018). A resilience loss will have net negative consequences for the Arctic species because they are adapted to the stratified, cold and nutrient-poor conditions and suffer from increased competition and predation from boreal species (e.g., Fossheim et al., 2015; Kortsch et al., 2015; Husson et al., 2020; Frainer et al., 2021). Although the full ecosystem impact of resilience loss is unknown, or less understood, the overall understanding of the role of the indicator is that declines in freshwater have negative total impact for the Arctic species. The understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as good.

There are knowledge gaps concerning the qualitative understanding of the dynamics related to the phenomenon and regarding potential threshold values for which levels of freshwater content the Arctic-type water column become vulnerable/less resilient, prone to transition to an Atlantic climate regime. There is a knowledge gap as to how easily the stratification may be re-established once it has been lost from an area. This likely depends on how easily the freshwater content is re-established from potential inflowing sea ice and related melt.

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Stratification [AI40]

Phenomenon: Decreasing stratification of the upper water column [AP40]

Ecosystem characteristic: Abiotic factors

Under the reference condition, there is strong stratification of the upper water column in the Arctic part due to input of freshwater from melting sea ice, causing increasing salinity (and thus density) with depth (Aagaard et al., 1981; Loeng, 1991). Data on temperature and salinity exist from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in the indicator is climate change (IPCC 2019). Anthropogenic global warming leads to sea-ice decline thereby reducing the surface salinity in the Arctic part (Lind et al., 2018), increase the summertime solar heating (Perovich et al., 2008) also beyond the melt season (Timmermans, 2015; Ivanov et al., 2016) and strengthened air-sea-ice fluxes and ventilation (Ivanov et al., 2016; Asbjørnsen et al., 2020; Polyakov et al., 2020a). All of these reduce the stratification in seasonal sea-ice covered areas. Decreasing stratification in the upper water column amplifies the sea-ice loss by increasing the heat fluxes from the warm Atlantic Water at depth (Ivanov et al., 2016; Lind et al., 2016; Polyakov et al., 2020a). Thus, decreasing stratification in the upper water column has profound impacts on Arctic climate. The understanding of the link between driver and change in the indicator is rated as certain.

Stratification of the water column can be considered of **ecosystem significance** as it strongly affects the local sea-ice formation and melting thereby influencing the sea-ice habitat and associated species (Macias-Fauria and Post, 2018). It also affects the vertical fluxes of new nutrients into the euphotic zone thereby controlling the primary production (Randelhoff et al., 2020). Weaker vertical stratification enhances the vertical fluxes of nutrients (during winter) setting mixed-layer properties, thereby facilitating larger new production (Randelhoff et al., 2020). The understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as good.

Sea-ice reduction in winter increases the winter ventilation and thus the mixing of the water column during the cold season (Asbjørnsen et al., 2020; Polyakov et al., 2020b). The understanding of how altered surface fluxes through the year affect the stratification in the Arctic Barents Sea is an important knowledge gap.

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pH [AI41]

Phenomenon: Decreasing pH [AP41]

Ecosystem characteristic: Abiotic factors

Under the reference condition, the water column is basic with a surface pH of about 8.

The most important anthropogenic driver of change in the indicator is climate change. Ocean uptake of excess atmospheric CO_2 caused by human activities, such as fossil fuel burning, and industrialization, has increased ocean CO_2 over a relatively short time period. Since 1750, the pH has decreased by about 0.1 units, corresponding to a 30% increase of hydrogen ions (less basic ocean). Currently, observations show a continued pH decrease of 0.02 per decade (Copernicus Marine Services, 2021). Continued pH decrease is rated as highly likely (IPCC, 2019). The understanding of the link between driver and change in the indicator is rated as certain.

Altered pH may directly affect the internal cellular processes in marine organisms, such as the ion pump and other redox reactions. pH may also change the availability and toxicity of vital metals, potentially changing the biological production. Also, increased pCO_2 may lead to hypercapnia in fish if exceeding levels 1000 ppm (McNeil and Sasse, 2016). However, the current understanding of the effect of reduced pH on ecosystems, is mainly based on acute, short term-experiments and ecosystem modelling (Browman, 2016). Hence the understanding of the importance of changes in the indicator for the ecosystem is rated as less good.

There are large knowledge gaps on the effect of reduced pH on organisms and marine ecosystems. The effects need to be related to studies of adaptive capacity and should include multi-stressors. This also requires multi-disciplinary observational long-term data sets in relevant areas (Browman, 2016).

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Aragonite saturation [AI42]

Phenomenon: Decreasing aragonite saturation [AP42]

Ecosystem characteristic: Abiotic factors

Under the reference condition, aragonite saturation sufficient for calcifying organisms to occur with biomasses high enough to sustain Arctic and Sub-Arctic food webs and ecological processes characterizing Arctic and Sub-Arctic ecosystems.

The most important anthropogenic driver of change in the indicator is climate change. Ocean uptake of excess atmospheric CO_2 caused by human activities, such as fossil fuel burning and industrialization, is causing ocean CO_2 to increase. The ocean carbonate ion concentration (CO_3^{2}-) is driving the aragonite saturation (Ω_{Ar}) and the chemical dissolution of the aragonite. Decreasing pH (increasing ocean CO_2) has resulted in decreasing saturation state with regard to calcium carbonate ($CaCO_3$), with consequences for the dissolution potential and calcification process. Aragonite is the most labile form of $CaCO_3$ in the ocean and the Arctic Ocean already has the lowest Ω_{Ar} compared to the world oceans (e.g. (Chierici and Fransson, 2009)). Continued decrease of Ω is expected is rated highly likely (IPCC, 2019). The understanding of the link between driver and change in the indicator is thus rated as certain.

The lowering of $CaCO_3$ saturation states (Ω), impacts shell-forming marine organisms from plankton to benthic molluscs, echinoderms, and corals. Many calcifying species exhibit reduced calcification and growth rates in laboratory experiments under high-CO_2 conditions (e.g., Kroeker et al., 2013; Manno et al., 2017). Another consequence is also the shoaling of aragonite saturation horizon ($\Omega_{Ar}<1$, i.e., dissolution of aragonite) which will continue and has consequences for cold-water corals and their ability to withstand erosion and continue to grow (ICES, 2014; AMAP, 2018). At $\Omega<1$ more energy is required to build $CaCO_3$ (e.g., Comeau et al., 2013). Climate change, such as warming, enhances the effect of low saturation states. However, the current understanding of the effect of Ω in the ecosystem is mainly based on acute, short term-experiments and ecosystem modelling (Browman, 2016). There are ocean observations, especially in upwelling sites and other low-aragonite areas that show clear evidence of shell deformation on shelled butterfly snails, crabs and mussels. This has been observed in the Pacific Arctic also where saturation states are lowest (Cross et al., 2018; Bednaršek et al., 2021; Niemi et al., 2021). Although this implies that the knowledge on the effect on calcifying organisms is good, the overall understanding of the importance of changes in the indicator for the ecosystem is rated as less good.

There are large knowledge gaps about the thresholds and adaptive capacity to perform calcification at low saturation states. Amplification and occurrence of corrosive events have been observed in the Arctic Ocean. However, the effects on the marine ecosystem are little understood. The effects need to be related to studies of adaptive capacity and should include multi-stressors (Rastrick et al., 2018). This also requires multi-disciplinary observational long-term data sets in relevant areas.

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5.2 Scientific evidence base for the phenomena in the Sub-Arctic Barents Sea

Annual primary productivity [SI01]

Phenomenon: Stable and later decreasing annual primary productivity [SP01]

Ecosystem characteristic: Primary productivity, Biomass distribution among trophic levels

Under the reference condition, primary production in the Sub-Arctic part of the Barents Sea is contributed by phytoplankton. Under the reference condition, there is a weak, but significant, stratification during summer in the upper water column of the Sub-Arctic, in part due to solar heating of the surface layer and input of freshwater from rivers (Loeng, 1991; Hordoir et al., 2022). The spring bloom can start when the upper water column stabilised through stratification and irradiance is high enough, typically in May-June (Sakshaug et al., 2009). Links found with variation in climate during the recent decades suggest that natural variation in key climatic parameters, such as temperature in advected waters, would have similar effects on primary production under the reference condition.

The most important anthropogenic driver of change in the indicator is climate change. Upper water column stratification in the Sub-Arctic part in summer and autumn is created by increasing temperatures and decreasing salinity (and thus density) toward the surface. Anthropogenic global warming leads to surface warming as well as freshening due to increased precipitation (Drinkwater et al., 2021). This causes a strengthening of the stratification and a shallower mixed-layer depth in summer (Hordoir et al., 2022). Stratification of the water column affects the vertical fluxes of new nutrients into the euphotic zone, thereby controlling new production (Randelhoff et al., 2020). Stronger vertical stratification decreases the vertical fluxes of nutrients into the surface mixed layer, and a shallower mixed layer decreases the inventory of nutrients available for primary production. Observed declining trends in phytoplankton concentrations have been linked to increased stratification (Boyce et al., 2010). A stronger stratification in Sub-Arctic parts is expected to decrease primary production (Drinkwater et al., 2021), although biogeochemical models differ when predicting future changes in primary production (Skaret et al., 2014; Slagstad et al., 2015; Skogen et al., 2018; Sandø et al., 2021). Also, for the North Atlantic sub-tropical gyre it has been shown that the upper-ocean stratification is at best weakly related to primary production on an interannual scale, pointing to a weaker effect of increased stratification (Lozier et al., 2011). Given this and the uncertainties indicated from the differences in model predictions, the understanding of the link between the driver (climate change) and change in the indicator is rated as less certain.

Both models and observations show that primary production is generally positively related to fisheries yield (Iverson, 1990; Ware and Thomson, 2005; Chassot et al., 2007; Chassot et al., 2010), thus providing strong evidence that changes in primary production have substantial impacts on other parts of marine ecosystems. The understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as good.

Specific levels of increase in primary production are hard to relate to specific ecosystem changes.

Knowledge gaps include a need for more *in situ* measurements and measurements of the ratio of new to regenerated production. It also includes a need for more information on changes in phytoplankton bloom phenology and the impact of changes in phytoplankton species composition on annual primary production and trophic transfer as well as high spatial resolution models with high-quality atmospheric forcing.

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Timing of spring bloom [SI02]

Phenomenon: Earlier start of the spring bloom [SP02]

Ecosystem characteristic: Primary productivity

The description of the indicator under the reference condition is as given for the phenomenon for annual net primary productivity [SI01].

The most important anthropogenic driver of change in the indicator is climate change. Increased thermal stratification, caused by increased temperature, and changed storms tracks, may cause the spring bloom to start earlier, but satellite observations do not indicate pronounced changes and variability in spring-bloom timing for the open water part of the Barents Sea (Oziel et al., 2017; Dalpadado et al., 2020). The current understanding of the link between climate change and changes in the indicator is rated as less certain.

Altered timing of the spring bloom may result in mismatches between phytoplankton and zooplankton grazers, which may affect zooplankton production and other parts of the ecosystem. However, little is known about this for the Sub-Arctic part of the Barents Sea or other Sub-Arctic systems. The understanding of the importance of changes in the indicator for the rest of the ecosystem is thus rated as less good.

Too little is known about the relationship between magnitude of spring bloom timing shift and effects on the ecosystem to evaluate how large changes should be for effects with ecosystem significance to occur.

Knowledge gaps include a need for more *in situ* measurements, as well as high spatial resolution models and better remote sensing data

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Zooplankton TL < 2.5 [SI03]

Phenomenon: Decreasing biomass of zooplankton that is predominantly herbivorous [SP03]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the biomass and turnover of herbivorous zooplankton is large enough to support populations of a variety of predators in the Sub-Arctic part of the Barents Sea, including pelagic fish such as capelin and herring (*Clupea harengus*), 0-group of both demersal and pelagic fish, carnivorous zooplankton such as the krill species *Meganyctiphanes norvegica,* and harp seals (*Pagophilus groenlandicus*) (Sakshaug et al., 1994; Haug et al., 2011; Planque et al., 2014; Eriksen et al., 2020). Copepod mesozooplankton is dominating, particularly *Calanus finmarchicus*, as well as the herbivorous krill *Thysanoessa inermis* (Dalpadado and Skjoldal, 1991, 1996; Eriksen et al., 2017; Aarflot et al., 2018; Dalpadado et al., 2020). A significant fraction of the mesozooplankton community in the northern regions of the Sub-Arctic part of the Barents Sea is made up of Arctic species under the reference condition, in particular *Calanus glacialis* and *Calanus hyperboreus,* although the Atlantic *C. finmarchicus* dominates in all parts of the Sub-Arctic regions (Aarflot et al., 2018).

The most important anthropogenic driver of change in this indicator is climate change, such as increased inflow of Atlantic Water, increased water temperatures and changes in bloom phenology, making the Sub-Arctic Barents Sea more favourable for Atlantic boreal zooplankton species that are extending their distribution into the Sub-Arctic areas while at the same time some of the larger, more Arctic species in the northern areas of the Sub-Arctic are decreasing in abundance (Eriksen et al., 2017; Dalpadado et al., 2020). Generally, we can expect similar changes in the zooplankton community in the Sub-Arctic part of the Barents Sea as observed further south in the North Sea, the shelf ecosystem adjacent to the Barents Sea, during the warming in the 1980-90s. The community in the North Sea before the warming in the 1980s was dominated by *Calanus finmarchicus,* but surface water warming could be related to a biogeographical shift in calanoid copepods assemblages with an increase in warm-water species (such as *C. helgolandicus*) and a decrease in boreal species (such as *C. finmarchicus*) as well as Arctic species residing in boreal areas (e.g. *C. glacialis* in Norwegian fjords) (Beaugrand, 2004; Helaouët and Beaugrand, 2007; Beaugrand et al., 2014; Hinder et al., 2014). Further northwards shift of *C. helgolandicus* towards the Sub-Arctic Barents Sea may be possible. Likely is also a shift in life history strategies in *C. finmarchicus* and *C. glacialis*, which tend to be smaller with higher turnover further south. Southern species such as *C. helgolandicus* often have shorter life cycles and may produce multiple generations per year, whereas *C. finmarchicus* in the Norwegian Sea may enter diapause earlier, in June-July (Bandara et al., 2021). With warming, earlier onset of spring bloom and more common occurrences of autumn blooms in the Sub-Arctic Barents Sea, we can expect that boreal species such as *C. finmarchicus* are able to develop faster and may even have a second generation in the autumn of the year. There are large uncertainties associated with what the overall effect on zooplankton biomass could be. A northward shift in larger Arctic spring spawning mesozooplankton and an increase in occurrence of small species such as *Calanus helgolandicus* may cause reductions zooplankton biomass in some areas. However, increased primary production and faster turnover in secondary producers will likely result in higher copepod biomass under a climate warming scenario in the Sub-Arctic Barents Sea. The annual mean production of *Calanus finmarchicus* will increase 23% in a 50-year future scenario, mostly in the southern and western area of the Barents Sea (Skaret et al., 2014; Renaud et al., 2018). Boreal krill species are more omnivorous/carnivorous than Sub-Arctic species (Falk-Petersen, 1981) meaning that the relative contribution of herbivorous krill may change as biomass of boreal species, e.g., *Meganyctiphanes norvegica*, is increasing, although the exact nature of this is hard to anticipate as the process will depend on trajectories of change of individual krill species. Given the uncertainties highlighted here, the understanding of the link between driver and indicator should be rated as less certain.

A s herbivorous species are efficient in transforming algae diet into high energy lipids, a reduction in herbivorous biomass could potentially lead to reduced food quality and/or energy content in the food web. However, there are uncertainties associated with this, and increased turn-over rates may compensate for decrease in individual biomass. Our understanding of the importance of changes in the indicator for other parts of the ecosystem should thus be rated as less good.

An example of a change that would be of **ecosystem significance**, is a decline in herbivore zooplankton biomass accompanied by an increase in carnivore zooplankton biomass, which, as described above, could profoundly alter energy flow in the ecosystem.

Knowledge gaps include lack of data on response of *C. finmarchicus* to warming and upper limit of warming it can cope with; and lack of data on ability of boreal species such as *C. helgolandicus* to establish themselves at high latitudes. It may be noted that the upper thermal limit for boreal zooplankton is probably rather high, so more influential will be changes in water masses and distribution ranges of more southern species.

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Zooplankton TL > 2.5 [SI04]

Phenomenon: Increasing biomass of zooplankton that is predominantly carnivorous [SP04]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, carnivorous zooplankton community in the Sub-Arctic part of the Barents Sea is likely dominated by chaetognaths, gelatinous species and carnivorous copepods and amphipods.

The most important anthropogenic driver of change in this indicator is likely climate change, with increasing temperature, less ice and reduced areas of Arctic Water as the important factors. The zooplankton community will likely develop towards what is seen further south. The omnivorous/carnivorous krill species *Thysanoessa longicaudata* and *Meganyctiphanes norvegica* are widely distributed in the Nordic Seas, while larger pelagic amphipods are less abundant (Dalpadado et al., 1998). Gelatinous species may also become more abundant, particularly large medusas, such as the Lion's mane jellyfish (*Cyanea capillata*) (Lynam et al., 2005). A northward expansion of these species may contribute to an increase in biomass of carnivorous zooplankton, although if gelatinous species increase to large densities, they can cause reductions in prey biomass. Given the uncertainties described here the knowledge about link between driver and indicator should be rated as less certain.

Although it is reasonable to assume that an increase in the biomass of carnivorous zooplankton in the Sub-Arctic part of the Barents Sea will have effects on at least parts of the ecosystem, such effects cannot be reasonably predicted. Increased biomass of macrozooplankton could benefit predatory fishes, seabirds and marine mammal species (Haug et al., 2007; Planque et al., 2014; Eriksen et al., 2020). Given these uncertainties, the understanding of the importance of changes in the indicator for other parts of the ecosystem is rated as less good.

The uncertainties also mean that examples of changes that can be of ecosystem significance are hard to determine with a reasonable degree of confidence.

Knowledge gaps: Lack of long-term data, particularly on gelatinous taxa; gelatinous taxa are generally poorly studied, and we have poor knowledge of life-history strategies, species interactions, ecophysiology and productivity hampering our ability to predict how they will cope with environmental changes such as changes in temperature and predators-prey field. In addition, there is lack of species-specific krill data, which could be used to correctly identify herbivorous and carnivorous krill biomass.

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Benthic suspensivores [SI05]

Phenomenon: Change in biomass of suspension feeding species [SP05]

Ecosystem characteristic: Biomass distribution among trophic levels

No description of the state of the indicator under reference conditions can be done.

The most important anthropogenic driver of change in this indicator may be climate change, which can directly and indirectly affect the phenology, quality, and quantity of phytodetritus reaching the seafloor. This is expected to occur due to changes in light climate because of altered ice cover (extent, thickness, seasonality). For instance, the production of coastal Arctic benthos is tightly linked to surface primary production and ice cover (Tremblay et al., 2011). Trawling will likely also lead to this phenomenon (Jørgensen et al., 2015, 2019), as it would tend to reduce the biomass of generally tall animals, more easily captured by the bottom trawls. In addition, potentially increased importance of advection/establishment of more southern phytoplankton taxa and/or elevated grazing by zooplankton may result in possibly lower likelihood of phytodetritus reaching the seafloor. The link to trawling needs to be verified through testing existing data and for now is moderately certain. The role of climatic change here is less certain. The overall knowledge of the link of the indicator to the driver is thus less certain.

Suspension-feeding benthos such as sponges, bryozoans, hydroids, some sea cucumbers, and other species make up local large biomass of the seabed fauna (Kędra et al., 2013). Epibenthos plays a major role in the carbon cycling of the Arctic ecosystems (Grebmeier et al., 1995; Klages et al., 2004), thus suspension feeders may be central for the functioning in the ecosystem. Such local biomass accumulations with complex, large bodied species may be refuge and feeding areas for fish and other benthic invertebrates (Kędra et al., 2015). The understanding of the importance for the rest of the ecosystem of decreasing proportion of suspension feeding biomass is good.

The ecosystem significance of decreasing proportion of suspension feeding biomass has not been verified for the Barents Sea, but the effect of structure-forming corals and sponges and their use as fish habitat have been described for the Bering Sea submarine canyons (Miller et al., 2012), and effects on fish habitat and general support of higher biodiversity are expected to be similar for Norwegian cold-water coral habitats.

Knowledge gaps that require further research include better insights into the functional importance of suspension feeders in the ecosystem and their sensitivity to climate change.

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0 group fish [SI06]

Phenomenon: Increasing biomass of 0-group fish [SP06]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the biomass of 0-group fish is large enough to support predator populations dependent on these fish larvae as prey, and also large enough to ensure sufficiently high recruitment to sustain the fish stocks themselves.

The most important anthropogenic drivers of change for this indicator in the Sub-Arctic part of the Barents Sea are i) climate change, through direct effects on their distribution and abundance, and ii) fisheries, through indirect effects on spawning stocks size and structure, and thus recruitment and 0-group abundance. Climate change is expected to be the main driver of 0-group biomass, and growth and survival of cod, haddock and herring juveniles has been shown to covary with interannual environmental variability (Ottersen and Loeng, 2000). Their core area of distribution has been shown to expand during warm years (Eriksen et al., 2011). However, positive relationships between temperature and recruitment of cod, haddock and herring have weakened since the 2000s (Eriksen et al., 2012). Links between variation in climate and fish recruitment have been explored, but so far evidence is weak for species in the Barents Sea (e.g. Garcia et al., 2021). It is thus uncertain how climate is going to affect 0-group biomass, although most of the southern 0-group stocks (haddock, herring) seem positively impacted by increasing temperatures. Fisheries strongly affect the spawning stock biomass and the size structure of the exploited stock. It is thus quite certain that 0-group biomass is negatively affected by fisheries. The knowledge about the links to these anthropogenic drivers are assessed as less certain.

The four most abundant 0-group fish species are capelin, cod, haddock and herring. Strong year classes of those species lead to better stock development of adults in the following years. Those species are key to the Barents Sea and have huge impacts on the ecosystem as prey (capelin and younger stages of haddock and cod), plankton consumers (capelin and herring) and predators (herring, cod and haddock). In addition, 0-group fish have a wide distribution in the entire Barents Sea and are an important part of the pelagic stock in the summer and early autumn (Eriksen et al., 2011). Because of their large consumption/biomass ratio, 0-group fish have a central role in the energy transfer across trophic levels and between regions. They are preyed upon by many piscivorous fish, birds and marine mammals (Barrett and Krasnov, 1996; Skaug et al., 1997; Dalpadado and Bogstad, 2004). The understanding of the importance of changes in the biomass of 0-group fish is assessed as good.

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Pelagic planktivorous fish [SI07]

Phenomenon: Change in biomass of pelagic planktivorous fish [SP07]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, the biomass of planktivorous fish stocks of herring, blue whiting, and capelin is large enough to support predator populations dependent on these species as prey, e.g., cod, redfish, Greenland halibut, saithe and skates (Eriksen et al., 2020). Pelagic planktivorous fish are predators on zooplankton and are important for energy transfer to higher trophic levels such as marine mammals, seabirds and fish (Sakshaug et al., 2009; Jakobsen and Ozhigin, 2011).

The most important anthropogenic drivers of change in the biomass of pelagic planktivores are fisheries and climate change. Fishing is expected to cause a decrease in planktivorous fish biomass if these are the target species, or an increase for fisheries targeting higher trophic level species. The understanding of the link to fisheries is assessed as certain. With climate change, the diversity of pelagic planktivores is expected to increase due to northward expansion of southern species. There is also a positive effect of temperature on recruitment, at least for herring (Garcia et al., 2021), but the presence and possible increase of piscivores may reduce any increase in biomass. NEA cod is one of the important predators on planktivorous fish that is expected to benefit from climate change in the Barents Sea (Kjesbu et al., 2014; Årthun et al., 2018). Thus, the net effect on planktivorous fishes from climate change is uncertain, and the understanding of the link to climate change is assessed as less certain.

Planktivorous fish have a key role in top-down regulation of pelagic consumers (zooplankton) (Gjøsæter et al., 2009), and are important for energy transfer to top predators, such as piscivorous fish, seabirds, and marine mammals (Planque et al., 2014; Eriksen et al., 2020). Capelin plays a key role in the Sub-Arctic part of the Barents Sea as the most important mid-trophic level species efficiently making energy from plankton available to top-predators (Dolgov, 2002; Orlova et al., 2009). In particular NEA cod is dependent upon capelin for sustaining its high abundance. Capelin is also key diet items for whales, several seabird species, harp seals and other fish species (Dolgov, 2002; Planque et al., 2014; Eriksen et al., 2020). There is also evidence that capelin can inflict top-down effects on its zooplankton prey (Hassel et al., 1991; Dalpadado and Skjoldal, 1996; Gjøsæter et al., 2009). Less is known about the influence of NSS herring and blue whiting on the dynamics of prey and predator species, but they are known to be prey of large numbers of piscivorous fish, seabirds and marine mammals (Planque et al., 2014), and thus likely to be of importance for many species. In addition, there are important direct trophic interactions between the pelagic fish stocks (Planque et al., 2014), in particular between herring and capelin, with herring being an important predator on capelin larvae and a likely significant contributor to collapses in the capelin stock (Hjermann et al., 2004; Hjermann et al., 2010). The understanding of the importance of changes in biomass of pelagic planktivores is thus assessed as good.

Increasing or decreasing biomass of pelagic planktivores can be considered of **ecosystem significance** if, for example, i) it has direct effects on zooplankton, such as increasing biomass causing a reduction in biomass and decreasing proportion of large species and size-classes, ii) increasing biomass has negative indirect effects on other planktivores through increased competition, e.g. seabirds, marine mammals (such as Atlantic puffin, common murre, minke whales, fin whales and harbor porpoises, (Planque et al., 2014)), iii) it has direct positive or negative effects on piscivores, e.g. seabirds, fish, mammals (cod, redfish, saithe, Greenland halibut, skates, (Planque et al., 2014; Eriksen et al., 2020)).

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High trophic level seabirds [SI08]

Phenomenon: Change in biomass of high trophic level seabirds [SP08]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, Atlantic puffin (*Fratercula arctica*) and common murre (*Uria aalge*) are important piscivorous predators in the Barents Sea ecosystem and a dominant part of the avifauna in the southern part of the Barents Sea (ICES, 2020). By-catch in fisheries (Strann et al., 1991) and fishery-induced collapses in the stocks of Norwegian spring spawning herring (Cury et al., 2011) and the Barents Sea capelin (Erikstad et al., 2013) had large impacts on the population dynamics of these species during the second half of the 20th century.

Climate change combined with prey availability are considered to be dominant drivers affecting the populations of common murres and puffins (Krashnov and Barrett, 1995; Durant et al., 2003; Erikstad et al., 2013). Puffins depend heavily on juvenile fish, and puffins from the colonies in northern Norway follow the drift of fish larvae into the Barents Sea after breeding, i.e., during late summer and early autumn. Juvenile fish, capelin and sand lance are important prey items for common murres (Barrett and Krasnov, 1996). Both seabird species are considered to be boreal, and the gradual borealization of the ecosystem following climate warming is expected to favor the two species, suggesting an increased abundance (e.g. Descamps and Strøm, 2021).

An unprecedented mass die-off of seabirds, most notably murres, was recently observed in the North Pacific following a marine heat wave causing widespread changes at lower trophic levels and subsequent starvation among seabirds (Piatt et al., 2020). The Barents Sea population of common murres experienced an incident of mass mortality and breeding failure in 1986-87 following a collapse in the capelin stock (Krashnov and Barrett, 1995; Erikstad et al., 2013). The Barents Sea common murre population stays in the southern Barents Sea throughout the winter, and the population is likely to be particularly vulnerable to collapses in local prey stocks caused by climate extremes such as heat waves. Such extremes are likely to increase in frequency under climate warming.

Most puffins leave the Barents Sea during winter and spread out over a large area in the North Atlantic. Recent studies suggest that seabirds could experience increased mortality during severe winter storms in the North Atlantic (Clairbaux et al., 2021). Storms are expected to increase in frequency and severity under climate change and could cause incidents of mass die-offs in puffins.

Competition with industrial fisheries targeting small pelagic fish has been argued to be an important factor affecting seabird populations worldwide (Cury et al., 2011; Grémillet et al., 2018). As experienced during the 1960s-80s, the pelagic fisheries of capelin and herring could cause collapses in the fish stocks with severe consequences for the populations of common murres and puffins. The current prudent regulations of the fisheries suggests that fisheries-induced collapses are a much less severe threat today, although capelin abundance is still very variable even at the low fishing pressure applied in the 2000s.

The knowledge about the links to climate change and fishery are assessed as certain. Fisheries are expected to affect populations negatively while climate change could affect populations both negatively, through increased frequency of extreme events, and positively through a borealization of the ecosystem. The mechanisms are well understood and there is good empirical evidence for anthropogenic impacts caused by over-fishing and climate change.

Atlantic puffin and common murres are, together with marine mammals and cod, important predators on pelagic fish in the Barents Sea and constitute a significant part of the top predator guild in the ecosystem (ICES, 2020). A large relative drop in the abundance of these species could impact their role as top predators in the ecosystem and would signal negative changes at lower trophic levels (Krashnov and Barrett, 1995; Barrett and Krasnov, 1996; Durant et al., 2003; Erikstad et al., 2013; Descamps and Strøm, 2021). The understanding of the importance of changes in the biomass of Atlantic puffin and common murre is assessed as good.

Changes in the biomass of high trophic level boreal seabirds can be considered of **ecosystem significance** if, i) there is a sudden drop in the biomass caused by a mass die-off of birds following a collapse in the availability of prey due to climate extremes or over-fishing, ii) there is a significant gradual long-term (> 10 years) increase in the biomass associated with climate warming and borealization of the ecosystem.

Knowledge gaps:

The time series from the ecosystem survey in the Barents Sea is relatively short (2004-2020). The indicator is sensitive to natural fluctuations in the Barents Sea climate and the abundance and distribution of key species such as capelin. The impact from anthropogenic drivers, such as fishing and climate change, are mediated through multiple direct and indirect pathways, and the relative importance of these drivers is therefore often unclear. More knowledge is needed to understand the mechanisms and dynamics related to these drivers.

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Low trophic level marine mammals [SI09]

Phenomenon: Change in abundance *of low trophic level mammals* [SP09]

Ecosystem characteristic: Biomass distribution among trophic levels

Blue whales and fin whales both feed at low trophic levels in the Barents Sea (Mackenzie et al. 2022). Both species were hunted extensively, but blue whales were hunted to near extirpation and remain at levels dramatically lower than the historical state. Fin whales appear to have recovered somewhat; however, the original stock sizes for both species are unknown.

Commercial whaling is the cause for the reduced current population size (biomass) of these species. Currently, climate change is likely to be a major driver (Kaschner et al., 2011, Kovacs et al., 2021). Blue whales are thought to be recovering, with an estimated 3,000 in the central north Atlantic (Pike et al., 2019), many of which have moved into the Svalbard area during recent summers (Bengtsson et al., 2022). Fin whales are increasing and thought to be recovering or mostly recovered to their pre-whaling state (Vikingsson et al., 2015, Leonard and Øien, 2020a, b). Blue whale and fin whale numbers will likely continue to increase as long as pelagic production increases, which is expected with ocean warming and less sea-ice cover (Dalpadado et al., 2012). The abundance of krill is currently increasing in the Sub-Arctic (Erikson et al., 2017); if sufficient densities occur this will, be an attractant for more blue and fin whales. These species are already extending their range northward, tracking the sea-ice retreat and may be spending a longer period in the Norwegian waters seasonally (Storrie et al. 2018, Ahonen et al., 2021; Bengtsson et al., 2022)

The knowledge about the link to anthropogenic drivers is assessed as certain ; however, confounding the effect of climate warming as a driver is the recovery from commercial whaling and lack of historical population-size data. It is not possible to separate these effects.

These lower trophic feeding species are thought to have considerable impacts on the ecosystems they occupy, similar to other marine mammals, largely because of their extreme (large) body size(s). They influence their ecosystems through nutrient recycling, competition, and top-down control, but these effects are not well measured. An increasing blue whale population would almost certainly have at least local influences on krill abundance. The understanding of the link to ecosystem impact is thus assessed as less good.

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Generalist mammals [SI10]

Phenomenon: Change in abundance of generalist mammals [SP10]

Ecosystem characteristic: Biomass distribution among trophic levels

Humpback whales and minke whales both have diets that vary across trophic levels in the Barents Sea (Mackenzie et al. 2022). Both species are likely depleted from their historical condition due to commercial whaling. Humpback whales were hunted extensively during the historical whaling period, while minke whales have been hunted continuously since the 1920’s. Although original stock sizes are not known with certainty, it is thought that humpback whale numbers have recovered somewhat in recent decades (Vikingsson et al., 2015; Leonard and Øien, 2020a, b).

Commercial harvest was a major driver of the abundance/biomass of humpback whales (historically) and minke whales (currently) in the Sub-Arctic. Commercial harvests are currently conducted within sustainable limits for minke whales, so are not defining population levels. Climate change is a current driver for the increasing biomass of generalist-feeding marine mammal species in the Sub-Arctic. Pelagic-feeding, seasonally resident minke and humpback whales are likely to continue to increase in response to temperature increases that drive prey species expansions northward with longer production seasons, warmer temperature and less sea ice (Dalpadado et al., 2012; Erikson et al., 2017). As generalists, these species are more successful in changing environments such as the Barents Sea, because they are able to take advantage of prey at varying trophic levels (Berta and Lanzetti, 2020). Since 1995, the number of humpback whales occurring in the Barents Sea during the summer months has increased from near zero in 1995 to an estimated 5000 animals, according to recent survey estimates (Leonard and Øien 2020a, b). In addition, the minke whale population in the North Atlantic, while remaining relatively constant in abundance, has undergone a shift in spatial distribution with a near doubling of the number of minke whales present in the Barents Sea in recent years (see Bengtsson et al., 2022 for sightings in Svalbard).

The understanding of the link of this indicator to anthropogenic drivers is assessed as certain.

Alteration of numbers/biomass of this indicator can alter the abundance of other species as well as altering the structure and functioning of the ecosystem. Similar to the other marine mammals, generalist feeding marine mammals are thought to exert considerable influences on the ecosystems they occupy, including, trophic structuring, nutrient recycling and carbon sequestration; however, quantifying these dynamics is complex and requires further study. The knowledge about the link to ecosystem impact is thus assessed as less good.

Minke and humpback whales occupy similar ecological niches as generalist predators of schooling fish and euphausiids. Both species can adapt by switching between prey species in response to their relative abundance (Haug et al., 2002); however, given the minke whale’s smaller body size, they are less able to buffer against interannual variation in food availability. There is evidence from the Southern Ocean that humpback whales tend to outcompete minke whales for prime feeding habitats, as the larger whales require larger prey patches and engage in cooperative feeding behaviors to concentrate prey (Friedlaender et al. 2006). A decline in body condition of minke whales between 1992-2013 may be an indication of an increase in competition for prey (Solvang et al., 2017). This decline coincides with higher abundances of humpback whales (Leonard and Øien 2020a, b) and also a higher abundance Atlantic cod, which are also a competitor of generalist marine mammals, and are thought to be increasing due to climate warming (Kjesbu et al., 2014; Bogstad et al., 2015). Thus, while the short-term changes in abundance of generalist marine mammals may be somewhat clear, the long-term trajectory is less clear and must account for competition with other species and fisheries, predator-prey dynamics, and corresponding food-web shifts.

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High trophic level mammals [SI11]

Phenomenon: Change in abundance of high trophic level mammals [SP11]

Ecosystem characteristic: Biomass distribution among trophic levels

Sperm whales, killer whales, bottlenose whales, harbour porpoises, white-beaked dolphins, and harp seals, harbour seals, and grey seals, all feed at a high trophic level, are represented in this indicator. Most cetacean species, including those feeding on higher trophic levels, that occupy Norwegian waters in the Sub-Arctic were hunted extensively, though white-beaked dolphins have not been exploited commercially. Bottlenose whales were present historically in the Sub-Arctic, as evident from harvest records, but remain at very low levels today, with few observations in the Barents Sea (Leonard and Øien 2020a, b).

Historically, harvest was the most important driver for most of these species. Presently climate change, competition with fisheries, by-catch in fisheries, and pollutants are the most likely anthropogenic drivers. Sperm whales, and possibly bottlenose whales may be increasing after protection, and their squid prey is unlikely to be negative impacted by climate change. However, they may be vulnerable due to their reduced genetic diversity and narrow dietary niche (Sousa et al., 2019). Increased underwater noise (ship traffic, sonars, airguns) may impact these two species in addition to pollutants, that all toothed whales have problems metabolizing. Killer whales will likely increase in a warming Arctic and may expand northwards following prey species, such as mackerel and herring (Bentley et al., 2017). Additionally, an increase in pelagic feeding whales and less protection for ice-associated whales will result in an increase in the prey base for mammal-eating killer whales. High levels of pollutants are common in all high trophic level marine mammals (Desforges et al., 2018). Harp seals numbers are reduced from earlier levels, but this species is still the most numerous pinnipeds in the Barents Sea (Haug et al., 2021). Commercial harvests are currently conducted within sustainable limits, so are not defining population levels. In the Sub-Arctic, harp seal numbers will likely decline as sea ice retreats northward and there is increased competition from seal species that are not ice dependent, such as harbour seals and grey seals, which are expanding their ranges northward and are expected to be “climate winners” (Blanchet et al. 2014). White beaked dolphins and harbour porpoises are pelagic feeders; thus, increases in production are likely to have positive effects. However, they are also likely to face increased competition from dolphin species moving northwards (i.e., white-sided and common dolphins) and from other pelagic predators. The understanding of the link to anthropogenic drivers is assessed as certain.

Similar to the lower-trophic feeders, top-trophic feeding marine mammals are thought to exert considerable influences on the ecosystems they occupy, including top-down control of lower trophic species and vertical circulation of nutrients (e.g., Devred et al. 2021; Katija, 2012; Lavery et al. 2014). Higher trophic consumers are likely to have greater impact because the energy that they draw from the system is greater than for lower trophic feeders, but the exact effects of species losses (or major reductions) are difficult to predict. The link to ecosystem impact is thus assessed as less good.

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High TL zooplankton functional groups [SI12]

Phenomenon: Change in biomass of carnivorous krill relative to gelatinous zooplankton [SP12]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the most important carnivorous krill species in the Barents Sea is *Meganyctiphanes norvegica* which preys on smaller zooplankton and is prey for fish, seabirds and marine mammals (Cabrol et al., 2019; Eriksen et al., 2020). Under the reference condition, the species is strongly associated with inflowing Atlantic Water in the southwestern part of the Barents Sea (Eriksen et al., 2016). Gelatinous zooplankton, with >95% water content in their body are generalist predators, feeding on zooplankton, fish larvae and eggs as well as other types of prey (Purcell and Arai, 2001). They are prey for many groups, including fish (such as cod) in the Barents Sea (Eriksen et al., 2018). Their role as prey is poorly known but has probably been underestimated in diet studies based on visual examinations of predator guts, as studies using stable isotope analysis of predator tissues, animal-borne cameras, and DNA analysis of faecal and gut samples (metabarcoding) are all indicating that many taxa routinely consume jellyfish (Hays et al., 2018). The latter approaches need to be further validated and, consequently, the understanding of role gelatinous zooplankton in ecosystems is still rather limited (Stoltenberg et al., 2021).

The most important anthropogenic driver of change in the indicator is likely climate change. Looking across both the Norwegian and Russian sector of the Barents Sea and for the time period from 1984 to 2005 and 2000 to 2011, an increase in the amount of krill has been observed, likely as a response to climate warming (Dalpadado et al., 2012; Eriksen et al., 2016). There are also indications that important groups of gelatinous zooplankton in the Barents Sea have been favoured by climate change in the same period (Eriksen et al., 2012, 2018). Given the uncertainties associated with the latter, the understanding of the link between driver and indicator is rated as less certain.

A considerable change in the biomass of carnivorous krill relative to that of gelatinous zooplankton may have a significant impact on both predator and prey functions in the carnivorous zooplankton community. However, as the understanding of the predator and prey dynamics of gelatinous zooplankton is limited generally (Purcell and Arai, 2001; Stoltenberg et al., 2021), and also for the Barents Sea (Eriksen et al., 2012, 2018), the understanding of the importance of changes in the indicator for other parts of the ecosystem is rated as less good.

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Benthic habitat engineers [SI13]

Phenomenon: Decreasing biomass of benthic habitat engineers [SP13]

Ecosystem characteristic: Functional groups within trophic levels

Under reference conditions, biomass of benthic habitat engineers should be sufficient to host local biodiversity hot spots and provide the ecosystem with habitat complexity promoting nursing and feeding.

The most important anthropogenic driver of change in this indicator is bottom-trawling impact. Local, large, erected, and immobile species will have a high likelihood of being hit by a bottom trawl compared to small, cryptic infaunal species. The effect of bottom trawling on habitat engineers has been assessed (Jørgensen et al., 2016, 2019).

The understanding of the effect of drivers is thus rated as certain.

Removal of existing benthic species constitutes a development away from intact nature (i.e. without human pressures). Habitat engineers provide substrate and food for a large number of species, and reduction in these habitat-forming species can reduce biodiversity levels.

The ecosystem significance of decreasing benthic habitat engineers has not been verified for the Barents Sea but the effect of structure-forming corals and sponges and their use as fish habitat have been described for the Barents Sea (Jørgensen et al., 2022) and for the Bering Sea Submarine Canyons (Miller et al., 2018). The term 'habitat engineer' specifically indicates how the species modifies the environment. Changes in seafloor/habitat heterogeneity, altered bottom-currents, and changes in resuspension and particle loads are just a few changes in the seafloor environment that will likely lead to changes in other components of the system. Indeed, some of the species forming habitat are highlighted as specifically important or vulnerable (sponges, corals, sea pens). Studies have addressed the vulnerability of such habitats in the northern or southern Barents Sea (Jørgensen et al.2015, 2019, 2020, 2022), but these patterns of impact have been observed elsewhere and can be expected to occur in the Barents Sea as well.

The understanding of the importance for the rest of the ecosystem of decreasing benthic habitat engineers is thus good.

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Fish size [SI14]

Phenomenon: Decreasing body length at maturity across species in a fish community [SP14]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, fish species with large body size are present in the demersal fish community. They have an important structuring role in the ecosystem, since larger species typically are feeding on a larger range of prey types.

The most important anthropogenic drivers of change in this indicator are fisheries and climate change. Fisheries are preferentially harvesting large size individuals and species, and as a result many fish communities in exploited ecosystems have a truncated size structure with lower abundance of large-sized individuals and species than expected under the absence of fisheries (Jennings and Blanchard, 2004). The understanding of the link between fisheries and community body size is assessed as certain. Climate might affect the size composition in the fish communities through climate-driven redistribution of species. It is, however, uncertain in what direction climate will affect size-structure of the Sub-Arctic demersal fish communities, and the knowledge about this link is assessed as less certain. Climate and fisheries might have antagonistic effect on changes in the size structure in the community; the understanding of the cumulative effect of these two pressures is thus less certain.

Body size is considered a master trait in the ocean, as an organism's body size can characterize many other traits such as metabolism and feeding ecology (Brown et al., 2004; Andersen et al., 2016). At the fish population level, changes in body-size composition can affect the regenerative capacity of the population, by for example affecting the reproduction potential of the population and impacting the resilience of the population to further climate change and fishery pressures (Hsieh et al., 2010). Body size truncation can also have impacts at higher organizational level, such as the community and food web level. Marine food webs are largely structured by species body size (Brose et al., 2006; Andersen, 2019) with large species generally eating a wider size range of prey. The Barents Sea food web is also size-structured (Pecuchet et al., 2020). As fisheries target large-size individuals, the abundance of large fish is decreasing, impacting the structure of the food web. Changes in the size structure of fish communities can have implications for top-down and bottom-up control in the ecosystem (Brose et al., 2012) and affect the energy flow across trophic levels. Changes in the body size composition in the community will thus impact the structure of the Sub-Arctic food web, and ultimately its functioning. The understanding of the importance of changes in the fish community body size is assessed as good.

Changes in the fish community mean length can be considered of **ecosystem significance** if, for example, i) the size structure of the fish community is truncated, e.g., no big fish, which could be seen by ii) an increased abundance of medium-sized individuals.

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Fish life history [SI15]

Phenomenon: Decreasing slow-life, equilibrium fish species [SP15]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, species with Equilibrium/slow life history strategies are an important part of the Sub-Arctic demersal fish community. Due to their long lifespan, late maturation and low fecundity, they typically have stable population dynamics and very low rates of intrinsic population increase, and are vulnerable to increased mortality. Under the reference condition, Equilibrium/slow-life species are not affected by increased mortality, e.g., from fisheries, and the total biomass is expected to have been higher compared to today.

One of the most important anthropogenic drivers of change in this indicator in the Sub-Arctic is fisheries. The ‘Equilibrium/slow-life species’ have a large body size, produce few but large offspring which have a higher chance of surviving the juvenile stage. Some typical Equilibrium species in the Barents Sea are sharks and rays such Velvet belly lanternshark (*Etmopterus spinax*), Rabbit fish (*Chimaera monstrosa*), Spinytail skate (*Bathyraja spinicauda*), and Thorny skate (*Amblyraja radiata*). These large, slow-growing, and low-fecundity species are characterized by a low intrinsic productivity, which make them especially vulnerable to fishing pressure (Stevens et al., 2000; King and McFarlane, 2003; Winemiller, 2005; Quetglas et al., 2016). These species are often suffering from high by-catch fishing mortality. The understanding of the link to fishing pressure is assesses as certain. However, the understanding of the combined effect of fisheries, climate and other pressures on the biomass of the Equilibrium/ slow-life species is less certain, and as a result it might be hard to disentangle the effect of only the fishing pressure.

Equilibrium/slow-life species are often top predators in the marine environment. The removal of these top predators can impact the size structure of the communities and as a result impact the structure of the food web. A decline in top predators can also lead to trophic cascades (Myers and Worm, 2003; Myers et al., 2007), it can have implications for top-down and bottom-up control in the ecosystem (Brose et al., 2012) and affect the energy flow across trophic levels. The understanding of the importance of changes in the biomass of Equilibrium/slow-life history strategies is assessed as good.

Decreasing trend in the biomass of Equilibrium/slow-life species can be considered of **ecosystem significance** if, for example, i) the top fish predator in the ecosystem are no longer slow-life/Equilibrium species, ii) it caused a trophic cascade.

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Fish habitat use [SI16]

Phenomenon: Change in proportion of benthic fish [SP16]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, fish species belonging to both benthic, bentho-pelagic and pelagic communities are present, and energy in the ecosystem is channelled through both benthic and pelagic pathways. However, large populations of bentho-pelagic species are common, and benthic species are not as dominating as in the Arctic parts of the Barents Sea.

The most important anthropogenic drivers of change in this indicator are climate change and fisheries. Climate change can influence fish recruitment and species distribution (e.g. Landa et al., 2014). Boreal fish species are expected to increase in biomass with climate change, and several of these are typically bentho-pelagic generalists and the most influential of these is NEA cod (Fossheim et al., 2015; Kortsch et al., 2015). The proportion of typically benthic fish species is thus expected to decrease with increased climate change due to the increase in typically boreal bentho-pelagic generalists. However, the NEA cod population is also affected by fisheries, and thus the fisheries management regime. Thus, the expected increase in cod biomass with climate change may be counteracted by decreasing biomass due to intensified fisheries. The knowledge about the links to these anthropogenic drivers are assessed as certain, although with antagonistic effects from climate and fisheries on the major bentho-pelagic fish species (NEA cod) the understanding of the cumulative effect is assessed as less certain.

The indicator reflects the biomass allocation in pelagic (bentho-pelagic) and benthic ecosystem compartments, respectively, and thus changes in the pelagic-benthic coupling (Griffiths et al., 2017). This is a key feature of ecosystem structure in aquatic ecosystems, providing a simple measure of the status of a fish community (e.g. Pennino and Bellido, 2012). Changes in the ratio likely reflects community-wide alterations in community structure and biomass allocation, and the indicator may therefore be indicative of regime shifts (Aschan et al., 2013). When interpreting changes in the ratio, many factors will need to be accounted for simultaneously, and the understanding of the importance of changes in this indicator is thus assessed as less good.

Changes in this indicator can be considered of **ecosystem significance** if, for example, i) a higher proportion of pelagic and bentho-pelagic species results in a higher proportion of the energy produced by lower trophic levels is being kept in the upper water layers, which in turn may negatively influence benthic biota.

Knowledge gaps:

Description of knowledge gaps related to the phenomenon include i) uncertainty as to what species will establish and dominate in the system under future anthropogenic disturbance, ii) uncertainty as to how future changes in species' relative abundance will be affected by cascade effects. Although changes may be expected, the definition of whether a species is "benthic" or "bentho-pelagic" clearly affects the temporal development of the indicator.

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Seabird feeding types [SI17]

Phenomenon: Decreasing proportion of diving to surface-feeding seabirds [SP17]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, the diving seabirds are important piscivorous predators in the Barents Sea ecosystem and a dominant part of the avifauna (ICES, 2020). Surface-feeding seabirds are, to a large degree, dependent on diving seabirds and other top predators for food accessibility (Harrison et al., 1991; Camphuysen and Webb, 1999). Extensive industrial fisheries and historical extirpation of cetaceans by the whaling industry during the 19th and 20th centuries did probably alter the ratio between diving and surface-feeding seabirds to an unknown extent.

Fisheries is the most important anthropogenic driver of change affecting the proportion of diving to surface-feeding seabirds. Surface-feeding seabirds typically forage in the upper meter of the ocean and are largely dependent on other top-predators (predatory fish, diving seabirds and marine mammals) for driving fish and krill to the surface and making the food accessible (Harrison et al., 1991; Camphuysen and Webb, 1999). In contrast, diving seabirds hunt in a larger portion of the water column and are less dependent on other top predators to access food (Fauchald, 2009; Veit and Harrison, 2017). During the last 50 years, surface-feeding seabirds have profited from large amounts of discards from the fishing industry (Garthe et al., 1996; Votier et al., 2004). At the same time, the same pelagic fisheries are competing with diving piscivorous seabirds, such as auks (Cury et al., 2011; Grémillet et al., 2018). It is therefore expected that increased industrial fisheries could change the functional composition of the seabird community, implying reduced abundance of diving piscivorous seabirds and increased abundance of surface-feeding and scavenging seabirds. In the Barents Sea, dominant surface-feeding birds include gulls (*Rissa tridactyla, Larus argentaus, L. marinus, L. hyperboreus*) and northern fulmar (*Fulmarus glacialis*); and dominant diving piscivorous seabirds include the large auks (*Fratercula arctica, Uria aalge, U. lomvia*) (ICES, 2020). While increased fisheries and discards are expected to result in a decreased proportion of diving to surface-feeding birds, regulatory measures aimed at reducing the discards (i.e., the “discard ban”, Gullestad et al. 2015) and sustainable harvesting could reverse this trend.

The understanding of the link to fisheries is assessed as certain. The mechanisms relating seabird abundance to fishery discards and competition with pelagic fisheries are well understood and have been documented extensively. A decreasing ratio of diving relative to surface-feeding seabirds is expected to be related to unsustainable pelagic fishing practices (i.e., high discard rates and poor regulation of catches). An increased ratio can be expected for reduced discards and sustainable catch regulations.

Seabirds are important top predators in the Barents Sea ecosystem. Facilitation (i.e., positive interactions) between top predators with different functions is considered to be important for top predators in the pelagic ecosystem (Fauchald et al., 2011; Veit and Harrison, 2017), and the function of the top predator guild is accordingly sensitive to changes in functional diversity. There is however still a relatively weak understanding of the importance of these mechanisms. The understanding of the importance of changes in the indicator is assessed as less good.

A decreasing trend in the indicator can be considered of **ecosystem significance** if there is a persistent and relatively large reduction in the ratio related to unsustainable pelagic fishing practices (i.e., high discard rates and poor regulation of catches). An increased ratio can be expected for reduced discards and sustainable catch regulations.

Knowledge gaps:

How functional diversity and facilitation affect top predators and their role in the pelagic ecosystem is poorly known. The time series from the ecosystem survey in the Barents Sea is relatively short (2004-2020) and the relative abundance of surface-feeding seabirds is biased by their attraction to the survey vessel. How climate change could affect the ratio is unknown.

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Mammals top-down control [SI18]

Phenomenon: Change in ratio of high vs low trophic level mammals [SP18]

Ecosystem characteristic: Functional groups within trophic levels

The marine mammal community in the Norwegian Sub-Arctic has been greatly changed from the historical condition by anthropogenic activities, first and foremost overharvesting (see above). All of the large whales and some smaller species of marine mammals (e.g., both whales and seals) have been reduced from the reference state.

The drivers of changes in this indicator have largely been described above in the phenomena SP09 to SP11, but harvest (both of marine mammals and their prey) and climate change are the greatest drivers of marine mammal community composition and diversity in the Norwegian Sub-Arctic. As whale populations recover to pre-industrial-harvesting levels and move northward, interspecific competition and changes to predator-prey relationships will become more likely. Pelagic species will likely increase with increasing productivity (Eriksen et al. 2014). Warming of the Arctic will likely lengthen food chains, dissipating energy flow, and reducing the feeding efficiency of top predators (Wesławski et al., 2009). Competition could shift the current balance between tropic levels and possibly lead to diet switching between trophic levels for some species (e.g., killer whales from herring to marine mammals (Vongraven and Bisther, 2014), or white-beaked dolphins from smaller fish to larger species). Other generalist marine mammal species could switch to lower trophic level prey species (planktonic species) (MacKenzie et al., 2022) due to competition with fisheries for higher trophic levels (small fish). Understanding how competitive predators of the Barents Sea ecosystem interact and respond to different prey stock regimes is especially important given the dynamic nature of the Barents Sea ecosystem and its current transition from polar to a more temperate ecoregion (Dalpadado et al., 2012).

The understanding of the link between drivers and change in the indicator is rated as certain.

Changes in the trophic levels of the marine mammal community are likely to have cascading impacts on the broader ecosystem. It is not currently possible to predict which marine mammal species are of greatest importance to ecosystems stability and function. Higher trophic consumers are likely to have greater impact at an individual level because the energy that they draw from the system is greater than for lower trophic feeders, but effects of species losses (or major reductions) are difficult to predict (Skern-Mauritzen et al., 2022). Modelling efforts that incorporate marine mammal community structure and function are much needed.

The understanding of the impact on the ecosystem is assessed as less good.

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Arctic Calanus [SI19]

Phenomenon: Decreasing abundance of Arctic Calanus species [SP19]

Ecosystem characteristic: Functionally important species and biophysical structures

Three *Calanus* species occur in the Barents Sea, *Calanus finmarchicus*, *Calanus glacialis* and *Calanus hyperboreus*. *Calanus finmarchicus* is mainly an Atlantic species and *C. glacialis* is a typical Arctic species that is distributed mainly in Arctic water masses in the Barents Sea. However, both species can co-occur in mixed water masses (Conover, 1988; Tande, 1991; Melle and Skjoldal, 1998; Hirche and Kosobokova, 2007; Aarflot et al., 2018), including coastal areas and fjords in mainland Norway (Choquet et al., 2018). *Calanus hyperboreus* is an Arctic deep-water species with low abundance in the Barents Sea (Aarflot et al., 2018). Approximately 80% of the total biomass of mesozooplankton in the Barents Sea consists of the *Calanus* species (Aarflot et al., 2018). Thus, this species complex is central for the functioning in the ecosystem. Under the reference condition, the two Arctic *Calanus* species made up a significant part of the zooplankton community even in the Sub-Arctic part of the region where they are also important for predators (Sakshaug et al., 1994; Orlova et al., 2009).

The most important anthropogenic driver of change in the indicator is climate change. The Arctic *Calanus* species, in particular, are adapted to deal with the high environmental variability in ice-covered seas and the extreme seasonality in primary production at high latitudes. They have large lipid reserves, can reproduce independently of the phytoplankton bloom, utilize ice algal blooms, and have flexible multi-year life cycles (Falk-Petersen et al., 2009; Daase et al., 2013; Daase et al., 2021). Arctic species may have declined in the southern margins of their oceanic distribution range (Chust et al., 2014; Aarflot et al., 2018), while coastal populations of *C. glacialis* show stable population levels (Weydmann et al., 2014; Aarflot et al., 2018; Hop et al., 2019; Møller and Nielsen, 2020). A northwards shift has been observed concomitant with the retreat of sea ice in the Arctic Ocean (Ershova et al., 2021). The understanding of the link between driver and indicator is rated as certain.

The two Arctic *Calanus* species are larger and have a higher lipid content than the Atlantic species. Thus, a decline in biomass of the Arctic species may have large effects on many of the species feeding on zooplankton and *Calanus* in particular (Karnovsky et al., 2003; Steen et al., 2007; Rogachev et al., 2008; Dalpadado and Mowbray, 2013). A change towards lower biomass of Arctic species will likely alter the overturning and availability of energy in the pelagic ecosystem due to the smaller size, lower lipid content, and faster life cycle of Sub-Arctic species compared to Arctic congeners. For example, in the Bering Sea, an unprecedented warm and ice-free year led to an increase in small, low-lipid zooplankton with concurrent poor catches of pelagic fish, low reproductive success and mass mortality in seabird colonies (Duffy-Anderson et al., 2019). However, a boreal plankton life-history also brings a shorter generation time and faster population turnover, which may compensate for, or possibly enhance, the transfer of energy to predators (Renaud et al., 2018). Given the evidence from the Barents Sea, the understanding of the importance of changes in the indicator for other parts of the ecosystem is rated as good.

Declining biomass of Arctic *Calanus* species might be important for the marine ecosystem if, for example: i) the decrease is large relative to historic variation, ii) the magnitude of the decrease is similar to what has been observed in the North Sea, where it has caused substantial ecosystem changes and iii) there is a concurrent decrease in recruitment or survival or both of key predators such as pelagic amphipods and little auks.

Knowledge gaps include some uncertainty in species identification between *C. finmarchicus* and *C. glacialis* (Gabrielsen et al., 2012; Choquet et al., 2018). These species are traditionally separated based on size classes (Kwasniewski et al., 2003). Recent studies based on molecular methods have shown that there is a much larger overlap in size than previously assumed (Choquet et al., 2017), especially in Sub-Arctic/boreal *Calanus* populations that can lead to an underestimation of *C. glacialis* and overestimation of *C. finmarchicus*. Changes in species distribution patterns (historically and current observations) may thus be biased, although less so in the high-Arctic.

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Atlantic Calanus [SI20]

Phenomenon: Increasing abundance of Atlantic Calanus species [SP20]

Ecosystem characteristic: Functionally important species and biophysical structures

A general description of the *Calanus* species under the reference condition is given in the phenomenon text for the indicator for Arctic *Calanus* [SP19]. Under the reference condition, *C. finmarchicus* is important for sustaining populations of predators in the Sub-Arctic part of the Barents Sea, such as 0 group fish, pelagic zooplankton feeding fish and carnivorous krill (Schmidt, 2010; Dalpadado and Mowbray, 2013; Eriksen et al., 2020; ICES, 2020).

The most important anthropogenic driver of change in the indicator is climate change. The Arctic *Calanus* species are adapted to the high environmental variability in ice-covered seas with prolonged life cycles, large body size with lipid reserves and overall flexible multi-year life cycles (Falk-Petersen et al., 2009; Daase et al., 2013; Daase et al., 2021). *Calanus finmarchicus* on the other hand, have smaller lipid reserves, rely on the open-water phytoplankton bloom as their main food source to fuel reproduction, growth and development, and must complete their life cycle in a single year (Jónasdóttir et al., 2002; Melle et al., 2014). While *C. finmarchicus* is constantly advected to the Arctic/northern Barents Sea with northward flowing Atlantic currents (Wassmann et al., 2015), this species seems to be incapable of Arctic residency over multiple generations (Melle et al., 2014). A late start of the algal bloom and short growing season, as well as slow development rates at low Arctic temperatures, impair the ability of *C. finmarchicus* to reach late developmental stages that can pack their lipid sacs sufficiently to overwinter successfully and reproduce the following spring (Ji et al., 2012; Melle et al., 2014). Looking over both the Norwegian and Russian parts of the Barents Sea, the habitat area of boreal-Atlantic species has increased in the Sub-Arctic and Arctic regions (increase in Atlantic water masses; (ICES, 2020)) in addition to increased primary production due to warming observed between 1998 and 2017 (more open water due to less ice; (Dalpadado et al., 2020)) providing good growth conditions for *C. finmarchicus.* With loss of sea ice, bloom phenology is expected to change (earlier, longer blooms) (Song et al., 2021), and increased temperature may accelerate developmental rates, thus *C. finmarchicus* may become more successful in surviving and establishing itself at higher latitudes. Indeed, increased habitat suitability has recently been demonstrated for *C. finmarchicus* in areas that were previously ice covered (Freer et al., 2021; Traling et al., 2021), and *C. finmarchicus* has recently undergone a poleward distributional shift (Chust et al., 2014), increasing its contribution to the total *Calanus* community biomass in several Arctic regions (Weydmann et al., 2014; Aarflot et al., 2018; Møller and Nielsen, 2020; Hop et al., 2021). Given the extensive knowledge basis on the influence on climate variation on occurrence of *Calanus* species, the understanding of the link between driver and indicator is rated as certain.

The two arctic *Calanus* species are larger and have higher lipid content than the Atlantic *C. finmarchicus* species. Thus, a change towards a dominance of the Atlantic species may have large effects on many of the species feeding on zooplankton and larger *Calanus* in particular (Karnovsky et al., 2003; Steen et al., 2007; Rogachev et al., 2008). A change towards *C. finmarchicus* will likely alter the overturning and availability of energy in the pelagic ecosystem due to their smaller size, lower lipid content, and faster life cycle compared to Arctic congeners. For example, in the Bering Sea, an unprecedented warm and ice-free year led to an increase in small, low-lipid zooplankton and concurrent poor catches of pelagic fish, low reproductive success and mass mortality at seabird colonies (Duffy-Anderson et al., 2019). However, a *C. finmarchicus*-like life history also brings a shorter generation time and faster population turnover, which may compensate or even enhance the transfer of energy to predators (Renaud et al., 2018). Biogeographical shifts in the *Calanus* community observed in the North Sea illustrate possible consequences of changes in the Arctic Barents Sea. There, a change towards more southern zooplankton species, including change in relative abundance from *Calanus* *finmarchicus* (a northern species there) towards *Calanus helgolandicus* (southern species) has been related to changes in water temperature (Planque and Fromentin, 1996; Beaugrand, 2004; Jónasdóttir et al., 2005; Beaugrand et al., 2014). Changes in distribution and abundance of *C. finmarchicus* have been related to the low recruitment observed in several fish populations (Beaugrand and Kirby, 2010; Clausen et al., 2018). The shift towards more southern species also contributes to a lower production of zooplankton in general (Edwards et al., 2016), which is expected to impact not only the recruitment of fish but the whole fish community, especially planktivorous species (Clausen et al., 2018). Changes in the zooplankton community are likely one of the causes for the decreased production in several fish stocks (ICES, 2016; Clausen et al., 2018). Given the evidence from both the Barents Sea and the North Sea, the understanding of importance of changes in the indicator for other parts of the ecosystem is rated as good.

Increasing the proportion of Atlantic *Calanus* species can be considered important for the ecosystem if, for example, i) the increase is large relative to historic variation, ii) the magnitude of the increase is similar to what has been observed for *Calanus helgolandicus* in the North Sea, where it caused significant ecosystem changes or iii) reduced pelagic fish production and/or reduced seabird recruitment and survival take place, as has been seen in the Bering Sea.

Knowledge gaps related to this phenomenon include some uncertainty in species identification between *C. finmarchicus* and *C. glacialis* (Gabrielsen et al., 2012; Choquet et al., 2018). These species are traditionally separated based on size classes. Recent studies based on molecular methods have shown that there is larger overlap in size than previously assumed (Choquet et al., 2017), especially in Sub-Arctic/boreal *Calanus* populations that can lead to an underestimation of *C. glacialis* and overestimation of *C. finmarchicus*. Changes in species distribution patterns (historically and current observations) are therefore likely biased.

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Krill [SI21]

Phenomenon: Increasing biomass of krill [SP21]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, krill made up an important component of the zooplankton community in the Sub-Arctic part of the Barents Sea. Several boreal and Sub-Arctic species contribute to the krill community, in particular *Thysanessa inermis*, *T. raschii*, *T. longicaudata* and *Meganyctiphanes norvegica* (Dalpadado and Skjoldal, 1991). *Thysanoessa inermis* and *T. longicaudata* are likely dominant species and are found mainly in Atlantic Water, not penetrating far into Arctic waters. *Thysanoessa raschii* is only common in the shallow waters of the eastern Barents Sea and is not a common species in the Norwegian sector of the Sub-Arctic Barents Sea. The largest of the krill species, *M. norvegica*, is restricted to the core area of Atlantic Water in the west (Dalpadado and Skjoldal, 1996). Krill is important prey for several predators, including cod, capelin, redfish and a number of other species as well as seabirds and harp seals (Planque et al., 2014; Eriksen et al., 2020; ICES, 2020).

The most important anthropogenic driver of change in the indicator is climate change. Time series analyses (1980-2015) of boreal krill from the entire Barents Sea have shown that warming and reduced ice cover have had positive effects on krill biomass (Stige et al., 2019). Other studies have shown that the Atlantic boreal *M. norvegica*, which was almost absent during cooler periods during 1970-1990’s, has reentered the Barents Sea following warming over the last two decades (Zhukova et al., 2009; Eriksen et al., 2017; ICES, 2019). After a nearly 30-year long absence, the sub-tropical *Nematoscelis megalops* was again observed in early 2000s in the Barents Sea (Zhukova et al., 2009). The robust evidence for the effects of climate change implies that the understanding of the link between driver and indicator is rated as certain.

As outlined above, krill are an important part of the diet of many ecological and commercially important fish species in the Barents Sea and for other groups of predators such as seabirds and whales (ICES, 2020). Krill have been shown to be important for growth of capelin, and krill stock size may be controlled by predator stock size, especially capelin (Dalpadado and Skjoldal, 1996; Gjøsæter et al., 2002). Krill lipids are important for adult capelin growth (Orlova et al., 2010). Different krill species are likely to function differently as prey. The largest species, *M. norvegica*, is twice the size of the *Thysanoessa* species, implying that a single individual of the former will contribute with significantly more biomass and lipids than individuals of the smaller species. Given the substantial knowledge about predator-prey dynamics and the importance of krill as prey, the understanding of the importance of changes in the indicator for other parts of the ecosystem is rated as good.

A significant increase in krill biomass in the Sub-Arctic part of the Barents Sea will provide higher availability of food for a number of predators, thus affecting the dynamics of a large part of the ecosystem. Increase in abundance of important predators may be the result, exemplified by the recent growth of the cod stock (Kjesbu et al., 2014). This may also initiate changes in the structure of entire food webs (Kortsch et al., 2015). If the carnivorous *M. norvegica* becomes relatively more abundant than the more herbivorous/omnivorous krill species, feeding chains from phytoplankton to fish and birds may be lengthened, with implication for energy transfer to higher trophic levels. It should be noted that there is still no evidence that *M. norvegica* reproduces in the Barents Sea.

An important knowledge gap is the lack of quantitative systematic monitoring of species composition of the krill community.

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Capelin [SI22]

Phenomenon: Decreasing biomass of the capelin stock [SP22]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, long-term population size of capelin is high enough to support viable populations of predators dependent on capelin (e.g., NEA cod, humpback whales, harp seals, puffins, and common murre). However, based on the life history of capelin being short lived and semelparous, it is likely that the capelin population size undergoes large fluctuations also under the reference condition (Gjøsæter, 1998). The capelin population in the Barents Sea has been heavily exploited since the mid-60s, while regular monitoring started in 1972. In addition, the population is heavily affected by Arctic cod, Norwegian spring spawning herring and marine mammals which have been exploited by humans long before that.

The most important anthropogenic driver of change in this indicator today is climate change. Climate change may significantly alter distribution of capelin (Rose, 2005), affect recruitment, and also the strength of the impact of key predators on capelin. Direct effects of warming that can be expected is a northward expansion during feeding which has already been observed (Carscadden et al., 2013), and possibly the use of spawning grounds further north as temperatures increase (Rose, 2005). Climate change is expected to lead to increased productivity in the pelagic zone in Arctic seas (Primary production phenomenon [AP1]), and changes in the zooplankton community composition (Zooplankton phenomena [AP3, AP15, AP25, AP26]), which can have both positive and negative effects on the capelin population (Dalpadado and Mowbray, 2013; Renaud et al., 2018; Duffy-Anderson et al., 2019). The capelin biomass is also strongly and directly affected by other ecosystem components such as Norwegian spring spawning herring, negatively affecting recruitment by feeding on capelin larvae (Gjøsæter and Bogstad, 1998; Huse and Toresen, 2000), and North East Arctic cod, feeding on adult capelin (Johannesen et al., 2012; Fall et al., 2018; Holt et al., 2019). Climate change is expected to lead to a northward expansion of NSS herring spawning possibly increasing the overlap with capelin larvae thereby reducing recruitment success (Gjøsæter and Bogstad, 1998). Similarly, the climate-change related increased distribution of cod may enhance predation pressure on capelin (Fall et al., 2018). These indirect effects of climate change on capelin may be more important drivers of capelin biomass than direct effects, and the net consequences of a warmer ocean for capelin are uncertain. The knowledge about the link to climate change is therefore assessed as less certain.

Fisheries have been an important anthropogenic driver of change in the past for capelin with particularly high harvest level in the 1970s and 1980s (Gjøsæter, 1998). A precautionary management regime in place for capelin where the fishery is only allowed to target a surplus of mature capelin after a proportion is allowed to spawn and after predator consumption (Gjøsæter et al., 2015). With this management regime, the fishery is not expected to be a strong driver of change in capelin biomass. The understanding of the link to fisheries is assessed as certain.

Capelin play a key role in the Sub-Arctic part of the Barents Sea as the most important mid-trophic level species efficiently making energy from plankton available to top-predators (Dolgov, 2002; Orlova et al., 2009). In particular NEA cod is dependent upon capelin for sustaining its high abundance. Capelin is also a key diet items for whales, several seabird species, harp seals and other fish species (Dolgov, 2002). There is also evidence that capelin can inflict top-down effects on its zooplankton prey (Hassel et al., 1991; Dalpadado and Skjoldal, 1996). The capelin population in the Barents Sea has undergone strong fluctuations including collapse periods during the period of monitoring from 1973-present (Gjøsæter et al., 2009). The two collapse periods in the mid-80s and 90s were particularly severe, and in particular the first of these likely lead to a range of cascade effects in the Barents Sea ecosystem, including recruitment failures in seabirds and harp seals and cannibalism and hampered growth in cod (Gjøsæter et al., 2009). The later collapses did not have as severe impacts on the ecosystem (Johannesen et al., 2012). The reason for this is likely the higher abundance of alternative prey in these periods (Gjøsæter et al., 2009). The understanding of the impact of changes in the biomass of capelin on the ecosystem is assessed as good.

Decreasing capelin stock biomass can be considered of **ecosystem significance** if, for example, i) lack of food affects breeding success in seabirds, distribution of marine mammals or growth and cannibalism in cod (Gjøsæter et al., 2009).

Knowledge gaps:

Capelin has large natural variation in recruitment, which is important for the stock development. It is known that predation by young herring may strongly influence the capelin recruitment, but not much is known about how change in the population of other predators such as whales may influence recruitment. There is also a lack of knowledge about potential change in predation pressure and survival at other life stages.

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Cod [SI23]

Phenomenon: Change in cod total stock size [SP23]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, long-term population size of North East Arctic cod is high enough to help supporting top predators on adult fish such as minke whales and harp seals, and also to produce large quantities of larvae and 0-group cod, which are important as food for other organisms in the ecosystem (Eriksen et al., 2011). It is difficult to know how the state of the NEA cod stock was under reference conditions, as it had been exploited by humans for many centuries. However, the impact of the relatively limited fisheries before ca 1900 on this stock was probably moderate.

The most important anthropogenic drivers of change in this indicator are fisheries and climate change (Kjesbu et al., 2014). The NEA cod stock has been exploited by humans for many centuries and was considered to be overharvested from the 1950s onwards (except for a few years in the early 1990s). However, since 2007 the fisheries have been regulated by a more precautionary management regime, and the NEA cod stock has recovered to a high level. The pressure from fisheries on the NEA cod stock is currently regulated through fishing quotas set in cooperation with Russia.

Climate change with warmer temperatures will increase the available feeding area for cod in the Barents Sea. This is suggested as one of the reasons for the increasing density of cod in the northern Barents Sea (Johansen et al., 2013; Kjesbu et al., 2014; Fossheim et al., 2015). In addition, cod recruitment is positively related to temperature (e.g. Bogstad et al., 2013). The maximal distribution area was observed in 2013, and expansion possibilities outside the area occupied that year are fairly limited as cod is not likely to migrate further northwards as deep waters outside the shelf are not suitable for cod. However, some further expansion to the northeast into the northern Kara Sea is possible if the warming continues. The understanding of the links to these drivers are assessed as certain.

The cod is a central species in the Barents Sea ecosystem, with many interactions to other organisms in the ecosystem (Kortsch et al., 2015). The cod is an important predator on many fish and shellfish species such as capelin, herring, haddock, shrimp, snow crab, polar cod etc. (see e.g. Dolgov et al., 2011; Holt et al., 2019) and thus changes in the abundance of cod affect the status of these prey species. It is also a competitor with marine mammals as top predators in the ecosystem (Bogstad et al., 2015). Cod are also important as food for other predators, both as larvae and 0-group cod and adults (e.g. Bogstad et al., 2000; Eriksen et al., 2011). It should also be noted that Barents Sea cod is cannibalistic (Yaragina et al., 2009) and thus to some extent regulates itself. The cod is the dominant piscivorous fish species in the Barents Sea, and there is no other fish species which can fill that role if cod abundance becomes very low. The understanding of the effect of changes in this indicator on the ecosystem is assessed as good. However, effects of changes in the cod abundance on their prey are more studied than effects on their predators. Weak density-dependence in growth of older (mature) cod, was observed in the 2010s when cod abundance was high (ICES, 2020).

Changes in the cod stock biomass can be considered of **ecosystem significance** if, for example, i) Increasing predation from a larger cod population causes declines in important prey populations in the Sub-Arctic Barents Sea. ii) Declining cod population has a negative effect on predators on cod eggs and larvae.

Knowledge gaps:

Effects on predators of changes in cod abundance are an important knowledge gap. Also, cod abundance has fortunately never been so low that we have any clues about how a ‘cod-less’ ecosystem in the Barents Sea would function.

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Cod size structure [SI24]

Phenomenon: Decreasing biomass of large cod [SP24]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, large cod is present in the population to such extent that they represent an important predator in the ecosystem. In addition, presence of cannibalistic large cod contributes to self-regulation of the cod population. It is likely that the proportion of old, large fish in the stock would be even larger under reference conditions than in the periods with low fishing pressure from which we have data (1940s, 2010s, see Kjesbu et al., 2014). From West Greenland there are observations of age distributions in a previously unfished cod stock (Hansen, 1949), but whether these observations are relevant for a situation where the Barents Sea cod stock is unfished, we do not know.

The most important anthropogenic driver of change in this indicator is fisheries, which typically target the largest cod individuals. The minimum size in the fisheries is 44 cm, but fishing mortality increases with size/age, both because of gear selectivity and because a considerable part of the catch is taken during the spawning season. Heavy exploitation over many generations may also have affected the genetic composition of the stock, as maturation now occurs at lower age and size than before (see Rørvik et al., 2021 for the most recent discussion and literature review on this). In the Barents Sea, cod have been heavily exploited, but following the strong reduction in fishing mortality around 2007 the age structure in the stock has now been rebuilt and resembles the situation in the late 1940s following a period of low fishing mortality during WWII. The understanding of the link to fisheries is assessed as certain.

Large and old cod are important predators on smaller fish, including being cannibalistic (Holt et al., 2019). There are no other abundant fish stocks with large fish (> 70 cm) in the Barents Sea so that niche in the ecosystem cannot be filled by other species. Also, the age/size structure in the spawning stock is important for the recruitment to the stock (see references in Kjesbu et al., 2014). The understanding of the importance of changes in the indicator is assessed as less good.

Decreasing or stable low biomass of large cod can be considered of **ecosystem significance** if, for example i) the genetic composition of cod has changed due to selective removal of large individuals, ii) it leads to bad recruitment and reduced population size.

Knowledge gaps:

Effects on genetic composition.

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Haddock [SI25]

Phenomenon: Change in haddock stock size [SP25]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the haddock stock has large fluctuations in recruitment, but is nevertheless an important fish species in the Barents Sea ecosystem, both as predator and prey.

The most important anthropogenic drivers of change in this indicator are climate change and fisheries (see e.g. Russkikh and Dingsør, 2011 for an overview of haddock biology). Haddock abundance is low in waters colder than 2° C, so the location of this isotherm for bottom temperatures is a good indication of the distribution range. Recruitment of haddock is positively related to temperature (Bogstad et al., 2013). The understanding of the link between climate change and haddock stock size is assessed as certain. Haddock has never been fished as hard as cod, and a large part of the haddock catch is taken as by-catch in cod fisheries. Fisheries as a driver certainly affect haddock abundance, but the haddock has not been fished down to levels low enough to hamper the recruitment to the stock. The understanding of the link between fisheries and haddock stock size is assessed as less certain.

The haddock is an important predator on various benthic organisms (Dolgov et al., 2011), and thus it may impact those organisms considerably. However, effects of variation in haddock abundance on such organisms have not yet been quantified. In recent years, growth of haddock has been observed to be markedly density-dependent (ICES, 2020). Also, the importance of haddock as prey is not well known (but see Johannesen et al., 2016; Holt et al., 2019 for importance in cod diet). The understanding of the importance of changes in the haddock stock size is assessed as less good.

Due to the limited knowledge about the importance of haddock as both predator and prey, there are limited expectations as to when changes in the indicator can be considered of **ecosystem significance**.

Knowledge gaps:

Effects of variation in haddock abundance on its prey are possible (cf. density-dependence in haddock growth) but have not been documented. Causes of recruitment variability are poorly known. It has also been observed in other areas that haddock recruitment is more variable than cod recruitment, but the reason for this is not well known.

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Redfish [SI26]

Phenomenon: Decreasing biomass of the beaked redfish stock [SP26]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, juvenile redfish are important secondary consumers in the ecosystem, and the biomass of redfish juveniles in the Barents Sea is large enough to constitute a substantial component of the diet of cod and to a lesser extent of halibut (ICES 2018). Several species of redfish are present as juveniles in the Barents Sea (Mukhina et al., 1992; Eriksen et al., 2021), and most adult beaked redfish (*Sebastes mentella*) migrate into the Norwegian Sea where they take up a pelagic lifestyle (Drevetnyak and Nedreaas, 2009). Still, stock size can be used as indicator since it depends on successful recruitment, which depends on the living conditions that the juveniles encounter in the Barents Sea (Zakharov et al., 1977; Barsukov et al., 1986; Drevetnyak and Nedreaas, 2009).

Historically, the most important anthropogenic driver has been fishing pressure. Beaked redfish was overfished in the 1990s and the early 2000s until directed fishing for the species was banned in 2003 and the stock successfully rebuilt, with a direct fishery in Norwegian waters starting again in 2014 (ICES, 2018). If the current management regime is maintained, it is likely that climate change proves to be a more important driver. Climate change may affect the population rather indirectly, through changes in currents that transport larvae extruded along the shelf break into the Barents Sea (Zakharov et al., 1977; Barsukov et al., 1986; Drevetnyak and Nedreaas, 2009), and through food-web mediated effects on important prey and predators. The former is likely to be negative, whilst the latter is difficult to evaluate. Climate change, including ocean acidification, may have negative effects on the plankton prey of the juvenile redfishes (Whiteley, 2011) and on calcifying benthic organisms that may serve as refuge for juvenile fish (Turley et al., 2007; Andersson et al., 2008). Oil extraction in the Barents Sea nurseries and places of larval extrusion along the Norwegian shelf may negatively affect the stock on a more localized scale (Sundby et al., 2013). The understanding of the link to fishing pressure is assessed as certain and represented by the history of overfishing and subsequent rebuilding of the stock (ICES, 2018). The understanding of the link to climate change is less certain as the several indirect effects are complex and poorly understood.

Juvenile redfish are an important secondary consumer in the Sub-Arctic Barents Sea and contribute to the transfer of energy from zooplankton to higher trophic levels, primarily large predatory fish (ICES, 2018). Before the reduction of the redfish stock by overfishing, and the associated reduction of juvenile redfish in the Barents Sea, juvenile redfish was a major component in the diet of NEA cod (ICES, 2018) and was also consumed by halibut. However, the consumption of juvenile redfish by cod did not increase again to the same extent as the number of juvenile redfish did after 2006 when the redfish stock was rebuilt (ICES, 2018). The understanding of the importance of changes in the indicator for the ecosystem functioning is assessed as less good, given that the increase in juvenile redfish did not have the expected effect on the diet of cod (ICES, 2018).

A decline in the redfish stock biomass can be considered of **ecosystem significance** if, for example, i) important predators, e.g. cod and halibut, are negatively affected or become more dependent on cannibalism, ii) juveniles of other species are positively affected as a reduction in juvenile redfish may release more copepod prey to them as redfish larvae and juveniles can digest copepod eggs and generally prefer earlier stages

(Konchina, 1970; Karamushko and Karamushko, 1995).

Knowledge gaps:

We assume that changes in juvenile beaked redfish in the Barents Sea are related to changes in the beaked redfish stock size (the indicator), even though the adult population mostly resides in the Norwegian Sea. The distribution of areas of larvae extrusion is currently poorly mapped, with the entire shelf break, from Shetland to Bear Island being marked as extrusion area (Jakobsen and Ozhigin, 2011). How changes in ocean currents may affect the distribution of redfish larvae, and later juveniles, in the Barents Sea cannot be accurately assessed. Juvenile redfish, up to a certain size are virtually indistinguishable morphologically and therefore there is no abundance index for separate species; all 0-group redfish are counted together (Eriksen et al., 2021).

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Bottom thermal niches [SI27]

Phenomenon: Decreasing area of bottom cold-water temperature niches [SP27]

Ecosystem characteristic: Landscape-ecological patterns

Under the reference condition, which for abiotic factors is defined as the climate in the period 1961-1990, the Sub-Arctic part of the Barents Sea is characterised by a climate with relatively warm water and with only limited occurrences of Arctic water masses and seasonal ice cover in the far northern parts of the area. Regions dominated by Sub-Arctic climate provides habitat mainly for boreal species. Data on temperature exists from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in this indicator is climate change (IPCC, 2019). Waters characterized by warm (T>0°C) temperatures are common near bottom in the Sub-Arctic part (Loeng, 1991; Lind and Ingvaldsen, 2012). Anthropogenic global warming leads to northward expansion of the warm-water temperature niches (Smedsrud et al., 2010; Smedsrud et al., 2013; Oziel et al., 2016). Given the massive evidence of anthropogenic influence on the climate in general (Masson-Delmotte et al., 2021) and for the Barents Sea locally described above, the understanding of the link between driver and change in the indicator is rated as certain.

The increasing extent of warm-water temperature niches at bottom has profound impacts on the local and regional Sub-Arctic climate and ecosystems. Examples of changes which can be considered of **ecosystem significance** include increases in size of habitat for boreal benthic and demersal fish species (Johannesen et al., 2012; Fossheim et al., 2015; Jørgensen et al., 2015; Johannesen et al., 2017; Jørgensen et al., 2019). Overall, the understanding of the importance of changes in the indicator for the rest of the ecosystem is therefore rated as good.

Knowledge gaps:

The extent of warm-water temperature niches near bottom depends on inflow of Atlantic Water and cooling during winter. Improved understanding is needed to address the relative contribution from these sources on the formation and distribution of warm-water temperature niches.

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Benthos sensitive to bottom trawling [SI28]

Phenomenon: Decrease in biomass of benthos species sensitive to trawling [SP28]

Ecosystem characteristic: Biological diversity

Areas of the southern Barents Sea are already heavily trawled and determining an intact nature state may be difficult (Jørgensen et al.2016). Other areas have not had considerable trawling, but may in the future, due to shifting distribution of commercial species (Jørgensen et al.2020).

Bottom trawling is the most important driver, although disturbance from cable laying, pipeline construction, and anchored petroleum-industry structures may have similar effects, but on a much smaller scale. The understanding of the link between physical bottom-disturbance and seafloor community biodiversity is certain. Bottom trawling has been compared with forest clearcutting in this regard (Watling and Norse, 1998). These effects are particularly evident in epifaunal organisms, but this may only represent a study bias whereby most studies of effects have focused on video surveys to document impacts. There is also good evidence from the Barents Sea for these impacts (Jørgensen et al., 2016).

Any substantial change in community structure can be viewed as a departure from intact nature, and the ecological significance of this phenomenon can include its effects on food-web interactions, elemental cycling in sedimentary environments, and carbon storage (Pilskaln et al., 1998; März et al., 2022). These effects are due to both changes in faunal composition/biodiversity and the physical disturbance to the seafloor (sediment resuspension and homogenization), which will likely be indicated by altered biodiversity. Knowledge about the link between the phenomenon and potential implications for the ecosystem is assessed as good.

Biodiversity will be likely to capture the expected change, although more subtle changes may not be documented, or may require a number of diversity metrics. There is good general knowledge about spatial variability in benthic biodiversity in the Barents Sea (Zenkevich, 1963; Cochrane et al., 2009; Jørgensen et al., 2015; Zakharov et al., 2020) including some historical data, although these exist with different spatial resolution (Denisenko, 2001).

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Fish sensitive to fisheries [SI29]

Phenomenon: Decreasing abundance of fish species sensitive to fisheries [SP29]

Ecosystem characteristic: Biological diversity

Note: This text is similar to the indicator "Fish life history" in the Sub-Arctic Barents Sea which is focusing on Equilibrium species decline. However, the life history indicator focuses on the life history strategy biomass changes, while this indicator focuses on abundance of species with typical Equilibrium life history strategy.

Under the reference condition, fish species sensitive to increased mortality from fisheries are well represented in the demersal fish community. These species can be identified by their typically "slow-type" life history traits, having a large body size, long lifespan, late maturation and low fecundity. They typically have stable population dynamics and a very low rate of intrinsic population increase, making them vulnerable to additional sources of mortality (Jennings et al., 1998; Hutchings et al., 2012; Le Quesne and Jennings, 2012). In addition, these species are often top predators in the system, and have an important structuring role in the ecosystem.

The most important anthropogenic driver of change in this indicator is fisheries. Fisheries preferentially harvest large-bodied species and individuals. In addition, species life history traits are known to be related to their vulnerability to increase mortality from fisheries (Jennings et al., 1998; Le Quesne and Jennings, 2012). Species with a slow-type, Equilibrium life history have a large body size, produce few but large offspring with high survival rate, this strategy is typically followed by sharks and rays (Pecuchet et al., 2017). Some typical Equilibrium species in the Barents Sea are sharks and rays such Greenland shark (*Somniosus microcephalus*), Velvet belly lanternshark (*Etmopterus spinax*), Rabbit fish (*Chimaera monstrosa*), Spinytail skate (*Bathyraja spinicauda*), and Thorny skate (*Amblyraja radiata*). These large, slow growing, and low fecundity species are characterized by a low intrinsic productivity, which make them especially vulnerable to fishing pressure (Stevens et al., 2000; King and McFarlane, 2003; Winemiller, 2005; Quetglas et al., 2016; Mérillet et al., 2021). Even though fisheries activities are rarely targeting these species, they are often suffering from high by-catch fishing mortality. In addition to the sharks and rays, also Redfishes (*Sebastes* spp.) are vulnerable to additional mortality from fisheries due to slow growth and late maturation, even though they have higher fecundity compared to the elasmobranch. The understanding of the link to fisheries is assessed as certain.

Slow-type, Equilibrium life history species are often top predators in the marine environment. The removal of these top predators can impact the size structure of the communities and as a result impact the structure of the food web. A decline in top predators can also lead to trophic cascades (Myers and Worm, 2003; Myers et al., 2007), it can have implications for top-down and bottom-up control in the ecosystem (Brose et al., 2012) and affect the energy flow across trophic levels. The understanding of the importance of changes in the abundance of fisheries sensitive species is assessed as good.

Decreasing trend in the abundance of fish species sensitive to increased mortality from fisheries can be considered of **ecosystem significance** if, for example, i) some of the species go extinct, ii) reduced abundance of these species triggers a trophic cascade through reduced predation pressure on its prey.

Knowledge gaps:

Climate change effects on these species may interact with fisheries impacts.

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Mammals sensitive to pollution [AI30]

Phenomenon: Decrease in abundance of marine mammals sensitive to pollution [SP30]

Ecosystem characteristic: Biological diversity

Because of their relatively high trophic positions and long lifetimes, all marine mammals are exposed to anthropogenic pollutants. Most higher trophic level marine mammals in the Sub-Arctic are susceptible to pollutants; these animals were hunted extensively and remain at reduced levels compared to the historical conditions, with the exception of white-beaked dolphins which were not exploited commercially.

The drivers are dumping of waste, industrial production of various substances that are released into the environment (often used in agriculture as pesticides or for treatment of plant diseases), emissions during industrial processes that in addition to local pollution are transported around the globe with ocean currents and via atmospheric transport – thus reaching the entire planet. Many of the substances bioaccumulate in food webs and are therefore found in higher concentrations in upper trophic level animals such as many marine mammal species. In addition, many contaminants are lipophilic and thus accumulate in lipid tissues, which all marine mammals have in large quantities as an adaptation for homeothermic mammals living in the world’s oceans. Killer whales, which are pinnacle predators, have high concentrations of most pollutants (Desforges et al., 2018). Toothed whales as a group feed at high trophic levels and have poor capacity to metabolize toxic substances and hence have extremely high contaminant burdens (Pinzone et al., 2015). However, some of the classical pollutants like PCBs and DDEs that have been banned from production, are declining as a result of substance bans (e.g. Wolkers et al. 2008, Routti et al. 2014).

The understanding of the links to drivers are less certain.

High levels of various pollutants have the potential to impact metabolism, reproduction and other vital processes in mammals. This will ultimately lead to decreased numbers (biomass) of marine mammals via increased mortality and reduced reproductive rates. Top predators are at the highest risk of being impacted by contaminants and reduction in top predators might have cascading effects on the whole ecosystem, but to date no direct linkage between pollution and reproductive success/survivorship has been demonstrated for marine mammals in the Barents Sea.

The understanding of the link to ecosystem impact is thus assessed as less good.

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Mammal diversity [AI31]

Phenomenon: Change in mammal species diversity [SP31]

Ecosystem characteristic: Biological diversity

Historical stock sizes for most marine mammals were much higher than they are currently (see above). Overharvesting removed some species completely from the Sub-Arctic (e.g., North Atlantic right whale); thus, the diversity of marine mammals is likely reduced from the historical condition.

The past driver of the diversity of marine mammals in the Sub-Arctic is harvest and the primary current driver is climate change. Continued recovery from overharvesting and increasing pelagic productivity in the Sub-Arctic due to climate change will likely increase the diversity of species overall (Frainer et al., 2021; Wesławski, 2009), with a shift northward for more southern species such as common dolphins, bottlenose dolphins, pilot whales, and sei whales (Evans and Bjørge, 2013; Silber et al., 2017; Van Weelden et al., 2021).

Understanding of the linkage to the drivers is ranked as certain.

As marine mammal diversity in the Sub-Arctic increases, interspecific competition and changes to predator-prey relationships will become more likely (Baum and Worm, 2009; Gallagher et al., 2022; Gulland et al., 2022), but how this will affect the ecosystem is unclear. Changes in either top-down and bottom-up pressures can influence prey-stock regimes and shift the balance, favoring some competitors over others, which may affect the underlying structure and functioning of the ecosystem in unpredictable ways.

The understanding of the link to ecosystem impact is assessed as less good.

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Temperature [SI32]

Phenomenon: Warming of the water column [SP32]

Ecosystem characteristic: Abiotic factors

Under the reference condition, which for abiotic factors is predefined as the climate in the period 1961-1990, the Sub-Arctic part of the Barents Sea was characterised by moderate temperatures. Regions with Sub-Arctic climate provides mainly habitat for boreal species. Data on temperature exist from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in the indicator is climate change, causing the water column to warm (IPCC, 2019). Anthropogenic global warming leads to increasing ocean temperature in the inflowing Atlantic Water (Sandø et al., 2014; Årthun et al., 2019) and less sea ice (Årthun et al., 2012; Onarheim et al., 2018; Årthun et al., 2019). Given the massive evidence of anthropogenic influence on the climate in general (Masson-Delmotte et al., 2021) and for the Barents Sea locally described above, the understanding of the link between driver and change in the indicator is rated as certain.

The ecosystem in the Sub-Arctic part of the Barents Sea is largely characterized by boreal species, and some changes have been observed due to warming for these, including increasing biomass of boreal plankton species like *Calanus finmarchicus* (Aarflot et al., 2018), krill and jellyfish (Eriksen et al., 2016, 2017; Stige et al., 2019). Increasing temperatures have also caused the total biomass of the pelagic compartment, i.e., macroplankton, pelagic fish and 0-group (young-of-the-year) fish, to increase substantially (Eriksen et al., 2017). The main commercial species in the Barents Sea, the boreal Northeast Arctic cod (*Gadus morhua)*, has responded positively to the observed warming (Kjesbu et al., 2014; Arthun et al., 2018). In addition, warming has caused intrusions of the coccolitophore *Emiliana huxleyi* (a tracer for temperate ecosystems) in the Barents Sea, (Oziel et al., 2020). The understanding of the importance of changes in the indicator for the rest of the ecosystem is rated as good.

Warming of the water column depends on the inflow of Atlantic Water, surface heating during summer and cooling during winter, and inflow of sea ice and Arctic Water from the north. Improved understanding is needed to address the relative contribution from these sources.

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Area of water masses [SI33]

Phenomenon: Increasing area covered by Atlantic Water [SP33]

Ecosystem characteristic: Abiotic factors

Under the reference condition, which for abiotic factors are predefined as the climate in the period 1961-1990, the Sub-Arctic part of the Barents Sea is characterised by a climate with some occurrences of Arctic water masses and seasonal ice cover in parts of the area. The climate provides mainly habitat for boreal species. Data on temperature exist from 1970 (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists only for part of the reference condition.

The most important anthropogenic driver of change in this indicator is climate change (IPCC, 2019). Atlantic Water, characterized by temperatures above 3°C and high salinity, occupies together with mixed waters ($0^{o}C<T<3^{o}$ C), the Sub-Arctic part (Loeng, 1991; Lind and Ingvaldsen, 2012). Anthropogenic global warming leads to northward expansion of Atlantic Water (Smedsrud et al., 2010; Smedsrud et al., 2013; Oziel et al., 2016) thereby reducing the regional sea ice in the Barents Sea (Årthun et al., 2012; Onarheim et al., 2018). Given the massive evidence of anthropogenic influence on the climate in general (Masson-Delmotte et al., 2021) and for the Barents Sea locally described above, the understanding of the link between driver and change in the indicator is rated as certain.

The increasing extent of Atlantic Water profoundly impacts the local and regional Sub-Arctic climate (Smedsrud et al., 2010; Smedsrud et al., 2013) and ecosystems (Dalpadado et al., 2012, 2014). Increasing size of boreal habitat has caused larger occupation area for macroplankton, pelagic fish and 0-group (young-of-the-year) fish (Eriksen et al., 2017). The main commercial species in the Barents Sea, the boreal Northeast Arctic cod (*Gadus morhua*), has also responded positively to the observed increase in habitat (Kjesbu et al., 2014; Årthun et al., 2018). The understanding of the importance of changes in the indicator for the rest of the ecosystem is therefore rated as good.

Atlantic Water extent increase depend on Atlantic Water inflow, regional heat loss, mixing with fresh water from rivers and formation of Arctic Water. Improved understanding to address water mass modifications during winter, and how this affects the distribution of Atlantic Water, is needed.

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Stratification [SI34]

Phenomenon: Increasing stratification of the upper water column [SP34]

Ecosystem characteristic: Abiotic factors

Under the reference condition, there was a weak, but significant, stratification during summer in the upper water column of the Sub-Arctic part due to solar heating of the surface layer and input of freshwater from rivers (Loeng, 1991; Hordoir et al., 2022). Data on temperature and salinity exist from 1970 onward (Johannesen et al., 2012; Michalsen et al., 2013), implying that quantitative information for the indicator exists for only part of the reference condition period.

The most important anthropogenic driver of change in the indicator is climate change (IPCC, 2019). Upper water column stratification in the Sub-Arctic part in summer and autumn is created by increasing temperatures and decreasing salinity (and thus density) toward the surface. Anthropogenic global warming leads to surface warming as well as freshening due to increased precipitation, glacier melt in polar regions etc (Drinkwater et al., 2021). This causes a strengthening of the stratification and a shallower mixed layer depth in summer (Hordoir et al., 2022). The understanding of the link between driver and change in the indicator is rated as certain.

Stratification of the water column can be considered of ecosystem significance as it affects the vertical fluxes of new nutrients into the euphotic zone, thereby controlling primary production (Randelhoff et al., 2020). Stronger vertical stratification decreases the vertical fluxes of nutrients into the surface mixed layer, and a shallower mixed layer decreases the inventory of nutrients available for primary production. Observed declining trends in phytoplankton concentrations have been linked to increasing stratification (Boyce et al., 2010). However, studies based on satellite data suggest that the net primary production in the Barents Sea more than doubled between 1998 and 2017 (Dalpadado et al., 2020). A stronger stratification in Sub-Arctic parts in the future is expected to decrease primary productivity (Drinkwater et al., 2021), although biogeochemical models differ when predicting future changes in primary production for this region (Skaret et al., 2014; Slagstad et al., 2015; Skogen et al., 2018; Sandø et al., 2021).

The understanding of the importance of long-term changes in the indicator for the rest of the ecosystem is thus rated as less good.

There are knowledge gaps related to how the interannual variability in Sub-Arctic stratification depend on local wind mixing and buoyancy forcing and how primary production will change with a combined change in stratification and advective supply of nutrients (Nishino et al., 2015; Oziel et al., 2017; Drinkwater et al., 2021).

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pH [SI35]

Phenomenon: Decreasing pH [SP35]

Ecosystem characteristic: Abiotic factors

Under the reference condition, the water column is basic with a surface pH of about 8.

The most important anthropogenic driver of change in the indicator is climate change and increased CO_2. Ocean uptake of excess atmospheric CO_2 caused by human activities, such as fossil fuel burning, and industrialization, has increased ocean CO_2 over a relatively short time period. Since 1750, the pH has decreased by about 0.1 units, corresponding to a 30% increase of hydrogen ions (less basic ocean). Currently, observations show a continued pH decrease of 0.02 per decade (Copernicus Marine Services, 2021). Continued pH decrease is rated as highly likely (IPCC, 2019). The understanding of the link between driver and change in the indicator is rated as certain.

Altered pH may directly affect the internal cellular processes in marine organisms, such as the ion pump and other redox reactions. pH may also change the availability and toxicity of vital metals, potentially changing the biological production. Also, increased pCO_2 may lead to hypercapnia in fish if exceeding levels above 1000 ppm (McNeil and Sasse, 2016). However, the current understanding of the effect of reduced pH on ecosystem is mainly based on acute, short term-experiments and ecosystem modelling (Browman, 2016). Hence the understanding of the importance of changes in the indicator for the ecosystem is rated as less good.

There are large knowledge gaps on the effect of reduced pH on organisms and marine ecosystems. The effects need to be related to studies of adaptive capacity and should include multi-stressors. This requires multi-disciplinary observational long-term data sets in relevant areas (Browman, 2016).

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Aragonite saturation [SI36]

Phenomenon: Decreasing aragonite saturation [SP36]

Ecosystem characteristic: Abiotic factors

Under the reference condition, aragonite saturation is high enough for calcifying organisms to occur with biomasses high enough to sustain Arctic and Sub-Arctic food webs and ecological processes characterizing Arctic and Sub-Arctic ecosystems.

The most important anthropogenic driver of change in the indicator is climate change and increased CO_2. Ocean uptake of excess atmospheric CO_2 caused by human activities, such as fossil fuel burning and industrialization, is causing ocean CO_2 to increase. The ocean carbonate ion concentration (CO32-) is driving the aragonite saturation (ΩAr) and the chemical dissolution of the aragonite. Decreasing pH (increasing ocean CO_2) has resulted in decreasing saturation state with regards to calcium carbonate ($CaCO_3$), with consequences for the dissolution potential and calcification process. Aragonite is the most labile form of $CaCO_3$ in the ocean and the Arctic Ocean already has the lowest ΩAr compared to the world oceans (e.g., Chierici and Fransson, 2009). Continued decrease of ΩAr is expected is rated highly likely (IPCC, 2019). The understanding of the link between driver and change in the indicator is thus rated as certain.

The lowering of $CaCO_3$ saturation states (Ω), impacts shell-forming marine organisms from plankton to benthic molluscs, echinoderms, and corals. Many calcifying species exhibit reduced calcification and growth rates in laboratory experiments under high-CO_2 conditions (e.g. Kroeker et al., 2013; Manno et al., 2017). Another consequence is also the shoaling of aragonite saturation horizon (Ω_{Ar}<1, i.e dissolution of aragonite) which will continue and has consequences for cold-water corals and their ability to withstand erosion and continue to grow (ICES, 2014; AMAP, 2018). At Ω<1 more energy is required to build $CaCO_3$ (e.g., Comeau et al., 2013). Climate change, such as warming, enhances the effect of low saturation states. However, the current understanding of the effect of Ω in the ecosystem is mainly based on acute, short-term experiments and ecosystem modelling (Browman, 2016). There are ocean observations, especially in upwelling sites and other low-aragonite areas that show clear evidence of shell deformation on shelled butterfly snails, crabs and mussels. This has been observed in the Pacific Arctic also where saturation states are lowest (Cross et al., 2018; Bednaršek et al., 2021; Niemi et al., 2021). Although this implies that the knowledge on the effect on calcifying organisms is good, the overall understanding of the importance of changes in the indicator for the ecosystem is rated as less good.

There are large knowledge gaps about the thresholds and adaptive capacity to perform calcification at low saturation states. Amplification and occurrence of corrosive events have been observed in the Arctic Ocean. However, the effects on the marine ecosystem are poorly understood. The effects need to be related to studies of adaptive capacity and should include multi-stressors (Rastrick et al., 2018). This also requires multi-disciplinary observational long-term data sets in relevant areas.

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6. Ecosystem characteristics

This section describes the role that each indicator and the associated phenomena are perceived to have for the assessment of the ecosystem characteristic they are assigned to. Closely related indicators associated with the same ecosystem characteristic are described together. The description is given in **Table 6.1 a, b**.

Table 6.1.a. Description of the indicators per ecosystem characteristic in Arctic Barents Sea, indicators gaps, and justification of assessment of indicator coverage for ecosystem characteristics

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Primary productivity	Annual primary productivity [AI01] Timing of spring bloom [AI02]	Annual primary productivity is a key indicator for this ecosystem characteristic, as it seeks to estimate the total input of photosynthetically fixed carbon for the ecosystem. Timing of the spring bloom can influence how the primary production matches or mismatches in time with other important ecological processes, such as reproduction in herbivorous zooplankton.	There is no indicator on **species composition** of phytoplankton. Variation in species composition can have huge impacts on other parts of the ecosystem, in particular the type of herbivorous zooplankton that dominates. In addition, there are no indicators on **ice-dependent species** (ice algae) and no indicators using data from **direct (*in situ*) measurements** of primary production. Given these gaps, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Biomass distribution among trophic levels	Annual primary productivity [AI01]	This indicator represents the producers (phytoplankton) in the ecosystem, making photosynthetically fixed carbon available for consumers.	Indicators on biomass of **low trophic level benthic fish and high trophic level benthic fish**, respectively, are lacking in the assessment. This is an important gap in the indicator coverage, as these two groups constitute a considerable part of the biomass at the trophic levels above secondary consumers. Data and analyses for these indicators are nevertheless presented in Appendix 8.5. For benthos, there are no indicators for **infauna**, as data were not available for this assessment. They will be available for the next assessment, though, and phenomena have already been written (Appendix 8.4). For epifauna, data are collected in a standardised way by a shrimp trawl and can be compared across time and space. The species used for the assessment in this report are based on large species (megafauna) that are better retained within the trawl compared to small species. This method is a semi-quantitative, but standardised method. Indicators on **microbes** are lacking altogether, meaning that there is no information on an important process such as the microbial loop. There are no indicators on **sea-ice flora and fauna**. **Bearded seals** estimates are lacking but will be available for the next assessment Biomasses of **marine mammals and seabirds** are hard to estimate because of the spatial scales needed for surveys and the need for correction factors for the proportion of the population(s) that can be sighted at a given time. Therefore, the “pyramid” of biomass across trophic levels is biased in the upper levels. Here, we used mean individual average weight for seabirds, but that does not allow for assessment of the variability of body condition in the populations. More generally, the indicators do not give a clear picture of the biomass distribution **across the entire ecosystem** because the biomass classifications differ too much among groups to allow for robust comparisons of biomass trends. However, indicators included here cover the most important biomass pools of the ecosystems. Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic	Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic
Biomass distribution among trophic levels	Zooplankton TL < 2.5 [AI03] Zooplankton TL > 2.5 [AI04]	Zooplankton constitute the trophic link between primary production and major other parts of the ecosystem. Whether this link mainly goes through herbivorous zooplankton, or whether also carnivorous species are important, can have large implications for overall energy flow in the ecosystem. This gives the background for why the development in these two indicators are important for assessing this ecosystem characteristic. In addition, it is of interest to observe whether the biomass held by zooplankton increases or decreases relative to other groups, such as fish, as such development has been observed due to strong anthropogenic impact in other ecosystems.	
Biomass distribution among trophic levels	Benthic suspensivores [AI05]	Although it is less easy to include this compartment in a clear food chain, it has an important role in carbon cycling, and an aim of the indicator is thus to observe change that may be relevant for this process.	
Biomass distribution among trophic levels	0-group fish [AI06]	As a trophic group, these low trophic level predators are important consumers of prey groups such as zooplankton and important prey for high trophic level predators such as piscivorous fish and seabirds. The indicator may thus inform about energy flow related to these ecological groups.	

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Biomass distribution among trophic levels	Pelagic planktivorous fish [AI07]	Pelagic planktivorous fish are a key component in the pelagic food web, important for making energy from plankton available to top predators.	
Biomass distribution among trophic levels	Low trophic level seabirds [AI08] High trophic level seabirds [AI09]	The role of these two indicators is to assess changes in biomass of two groups of top predators in the Arctic Barents Sea ecosystem, feeding on two different trophic levels. Changes in low trophic level seabirds are represented by little Auk, an abundant species which is an important part in the ice-associated food-web, feeding on large (Arctic) zooplankton, and a competitor to pelagic planktivorous fish (e.g., capelin, herring). Changes in high trophic level seabirds is represented by two Arctic species, Brünnich’s guillemot and black-legged kittiwake, which are important predators on pelagic fish.	
Biomass distribution among trophic levels	Low trophic level [AI10], Generalist [AI11], and High trophic level [AI12] marine mammals	Marine mammals constitute a significant part of the biomass at trophic levels above secondary consumers, and the role of these indicators is thus to assess biomass changes that may be important for overall energy flow.	

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Functional groups within trophic levels	High TL zooplankton functional groups [AI13]	Different groups of carnivorous zooplankton have different impacts on the length of food chains in the ecosystem. The role of the indicator is thus to assess changes in the level of these functions by using data on two groups of carnivorous zooplankton, gelatinous species, and pelagic amphipods.	Due to lack of data, there is no indicator **on herbivorous zooplankton body size** (a phenomenon for this indicator is given in Appendix 8.4). For carnivorous zooplankton, data lack for **important groups** that could have been included, such chaetognaths. Due to lack of data, an indicator for infauna species **stabilizing the seafloor** is lacking (phenomenon for this indicator is given in Appendix 8.4) Due to lack of data, there are no indicators for the role of marine mammals in **vertical nutrient circulation, top-down control** or for mammal **carcasses as temporary biodiversity hotspots in the deep sea** (phenomena for these indicators are given in Appendix 8.4). An indicator for **fish feeding guilds** is lacking in the assessment. It should be noted that data and analyses for this indicator are nevertheless presented in Appendix 8.5. Relevant indicators for functions performed by **ice-associated species**, phytoplankton and **microbes** are missing due to lack of data. Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Functional groups within trophic levels	Benthic habitat engineers [AI14]	These group reflects the habitat three-dimensional complexity of the ecosystem and is associated with biodiversity hotspots and nursing areas. The role of the indicator is thus to assess changes in this.	
Functional groups within trophic levels	Fish size [AI15]	The role of this set of indicators is to assess changes in important aspects related to the functional characteristics of the demersal fish community. Under the reference condition, the Arctic demersal fish community typically consist of Arctic benthic species which are relatively small, mature early, and have an opportunistic, “fast” type of life history. Thus, this set of three indicators are tightly linked and need to be viewed together. Changes in these indicators can have implications for ecosystem structure, function, and resilience.	
Functional groups within trophic levels	Fish life history [AI16]		
Functional groups within trophic levels	Fish habitat use [AI17]		

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Functional groups within trophic levels	Seabird feeding types [AI18]	The role of this indicator is to assess changes in feeding guild composition within the high trophic level seabirds. Under the reference condition, diving seabirds are expected to be favoured compared to surface-feeding seabirds which are dependent on diving seabirds and other top predators for food accessibility. Fisheries is expected to favour surface-feeding seabirds, while competing for food with diving seabirds. Changes in the indicator may have implications for other pelagic predators and the dynamics within the pelagic food web.	
Functional groups within trophic levels	Marine Mammal bioturbation [AI19]	Walrus, white whales, and bearded seal bioturbation of the ocean floor is thought to have important impacts on benthic communities – production, colonization, diversity etc. This indicator thus aims at representing trends in this function.	
Functionally important species and biophysical structures	Pelagic amphipods [AI20]	Pelagic amphipods are important prey in the Arctic food web.	There are no indicators for **Arctic and Atlantic *Calanus*** species due to lack of data (phenomena for these indicators are given in Appendix 8.4). Indicator for **deep-water shrimp** (*Pandalus borealis*) is lacking. **Ice algae** are not included, although species dependent on these are included (e.g., pelagic amphipods, polar cod). There is no indicator on **snow crab**, which may develop into a functionally important species in the Norwegian sector of the Arctic part of the Barents Sea in the future. There are no indicators on **microbial species**, which could have provided information about the microbial loop. Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Functionally important species and biophysical structures	Krill [AI21]	Krill species are important prey in both Arctic and Sub-Arctic food webs.	

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Functionally important species and biophysical structures	Polar cod [AI22]	Polar cod are the one of the most abundant secondary consumers in the Arctic Barents Sea ecosystem, and an important part of the ice-associated ecosystem. The polar cod is an important prey species for several Arctic seabirds and marine mammals as well as for fish and is present year-round in the ecosystem.	
Functionally important species and biophysical structures	Capelin [AI23]	Capelin are considered a key species in the Barents Sea food web and is functionally important both as predator on zooplankton and as prey for a variety of predators, including cod, marine mammals and seabirds.	
Functionally important species and biophysical structures	Cod [AI24]	Cod are one of the most important top predators in the Barents Sea. Substantial changes in the cod stock size, size structure of the population and/or spatial distribution have implications for a range of other species, and impact structure, function, and dynamics of the ecosystem. The role of this set of three indicators is to assess changes in the cod stock relevant for the Arctic Barents Sea ecosystem.	
Functionally important species and biophysical structures	Cod size structure [AI25]		
Functionally important species and biophysical structures	Cod distribution [AI26]		
Landscape-ecological patterns	Bottom thermal niches [AI27]	The role of the indicator is to assess changes in the size of cold-water bottom temperature niches, which are habitat for benthic and demersal Arctic species.	There are no indicators for area that are not significantly negatively impacted by **bottom trawling**, or for size of important **spawning** and **nursery** areas. Given these missing indicators, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Landscape-ecological patterns	Sea-ice area [AI28]	A large assemblage of endemic Arctic species is dependent on sea ice as habitat. The role of the indicator is to assess change in size of this habitat type.	
Biological diversity	Arctic amphipod [AI29]	The role of this indicator is to follow the dynamic of the climate-sensitive amphipod species *Themisto libellula.*	The indicators are assessing **species affected directly by key drivers** and not species that are indirectly affected or affected to a lesser extent or by other drivers than the main ones. Thus, it is not a global assessment of biodiversity changes. There is no indicator for **Arctic *Calanus*** species due to lack of data (phenomena for this indicator are given in Appendix 8.4). This could be an important indicator to consider as Arctic *Calanus* species are sensitive to climate change. Indicators are **lacking entirely for some groups**, including phytoplankton, ice algae and fauna, microbes, and infectious organisms (from virus and bacteria to multicellular parasites), and sub-groups, including many groups of zooplankton (such as copepods, krill, chaetognaths and gelatinous zooplankton). Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Biological diversity	Cold-water benthos [AI30]	The role of the indicator is to assess changes in abundance of benthos sensitive to negative impact from climate change.	
Biological diversity	Arctic fish [AI31]	The role of the indicator is to assess change in abundance of Arctic fish species, which are sensitive to negative impact from climate change, both through direct effects and indirect ones from increased competition and predation from boreal species (e.g., NEA cod).	
Biological diversity	Fish sensitive to fisheries [AI32]	The role of the indicator is to assess change in abundance of fish species that due to their life history can be considered vulnerable to negative impact from fisheries. These species typically also have slow recovery after population declines.	

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic	Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic
Biological diversity	Seabirds sensitive to pollution [AI33]	Changes in this indicator is represented by Glaucous gull, an important top predator and scavenger in both the Arctic and Sub-Arctic Barents Sea ecosystems, known to be negatively affected by long-transported pollution. The role of this indicator is to assess possible population declines related to pollution pressure.	
Biological diversity	Arctic seabirds [AI34]	The role of this indicator is to assess effects of climate change on populations of typical Arctic seabird species. Under the reference condition in the Arctic Barents Sea, these are an important and conspicuous part of the ice-associated ecosystem.	
Biological diversity	Mammals sensitive to pollution [AI35]	The role of the indicator is to assess changes in abundance of marine mammals that are sensitive to impact from pollution. All Arctic marine mammals are long-lived, and all depend on lipid storage to remain in energy balance through the dark, winter season. Thus, lipophilic pollutants (in particular) are a threat to population status and at a larger scale Arctic biodiversity. But, to date linkage between population size (biomass) and pollutants is lacking.	

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Biological diversity	Arctic mammals [AI36]	Loss of genetic diversity often accompanies extreme population reductions and small populations are subject to random losses of genetic diversity. Hence, Arctic marine mammal populations in the Barents Sea are at particular risk in this biodiversity context. The role of the indicator is to assess change in abundance of Arctic marine mammals, which are sensitive to negative impact from climate change. Ironically, species richness is likely to increase in the Arctic for marine mammals with climate change, while endemic species declines are certain.	
Abiotic factors	Temperature [AI37]	The role of the indicator is to assess and quantify changes in temperature in different depth layers over the period with available hydrographic observations 1970-2019, which are of importance to key ecological processes.	The set of indicators covers the key aspects of the abiotic part of the ecosystem, the only main shortcoming being that there is no indicator for **nutrients**. In addition, more information could be useful for sea ice, such as ice thickness and snow on ice. These gaps are nevertheless considered minor compared with the coverage provided by the established indicators, and the indicator coverage for this ecosystem characteristic is therefore rated as **adequate**.
Abiotic factors	Area of water masses [AI38]	The role of the indicator is to assess and map the changes in area covered by Arctic, Atlantic and Mixed water masses in the 50-100m depth interval defined by their temperature ranges, which define habitat areas and are of importance to key ecological processes.	
Abiotic factors	Freshwater content [AI39]	The role of the indicator is to assess changes in freshwater content, which is of importance for sea-ice formation and resilience to sea-ice loss.	

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic	Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic
Abiotic factors	Stratification [AI40]	The role of the indicator is to assess changes in stratification, which are of importance for primary production.	
Abiotic factors	Sea-ice area [AI28]	The role of the indicator is to assess changes in sea-ice coverage both at min and max ice extent, which can inform about changes in both seasonal and permanent ice cover, which are of importance to key ecological processes.	
Abiotic factors	PH [AI41]	The role of the indicator is to assess changes in pH, which is affected by anthropogenic emission of greenhouse gases and can influence ecological processes.	
Abiotic factors	Aragonite saturation [AI42]	The role of the indicator is to assess changes in aragonite saturation, which is affected by anthropogenic emission of greenhouse gases and can influence ecological processes through impact on shell forming organisms.	

Table 6.1b. Description of the indicators per ecosystem characteristic in Sub-Arctic Barents Sea, indicators gaps, and justification of assessment of indicator coverage for ecosystem characteristics

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Primary productivity	Annual primary productivity [SI01] Timing of spring bloom [SI02]	Annual primary productivity is a key indicator for this ecosystem characteristic, as it seeks to estimate the total input of photosynthetically fixed carbon for the ecosystem. Timing of the spring bloom can influence how the primary production matches or mismatches in time with other important ecological processes, such as reproduction in herbivorous zooplankton.	There is no indicator on **species composition** of phytoplankton. Variation in species composition can have huge impacts on other parts of the ecosystem, in particular the type of herbivorous zooplankton that dominates. There is also a lack of indicators using data from **direct (*in situ*) measurements** of primary production. Given these gaps, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Biomass distribution among trophic levels	Annual primary productivity [SI01]	This indicator represents the producers (phytoplankton) in the ecosystem, making photosynthetically fixed carbon available for consumers.	Indicators on biomass of **low trophic level benthic fish and high trophic level benthic fish**, respectively, are lacking in the assessment. This is an important gap in the indicator coverage, as these two groups constitute a considerable part of the biomass at the trophic levels above secondary consumers. Data and analyses for these indicators are nevertheless presented in Appendix 8.5. For **benthos**, there are no indicators for infauna, as data were not available for this assessment. They will be available for the next assessment, and phenomena are presented in Appendix 8.4. For **epifauna,** data are collected in a standardised way by a shrimp trawl and can be compared across time and space. The species used for the assessment in this report are based on large species (megafauna) that are better retained within the trawl compared to small species. This method is a semi-quantitative, but standardised method. Indicators on **microbes** are lacking altogether, meaning that there is no information on an important process such as the microbial loop. Biomasses of **marine mammals and seabirds** are hard to estimate, as those are usually observed through visual counting. Therefore, the “pyramid” of biomass across trophic levels is biased in the upper levels. Here, we used mean individual weight for seabirds, but that does not allow to cover the variability of body condition in the populations. More generally, the indicators do not give a clear picture of the biomass distribution **across the entire ecosystem** because the biomass classifications differ too much among groups to allow for robust comparisons of biomass trends. However, indicators included here cover the most important biomass pools of the ecosystems. Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Biomass distribution among trophic levels	Zooplankton TL < 2.5 [SI03] Zooplankton TL > 2.5 [SI04]	Zooplankton constitute the trophic link between primary production and major other parts of the ecosystem. Whether this link mainly goes through herbivorous zooplankton, or whether also carnivorous species are important, can have large implications for overall energy flow in the ecosystem. This gives the background for why the development in these two indicators are important for assessing this ecosystem characteristic. In addition, it is of interest to observe whether the biomass held by zooplankton increases or decreases relative to other groups, such as fish, as such development has been observed due to strong anthropogenic impact in other ecosystems.	

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic	Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic
Biomass distribution among trophic levels	Benthic suspensivores [SI05]	Although it is less easy to include this compartment in a clear food chain, it has an important role in carbon cycling, and an aim of the indicator is thus to observe change that may be relevant for this process.	
Biomass distribution among trophic levels	0-group fish [SI06]	As a trophic group, these low trophic level predators are important consumers of prey groups such as zooplankton and important prey for high trophic level predators such as piscivorous fish and seabirds. The indicator may thus inform about energy flow related to these ecological groups.	
Biomass distribution among trophic levels	Pelagic planktivorous fish [SI07]	Pelagic planktivorous fish are a key component in the pelagic food web, important for making energy from plankton available to top predators.	
Biomass distribution among trophic levels	High trophic level seabirds [SI08]	The role of this indicator is to assess changes in biomass of top-predator seabirds in the Sub-Arctic Barents Sea ecosystem. Changes in high trophic level seabirds are represented by two Sub-Arctic species, common murre and puffin, which are important predators on pelagic fish.	
Biomass distribution among trophic levels	Low trophic level [SI09], Generalist [SI10], and High trophic level marine mammals [SI11]	Marine mammals constitute a significant part of the biomass at trophic levels above secondary consumers, and the role of these indicators is thus to assess biomass changes that may be important for overall energy flow.	

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Functional groups within trophic levels	High TL zooplankton functional groups [SI12]	Different groups of carnivorous zooplankton have different impacts on the length of food chains in the ecosystem. The role of the indicator is thus to assess changes in the level of these functions by using data on two groups of carnivorous zooplankton, gelatinous species, and pelagic amphipods.	Due to lack of data, there is no indicator **on herbivorous zooplankton body size** (a phenomenon for this indicator is given in Appendix 8.4). For carnivorous zooplankton, data lack for **important groups** that could have been included, such chaetognaths. Due to lack of data, an indicator for infauna species **stabilizing the seafloor** is lacking (phenomenon for this indicator is given in Appendix 8.4) Due to lack of data, there are no indicators for the role of marine mammals in **vertical nutrient circulation,** for marine **carcasses as temporary biodiversity hotspots in the deep sea**, or for **pelagic prey aggregation by marine mammals** (phenomena for these indicators are given in Appendix 8.4). An indicator for **fish feeding guilds** is lacking in the assessment. It should be noted that data and analyses for this indicator are nevertheless presented in Appendix 8.5. Relevant indicators for functions performed by **phytoplankton** and **microbes** are missing due to lack of data. Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Functional groups within trophic levels	Benthic habitat engineers [SI13]	This group reflects the habitat three-dimensional complexity of the ecosystem and is associated with biodiversity hotspots and nursing areas. The role of the indicator is thus to assess changes in benthic habitats.	
Functional groups within trophic levels	Fish size [SI14]	The role of this set of indicators is to assess changes in important aspects related to the functional characteristics of the demersal fish community. Under the reference condition, the Arctic demersal fish community typically consists of Arctic benthic species which are relatively small, mature early, and has an opportunistic, “fast” type of life history. Thus, this set of three indicators are tightly linked and need to be viewed together. Changes in these indicators can have implications for ecosystem structure, function, and resilience.	
Functional groups within trophic levels	Fish life history [SI15]		
Functional groups within trophic levels	Fish habitat use [SI16]		

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Functional groups within trophic levels	Seabird feeding types [SI17]	The role of this indicator is to assess changes in feeding guild composition within the high trophic level seabirds. Under the reference condition, diving seabirds are expected to be favoured compared to surface-feeding ones which are dependent on diving seabirds and other top predators for food accessibility. Fisheries is expected to favour surface-feeding seabirds, while competing for food with diving seabirds. Changes in the indicator may have implications for other pelagic predators and the dynamics within the pelagic food web.	
Functional groups within trophic levels	Mammal top-down control [SI18]	The role of this indicator is to track changes occurring in the predation pressure expressed by marine mammals on the different trophic levels in the Sub-Arctic Barents Sea.	
Functionally important species and biophysical structures	Arctic *Calanus* -species [SI19] Atlantic *Calanus* species [SI20]	Copepod species are important prey items in the Barents Sea. Arctic *Calanus* species are usually richer in fat content than Atlantic *Calanus* species. This indicator aims to track the respective and relative importance of both biogeographical groups as it will impact prey quality for many predators.	Indicator for **deep-water shrimp** (*Pandalus borealis*) is lacking There is no indicator on **snow crab**, which may develop into a functionally important species in the Norwegian sector of the Sub-Arctic part of the Barents Sea in the future. There are no indicators on **microbial species**, which could have provided information about the microbial loop. Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Functionally important species and biophysical structures	Krill [SI21]	Krill species are important prey in the Sub-Arctic food web.	

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic	Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic
Functionally important species and biophysical structures	Capelin [SI22]	Capelin is considered a key species in the Barents Sea food web and is functionally important both as predator on zooplankton and as prey for a variety of predators, including cod, marine mammals and seabirds.	
Functionally important species and biophysical structures	Cod [SI23]	Cod is one of the most important top predators in the Barents Sea. Substantial changes in the cod stock size and/or size structure of the population have implications for a range of other species, and impact structure, function, and dynamics of the ecosystem. The role of this set of indicators is to assess changes in the cod stock relevant for the Sub-Arctic Barents Sea ecosystem.	
Functionally important species and biophysical structures	Cod size structure [SI24]		
Functionally important species and biophysical structures	Haddock [SI25]	Haddock is a demersal fish species and an important predator in the Sub-Arctic Barents Sea. Changes in the haddock stock size have implications for a range of other species, and impact structure, function and dynamics of the ecosystem.	
Functionally important species and biophysical structures	Redfish [SI26]	Beaked redfish is a deep-water species that uses the Barents Sea mainly as a nursery ground, although about 20% of the adult population remains in the Barents Sea. The majority of the adults resides in the adjacent Norwegian Sea and only returns to the shelf break to release larvae. The indicator shall assess changes in the stock of beaked redfish relevant for the Sub-Arctic Barents Sea ecosystem.	
Landscape-ecological patterns	Bottom thermal niches [SI27]	The role of the indicator is to assess changes in the size of cold-water bottom temperature niches, which are habitat for benthic and demersal Arctic species.	There are no indicators for areas that are not significantly negatively impacted by **bottom trawling**, or for sizes of important **spawning** and **nursery** areas. Given these gaps, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.

Ecosystem characteristic	**Indicator(s)**	**The role of the indicator(s) in the assessment of the ecosystem characteristic**	**Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic**
Biological diversity	Benthos sensitive to bottom trawling [SI28]	Bottom trawling has been shown to impact bottom fauna diversity. The role of this indicator is to assess changes in abundance of benthos sensitive to negative impact from bottom trawling.	The indicators are assessing **species affected directly by key drivers** and not species that are indirectly affected or affected to a lesser extent or by other drivers than the main ones. Thus, it is not a global assessment of biodiversity changes. Indicators **are lacking entirely for some groups**, including phytoplankton, microbes, infectious organisms (from virus and bacteria to multicellular parasites), and many groups of zooplankton (such as copepods, krill, chaetognaths and gelatinous zooplankton). Given the gaps described here, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Biological diversity	Fish sensitive to fisheries [SI29]	The role of the indicator is to assess change in abundance of fish species that due to their life history can be considered vulnerable to negative impact from fisheries. These species typically also have slow recovery after population declines.	
Biological diversity	Mammals sensitive to pollution [SI30]	The role of the indicator is to assess changes in abundance of marine mammals that are sensitive to impact from pollution.	
Biological diversity	Mammals' diversity [SI31]	This indicator aims at following the diversity of Sub-Arctic marine mammals.	
Abiotic factors	Temperature [SI32]	The role of the indicator is to assess and quantify changes in temperature in different depth layers over the period with available hydrographic observations 1970-2019, which is of importance for key ecological processes.	The set of indicators covers the key aspects of the abiotic part of the ecosystem, the only main shortcoming being that there is no indicator for **nutrients**. This gap is nevertheless considered minor compared with the coverage provided by the established indicators, and the indicator coverage for this ecosystem characteristic is therefore rated as **adequate**.
Abiotic factors	Area of water masses [SI33]	The role of the indicator is to assess and map the changes in area covered by Arctic, Atlantic and Mixed water masses in the 50-200m depth interval defined by their temperature ranges, which define habitat areas and are of importance to key ecological processes.	
Abiotic factors	Stratification [SI34]	The role of the indicator is to assess changes in stratification, which is of importance for primary production.	

Ecosystem characteristic	Indicator(s)	The role of the indicator(s) in the assessment of the ecosystem characteristic	Indicator gaps and rationale for indicator coverage assessment of the ecosystem characteristic
Abiotic factors	pH [SI35]	The role of the indicator is to assess changes in pH, which is affected by anthropogenic emission of greenhouse gases and can influence ecological processes.	
Abiotic factors	Aragonite saturation [SI36]	The role of the indicator is to assess changes in aragonite saturation, which is affected by anthropogenic emission of greenhouse gases and can influence ecological processes through impact on shell forming organisms.	

7. Assessments

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

7.1 Assessment of the knowledge base

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

1. At a *data level*, we summarise the spatial (SR) and temporal (TR) representativity of the datasets for each individual indicator.
    a. The spatial representativity (*SR*) of *each dataset* relative to the target ecosystem (Ch. 3) is determined by the sampling design employed (design-based, model-based, no design). Design-based sampling is evaluated based on three criteria: 1) whether the entire population is included in the sampling (*SRd1*), 2) whether sampling is based on randomisation (*SRd2*), and 3) whether there is a known probability of including each sampling unit (*SRd3*). Model-based sampling (*SRm*) is evaluated based on just one criterium; whether sampling is based on a model (i.e., a sampling design) that is relevant for the indicator or phenomenon in question. It should be noted that randomization is generally not used in the datasets used in this assessment, where the design is to cover everything, e.g., all grid cells in a regular grid, all known seal breeding sites. In these cases, SRd2 (design-based sampling based on randomization) is assessed as fulfilled.
    b. The temporal representativity (*TR*) of *each dataset* relative to a relevant temporally defined reference condition. A temporally defined reference condition includes explicit definitions (e.g., the reference condition equals the condition of the ecosystem at a particular point in time), and implicit definitions (e.g., the reference condition equals the condition of the ecosystem in, for instance, a preindustrial climate). It should be noted that the reference condition chosen for this assessment, “intact nature”, is not temporally defined (except for climate), and that different time periods are considered representative for different indicators depending on the history of anthropogenic impact on each indicator (see Ch. 2). Temporal representativity is evaluated with respect to 1) years (*TRyr* ; the length of the time series relative to relevant dynamics and any temporally defined reference conditions), and 2) seasonality (*TRse*; whether relevant seasonality is taken into account in the sampling).
2. At an *indicator level* we assess the indicator’s total data coverage based on the overall assessment of spatial (SRtotal) and temporal (TRtotal) representativity of each dataset included.
3. At an *ecosystem characteristic level,* we assess indicator coverage for the entire *characteristic*. This reflects the degree to which the set of indicators on which the assessment is based has sufficient coverage and relevance for assessment of the condition of the ecosystem characteristic. Justifications for these assessments are found in Table 6.1.

All assessments are assigned to clearly defined colour-coded categories (Fig. 7.1) as specified in the technical protocol (Jepsen et al. 2020). Each individual assessment is justified in an endnote, which can be found in Appendix 8.3.

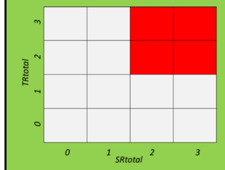
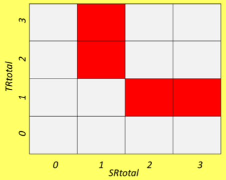
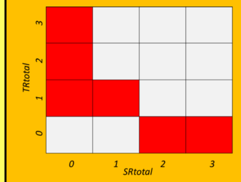
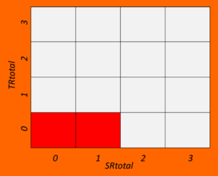
		Categories			
SpatialRepresentativity (SR)	SRd1	**Fulfilled** : Design-based sampling where the entire sampling population has a possibility of being included.		**Not fulfilled** : Design-based sampling where only a SUBSET of the sampling population has a possibility of being included.	
	SRd2	**Fulfilled** : Design-based sampling based on randomisation.		**Not fulfilled** : Design-based sampling NOT based on randomisation.	
	SRd3	**Fulfilled** : Design-based sampling, with known probability of including each sampling unit.		**Not fulfilled :** Design-based sampling, with UNKNOWN probability of including each sampling unit.	
	SRm	**Fulfilled** : Model-based sampling based on a model that is relevant for the indicator and the phenomenon in question.		**Not fulfilled** : Model-based sampling based on a model that is NOT relevant for the indicator and the phenomenon in question.	
	SRtotal	**Category 3** : *SRm* fulfilled with an adequate sample size OR S *Rd1* -S *Rd3* all fulfilled.	**Category 2** : *SRm* fulfilled with a limited sample size OR two of S *Rd1* -S *Rd3* fulfilled.	**Category 1 :** *SRm* not fulfilled, one of S *Rd1* -S *Rd3* fulfilled.	**Category 0** : *SRm* not fulfilled, none of S *Rd1* -S *Rd3* fulfilled.
Temporal Representativity (TR)	TRyr	**Adequate:** A long time series relative to relevant dynamics. In case of a temporally defined reference condition, time series is partly or fully overlapping with the reference period.	**Partially adequate** : A long time series relative to relevant dynamics. In case of a temporally defined reference condition, time series are NOT overlapping with the reference period.		**Inadequate** : A short time series relative to relevant dynamics.
	TRse	**Adequate** : Seasonal variability is relevant and taken into account in the sampling OR seasonal variability is not relevant.		**Inadequate** : Seasonal variability is relevant, but not, or to a very limited degree taken into account in the sampling.	
	TRtotal	**Category 3:** Both *TRyr* and *TRse* are Adequate.	**Category 2** : *TRyr* Adequate and *TRse* Inadequate OR *TRyr* Partially adequate and *TRse* Adequate.	**Category 1** : *TRyr* Inadequate and *TRse* Adequate OR *TRyr* Partially adequate and *TRse* Inadequate.	**Category 0 :** Both *TRyr* and *TRse* Inadequate.
Data coverage	DC	**Very good:** 	**Good:** 	**Intermediate:** 	**Poor:** 
Indicator coverage	IC	**Adequate** : The set of indicators represent the major aspects of the ecosystem characteristic with no obvious shortcomings.	**Partially adequate:** The set of indicators has certain shortcomings which might limit our ability to assess the condition of the ecosystem characteristic.		**Inadequate** : The set of indicators has severe shortcomings which will definitely limit our ability to assess the condition of the ecosystem characteristic.

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

Table 7.1a. Assessment of the knowledge base for the datasets, indicators and ecosystem characteristics for Arctic Barents Sea. Numbers refer to listed comments in Appendix 8.3.

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	**SRd2**	**SRd3**	**SRm**	**SRtotal**	**TRyr**	**TRse**	**TRtotal**	**DC**	**IC**
D04	1	2	3	4	🟩	5	6	🟨	Annual primary productivity [AI01]	Primary productivity ***7***
D04	1	2	3	4	🟩	5	6	🟨	Timing of spring bloom [AI02]	Primary productivity ***7***
D04	1	2	3	4	🟩	5	6	🟨	Annual primary productivity [AI01]	Biomass distribution among trophic levels ***138***
D06	8	9	10	11	🟨	12	13	🟧	Zooplankton TL < 2.5 [AI03] ***20***	Biomass distribution among trophic levels ***138***
D08	14	15	16	17	🟨	18	19	🟧	Zooplankton TL < 2.5 [AI03] ***20***	Biomass distribution among trophic levels ***138***
D08	14	15	16	17	🟨	18	19	🟧	Zooplankton TL > 2.5 [AI04]	Biomass distribution among trophic levels ***138***
D07	21	22	23	24	🟨	25	26	🟧	Benthic suspensivores [AI05]	Biomass distribution among trophic levels ***138***
D08	27	28	29	30	🟨	31	32	🟨	0-group fish [AI06]	Biomass distribution among trophic levels ***138***
D09	33	34	35	36	🟧	37	38	🟨	Pelagic planktivorous fish [AI07] ***45***	Biomass distribution among trophic levels ***138***
D10	39	40	41	42	🟩	43	44	🟨	Pelagic planktivorous fish [AI07] ***45***	Biomass distribution among trophic levels ***138***
D17	52	53	54	55	🟩	56	57	🟧	Low trophic level seabirds [AI08]	Biomass distribution among trophic levels ***138***
D17	52	53	54	55	🟩	56	57	🟧	High trophic level seabirds [AI09] ***64***	Biomass distribution among trophic levels ***138***
D18	58	59	60	61	🟥	62	63	🟨	High trophic level seabirds [AI09] ***64***	Biomass distribution among trophic levels ***138***
D19	65	66	67	68	🟩	73	74	🟩	Low trophic level mammals [AI10] ***85***	Biomass distribution among trophic levels ***138***
D20	69	70	71	72	🟥	73	74	🟩	Low trophic level mammals [AI10] ***85***	Biomass distribution among trophic levels ***138***
D21	75	76	77	78	🟨	83	84	🟩	Low trophic level mammals [AI10] ***85***	Biomass distribution among trophic levels ***138***
D22	79	80	81	82	🟩	83	84	🟩	Biomass distribution among trophic levels ***138***	Biomass distribution among trophic levels ***138***
D23	86	87	88	89	🟩	90	91	🟨	Generalist mammals [AI11] ***110***	Biomass distribution among trophic levels ***138***
D24	92	93	94	95	🟩	96	97	🟨	Generalist mammals [AI11] ***110***	Biomass distribution among trophic levels ***138***
D25	98	99	100	101	🟨	102	103	🟧	Generalist mammals [AI11] ***110***	Biomass distribution among trophic levels ***138***
D26	104	105	106	107	🟨	108	109	🟧	Generalist mammals [AI11] ***110***	Biomass distribution among trophic levels ***138***
D27	111	112	113	114	🟩	119	120	🟨	High trophic level mammals [AI12] ***137***	Biomass distribution among trophic levels ***138***

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	**SRd2**	**SRd3**	**SRm**	**SRtotal**	**TRyr**	**TRse**	**TRtotal**	**DC**	**IC**
D28	*115*	*116*	*117*	*118*	🟧	*119*	*120*	🟨	High trophic level mammals [AI12] ***137***	Biomass distribution among trophic levels ***138***
D29	*121*	*122*	*123*	*124*	🟨	*125*	*126*	🟨	High trophic level mammals [AI12] ***137***	Biomass distribution among trophic levels ***138***
D30	*127*	*128*	*129*	*130*	🟩	*135*	*136*	🟨	High trophic level mammals [AI12] ***137***	Biomass distribution among trophic levels ***138***
D31	*131*	*132*	*133*	*134*	🟨	*135*	*136*	🟨	High trophic level mammals [AI12] ***137***	Biomass distribution among trophic levels ***138***
D08	*14*	*15*	*16*	*17*	🟨	*18*	*19*	🟧	High TL zooplankton functional groups [AI13]	Functional groups within trophic levels ***140***
D07	*21*	*22*	*23*	*24*	🟨	*25*	*26*	🟧	Benthic habitat engineers [AI14]	Functional groups within trophic levels ***140***
D07	*46*	*47*	*48*	*49*	🟨	*50*	*51*	🟨	Fish size [AI15]	Functional groups within trophic levels ***140***
D07	*46*	*47*	*48*	*49*	🟨	*50*	*51*	🟨	Fish life history [AI16]	Functional groups within trophic levels ***140***
D07	*46*	*47*	*48*	*49*	🟨	*50*	*51*	🟨	Fish habitat use [AI17]	Functional groups within trophic levels ***140***
D17	*52*	*53*	*54*	*55*	🟩	*56*	*57*	🟧	Seabird feeding types [AI18]	Functional groups within trophic levels ***140***
D19	*65*	*66*	*67*	*68*	🟩	*73*	*74*	🟩	Mammal bioturbation [AI19] ***139***	Functional groups within trophic levels ***140***
D20	*69*	*70*	*71*	*72*	🟥	*73*	*74*	🟩	Mammal bioturbation [AI19] ***139***	Functional groups within trophic levels ***140***
D27	*111*	*112*	*113*	*114*	🟩	*119*	*120*	🟨	Mammal bioturbation [AI19] ***139***	Functional groups within trophic levels ***140***
D28	*115*	*116*	*117*	*118*	🟧	*119*	*120*	🟨	Mammal bioturbation [AI19] ***139***	Functional groups within trophic levels ***140***
D08	*14*	*15*	*16*	*17*	🟨	*18*	*19*	🟧	Pelagic amphipods [AI20]	Functionally important species and biophysical structures ***153***
D08	*14*	*15*	*16*	*17*	🟨	*18*	*19*	🟧	Krill [AI21]	Functionally important species and biophysical structures ***153***
D09	*33*	*34*	*35*	*36*	🟧	*37*	*38*	🟨	Polar cod [AI22]	Functionally important species and biophysical structures ***153***
D10	*39*	*40*	*41*	*42*	🟩	*43*	*44*	🟨	Capelin [AI23]	Functionally important species and biophysical structures ***153***
D13	*141*	*142*	*143*	*144*	🟨	*145*	*146*	🟩	Cod [AI24]	Functionally important species and biophysical structures ***153***
D16	*147*	*148*	*149*	*150*	🟨	*151*	*152*	🟩	Cod size structure [AI25]	Functionally important species and biophysical structures ***153***
D07	*46*	*47*	*48*	*49*	🟨	*50*	*51*	🟨	Cod distribution [AI26]	Functionally important species and biophysical structures ***153***
D01	*154*	*155*	*156*	*157*	🟨	*158*	*159*	🟨	Bottom thermal niches [AI27]	Landscape-ecological patterns ***166***
D02	*160*	*161*	*162*	*163*	🟩	*164*	*165*	🟩	Sea-ice area [AI28]	Landscape-ecological patterns ***166***

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	**SRd2**	**SRd3**	**SRm**	**SRtotal**	**TRyr**	**TRse**	**TRtotal**	**DC**	**IC**
D08	*167*	*168*	*169*	*170*	🟨	*171*	*172*	🟥	Arctic amphipod [AI29]	Biological diversity ***177***
D07	21	22	23	24	🟨	25	26	🟨	Cold-water benthos [AI30]	Biological diversity ***177***
D07	*46*	*47*	*48*	*49*	🟨	*50*	*51*	🟨	Arctic fish [AI31]	Biological diversity ***177***
D07	*46*	*47*	*48*	*49*	🟨	*50*	*51*	🟨	Fish sensitive to fisheries [AI32]	Biological diversity ***177***
D17	*52*	*53*	*54*	*55*	🟩	*56*	*57*	🟧	Seabirds sensitive to pollution [AI33] ***173***	Biological diversity ***177***
D18	*58*	*59*	*60*	*61*	🟥	*62*	*63*	🟨	Seabirds sensitive to pollution [AI33] ***173***	Biological diversity ***177***
D17	*52*	*53*	*54*	*55*	🟩	*56*	*57*	🟧	Arctic seabirds [AI34] ***174***	Biological diversity ***177***
D18	*58*	*59*	*60*	*61*	🟥	*62*	*63*	🟨	Arctic seabirds [AI34] ***174***	Biological diversity ***177***
D25	*98*	*99*	*100*	*101*	🟨	*102*	*103*	🟧	Mammals sensitive to pollution [AI35] ***175***	Biological diversity ***177***
D27	*111*	*112*	*113*	*114*	🟩	*119*	*120*	🟨	Mammals sensitive to pollution [AI35] ***175***	Biological diversity ***177***
D28	*115*	*116*	*117*	*118*	🟧	*119*	*120*	🟨	Mammals sensitive to pollution [AI35] ***175***	Biological diversity ***177***
D29	*121*	*122*	*123*	*124*	🟨	*125*	*126*	🟧	Mammals sensitive to pollution [AI35] ***175***	Biological diversity ***177***
D30	*127*	*128*	*129*	*130*	🟩	*135*	*136*	🟨	Mammals sensitive to pollution [AI35] ***175***	Biological diversity ***177***
D31	*131*	*132*	*133*	*134*	🟨	*135*	*136*	🟨	Mammals sensitive to pollution [AI35] ***175***	Biological diversity ***177***
D19	*65*	*66*	*67*	*68*	🟩	*73*	*74*	🟩	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D20	*69*	*70*	*71*	*72*	🟥	*73*	*74*	🟩	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D21	*75*	*76*	*77*	*78*	🟨	*83*	*84*	🟩	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D22	*79*	*80*	*81*	*82*	🟩	*83*	*84*	🟩	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D23	*86*	*87*	*88*	*89*	🟩	*90*	*91*	🟨	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D24	*92*	*93*	*94*	*95*	🟩	*96*	*97*	🟨	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D25	*98*	*99*	*100*	*101*	🟨	*102*	*103*	🟧	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D26	*104*	*105*	*106*	*107*	🟨	*108*	*109*	🟧	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D27	*111*	*112*	*113*	*114*	🟩	*119*	*120*	🟨	Arctic mammals [AI36] ***176***	Biological diversity ***177***

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	**SRd2**	**SRd3**	**SRm**	**SRtotal**	**TRyr**	**TRse**	**TRtotal**	**DC**	**IC**
D28	*115*	*116*	*117*	*118*	🟧	119	120	🟨	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D29	*121*	*122*	*123*	*124*	🟨	*125*	*126*	🟧	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D30	*127*	*128*	*129*	*130*	🟩	*135*	*136*	🟨	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D31	*131*	*132*	*133*	*134*	🟨	135	136	🟨	Arctic mammals [AI36] ***176***	Biological diversity ***177***
D01	*154*	*155*	*156*	*157*	🟨	*158*	*159*	🟨	Temperature [AI37]	Abiotic factors ***184***
D01	*154*	*155*	*156*	*157*	🟨	*158*	*159*	🟨	Area of water masses [AI38]	Abiotic factors ***184***
D01	*154*	*155*	*156*	*157*	🟨	*158*	*159*	🟨	Freshwater content [AI39]	Abiotic factors ***184***
D01	*154*	*155*	*156*	*157*	🟨	*158*	*159*	🟨	Stratification [AI40]	Abiotic factors ***184***
D02	*160*	*161*	*162*	*163*	🟩	*164*	*165*	🟩	Sea-ice area [AI28]	Abiotic factors ***184***
D03	*178*	*179*	*180*	*181*	🟩	*182*	*183*	🟥	pH [AI41]	Abiotic factors ***184***
D03	*178*	*179*	*180*	*181*	🟩	*182*	*183*	🟥	Aragonite saturation [AI42]	Abiotic factors ***184***

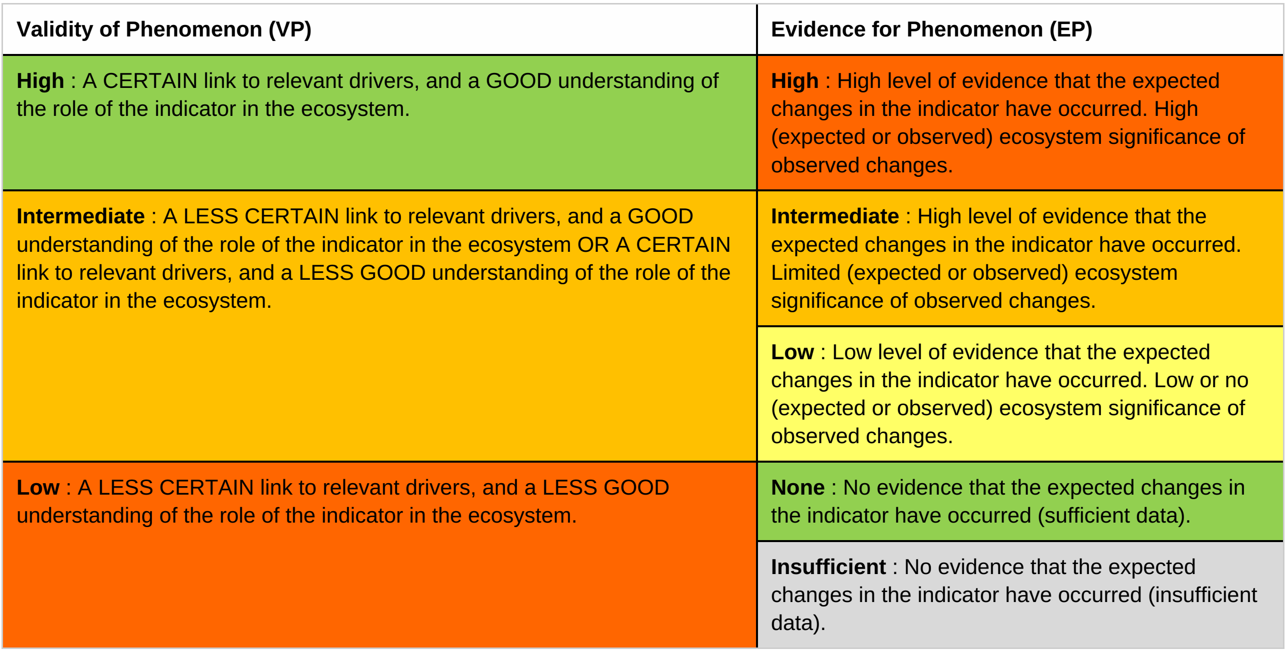
Table 7.1b. Assessment of the knowledge base for the datasets, indicators and ecosystem characteristics for Sub-Arctic Barents Sea. Numbers refer to listed comments in Appendix 8.3.

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	**SRd2**	**SRd3**	**SRm**	**SRtotal**	**TRyr**	**TRse**	**TRtotal**	**DC**	**IC**
D04	185	186	187	188	🟩	189	190	🟨	Annual primary productivity [SI01]	Primary productivity ***191***
D04	185	186	187	188	🟩	189	190	🟨	Timing of spring bloom [SI02]	Primary productivity ***191***
D04	185	186	187	188	🟩	189	190	🟨	Annual primary productivity [SI01]	Biomass distribution among trophic levels ***255***
D06	192	193	194	195	🟩	196	197	🟧	Zooplankton TL < 2.5 [SI03] ***204***	Biomass distribution among trophic levels ***255***
D08	198	199	200	201	🟩	202	203	🟧	Zooplankton TL < 2.5 [SI03] ***204***	Biomass distribution among trophic levels ***255***
D08	198	199	200	201	🟩	202	203	🟧	Zooplankton TL > 2.5 [SI04]	Biomass distribution among trophic levels ***255***
D07	205	206	207	208	🟩	209	210	🟧	Benthic suspensivores [AI05]	Biomass distribution among trophic levels ***255***
D08	211	212	213	214	🟩	215	216	🟨	0-group fish [SI06]	Biomass distribution among trophic levels ***255***
D11	217	218	219	220	🟩	221	222	🟨	Pelagic planktivorous fish [SI07] ***235***	Biomass distribution among trophic levels ***255***
D12	223	224	225	226	🟩	227	228	🟨	Pelagic planktivorous fish [SI07] ***235***	Biomass distribution among trophic levels ***255***
D10	229	230	231	232	🟩	233	234	🟨	Pelagic planktivorous fish [SI07] ***235***	Biomass distribution among trophic levels ***255***
D17	236	237	238	239	🟩	240	241	🟧	High trophic level seabirds [SI08] **248**	Biomass distribution among trophic levels ***255***
D18	242	243	244	245	🟥	246	247	🟨	High trophic level seabirds [SI08] **248**	Biomass distribution among trophic levels ***255***
D32	249	250	251	252	🟨	253	254	🟧	Low trophic level mammals [SI09]	Biomass distribution among trophic levels ***255***
D32	249	250	251	252	🟨	253	254	🟧	Generalist mammals [SI10]	Biomass distribution among trophic levels ***255***
D32	249	250	251	252	🟨	253	254	🟧	High trophic level mammals [SI11]	Biomass distribution among trophic levels ***255***
D08	198	199	200	201	🟩	202	203	🟧	High TL zooplankton functional groups [SI12]	Functional groups within trophic levels ***262***
D07	205	206	207	208	🟩	209	210	🟧	Benthic habitat engineers [SI13]	Functional groups within trophic levels ***262***
D07	256	257	258	259	🟩	260	261	🟨	Fish size [SI14]	Functional groups within trophic levels ***262***
D07	256	257	258	259	🟩	260	261	🟨	Fish life history [SI15]	Functional groups within trophic levels ***262***
D07	256	257	258	259	🟩	260	261	🟨	Fish habitat use [SI16]	Functional groups within trophic levels ***262***

DATA									**INDICATOR**	**ECOSYSTEM CHARACTERISTIC**
Dataset ID	**Spatial representativity (SR)**					**Temporal representativity (TR)**			**Data coverage**	**Indicator coverage**
	SRd1	**SRd2**	**SRd3**	**SRm**	**SRtotal**	**TRyr**	**TRse**	**TRtotal**	**DC**	**IC**
D17	236	237	238	239	🟩	240	241	🟧	Seabird feeding types [SI17]	Functional groups within trophic levels ***262***
D32	249	250	251	252	🟨	253	254	🟧	Mammals top-down control [SI18]	Functional groups within trophic levels ***262***
D05	263	264	265	266	🟧	267	268	🟧	Arctic *Calanus* [SI19]	Functionally important species and biophysical structures ***293***
D05	263	264	265	266	🟧	267	268	🟧	Atlantic *Calanus* [SI20]	Functionally important species and biophysical structures ***293***
D08	198	199	200	201	🟩	202	203	🟧	Krill [SI21]	Functionally important species and biophysical structures ***293***
D10	229	230	231	232	🟩	233	234	🟨	Capelin [SI22]	Functionally important species and biophysical structures ***293***
D13	269	270	271	272	🟨	273	274	🟩	Cod [SI23]	Functionally important species and biophysical structures ***293***
D16	275	276	277	278	🟨	279	280	🟩	Cod size structure [SI24]	Functionally important species and biophysical structures ***293***
D14	281	282	283	284	🟩	285	286	🟨	Haddock [SI25]	Functionally important species and biophysical structures ***293***
D15	287	288	289	290	🟧	291	292	🟨	Redfish [SI26]	Functionally important species and biophysical structures ***293***
D01	294	295	296	297	🟩	298	299	🟨	Bottom thermal niches [SI27]	Landscape-ecological patterns ***300***
D07	205	206	207	208	🟩	209	210	🟧	Benthos sensitive to bottom trawling [SI28]	Biological diversity ***301***
D07	256	257	258	259	🟩	260	261	🟨	Fish sensitive to fisheries [SI29]	Biological diversity ***301***
D32	249	250	251	252	🟨	253	254	🟧	Mammals sensitive to pollution [SI30]	Biological diversity ***301***
D32	249	250	251	252	🟨	253	254	🟧	Mammal diversity [SI31]	Biological diversity ***301***
D01	294	295	296	297	🟩	298	299	🟨	Temperature [SI32]	Abiotic factors ***308***
D01	294	295	296	297	🟩	298	299	🟨	Area of water masses [SI33]	Abiotic factors ***308***
D01	294	295	296	297	🟩	298	299	🟨	Stratification [SI34]	Abiotic factors ***308***
D03	302	303	304	305	🟩	306	307	🟥	pH [SI35]	Abiotic factors ***308***
D03	302	303	304	305	🟩	306	307	🟥	Aragonite saturation [SI36]	Abiotic factors ***308***

7.2 Assessment of the phenomena

The assessment of the phenomena consists of an assessment of the validity of each phenomenon (VP), and an assessment of the level of evidence that a given phenomenon has occurred (EP). VP and EP are scored according to predefined categories (**Fig. 7.2**) and presented in a table (**Table 7.2a and b**). In the table, the columns for VP and EP are colour-coded to present a relatively quick overview of phenomena of higher and lower validity, and the level of evidence for their occurrence.



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

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

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

Ecosystem characteristic	**Indicator**	**Phenomenon**	**Validity of Phenomenon (VP)**	**Evidence for Phenomenon (EP)**		**Comments EP**
Primary productivity	Annual primary productivity [AI01]	Increasing annual primary productivity [AP01]	High	None	Low	There are indications of an increase in NPP in polygons 21, 23 and 24 (i.e., in the south and west) from standard linear analyses and Bayesian-based trend analyses. Although the p-values from the standard linear analyses indicate significant relationships, this should be treated with caution for short (i.e., 50 < observations) time series. Also, the Bayesian-based analyses, which are more robust for short time series, come with wide prediction bands, suggesting the trends are not strong. In addition, there are considerations about the robustness of the estimates themselves, as satellite based NPP estimates are severely limited by sea ice and cloud cover (opaque to optical ocean color sensors) at high latitudes. Generally, for >90% of the year all grid cells in the Barents Sea area are covered by ice or clouds in the time period 1998-2022. This introduces a considerable bias when interpolating data over large temporal and spatial gaps. Thus, the evidence for the phenomenon is assessed as “low” for polygons 21, 23 and 24, while it is assessed that there is no evidence for the phenomenon for the other polygons.
Primary productivity	Timing of spring bloom [AI02]	Earlier start of the spring bloom [AP02]	High	None	Low	Evidence set to “none” for the two westernmost polygons (21, 23 and 24) and “low” for the ones further to the east (not evaluated for 48 and 49 because of lack of data)
Biomass distribution among trophic levels	Annual primary productivity [AI01]	Increasing annual primary productivity [AP01]	High	None	Low	See above
Biomass distribution among trophic levels	Zooplankton TL < 2.5 [AI03]	Increasing biomass of zooplankton that is predominantly herbivorous [AP03]	Low	None	-	Interannual variation dominates the time series with no indications of temporal trends in the data

Ecosystem characteristic	Indicator	Phenomenon	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)		Comments EP
Biomass distribution among trophic levels	Zooplankton TL > 2.5 [AI04]	Change in biomass of zooplankton that is predominantly carnivorous [AP04]	Low	None	-	There is no evidence of decrease of amphipod occurrence due to climate change. Interannual variability dominates gelatinous zooplankton time series.
Biomass distribution among trophic levels	Benthic suspensivores [AI05]	Change in biomass of suspension feeding species [AP05]	Intermediate	None	-	There is no evidence for the suggested phenomenon based on these data; trends are weak and inconsistent
Biomass distribution among trophic levels	0-group fish [AI06]	Increasing biomass of 0-group fish (except for polar cod) [AP06]	High	None	-	No trend, but peaks in biomass of 0-group fish in warm years, especially in areas affected by fluctuations in inflow of Atlantic water (e.g., polygons 21, 23).
Biomass distribution among trophic levels	Pelagic planktivorous fish [AI07]	Decreasing biomass of pelagic planktivorous fish [AP07]	Intermediate	None	-	Time-series dominated by fluctuations in the capelin stock size, with no clear long-term trend.
Biomass distribution among trophic levels	Low trophic level seabirds [AI08]	Decreasing biomass of low trophic level seabirds [AP08]	High	Low	-	Bjørnøya population and southern polygons show negative trends, while Spitsbergen population and northern polygons show positive or U-shaped trends. This is in line with expectations for climate change and northward displacement
Biomass distribution among trophic levels	High trophic level seabirds [AI09]	Decreasing biomass of high trophic level seabirds [AP09]	High	Intermediate	-	Black-legged kittiwakes decreasing at-sea and in breeding colonies. Brünnich’s guillemots show stronger negative trends in breeding colonies compared to at-sea.

Ecosystem characteristic	Indicator	Phenomenon	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)		Comments EP
Biomass distribution among trophic levels	Low trophic level mammals [AI10]	Decreasing abundance of low trophic level mammals [AP10]	Intermediate	High	-	Bowhead whales and walruses’ populations remain significantly depressed from the natural ecosystem state due to past harvests. The Spitsbergen bowhead population is currently classified as Endangered because of its size and the ongoing loss of critical habitat (sea ice). The Svalbard walrus population is classified as Vulnerable, based on the same criteria, despite the current short-term increasing trend. Both populations are expected to decline in the future based on sea-ice losses and concomitant changes expected in the ecosystem
Biomass distribution among trophic levels	Generalist mammals [AI11]	Decreasing abundance of generalist mammals [AP11]	Intermediate	Intermediate	-	The certainty of the indicator is mixed due to variable availability of data. The harp seal population model suggests some recovery after overhunting during the 1950s and 1960s, but the population has not recovered to its former state. The hooded seal population has been drastically reduced and despite protection is not showing signs of recovery, likely due to climate-change impacts on the ecosystem and perhaps also some commercial fisheries interactions (i.e., red fish overfishing). For ringed, harbour and bearded seals, there are no time series data.
Biomass distribution among trophic levels	High trophic level mammals [AI12]	Decreasing abundance of high trophic level mammals [AP12]	Intermediate	Intermediate	-	Robust estimates of population size pre-harvesting are lacking for all three species considered. For polar bear, recent population estimates are close to the upper range of the past harvested statistics, which implies that the population is still well below its past levels. Similarly, white whales’ current population estimates are well under past harvested number. Data for narwhals are missing to properly assess their trend.
Functional groups within trophic levels	High TL zooplankton functional groups [AI13]	Decreasing biomass of pelagic amphipods relative to gelatinous zooplankton [AP13]	Low	None	-	There is no evidence of decrease in amphipod occurrence due to climate change. Interannual variability dominates gelatinous zooplankton time series. The ratio of the two groups shows no trends.
Functional groups within trophic levels	Benthic habitat engineers [AI14]	Decreasing biomass of benthic habitat engineers [AP14]	High	Low	-	There is a slight decreasing trend in some of the polygons, but with strong interannual variability that, given that habitat engineers are expected to be relatively long-lived, reflects a patchy distribution and varied seabed habitats. Long timelines, and an analysis of sensitivity of the indicators’ value to the outlier catches of *Geodia*, are needed before knowing if data are suitable for this indicator. There is thus low evidence that the phenomenon has occurred. Given the polygon-wise slight to strong decrease in most of the polygons, we may be able to suggest that the evidence for the phenomenon is regional.

Ecosystem characteristic	Indicator	Phenomenon	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)		Comments EP
Functional groups within trophic levels	Fish size [AI15]	Increasing body length at maturity across species in a fish community [AP15]	High	None	-	No overall trends. Polygon-specific data indicate a small increase in western-most polygons around Spitsbergen (21, 23).
Functional groups within trophic levels	Fish life history [AI16]	Increasing slow-life, periodic fish species [AP16]	Low	None	-	No overall trends. Relative biomass of periodic fish species increased from 2004-2014, and then decreased, possibly following the warming and cooling during this period.
Functional groups within trophic levels	Fish habitat use [AI21]	Change in proportion of benthic fish [AP17]	Low	Low	-	Weak increasing trend, mostly in northern polygons.
Functional groups within trophic levels	Seabird feeding types [AI18]	Decreasing proportion of diving to surface-feeding seabirds [AP18]	Intermediate	Insufficient	-	U-shaped trend with decrease from 2004 and then an increase from 2011 onward. However, not possible to attribute to changes in the fisheries due to short time-series.
Functional groups within trophic levels	Mammal bioturbation [AI19]	Decreasing abundance of mammals involved in bioturbation [AP19]	Low	Intermediate	-	Both walruses and white whales' recent estimates are lower than pre-harvesting estimates. No data are available on bearded seals.
Functionally important species and biophysical structures	Pelagic amphipods [AI20]	Decreasing biomass of Arctic pelagic amphipod species [AP20]	High	None	-	Increase in eastern polygons

Ecosystem characteristic	**Indicator**	**Phenomenon**	**Validity of Phenomenon (VP)**	**Evidence for Phenomenon (EP)**		**Comments EP**
Functionally important species and biophysical structures	Krill [AI21]	Increasing biomass of krill [AP21]	High	None	-	Interannual variation dominates the time series with no indications of temporal trends in the data.
Functionally important species and biophysical structures	Polar cod [AI22]	Decreasing biomass of the polar cod stock [AP22]	High	None	-	Increasing trend in the start of the time-series (1986) to c. 2000. Decreasing from c.2000-2019. The last two years (2020, 2021) the stock seems to have increased to high levels again.
Functionally important species and biophysical structures	Capelin [AI23]	Decreasing biomass of the capelin stock [AP23]	Intermediate	None	-	Time-series dominated by fluctuations and without clear long-term trend. Larger stock size in the start of the time-series (1970s) likely a result of low NEA cod stock and very low abundance of NSS herring, both at least in part caused by heavy fishing.
Functionally important species and biophysical structures	Cod [AI24]	Change in cod total stock size [AP24]	High	None	-	Decreasing trend from 1946 to early 1980s, likely caused by heavy fishing pressure. Increasing population since 1980ies as a result of less intensive fishery and ocean warming. The cod stock was at its largest in 2013, similar to levels after WWII (which can be considered a reference state due to very low fishing pressure during the war). The decrease in stock size the last years is likely related to the recent cooling in the Barents Sea and cannot be attributed to increasing human pressure.
Functionally important species and biophysical structures	Cod size structure [AI25]	Decreasing biomass of large cod [AP25]	Intermediate	None	-	Increase in proportion of large cod in the most recent period, to similar levels as the “after WWII” low fishing pressure conditions.
Functionally important species and biophysical structures	Cod distribution [AI26]	Increasing biomass of cod in the Arctic Barents Sea [AP26]	High	High	-	Average density of cod increased, especially in the beginning of the time-series (2004-2010). This can be attributed to ocean warming, but also to larger population size following reduced fishing pressure.
Landscape-ecological patterns	Bottom thermal niches [AI27]	Decreasing area of bottom cold-water temperature niches [AP27]	High	High	-	Despite strong interannual variability during the part of the reference period available, there is a strong (-1.8*1000 km2 yr-1) negative trend in the indicator when evaluating the 1970-2019 period.

Ecosystem characteristic	**Indicator**	**Phenomenon**	**Validity of Phenomenon (VP)**	**Evidence for Phenomenon (EP)**		**Comments EP**
Landscape-ecological patterns	Sea-ice area [AI28]	Decreasing sea-ice area in winter and summer [AP28]	High	High	-	Despite substantial interannual variability in sea-ice area, there is a clear decreasing trend (-2.7*1000 km^{2} yr^{-1}) in the indicator for April in the period of 1979-2020, while for September, when sea-ice area levels in general are very low in the region, the decreasing trend is relatively weak (-0.6*1000 km^{2} yr^{-1}).
Biological diversity	Arctic amphipod [AI29]	Decreasing biomass of the Arctic amphipod *Themisto libellula* [AP29]	High	Insufficient	-	Too short time-series (2014-2020) to detect trends.
Biological diversity	Cold-water benthos [AI30]	Decreasing proportion of Arctic benthos species [AP30]	High	Low	-	This phenomenon is better evaluated using the relative biomass indicator (Arctic to total biomass proportion), but the biomass data themselves are also informative. There is low-moderate evidence for this general trend, although interannual and spatial variability are high.
Biological diversity	Arctic fish [AI31]	Decreasing abundance of Arctic fish species [AP31]	High	None	Low	Low evidence for reduction in abundance of arctic fish species in north-eastern polygons (47, 48), which are normally harbouring a large amount of Arctic fish. Polygon 49 had an increase in Arctic species, indicating northward displacement. There is no overall trend. However, the abundance decreased during years with warm temperature (2010-2014) and increased in recent years coinciding with lower water temperature.
Biological diversity	Fish sensitive to fisheries [AI32]	Decreasing abundance of fish species sensitive to fisheries [AP32]	High	None	-	Weak increase in abundance in polygons north and west of Spitsbergen (21, 49).
Biological diversity	Seabirds sensitive to pollution [AI33]	Decreasing abundance of Glaucous gull [AP33]	High	Intermediate	-	Strongly long-term declining population at Bjørnøya (1987-2020), at least partly attributed to high levels of PCBs in the 1980s and 1990s, but the population has still not recovered. Less clear trends at-sea with increase from 2004-2011/12, and then decrease to 2020. Increasing population on Svalbard (2005-2020), could be expected due to reduced emissions.

Ecosystem characteristic	Indicator	Phenomenon	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)		Comments EP
Biological diversity	Arctic seabirds [AI34]	Decreasing abundance of Arctic seabird species [AP34]	High	Intermediate	-	Negative trends for breeding populations of several species (Brünnich's guillemot, little auk, glaucous gull). No clear trend at- sea
Biological diversity	Mammals sensitive to pollution [AI35]	Decreasing abundance of mammal species sensitive to pollution [AP35]	Low	Insufficient	-	There is high evidence of a decrease of white whales and polar bears, but due to a lack of data, it is not possible to assess evidence for the phenomenon for narwhals and ringed seals. In addition, it is impossible to assess the role of pollutants for in the decreases or recovery rates.
Biological diversity	Arctic mammals [AI36]	Decreasing abundance of Arctic mammal species [AP36]	Low	Intermediate	-	Polar bears, white whales, bowhead whales, walruses, hooded and harp seals have not recovered from previous overharvesting pressures. The very low population level might for some of them threaten their genetic diversity and thus their population viability; in turn affecting arctic biodiversity
Abiotic factors	Temperature [AI37]	Increasing in temperature of the water column [AP37]	High	High	-	While there is considerable interannual variability over the observational time period (1970-2019), all depth ranges display significant positive temperature trends over this period that range from 0.028 to 0.032 °C yr^{-1}
Abiotic factors	Area of water masses [AI38]	Decreasing area covered by Arctic water [AP38]	High	High	-	There is a strong (-0.8*1000 km^{2} yr^{-1}) decreasing trend in the data, and the mean Arctic Water area reduced with 61 % from the reference period available (1970-1990) to the most recent period (2004-2019)
Abiotic factors	Freshwater content [AI39]	Decreasing freshwater content [AP39]	High	High	-	The freshwater content over the upper 100 m has high interannual variability, with a long-term significant decline over the period 1970–2019 of 6.8 cm m^{-2} decade^{-1} for the Arctic region overall
Abiotic factors	Stratification [AI40]	Decreasing stratification of the upper water column [AP40]	High	Intermediate	-	The maximum stratification shows large interannual and decadal variability, with clearly stronger stratification in some years during 1995-2003 than before and after. Due to the non-linear changes in the indicator, the assessment of the phenomenon is highly dependent on the time periods chosen for evaluation.

Ecosystem characteristic	**Indicator**	**Phenomenon**	**Validity of Phenomenon (VP)**	**Evidence for Phenomenon (EP)**		**Comments EP**
Abiotic factors	Sea-ice area [AI28]	Decreasing sea-ice area in winter and summer [AP28]	High	High	-	Despite substantial interannual variability in sea-ice area, there is a clear decreasing trend (-2.7*1000 km^2 yr^{-1}) in the indicator for April in the period of 1979-2020, while for September, when sea-ice area levels in general are very low in the region, the decreasing trend is relatively weak (-0.6*1000 km^2 yr^{-1}).
Abiotic factors	pH [AI41]	Decreasing pH [AP41]	Intermediate	Intermediate	-	The linear fit in the relatively short time period from 2013 to 2020 shows a significant trend of decreasing pH of 0.0022 yr^{-1} in the Arctic waters. Consequences of such changes for the ecosystem are however poorly known, and the evidence for the phenomenon is thus rated as “intermediate” rather than “high”.
Abiotic factors	Aragonite saturation [AI42]	Decreasing aragonite saturation [AP42]	Intermediate	Intermediate	-	The linear fit in the relatively short time period from 2013 to 2020 shows a trend of decreasing Ω_{Ar} of 0.0037 yr^{-1} in the Arctic waters which is slower than what has been observed in the interior of the Arctic Ocean of -0.018 yr^{-1}. Consequences of such changes for the ecosystem are however poorly known, and the evidence for the phenomenon is thus rated as “intermediate” rather than “high”.

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

Ecosystem characteristic	Indicator	Phenomenon	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)		Comments EP
Primary productivity	Annual primary productivity [SI01]	Stable and later decreasing annual primary productivity [SP01]	Intermediate	None	-	There is a weak tendency for an increase in annual primary production across the region. Thus, there is no evidence that annual net primary production has remained stable and later decreased over the last two decades.
Primary productivity	Timing of spring bloom [SI02]	Earlier start of the spring bloom [SP02]	Low	None	-	There is no clear trend in the data and thus no evidence for an earlier start of the spring bloom.
Biomass distribution among trophic levels	Annual primary productivity [SI01]	Stable and later decreasing annual primary productivity [SP01]	Intermediate	None	-	There is a weak tendency for an increase in annual primary production across the region. Thus, there is no evidence that annual net primary production has remained stable and later decreased over the last two decades.
Biomass distribution among trophic levels	Zooplankton TL < 2.5 [SI03]	Decreasing biomass of zooplankton that is predominantly herbivorous [SP03]	Low	None	-	There is no evidence that the phenomenon has occurred as there is no indication of a negative trend in either of the two time-series
Biomass distribution among trophic levels	Zooplankton TL > 2.5 [SI04]	Increasing biomass of zooplankton that is predominantly carnivorous [SP04]	Low	None	-	For gelatinous zooplankton, there is no evidence of a trend in the time series based on the fitted linear model. Similarly, for carnivorous krill, interannual variation dominates the time series with no clear trend based on the fitted linear model
Biomass distribution among trophic levels	Benthic suspensivores [AI05]	Change in biomass of suspension feeding species [SP05]	Intermediate	Low	-	All polygons show increasing trends but with high interannual variability. However, those samples include outlier catches of *Geodia*, which are characteristic for those areas, benefit from increasing temperatures, and might drive the strong slope of this indicator. Further work will assess the robustness of the slope to those outliers. This evidence for this phenomenon is thus low

Biomass distribution among trophic levels	0-group fish [SI06]	Increasing biomass of 0-group fish [SP06]	Intermediate	None	-	The observed trend is decreasing biomass of 0-group fish, while an increase was expected from climate change.
Biomass distribution among trophic levels	Pelagic planktivorous fish [SI07]	Change in biomass of pelagic planktivorous fish [SP07]	Intermediate	None	-	No trend, relatively short time-series (2004-2020). Even with the longer time-series of capelin, the pattern is dominated by fluctuations with no long-term trend.
Biomass distribution among trophic levels	High trophic level seabirds [SI08]	Change in biomass of high trophic level seabirds [SP08]	High	Intermediate	-	Common guillemot breeding population was decimated by starvation after the collapse in the capelin stock in 1986, and the decline can be attributed to fisheries. The population is recovering, but still smaller than the historic population. Atlantic puffin was negatively affected by fisheries in the period from 1960-1989, and time-series show that breeding populations are declining or stable. At-sea data show no clear trends for these species. Improved sustainability of fisheries and present recovery of common guillemot suggest that the phenomenon has limited ecosystem significance.
Biomass distribution among trophic levels	Low trophic level mammals [SI09]	Change in abundance of low trophic level mammals [SP09]	Intermediate	None	-	The timeseries used here is likely too short to fully capture the trend. An increase in fin whale sightings, however, is consistent with the trend in abundance estimates for the Barents Sea. Blue whales were not captured in the Sub-Arctic regions of the BESS survey as sightings are generally rare and they are typically sighting further north on the surveys.
Biomass distribution among trophic levels	Generalist mammals [SI10]	Change in abundance of generalist mammals [SP10]	Intermediate	None	-	These data do not show an increasing trend as expected, likely due to the short time series and the variability within the data. The sighting rates are not modelled to account for factors affecting visibility of species, though survey effort was restricted to reasonable conditions (Beaufort Sea State 4 or less and at least 1000 m of visibility).
Biomass distribution among trophic levels	High trophic level mammals [SI11]	Change in abundance of high trophic level mammals [SP11]	Intermediate	None	-	These data do not show significant trends. The certainty of the indicator is mixed due to the short time series for some species and the high levels of variability within the data.
Functional groups within trophic levels	High TL zooplankton functional groups [SI12]	Change in biomass of carnivorous krill relative to gelatinous zooplankton [SP12]	Low	None	-	There are no trends in either of the two time-series or in the ratio between them.

Functional groups within trophic levels	Benthic habitat engineers [SI13]	Decreasing biomass of benthic habitat engineers [SP13]	High	None		Most polygons show no trend. Polygons 25 and 41, which are offshore polygons with more samples, show an increasing trend. However, those samples include outlier catches of *Geodia*, which are characteristic for those areas and benefit from climate change and might drive the strong slope of this indicator. Further work will assess the robustness of the slope to those outliers. There is thus no evidence of decrease
Functional groups within trophic levels	Fish size [SI14]	Decreasing body length at maturity across species in a fish community [SP14]	Intermediate	None	-	The observed trend is increasing body length at maturation, weighted by biomass.
Functional groups within trophic levels	Fish life history [SI15]	Decreasing slow-life, equilibrium fish species [SP15]	High	None	-	The observed trend is increasing biomass proportion of the equilibrium and slow life-history strategies from 2004-2020, especially in the offshore polygons 25 and 41. This is opposite to the phenomenon specifying a decrease as a response to increasing fishing pressure.
Functional groups within trophic levels	Fish habitat use [SI16]	Change in proportion of benthic fish [SP16]	Intermediate	None	Low	Most polygons show no trend. Increasing trends in southwest (polygons 5, 27), possibly climate driven. Signs of negative trends in other polygons (e.g., 40, 41), possibly related to fishing.
Functional groups within trophic levels	Seabird feeding types [SI17]	Decreasing proportion of diving to surface-feeding seabirds [SP17]	Intermediate	Insufficient	-	U-shaped trend with decrease from 2004 then an increase from 2011 onward. However, it is not possible to attribute to changes in the fisheries due to short time-series.
Functional groups within trophic levels	Mammals top-down control [SI18]	Change in ratio of high vs low trophic level mammals [SP18]	Intermediate	None	-	These data do not show a significant trend. The certainty of the indicator is mixed due to the short time series for some species and the high levels of variability within the data.
Functionally important species and biophysical structures	Arctic *Calanus* [SI19]	Decreasing abundance of Arctic *Calanus* species [SP19]	High	Intermediate	-	There is a negative trend in the time series. It is hard to assess the ecosystem consequences of the changes in the indicator, implying that although there is high level of evidence for expected change, the evidence for occurrence of the phenomenon should be set to intermediate rather than high
Functionally important species and biophysical structures	Atlantic *Calanus* [SI20]	Increasing abundance of Atlantic *Calanus* species [SP20]	High	None	-	Although the estimated linear trend in the time series is positive, it is not significant

Functionally important species and biophysical structures	Krill [SI21]	Increasing biomass of krill [SP21]	High	None	-	There is no net change over the time period covered by the time series
Functionally important species and biophysical structures	Capelin [SI22]	Decreasing biomass of the capelin stock [SP22]	Intermediate	None	-	Time-series dominated by fluctuations and without clear long-term trend. Larger stock size in the start of the time-series (1970s) is likely a result of low NEA cod stock and very low abundance of NSS herring, both at least in part caused by heavy fishing.
Functionally important species and biophysical structures	Cod [SI23]	Change in cod total stock size [SP23]	High	None	-	Decreasing trend from 1946 to early 1980s, likely caused by heavy fishing pressure. Increasing population since 1980s as a result of less intensive fishery and ocean warming. The cod stock was at its largest in 2013, similar to levels after WWII (which can be considered a reference state due to very low fishing pressure during the war). The decrease in stock size the last years is likely related to the recent cooling in the Barents Sea, and cannot be attributed to increasing human pressure
Functionally important species and biophysical structures	Cod size structure [SI24]	Decreasing biomass of large cod [SP24]	Intermediate	None	-	Increase in proportion of large cod in the most recent period, to similar levels as the “after WWII” low fishing pressure conditions.
Functionally important species and biophysical structures	Haddock [SI25]	Change in haddock stock size [SP25]	Intermediate	Low	-	Decreasing stock in beginning of time-series (c. 1950-1980), likely caused by intensive fishing. The decrease was followed by an increase, likely caused by a combination of reduced fishing pressure and warming ocean. However, these attributions are uncertain due to very variable recruitment in haddock. Despite a decreasing trend the most recent years, the stock size seems to be somewhat higher the last two decades.
Functionally important species and biophysical structures	Redfish [SI26]	Decreasing biomass of the beaked redfish stock [SP26]	Low	None	-	The population has increased during the time for observations (1992-2019), likely due to recovery since the reduction of fishing pressure.
Landscape-ecological patterns	Bottom thermal niches [SI27]	Decreasing area of bottom cold-water temperature niches [SP27]	High	High	-	Despite strong interannual variability during, there are increasing trends in the warm-water temperature niches at bottom (3.2*1000 km ^{2} yr $^{-1}$ for T>3°C and 1.2*1000 km ^{2} yr $^{-1}$ for 0<T<3°C respectively) when evaluating the 1970-2019 period.

Biological diversity	Benthos sensitive to bottom trawling [SI28]	Decreasing biomass of benthos species sensitive to trawling [SP28]	High	None	-	The are no sign of decrease in trawl-sensitive megabenthos biomass. On the contrary there are some increasing trends that may be due to outlier data (*Geodia*) and positive effects of climate change. The areas with highest biomass of presumed trawl-sensitive taxa are also areas known for high trawling intensity (Tromsøflaket, Barents Sea opening, polygons 5, 27 and 25). Two of those polygons have very low number of stations every year. Thus, our assessment of sensitivity to trawling may require modification (e.g., expanding the OSPAR list of species sensitive to trawling to also include other species, treating *Geodia* separately)
Biological diversity	Fish sensitive to fisheries [SI29]	Decreasing abundance of fish species sensitive to fisheries [SP29]	High	None	-	No overall trend in the indicator value (2004-2020) but increase in proportion (based on abundance) of fish sensitive to increased mortality from fisheries.
Biological diversity	Mammals sensitive to pollution [SI30]	Decreasing abundance of mammal species sensitive to pollution [SP30]	Intermediate	None	-	These data do not show a significant trend. This indicator is complicated by the fact that these populations are not fixed, but highly mobile and show high seasonal variation in their distributions. To truly capture changed in abundance due to the effects of pollutions, a much longer time series is needed, as these animals are long lived.
Biological diversity	Mammal diversity [SI31]	Change in mammal species diversity [SP31]	Intermediate	None	-	These data do not show a trend, likely due to the short time series for some species and the high levels of variability within the data. The certainty of the indicator is mixed due to the short time series and the variability within the data.
Abiotic factors	Temperature [SI32]	Increasing in temperature of the water column [SP32]	High	High	-	While there is considerable interannual variability over the observational time period (1970-2019), all depth ranges display significant positive temperature trends over this period that range from 0.028 to 0.032 °C yr^{-1}.
Abiotic factors	Area of water masses [SI33]	Increasing area covered by Atlantic Water [SP33]	High	High	-	Despite strong interannual variability, there is an increasing trend (29*1000 km^{2} yr^{-1}) in the data for the full study period (1970-2019), implying high evidence that the area of Atlantic Water has increased with warming of the climate in this region.
Abiotic factors	Stratification [SI34]	Increasing stratification of the upper water column [SP34]	Intermediate	Intermediate	-	All time-series (except polygon 6) show stronger mean stratification during 2004-2019 as compared to 1970-1990, and a few of them (including the largest polygon covering the central Sub-Arctic Barents Sea) show a significant increasing trend during the full period 1970-2019.
Abiotic factors	pH [SI35]	Decreasing pH [SP35]	High	Intermediate	-	The linear fit in the relatively short time period from 1999 to 2020 shows a significant trend of decreasing pH of 0.0025 yr-1 in the sub-Arctic waters. Consequences of such changes for the ecosystem are however poorly known, and the evidence for the phenomenon is thus rated as “intermediate” rather than “high”.

Abiotic factors	Aragonite saturation [SI36]	Decreasing aragonite saturation [SI36]	High	Intermediate	-	The linear fit in the relatively short time period from 1999 to 2020 shows a significant trend of decreasing Ω_{Ar} of 0.0083 yr^{-1} in the Sub-Arctic waters. Consequences of such changes for the ecosystem are however poorly known, and the evidence for the phenomenon is thus rated as “intermediate” rather than “high”.

7.3 Assessment of ecosystem condition

Following the PAEC protocol (Jepsen et al., 2020), the assessment of ecosystem condition consists of the following sections: an assessment of each ecosystem characteristics based on all associated phenomena (Chapter 7.3.1); an assessment of the ecosystem as a whole (Chapter 7.3.2); a discussion of likely future trajectories in the condition of the ecosystem (Chapter 7.3.3); and recommendations for further monitoring and research in order to improve future assessments of the condition of the ecosystem (Chapter 7.3.4).

7.3.1 Assessment of the condition of individual ecosystem characteristics

In this chapter we present the assessment of the condition of each of the seven selected ecosystem characteristics. The assessment is supported by 1) Appendix 8.1 and 8.2, which provide time-series plots and trend analyses for each indicator in the Arctic and Sub-Arctic Barents Sea, respectively, and 2) the PAEC assessment diagrams (Fig. 7.3.1a for the Arctic Barents Sea, and Fig. 7.3.1b for the Sub-Arctic Barents Sea). The diagrams summarize information for all phenomena in each characteristic regarding the *validity of the phenomenon* (VP, y-axis) and the *evidence for the phenomenon* (EP, x-axis). In addition, point size is related to *data coverage* (DC) for the indicator, so that phenomena with lower data coverage can be down weighted in the assessment of the characteristic. Note that phenomena which are scored as “insufficient” on the EP-axis are not included in the assessment but are plotted to indicate phenomena which need to be improved for future assessments. Based on the distribution of phenomena in the diagram, the ecosystem characteristic is assessed as being in one of three categories: 1) No change; 2) limited change; or 3) substantial deviation from the reference condition. The criteria for the three categories are described in Box 3. Additional summarising figures are given at the end of this sub-chapter, showing an overview of all indicators discussed in the assessment (i.e., both those included and those not included) with the assessment category for those included, and the assessment category indicator coverage for the ecosystem characteristics (Fig. 7.3.2a for the Arctic Barents Sea, and Fig. 7.3.2b for the Sub-Arctic Barents Sea).

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

No deviation from the reference condition

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

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

Limited deviation from the reference condition

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

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

Substantial deviation from the reference condition

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

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

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

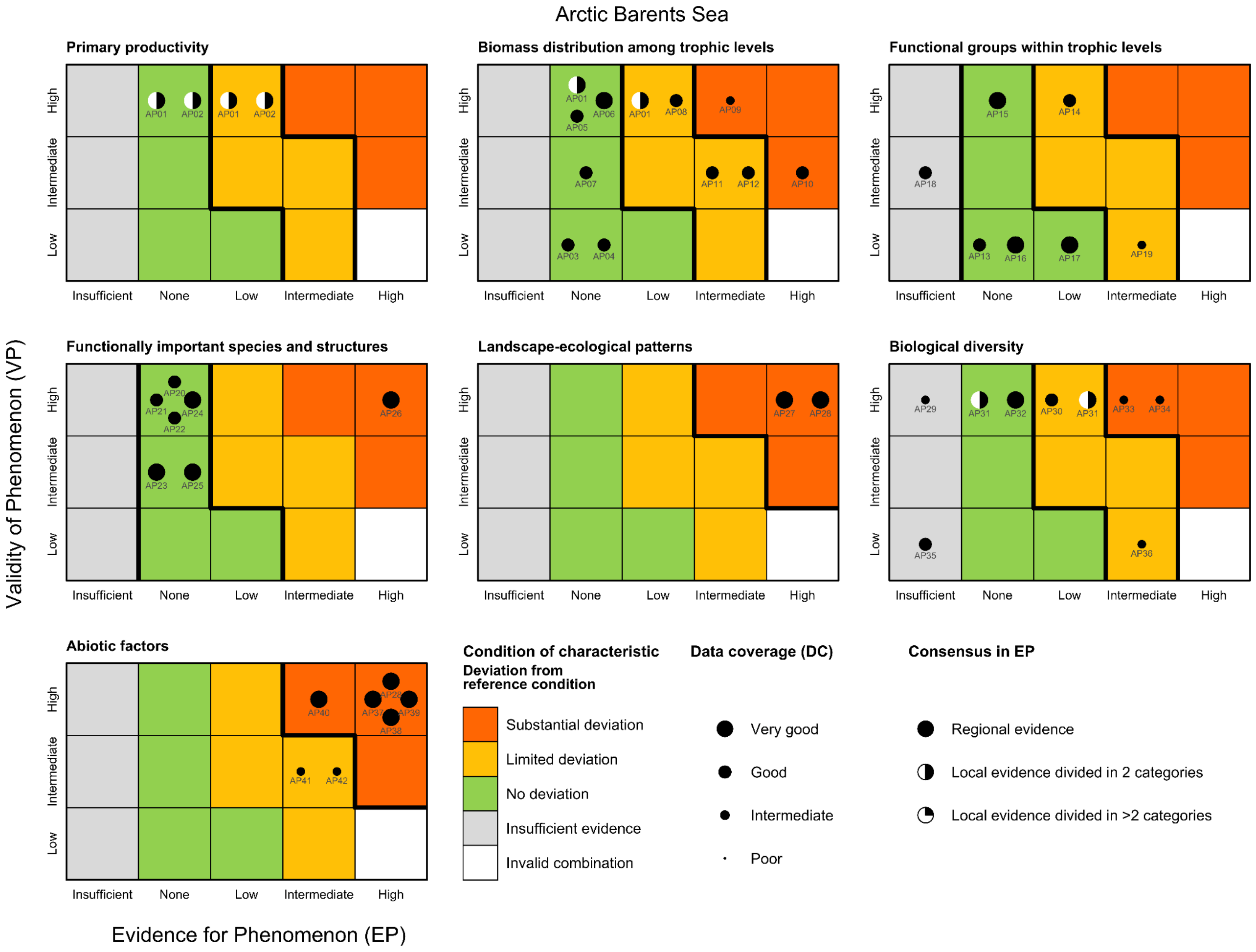
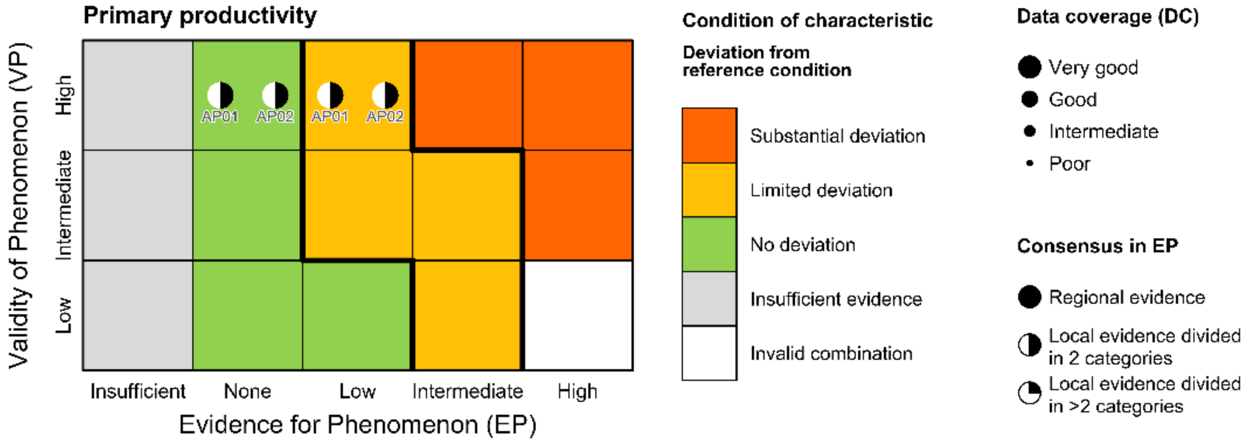


Figure 7.3.1a. The PAEC assessment diagram for the Arctic part of the Barents Sea provides an overview of all phenomena for all ecosystem characteristics. Each dot represents the assessment of a phenomenon with ID (from Table 5.1a). The size of the dot indicates the data coverage (DC; larger symbols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

Arctic Barents Sea – Primary productivity



ID	Phenomenon	Time-period
AP01	Increasing annual primary productivity	2003-2020
AP02	Earlier start of the spring bloom	2003-2020

Figure 7.3.1a(i): The PAEC assessment diagram for the Primary productivity ecosystem characteristic of the Arctic part of the Barents Sea.

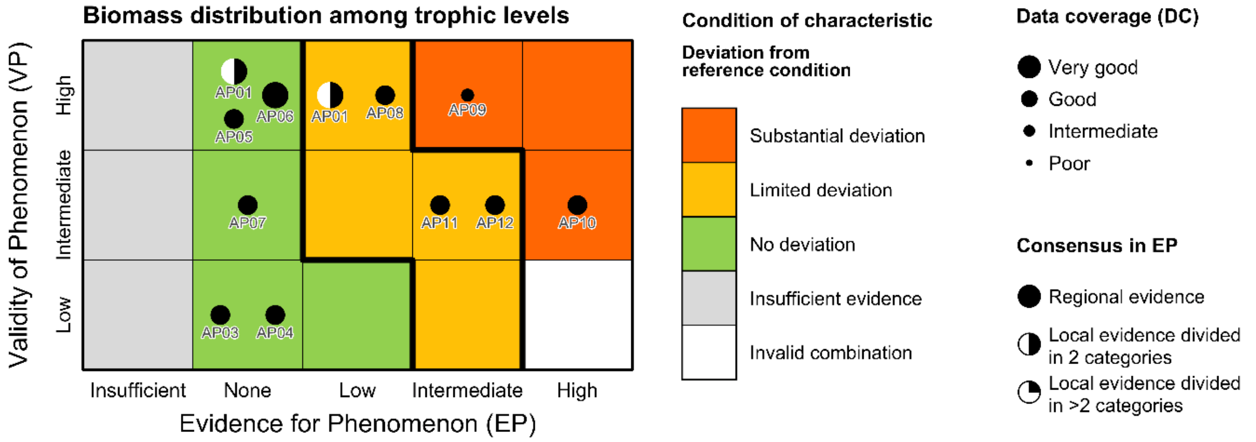
Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing evidence of **limited deviation from the reference condition**. There is evidence for an increase in annual primary production in the western part of the region. There is also some evidence for an earlier start of the spring bloom in the easternmost part of the region.

Justification for choice of assessment category : This assessment is based on 2 indicators with 2 associated phenomena (AP01 indicator *Annual primary* productivity and AP02 indicator *Timing of the spring bloom).* Both phenomena are of high validity. The geographically split evidence for change in annual primary production and timing of spring bloom justifies the assessment of limited deviation for this ecosystem characteristic. The earlier timing of spring bloom in the easternmost part of the area is consistent with the largest changes in sea-ice cover (main driver of the timing of spring bloom in that region) happening there. Contrastingly, there is no evidence for earlier start of the spring bloom in the southern area, which has traditionally had less sea-ice cover.

Uncertainties related to the choice of assessment category :

Some uncertainty related to these indicators was brought up during the assessment process. Longer time series (e.g., including data from SeaWiFS satellite) would increase certainty and might have shown stronger trends in net primary production and spring bloom timing (Dalpadado et al., 2020). However, the area chosen for this assessment report showed the least trend in annual primary production within the Barents Sea (Frey et al., 2021), which is consistent with our findings. In addition, sea ice and cloud cover are major obstacles for satellite observations of chlorophyll *a*, with particularly poor coverage during the spring and autumn months. Furthermore, the subsurface chlorophyll *a* maximum, a characteristic feature in the Barents Sea during the summer months, cannot be detected by satellite. These uncertainties limit the estimation of trends in the indicator time series, especially for the ice-covered part of the Barents Sea. However, indicator coverage is assessed as partially adequate, mainly because of lack of seasonally-resolved long time-series on phytoplankton and ice algal biomass and species composition and *in situ* primary production measurements.

Arctic Barents Sea – Biomass distribution among trophic levels



ID	Phenomenon	Time-period
AP01	Increasing annual primary productivity	2003-2020
AP03	Increasing biomass of zooplankton that is predominantly herbivorous	2004-2020
AP04	Change in biomass of zooplankton that is predominantly carnivorous	2004-2020
AP05	Change in biomass of suspension feeding species	2009-2020
AP06	Increasing biomass of 0-group fish (except for polar cod)	2004-2020
AP07	Decreasing biomass of pelagic planktivorous fish (capelin, polar cod)	1986-2020
AP08	Decreasing biomass of low trophic level seabirds (little Auk)	2004-2020
AP09	Decreasing biomass of high trophic level seabirds (kittiwake, thick-billed murre)	1980/1987/2004-2020
AP10	Decreasing abundance of low trophic level mammals (walrus, bowhead whale)	1600 and 2006-2018
AP11	Decreasing abundance of generalist mammals (harp and hooded seal)	1946-2019
AP12	Decreasing abundance of high trophic level mammals (white whale, polar bear)	1871-1960 and 2018; 1871-1973, 2004, and 2015

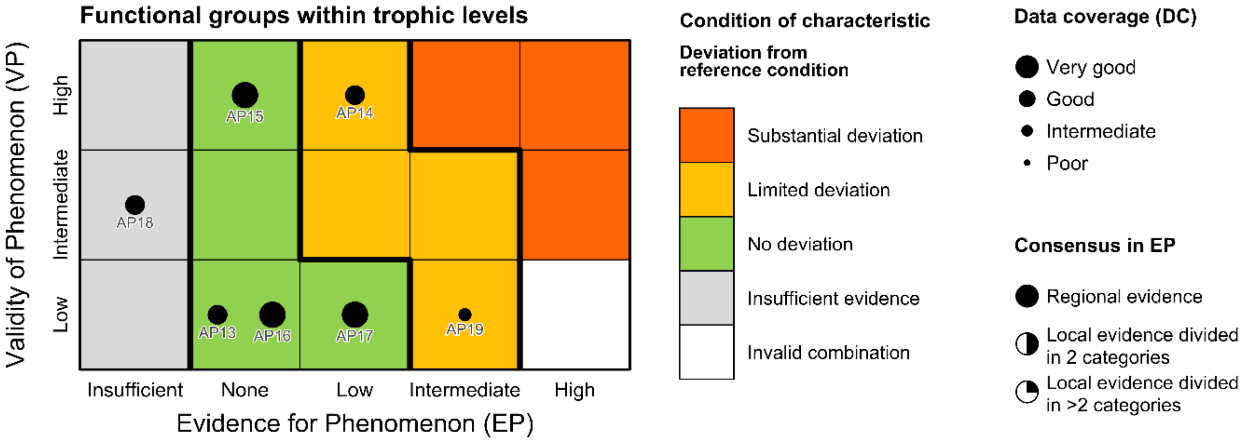
Figure 7.3.1a(ii): The PAEC assessment diagram for the Biomass among trophic levels ecosystem characteristic of the Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing evidence for **limited deviation from the reference condition.** Although low and intermediate trophic levels show no change over the observed time period, there is some evidence of change in abundance/biomass of top predators (seabirds and mammals). These changes in upper trophic levels could warn of some emerging changes in trophic structure in the Arctic food-web.

Justification for choice of assessment category : This assessment is based on eleven indicators associated with eleven phenomena (AP01 and AP03-AP12). It is driven by the intermediate and substantial evidence for changes in top trophic levels for which we have quite good understanding of the links to the drivers and their impact on the ecosystem (intermediate to high validity of the phenomena). For example, it has been shown that whales are important for the trophic structure of the ecosystem and for nutrient cycling in the Southern Ocean (Nicol et al., 2010). Upper trophic levels (marine mammals, seabirds) show limited or substantial deviation from reference conditions. Intermediate trophic levels (zooplankton, benthic suspensivores, 0-group fish, pelagic planktivorous fish) show no evidence of deviation from the reference conditions, but two of the five phenomena have low validity as the link between indicator and the rest of the ecosystem is less well understood, and most of those indicators are based on short time series (2004-2020).

Uncertainties related to the choice of assessment category : There are uncertainties regarding the choice of category. Primary producers’ biomass has high turnover and spatial and temporal variability, so getting reliable data is complicated. Instead, productivity was used, which does not necessarily reflect changes in biomass. Also, this assessment is strongly driven by the long time series of marine mammals, while shorter time series on most groups show no changes. Indicator coverage for this ecosystem characteristic is partially adequate, mainly because of lack of indicators for benthic fish communities, ice-associated production and infauna. Finally, because of the diversity of methods used and data produced for each of these ecosystem compartments, it is difficult to integrate trends of those indicators to give an overview of the biomass across trophic levels.

Arctic Barents Sea – Functional groups within trophic levels



ID	Phenomenon	Time-period
AP13	Decreasing biomass of pelagic amphipods relative to gelatinous zooplankton	2004-2020
AP14	Decreasing biomass of benthic habitat engineers	2009-2020
AP15	Increasing body length at maturity across species in a fish community	2004-2020
AP16	Increasing slow-life, periodic fish species	2004-2020
AP17	Change in proportion of benthic fish	2004-2020
AP18	Decreasing proportion of diving to surface feeding seabirds	2004-2020
AP19	Decreasing abundance of mammals involved in bioturbation (walrus, white whale)	1600 and 2006-2018; 1871-1960 and 2018

Figure 7.3.1a(iii): The PAEC assessment diagram for the Functional groups within trophic levels ecosystem characteristic of the Arctic part of the Barents Sea.

Assessment category : For this characteristic, the scientific panel did not reach an agreement, and the assessment was split between **no evidence** and **evidence of limited deviation from the reference condition.** Most of the indicators show no deviation, including one phenomenon (fish size AP15) with high validity showing some weak evidence in the western part of the region. Two phenomena show limited deviation, one of them with high validity.

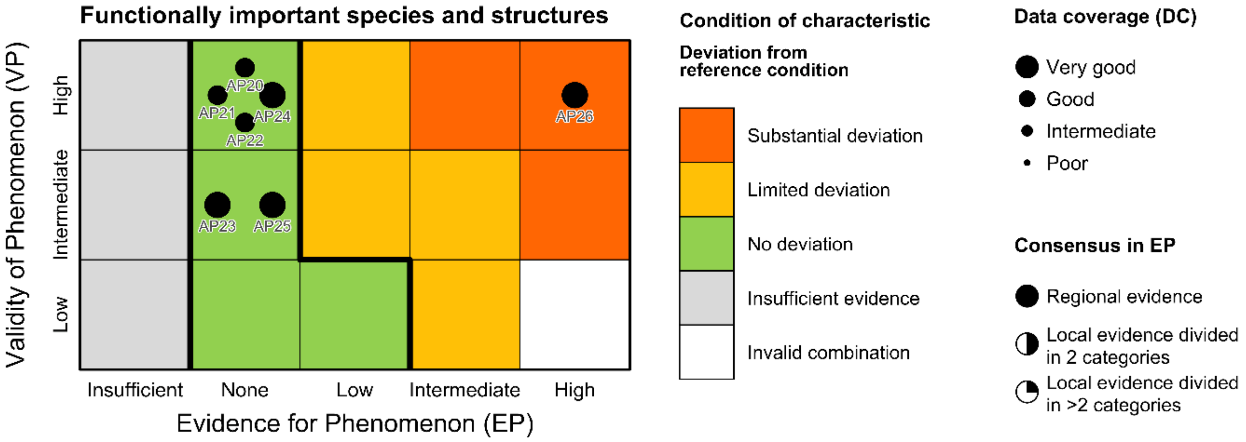
Justification for choice of assessment category : This assessment is based on seven indicators associated with seven phenomena (AP13-AP19). Four of the seven phenomena have low validity as there is poor understanding of the links to both the ecosystem and the drivers.

Justification for **no deviation** : Four of the seven phenomena are in the no deviation category, although many of them have low validity. One of the two phenomena with high validity, the change in biomass of habitat engineers (AP14), is in the category limited deviation, and is assessed with a short time series (2009-2020). The other phenomenon showing limited deviation from the reference condition is decreasing abundance of mammals involved in bioturbation (AP19), for which there are several shortcomings with the assessment. First, the data used to represent this indicator are only a coarse proxy of the bioturbating activity of marine mammals. Second, the impact of the indicator on the ecosystem is not well understood and the validity of the phenomenon is low. If the category of no deviation is deemed correct, there should still be raised a “red flag” regarding the future considering the observed negative effects from trawling on the benthic habitat engineers, since less ice in the Arctic is expected to increase the pressure from bottom trawling (Fauchald et al., 2021).

Justification for **limited deviation** : Benthic habitat engineer biomass (AI14) is an indicator associated with a high validity phenomenon with a clear decreasing trend, likely related to trawling effects, even on a short timescale (2009-2020). There is also weak evidence of a decrease in fish size (AP15) in some polygons (albeit too weak for considering evidence for the phenomena to have occurred) and strong evidence for decreased abundance of mammals involved in bioturbation (AP19), assessed with a longer time series. This shows that very different compartments of the ecosystem (benthos, fish, marine mammals) are showing signs of deviation from the reference conditions.

Uncertainties related to the choice of assessment category : The disagreement between the panel members reflects the large uncertainties regarding choice of category for this ecosystem characteristic. Evidence for the phenomena is spread out among the lower categories, and mostly with low validity. As described in the justification, two indicators (AP14, AP19) showing limited deviation from the reference condition are also associated with large uncertainties. As indicated in the assessment of indicator coverage (Table 6.1a), time and data constraints have prevented the inclusion of indicators for many important functions and groups in this ecosystem characteristic.

Arctic Barents Sea – Functionally important species and biophysical structures



ID	Phenomenon	Time-period
AP20	Decreasing biomass of Arctic pelagic amphipod species	2004-2020
AP21	Increasing biomass of krill	2004-2020
AP22	Decreasing biomass of the polar cod stock	1986-2020
AP23	Decreasing biomass of the capelin stock	1972-2020
AP24	Change in cod stock size	1946-2021
AP25	Decreasing biomass of large cod	1946-2021
AP26	Increasing biomass of cod in the Arctic Barents Sea	2004-2020

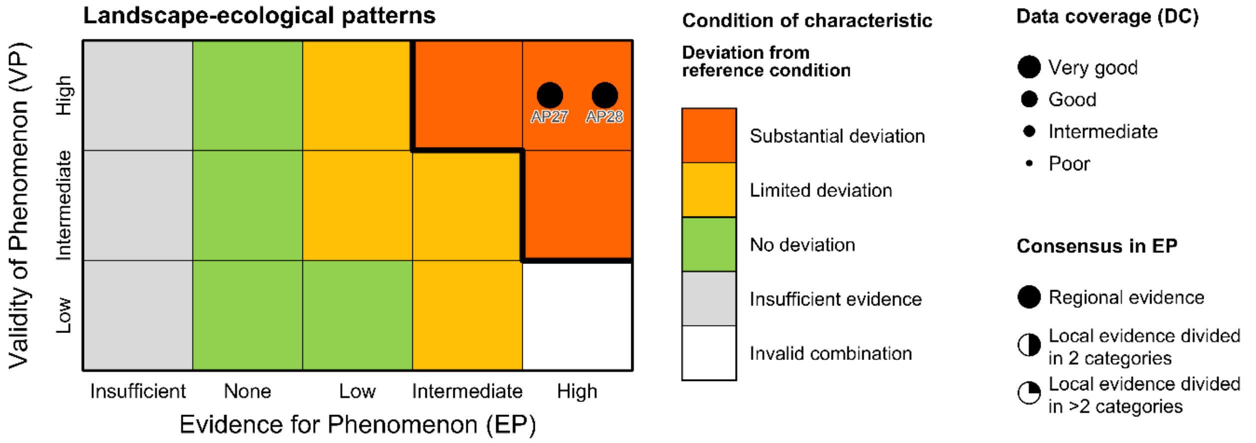
Figure 7.3.1a(iv): The PAEC assessment diagram for the Functionally important species and biophysical structures ecosystem characteristic of the Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **no evidence for deviation from the reference condition**.

Justification for choice of assessment category : This assessment is based on seven indicators associated with seven phenomena (AP20-AP26). All phenomena have intermediate to high validity, highlighting the good understanding of the importance of key species for the ecosystem and their link to the drivers. Most of the indicators have good data coverage, and six of the seven phenomena suggest no deviation from the reference condition. Only one phenomenon shows substantial deviation from the reference condition - increasing biomass of cod in the Arctic Barents Sea (AP26). This indicator is based on data from BESS collected over a relatively short period (2004-2020), while longer time series on total cod stock size (AP24), covering the entire extent of the stock, show no indication of net change away from the reference conditions.

Uncertainties related to the choice of assessment category : A major uncertainty in the assessment emerges from the relative weighting of the two different cod biomass estimates (AI24, AI26), which do not represent the same area or time scale. It was argued that the northward shift of cod into historically Arctic areas has been reported to have had strong impacts on the ecosystem, although this mainly concerns studies that also included the Russian sector of the Barents Sea. Although many key species in the ecosystem are included as indicators, some important species and biophysical structures are missing from this ecosystem characteristic: zooplankton species, ice algae, shrimp, snow crab, and benthic habitat engineers. The indicator Benthic habitat engineers (AI14) should be included in this characteristic in the next assessment.

Arctic Barents Sea – Landscape-ecological patterns



ID	Phenomenon	Time-period
AP27	Decreasing area of bottom cold-water temperature niches	1970-2020
AP28	Decreasing sea ice area in winter and summer	1979-2020

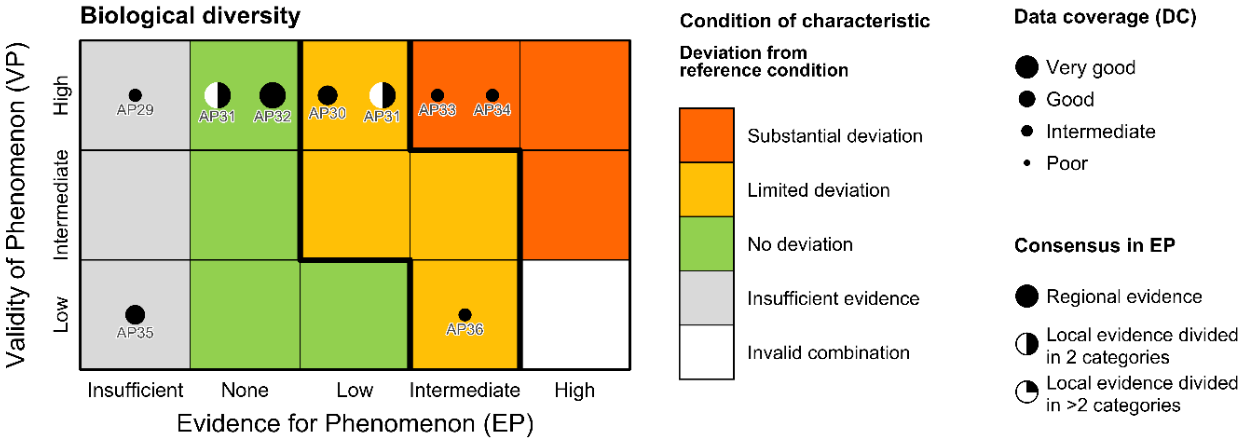
Figure 7.3.1a(v): The PAEC assessment diagram for the Landscape-ecological patterns ecosystem characteristic of the Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing evidence for **substantial deviation from the reference condition**. The mean area of cold-water (T<0°C) temperature niches at bottom was reduced to almost 20 % from the reference period available (1970-1990) to the most recent period (2004-2019), and April sea-ice area decreased by ~2700 km² per year over the period.

Justification for choice of assessment category : This assessment is based on 2 indicators with 2 phenomena (AP27-28) that are of high validity and relying on data with good spatial and temporal coverage.

Uncertainties related to the choice of assessment category : Uncertainties related to the indicators are mentioned under Abiotic factors. In addition, indicator coverage is assessed as partially adequate, and indicators related to impact from bottom trawling and important spawning and nursery areas could be included in future assessments.

Arctic Barents Sea – Biological diversity



ID	Phenomenon	Time-period
AP29	Decreasing abundance of the Arctic amphipod Themisto libellula	2014-2020
AP30	Decreasing proportion of Arctic benthos species	2009-2020
AP31	Decreasing abundance of Arctic fish species	2004-2020
AP32	Decreasing abundance of fish species sensitive to fisheries	2004-2020
AP33	Decreasing abundance of Glaucous gull	1987/2004-2020
AP34	Decreasing abundance of Arctic seabird species (glaucous gull, little auk, thick-billed murre)	1987/2004-2020
AP35	Decreasing abundance of mammal species sensitive to pollution (white whale, polar bear)	1871-1960 and 2018; 1871-1973, 2004, and 2015
AP36	Decreasing abundance of Arctic mammal species (polar bear, white whale, walrus, bowhead, hooded and harp seal)	various

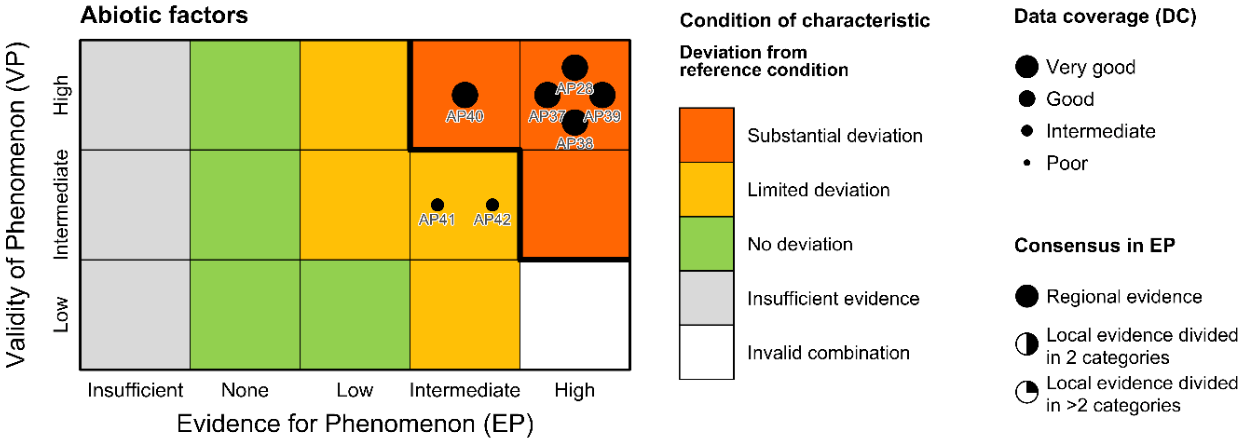
Figure 7.3.1a(vi): The PAEC assessment diagram for the Biological diversity ecosystem characteristic of the Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing evidence for **limited deviation from the reference condition**. For this ecosystem characteristic, changes in populations of vulnerable species are investigated. Endemic Arctic species (fish, seabirds, marine mammals) indicate limited to high evidence of deviation from reference conditions, thus highlighting the recent transformation of the Arctic ecosystem.

Justification for choice of assessment category : This assessment is based on eight indicators associated with eight phenomena (AP29-36) of which six are of high validity. Two phenomena have insufficient evidence and were ignored when doing the assessment. Of the six remaining phenomena, two indicate substantial deviation from the reference condition, two indicate limited deviation, one indicates no deviation, and one is split into no and limited deviation in different areas. There is thus numerically more evidence of limited deviation, and phenomena included in this category (decreasing proportion of Arctic benthos [AP30], decreasing abundance of Arctic fish species [AP31], and decreasing abundance of Arctic mammal species [AP36]) include many species, highlighting deviations in important compartments of the ecosystem. Seabirds sensitive to pollution are represented by only one species, Glaucous gull, and the corresponding phenomenon (AP33), showing substantial deviation is thus considered to have a lower weight. The same species is also included in the only other phenomenon showing substantial deviation, the decline in Arctic seabirds (AP34), and this phenomenon included only three species. Also, t here have been few, if any, regional extinctions in the area, which suggests that the category should not be substantial deviation from the reference condition. Finally, phenomena in the categories limited and substantial deviation from the reference condition are related to climate change and pollution, while the phenomenon with no deviation (Fish sensitive to fisheries (AP32)) is related to fishing pressure, and this indicator shows signs of improvement, likely due to more sustainable fisheries management in recent years.

Uncertainties related to the choice of assessment category : Uncertainties in the assessment are related to the spread of phenomena across all categories of deviation from the reference condition. This is partly related to diverging trends in different human pressures (climate change and fisheries as described above). The panel suggests that uncertainties may be reduced by including more than three seabird species, and indicators for phytoplankton, zooplankton, and ice biota are also lacking. There is also some uncertainty related to the approach to the characteristic, focusing on population trends of sensitive species. With this focus, species that we already know are sensitive to human impacts are followed, and other unforeseen impacts on the ecosystem biodiversity might be missed. Finally, the consequences of the observed changes on the ecosystem functioning are unclear, as the diversity of Arctic species is decreasing, but the overall diversity in Arctic marine areas is increasing due to incoming boreal species, as revealed in the literature.

Arctic Barents Sea – Abiotic factors



ID	Phenomenon	Time-period
AP28	Decreasing sea ice area in winter and summer	1979-2020
AP37	Warming of the water column	1970-2019
AP38	Decreasing area covered by Arctic water	1970-2019
AP39	Decreasing freshwater content	1970-2019
AP40	Decreasing stratification of the upper water column	1970-2019
AP41	Decreasing pH	2013-2020
AP42	Decreasing aragonite saturation	2013-2020

Figure 7.3.1a(vii): The PAEC assessment diagram for the Abiotic factors ecosystem characteristic of the Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **evidence of substantial deviation from the reference condition**. Areas of warmer water masses have increased (AP38), while sea-ice area (AP28), freshwater content (AP39) and stratification (AP40) have decreased, highlighting a high degree of “Atlantification”.

Justification for choice of assessment category : This assessment is based on seven indicators associated with seven phenomena (AP28 and AP37-42). For five of the seven phenomena, evidence is assessed as intermediate or high, with high validity and very good data coverage. Even with much shorter time-series and lower spatial coverage, pH, and aragonite saturation (AP41 and AP42) show signs of expected decreases with changes in climate. There is also evidence from much larger area and with data for longer time periods that ocean acidification is happening (Qi et al., 2022) and could with a high probability been detected with higher confidence in the Barents Sea if the time series had been longer.

Uncertainties related to the choice of assessment category : There are no major uncertainties to the choice of assessment category. Most uncertainties discussed by the panel are related to data coverage.

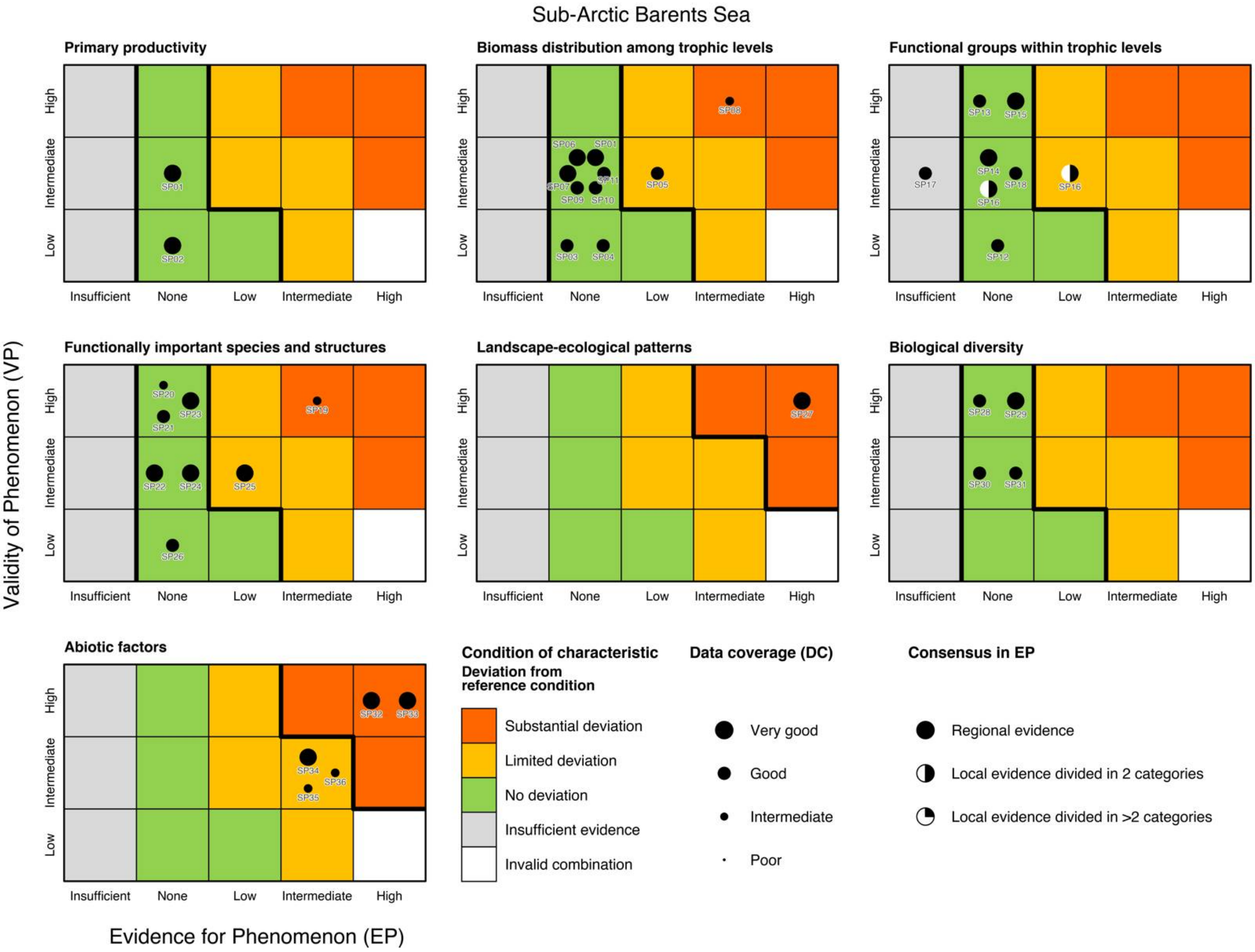
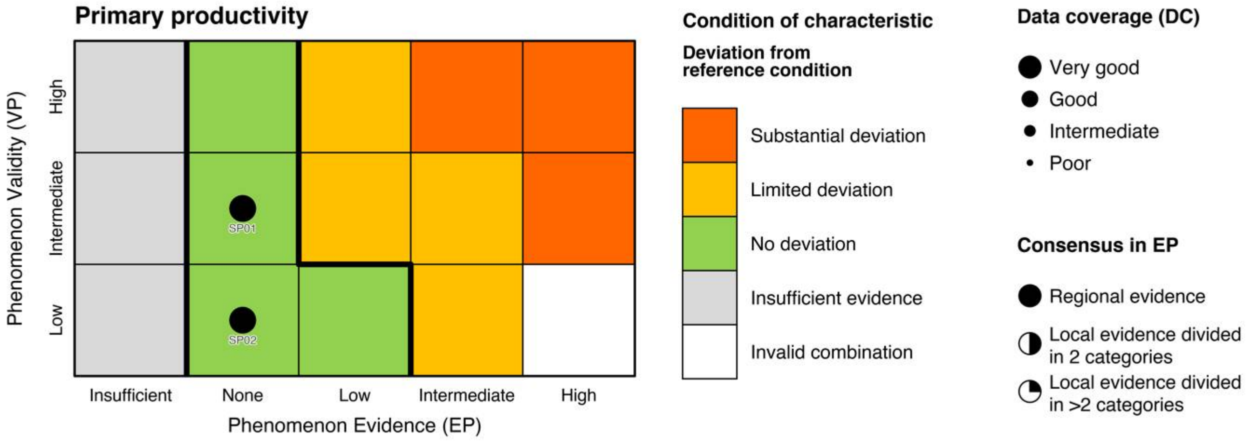


Figure 7.3.1b. The PAEC assessment diagram for the Sub-Arctic part of the Barents Sea provides an overview of all phenomena for all ecosystem characteristics. Each dot represents the assessment of a phenomenon with ID (from Table 5.1a). The size of the dot indicates the data coverage (DC; larger symbols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

Sub-Arctic Barents Sea – Primary productivity



ID	Phenomenon	Time-period
SP01	Stable and later decreasing annual primary productivity	2003-2020
SP02	Earlier start of the spring bloom	2003-2020

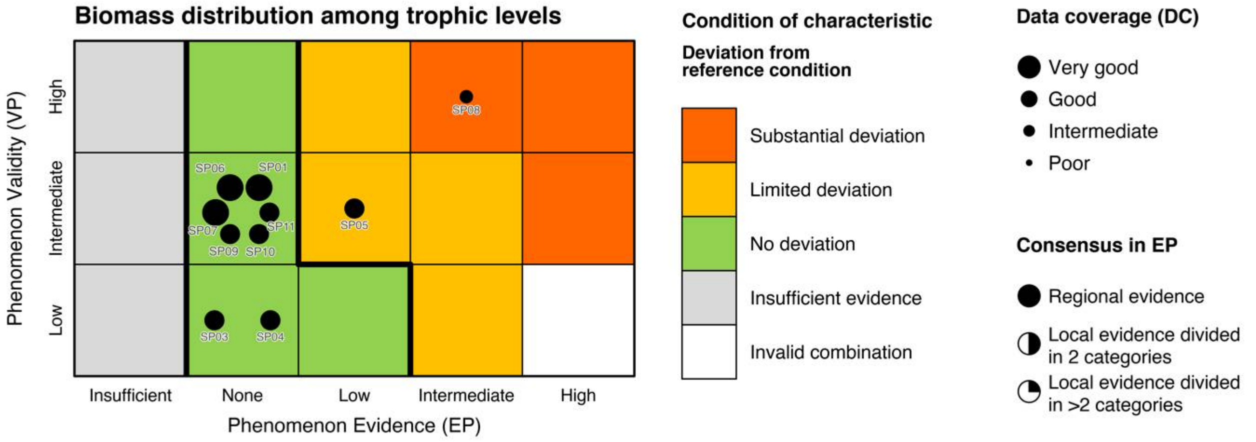
Figure 7.3.1b(i): The PAEC assessment diagram for the Primary productivity ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **no evidence of deviation from the reference condition**. There was no evidence of changes in the directions expected for increasing effects of climate change in the two indicators related to primary productivity.

Justification for choice of assessment category : This assessment is based on two indicators with two phenomena (SP01 and SP02) that are of low/intermediate validity, which are both in the category of no deviation from the reference condition.

Uncertainties related to the choice of assessment category : There were no major uncertainties to the assessment category. Even though there are only two indicators, they cover the most important aspects of the characteristic. However, the validity of these phenomena is lower compared to the Arctic part of the Barents Sea, as we have less understanding of the consequences for the ecosystem. As for the Arctic part, we lack detailed information e.g., on taxonomic composition of phytoplankton, and *in situ* measurements for calibration of satellite-based estimates.

Sub-Arctic Barents Sea – Biomass distribution among trophic levels



ID	Phenomenon	Time-period
SP01	Stable and later decreasing annual primary productivity	2003-2020
SP03	Decreasing biomass of zooplankton that is predominantly herbivorous	1990/2004-2020
SP04	Increasing biomass of zooplankton that is predominantly carnivorous	2004-2020
SP05	Change in biomass of suspension feeding species	2009-2020
SP06	Increasing biomass of 0-group fish	2004-2020
SP07	Change in biomass of pelagic planktivorous fish (capelin, herring, blue whiting)	2004-2020
SP08	Change in biomass of high trophic level seabirds (puffin, common murre)	1980/2009-2020
SP09	Change in abundance of low trophic level mammals (fin whale)	2004-2021
SP10	Change in abundance of generalist mammals (humpback, minke whale)	2004-2021
SP11	Change in abundance of high trophic level mammals (sperm, killer whales, white-beaked dophin, harbour porpoise)	2004-2021

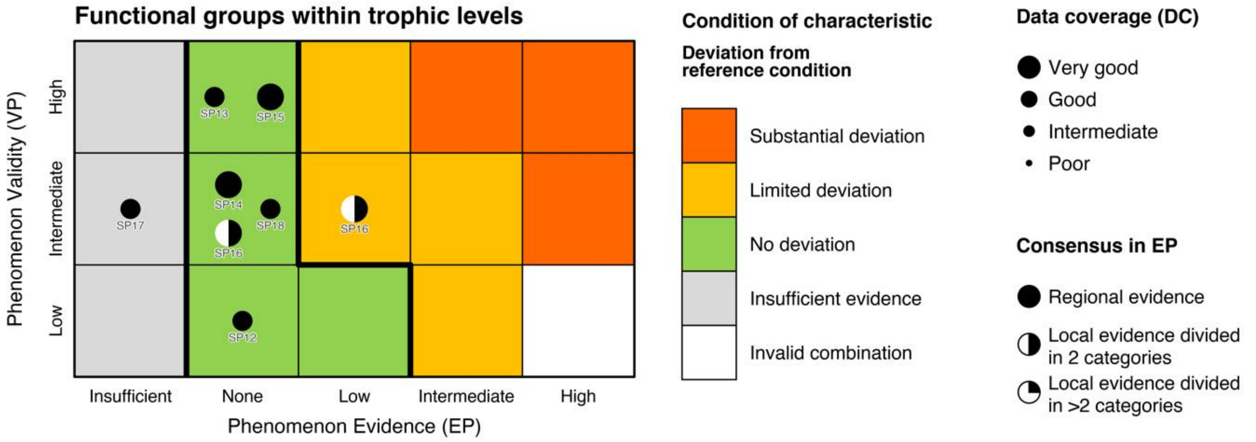
Figure 7.3.1b(ii): The PAEC assessment diagram for the Biomass distribution among trophic levels ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **no evidence of deviation from the reference condition**.

Justification for choice of assessment category : This assessment is based on ten indicators with ten associated phenomena (SP01 and SP03-11). Seven of the phenomena have intermediate validity, two have low validity and only one has high validity. The majority (eight) of the phenomena are in the category of no deviation from the reference condition, including a wide range of trophic levels and organismal groups in the ecosystem: primary productivity, zooplankton, planktivorous fish, and marine mammals. The phenomenon for high trophic level seabirds (SP08) has high validity and observations indicate decreasing populations (intermediate evidence). However, the indicator has intermediate data coverage, and only consists of two species, which puts less weight on this phenomenon. The phenomenon for benthic suspensivores (SP05) has intermediate validity, and observations show a slightly increasing biomass (low evidence) as expected with climate warming. However, the time-series for the indicator is very short (2009-2020). In the past, the ecosystem went through states that could have been described as substantial deviations from the reference conditions, with very low abundances of pelagic fish and 0-group individuals, and clear indications that some marine mammals were impacted by these low fish abundances (whales, humpback whales etc., Haug et al. (1991)).

Uncertainties related to the choice of assessment category : There are uncertainties related to the assessment category for this characteristic. All phenomena in the “none” category have low/intermediate validity. Even though data coverage is good or very good for the indicators, time-series are short (all starting in 2003/2004), especially with regard to top predator life spans, and only covers a time period with no trend in the abiotic climate indicators in the ecosystem (see Appendix 8.5). In addition, phenomena might need to be reformulated in future assessments to properly represent expectations at the spatial scale of the study. For example, according to the phenomenon on 0-group fish, biomass of 0-group fish should increase due to favourable conditions under increasing climate change. However, observations show a decrease, likely due to the north-eastward shift of 0-group fish, out of the assessment domain. Thus, with a revised phenomenon, this component of the ecosystem could show deviation from the reference condition. Indicator coverage for this characteristic is assessed as partly adequate, with the main missing indicators related to biomass trends in the benthic fish community. Finally, because of the diversity of methods used and data produced for each of these ecosystem compartment, it is difficult to integrate trends of those indicators to give an overview of the biomass across trophic levels.

Sub-Arctic Barents Sea – Functional groups within trophic levels



ID	Phenomenon	Time-period
SP12	Change in biomass of carnivorous krill relative to gelatinous zooplankton	2004-2020
SP13	Decrease in biomass of benthic habitat engineers	2009-2020
SP14	Decreasing body length at maturity across species in a fish community	2004-2020
SP15	Decreasing slow-life, equilibrium fish species	2004-2020
SP16	Change in proportion of benthic fish	2004-2020
SP17	Decreasing proportion of diving to surface feeding seabirds	2004-2020
SP18	Change in ratio of high vs low trophic level mammals	2004-2021

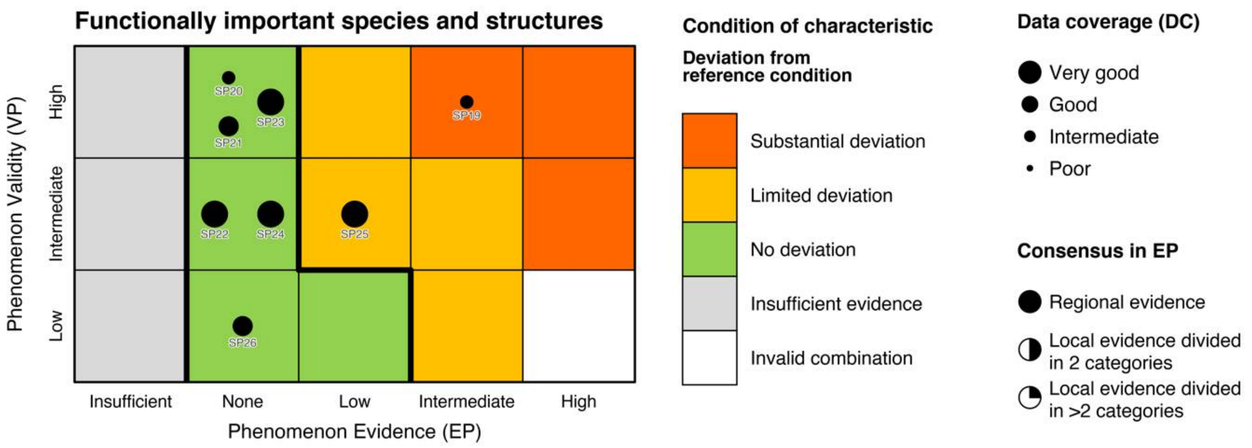
Figure 7.3.1b(iii): The PAEC assessment diagram for the Functional groups within trophic levels ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **no evidence of deviation from the reference condition**.

Justification for choice of assessment category : This assessment is based on seven indicators with seven associated phenomena (SP12-18) that are of low to high validity. Most phenomena (five and one split) are in the category of no deviation from the reference condition. The indicator for fish habitat use (SI16) shows an increasing biomass proportion of benthic fish (low evidence), but only in the south-western polygon (polygon 5) around the Lofoten archipelago. For one phenomenon, data are assessed as insufficient (SP17). Several of the phenomena show trends in the opposite direction compared to expectations from increasing human pressure. Fish size (SI14) and fish life history (SI15) indicators are closely related (larger fish tend to have slower life histories), and display increasing trends suggested to be related to less pressure from fisheries. The indicator for benthic suspensivores (SI13) does not show an overall trend but increases in offshore polygons (25 and 41), which could also be explained by reduced negative impact from bottom trawling in these areas combined with favorable conditions set by climate change. These three phenomena suggesting reduced pressure from fisheries activity are all of high/intermediate validity and have good/very good data coverage.

Uncertainties related to the choice of assessment category : There were no major uncertainties related to the choice of assessment category. However, most of the phenomena (5) have low or intermediate validity. The combined and often opposite expected effect of different human pressures, including climate change, drives the system in unexpected directions, and it is hard to assess what is driving the variability observed. Regarding indicator coverage of the characteristic, important functions identified but not included as indicators include seafloor stabilization by benthos, fish feeding guilds, and nutrient circulation and prey aggregation by marine mammals, as well as the role of marine mammal carcasses on the seafloor as biodiversity hotspots.

Sub-Arctic Barents Sea – Functionally important species and biophysical structures



ID	Phenomenon	Time-period
SP19	Decreasing abundance of Arctic Calanus species (C. glacialis, C. hyperboreus)	1995-2019
SP20	Increasing abundance of Atlantic Calanus species (C. finmarchicus)	1995-2019
SP21	Increasing biomass of krill	2004-2020
SP22	Decreasing biomass of the capelin stock	1972-2020
SP23	Change in cod stock size	1946-2021
SP24	Decreasing biomass of large cod	1946-2021
SP25	Change in haddock stock size	1950-2021
SP26	Decreasing biomass of the beaked redfish stock	1992-2019

Figure 7.3.1b(iv): The PAEC assessment diagram for the Functionally important species and biophysical structures ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **no evidence of deviation from the reference condition**.

Justification for choice of assessment category : This assessment is based on eight indicators associated with eight phenomena (SP19-26). Four of them have high validity, three have intermediate validity and one has low validity (decrease in redfish biomass SP26). The majority (6) of the phenomena are assessed as showing no deviation from the reference condition. Only two indicators fall into the limited or substantial deviation from reference condition categories: Haddock (SI25) and Arctic *Calanus* (SI19). Although it is an important biomass pool in the ecosystem, haddock is considered somewhat less important in the ecosystem functioning compared to e.g., cod and capelin, because of its lower biomass. The indicator for Arctic *Calanus* (SI19) was assigned lower weight due to intermediate data coverage.

Uncertainties related to the choice of assessment category : There is some uncertainty related to the choice of assessment category. This is mainly related to the importance of the observed changes in Arctic *Calanus* abundance (SP19). There is intermediate evidence for decreasing abundance of Arctic *Calanus* species at the Atlantic Water inflow in the Barents Sea transect, which highlights the impact of climate change in the region. This indicator (SI19) has intermediate data coverage. There are also some uncertainties related to the distribution of redfish, with the majority of the adult population residing in the Norwegian Sea. Regarding indicator coverage of the characteristic, no indicators for biophysical structures are included, nor are indicators for snow crab and deep-water shrimp.

Sub-Arctic Barents Sea – Landscape-ecological patterns

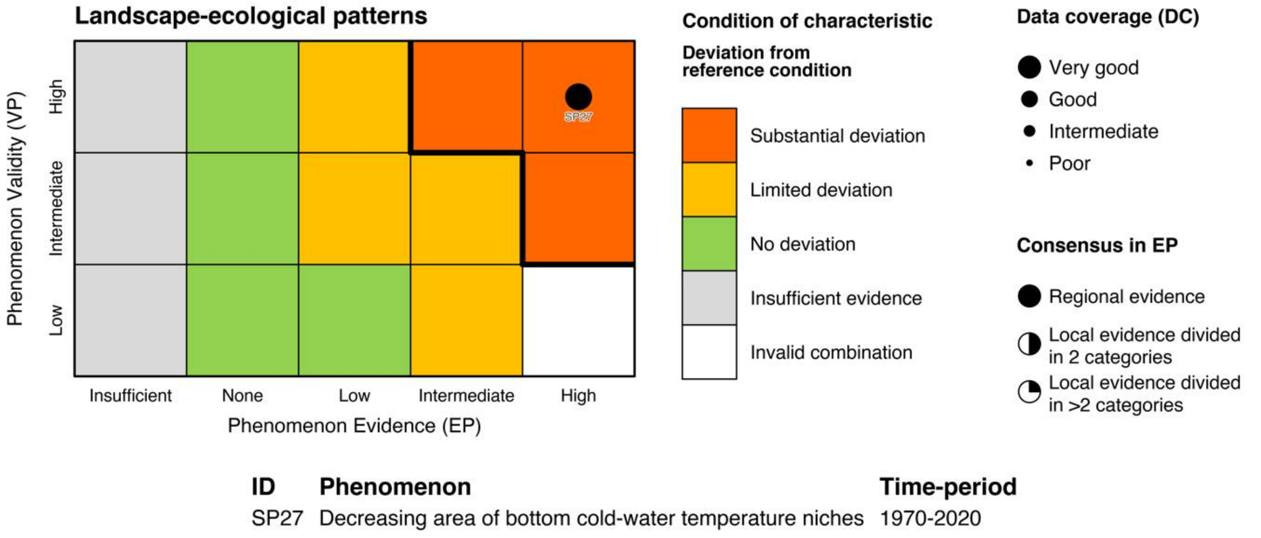


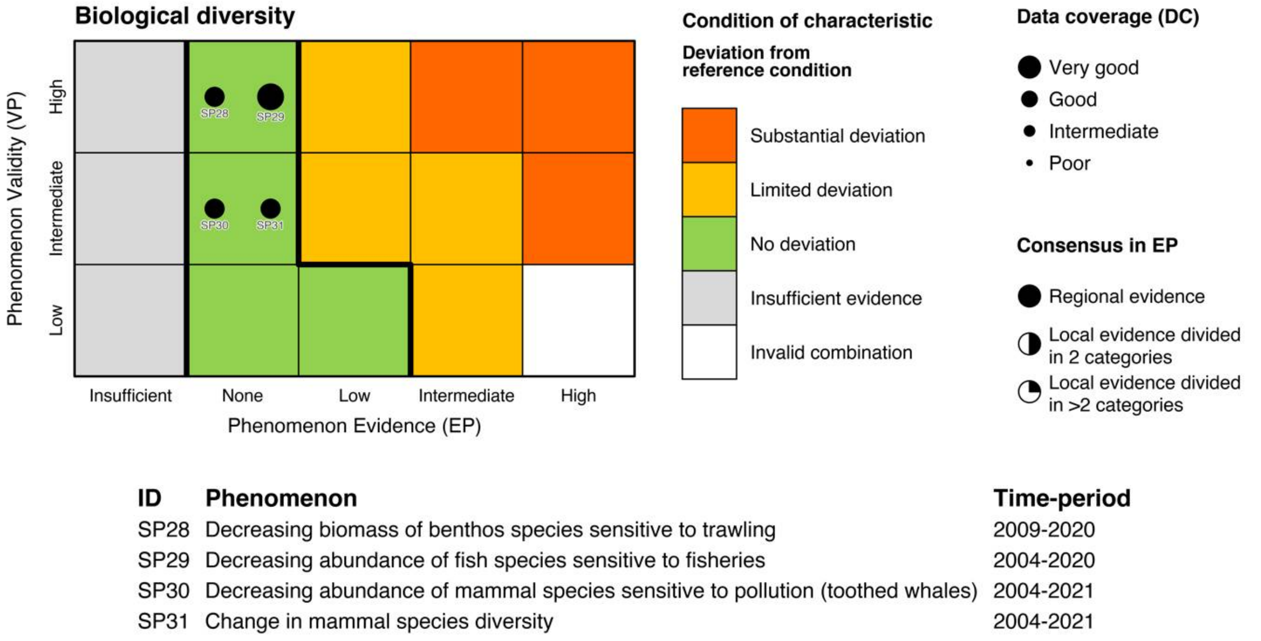
Figure 7.3.1b(v): The PAEC assessment diagram for the Landscape-ecological patterns ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **evidence for substantial deviation from the reference condition**. The area of cold-water temperature niches at the bottom [SI27] has decreased since the climatic reference period, which is likely to have implications for the ecosystem. Demersal fish and benthic habitat, for example, have warmed, which likely facilitate northward shifts in mobile bottom communities and negatively affects sedentary species with cooler thermal preferences.

Justification for choice of assessment category : This assessment is based on one single indicator with one phenomenon (SP27) that is of high validity.

Uncertainties related to the choice of assessment category : There are uncertainties related to the choice of assessment category of this characteristic, due to the limited indicator coverage. Useful indicators to consider for the future assessments are the area of seafloor impacted by bottom trawling, and the persistence of important spawning or nursery areas.

Sub-Arctic Barents Sea – Biological diversity



ID	Phenomenon	Time-period
SP28	Decreasing biomass of benthos species sensitive to trawling	2009-2020
SP29	Decreasing abundance of fish species sensitive to fisheries	2004-2020
SP30	Decreasing abundance of mammal species sensitive to pollution (toothed whales)	2004-2021
SP31	Change in mammal species diversity	2004-2021

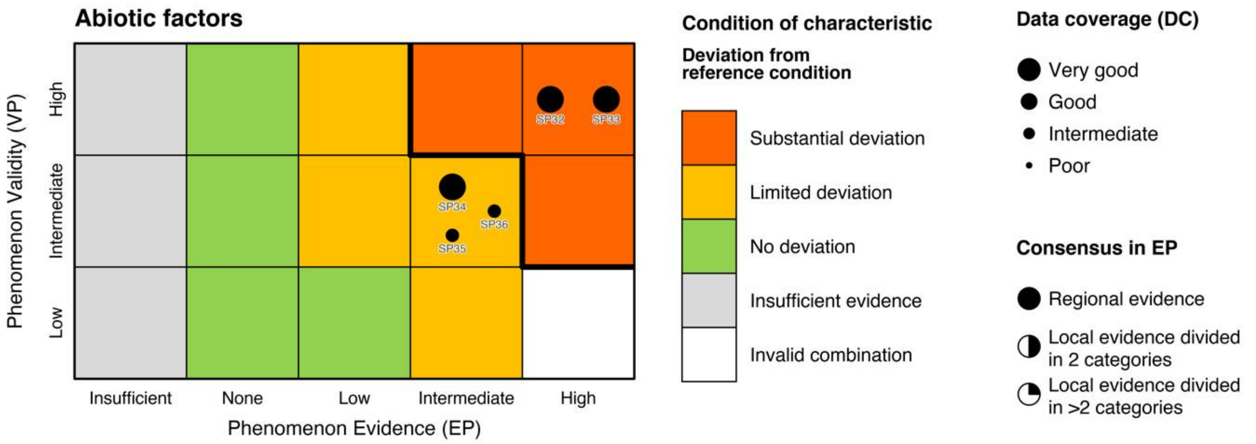
Figure 7.3.1b(vi): The PAEC assessment diagram for the Biological diversity ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **no evidence of deviation from the reference condition.**

Justification for choice of assessment category : This assessment is based on four indicators with four associated phenomena (SP28-31) that are of intermediate and high validity, which are all in the category of no deviation from the reference condition. For some of the indicators, there were signs of trends indicating reduced impacts from human pressures. The biomass of benthos species sensitive to trawling [SI28] increased during the period with available data (2009-2020). The abundance proportion of fish species sensitive to fisheries (SI29) increased from 2004-2020, indicating less impact from fisheries.

Uncertainties related to the choice of assessment category : There are large uncertainties related to the choice of assessment category for this characteristic. The two mammal indicators (SI30) and (SI31) are based on very short time-series (2004-2020) for these long-lived animals. In addition, they are based on sighting rates and not on abundance estimates, which would have been more robust. Thus, the values cannot be compared to estimates of historic population sizes which would be necessary in order to capture effects of historic hunting of several of these species. The observed increase in biomass of benthos species sensitive to trawling (SI28) was mainly due to large sponges (*Geodia*), which is likely to benefit from climate warming and seems to drive the trend. Future iteration of this assessment will test the robustness of the trend to those samples. The indicator for fish species sensitive to fisheries (SI29) seems to be dominated by the trend in the redfish species complex, which has been increasing during the period (2004-2020) mainly due to more restrictive fisheries. However, the indicator does not capture well the situation for other fisheries sensitive species such as several elasmobranch species. There is also some uncertainty related to the approach to the characteristic, focusing on population trends of sensitive species. With this focus, we follow species that we already know are sensitive to human impacts and might miss other unforeseen impacts on the ecosystem biodiversity. Finally, the ecosystem characteristic is not providing an exhaustive overview of the biodiversity in the ecosystem, as only known sensitive species are monitored, and as many ecosystem compartments (e.g., phytoplankton and zooplankton), are not considered.

Sub-Arctic Barents Sea – Abiotic factors



ID	Phenomenon	Time-period
SP32	Warming of the water column	1970-2019
SP33	Increasing area covered by Atlantic water	1970-2019
SP34	Increasing stratification of the upper water column	1970-2019
SP35	Decreasing pH	1999, 2012, and 2014-2020
SP36	Decreasing aragonite saturation	1999, 2012, and 2014-2020

Figure 7.3.1b(vii): The PAEC assessment diagram for the Abiotic factors ecosystem characteristic of the Sub-Arctic part of the Barents Sea.

Assessment category : Based on the set of indicators, this ecosystem characteristic is assessed as showing **evidence for substantial deviation from the reference condition**. There has been a significant increase in water temperature (SP32) and area covered by Atlantic water masses (SP33) since the climatic reference period. These changes are likely to have implications for oceanographic features and properties such as mixing in the water column, in turn impacting biological compartments through changes in habitat and productivity.

Justification for choice of assessment category : This assessment is based on five indicators with five associated phenomena (SP32-36) that are of intermediate (3) and high (2) validity.

Temperature (SI32) and area of Atlantic water masses (SI33) are important indicators related to the control of the heat content in the Sub-Arctic part of the Barents Sea and show strong evidence of deviation from the climate reference period. There is also high evidence of increasing stratification (SI34) of the upper water column, especially in the most important inflow areas in the Sub-Arctic Barents Sea (polygons 25 and 27), but the consequences for the ecosystem are unclear, hence the intermediate EP. The indicators related to the carbonate system, pH (SI35) and aragonite saturation (SI36), are closely related, and both have lower data coverage than the others, with shorter time series and lower spatial representability.

Uncertainties related to the choice of assessment category : There are uncertainties related to the choice of assessment category for this characteristic. Changes in the abiotic factors are less pronounced in the Sub-Arctic compared to the Arctic part of the Barents Sea, and there are some arguments that the assessment category should be lower. The importance of the carbonate system, pH (SI35), aragonite saturation (SI36), and stratification (SI34) for e.g. phytoplankton is a reason to put more weight on the phenomena in the limited category. Also, some of the trends are affected by very different temporal physical patterns in the Lofoten area (Polygon 6). However, the ecology in this polygon differs from that in the rest of the Sub-Arctic Barents Sea.

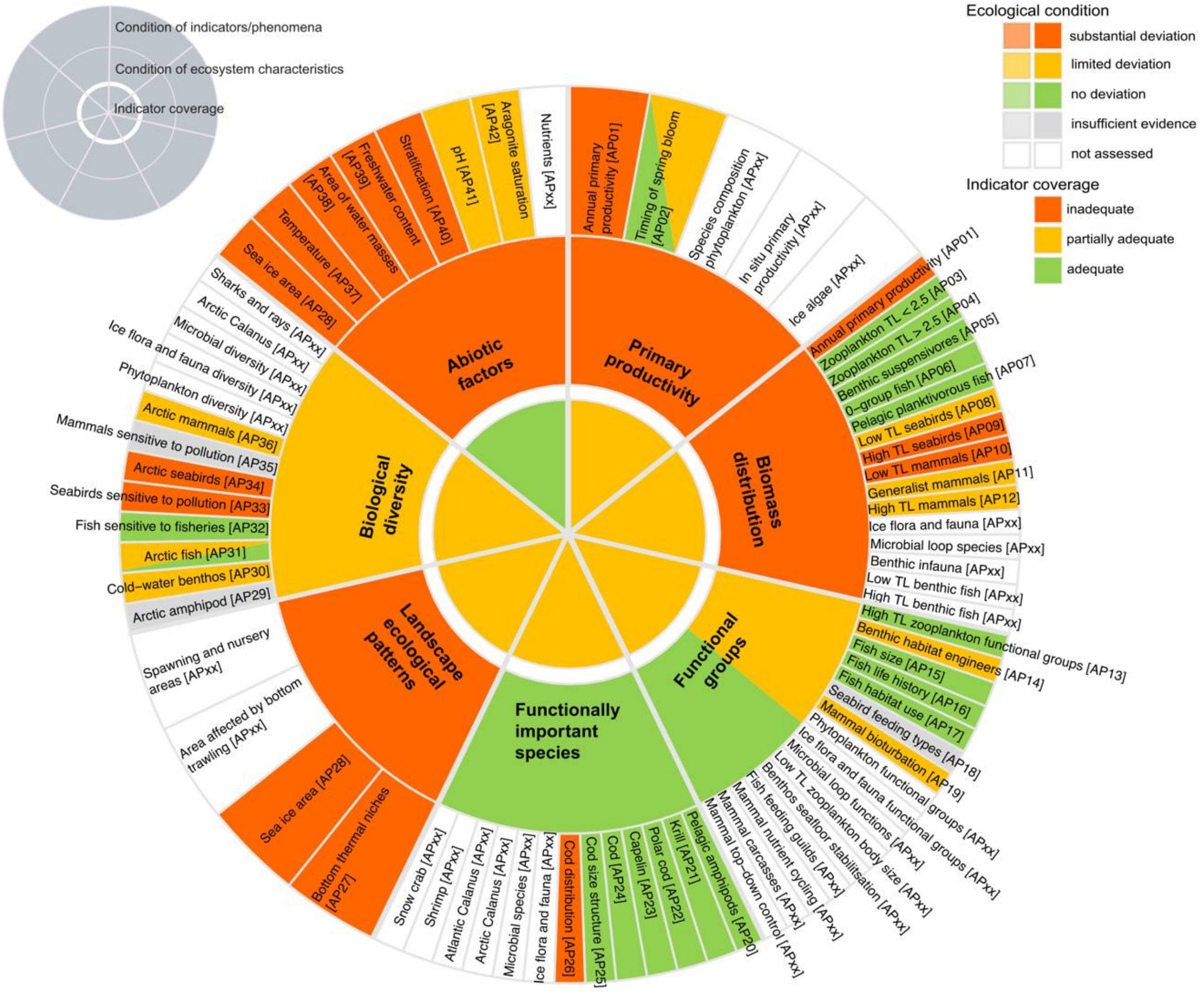


Figure 7.3.2a. A graphical summary of the assessment of the Arctic Norwegian sector of the Barents Sea. The outer circle shows the assessment of ecological condition at the level of the individual indicators with associated phenomena ID in square brackets. Indicators which have been recommended for inclusion (Table 7.3.4), but not included in the current assessment are shown in white to illustrate the perceived most important deficiencies in the current indicator set. The two innermost circles show the assessment at the level of ecosystem characteristics, in the form of ecological condition (middle circle) and indicator coverage (innermost circle), based on the set of indicators included in the assessment.

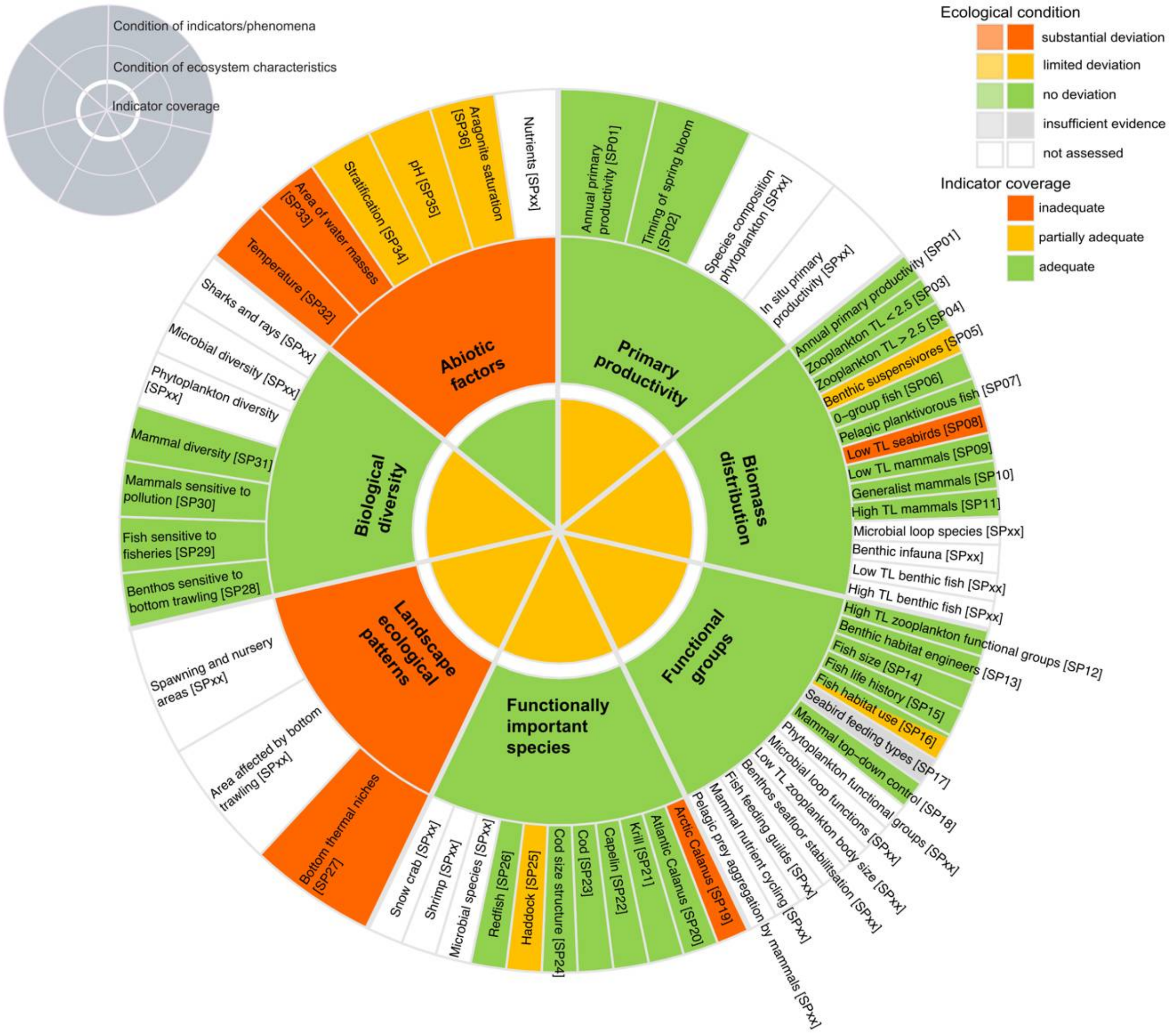


Figure 7.3.2b. A graphical summary of the assessment of the Sub-Arctic Norwegian sector of the Barents Sea. The outer circle shows the assessment of ecological condition at the level of the individual indicators with associated phenomena ID in square brackets. Indicators which have been recommended for inclusion (Table 7.3.4), but not included in the current assessment are shown in white to illustrate the perceived most important deficiencies in the current indicator set. The two innermost circles show the assessment at the level of ecosystem characteristics, in the form of ecological condition (middle circle) and indicator coverage (innermost circle), based on the set of indicators included in the assessment.

7.3.2 Assessment of the condition of the ecosystem as a whole

The scientific panel assessed the ecological condition of two ecosystems, the Arctic and sub-Arctic shelf ecosystems in the Norwegian sector of the Barents Sea. The panel concludes that the climate and physical environment are substantially impacted by anthropogenic drivers, based on long monitoring time series starting around 1970, in particular through increasing temperatures and declining sea ice area. The panel also identified climate change as a potentially important driver for more than 80% of the indicators in the assessment. However, most of the data on biological components of the ecosystem were available only from 2004, a period with a weaker warming trend than the 1970 to early 2000s part of the climate time series, and the biological indicators showed only moderate changes. Based on these data, the scientific panel concludes that there is evidence for limited impact of human pressures on the Arctic ecosystem, and no evidence for the Sub-Arctic ecosystem, but point out that there are considerable uncertainties associated with this, due to the short times series for biological indicators. As warming is expected to continue in the future, more substantial changes are expected to be observed also for the biological components of the two ecosystems. In addition to anthropogenic climate impacts, fisheries are another important human pressure in the Barents Sea, and some of its impacts appear to have diminished in recent years.

Current state of knowledge of the reference condition

Following the description of the phenomena (chapter 5.1), the shelf ecosystem in the Norwegian sector of the Arctic part of the Barents Sea in the reference condition should have structures and functions which are determined by an Arctic climate characterised by seasonal or whole-year ice cover, dominance of Arctic water masses and a reservoir of freshwater and strong stratification in the upper water column. Reference water chemistry should be unaffected by anthropogenic greenhouse gas emissions and harvesting and fishing should be carried out sustainably. An entire species assemblage dependent on sea ice as habitat (sympagic species) should be found in the northern part of the ecosystem, where there should be ice. Primary production by phytoplankton and ice algae should exhibit high seasonality due to seasonality in incoming light, and the strong seasonal stratification of the upper water column should limit replenishment of nutrients from below the photic zone. The zooplankton community should be dominated by large and lipid-rich species such as the copepod *Calanus glacialis* and the pelagic amphipod *Themisto libellula*, which should occur in biomasses large enough to sustain the community of Arctic predators, including polar cod, little auk and bowhead whales. Krill should not be a dominant zooplankton group. Benthic invertebrates, including cold-water associated communities, should be undisturbed by trawling and receive significant food input from ice algae sinking to the bottom during melting of sea ice. Pelagic planktivorous fish such as capelin and polar cod should be abundant enough to support viable populations of endemic Arctic predators of fish, seabirds and marine mammal species that depend on these species as prey. The demersal fish communities should be characterized by a relatively high proportion of cold-water associated, small, specialised species. Fish species with typically “slow-type” life history traits that make them particularly vulnerable to impact from fisheries, should also be abundant. Under the reference condition, several Arctic marine mammal endemic species should occur with substantially larger populations than today because of over-harvesting that took place over several centuries, and in the case of some populations also into recent decades, including bowhead whale, white whale, polar bear, walrus and harp and hooded seals.

For the Sub-Arctic part of the Norwegian sector of the Barents Sea, the description of the phenomena shows that the shelf ecosystem in the reference condition should have structures and functions that are determined by a climate with moderate water temperatures and with only limited occurrences of Arctic water masses and seasonal ice cover in the far northern parts of the area. T here should be a weak, but significant, stratification during summer in the upper water column due to solar heating of the surface layer and input of freshwater from rivers. Water chemistry should be unaffected by anthropogenic greenhouse gas emissions and harvesting and fishing should be carried out sustainably. Primary production should be contributed by phytoplankton and the spring bloom should start when the upper water column stabilises through stratification and irradiance is high enough. The zooplankton community should be dominated by copepods, particularly *Calanus finmarchicus*, and krill, with chaetognaths and gelatinous species as other important groups. Benthic invertebrate communities should be undisturbed by bottom trawling. In the demersal fish community, species with large body size, including North-East Arctic cod, should have an important structuring role in the ecosystem, since larger species typically are feeding on a larger range of prey types. Species with equilibrium/slow life history strategies should be an important part of the demersal fish community under the reference condition, and due to their long lifespan, late maturation, and low fecundity, they typically have stable population dynamics and very low rates of intrinsic population increase. They are vulnerable to increased mortality, and the total biomass is expected to have been higher than today. Planktivorous fish stocks of herring, blue whiting, and capelin should be large enough to support predator populations dependent on these species as prey, e.g., cod, redfish, saithe, and skates, and be key to the overall energy transfer to higher trophic levels. Diving seabirds should be important piscivorous predators in the Barents Sea ecosystem and a dominant part of the avifauna. Most marine mammals, such as blue whale, fin whale, humpback whale, minke whale, sperm whale, harp seals and hooded seals would all probably occur on much greater abundances under the reference condition than today because of historical over-harvesting.

For both ecosystems, systematic monitoring rarely stretches back to periods with an unimpacted climate and sustainable fishing and harvesting. Robust quantitative descriptions of the reference condition are therefore beyond reach for both systems, except for a few mammals in the Arctic part, for which pre harvest population sizes have been assessed (see phenomenon for indicator AI10, chapter 5.1). The qualitative description that can be made of the reference condition beyond this, is fragmented. While there is good knowledge of the composition of the key species assemblages, i.e., ice-dependent (sympagic) and Arctic species assemblages in the Arctic part and boreal species assemblages in the Sub-Arctic part, less is known about ecological functions and relationships. Some species groups are also poorly known, such as species involved in the microbial loop and infectious organisms (e.g., parasites, viruses, bacteria).

Main drivers of change

The main drivers of change in both the Sub-Arctic and Arctic part of the shelf in the Norwegian Sector of the Barents Sea are harvesting, fishing, climate change and pollution. Harvesting has the longest history of industrial scale impact, stretching back to the late 16th century in the Arctic part of the Barents region. Massive over-harvesting of most species of marine mammals caused population declines, sometimes to the edge of extinction, from which many of the species have still not recovered (e.g. Kovacs et al. (2020)). The minke whale and harp seals are now the only marine mammal species subject to harvesting, which is assessed as sustainable. All other marine mammal species are protected from commercial harvesting. Recovery is ongoing for several species and pre-harvesting population levels are therefore relevant to consider when assessing the current ecological state (Aars et al., 2009; Kovacs et al., 2014).

Industrial scale impact from fisheries date back to the 1930s, and massive overfishing occurred in periods after WWII. Revisions of the fisheries management approach has reduced the fishing pressure (Gullestad et al., 2013), and the large commercially harvested stocks have generally been fished sustainably for the last 10-15 years (Kjesbu et al., 2014; ICES, 2020). The commercially exploited stocks have since then generally recovered, with the golden redfish (*Sebastes norvegicus*) as a notable exception. It should be noted that fishing in the Arctic ecosystem only affects the southern areas, whereas north of Svalbard hardly any fishing occurs.

Fisheries affects non-target species through by-catch and bottom trawling impacts benthic invertebrate communities. As measured from Norwegian trawlers, intensity of trawling may have declined during the last three decades (Fig. 7.3.3). Although loss of sea ice means that trawling tends to expand quickly into new and more pristine areas (Fauchald et al., 2021), areas protected from bottom trawling are under establishment in the Arctic part of the Barents Sea as a response to this (Jørgensen et al., 2020).

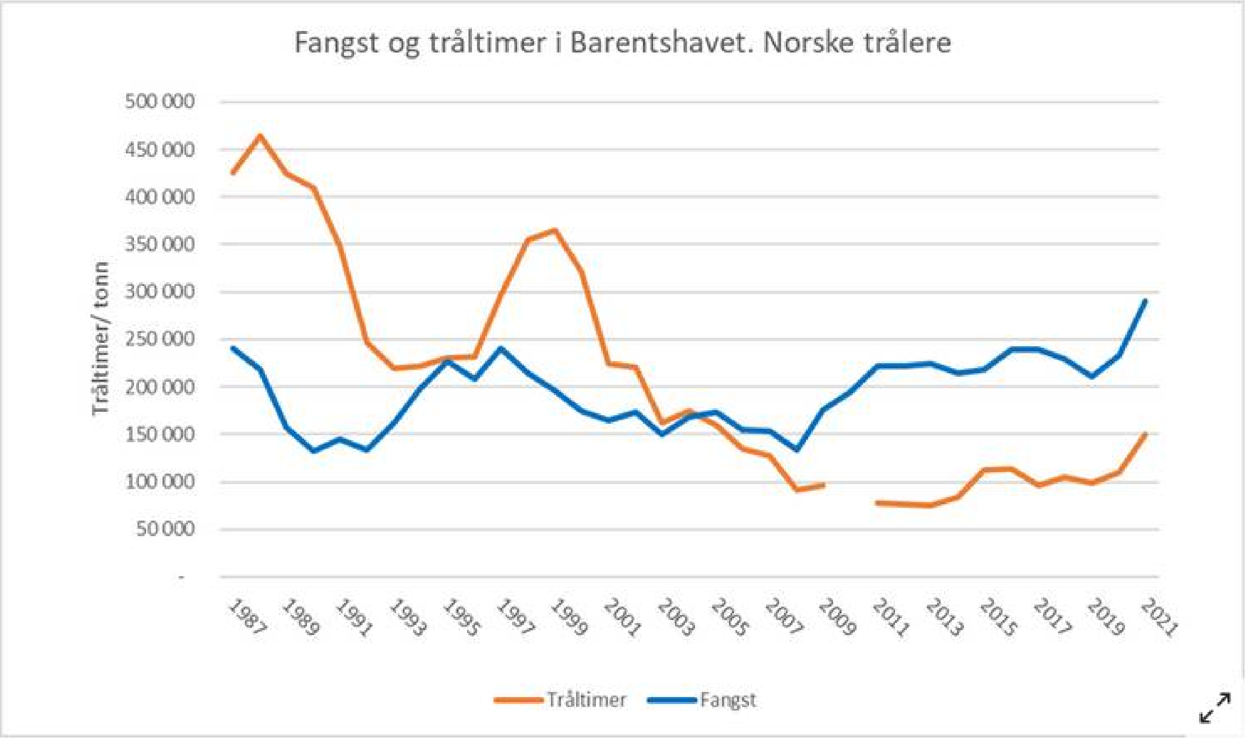


Figure 7.3.. Hours trawled (orange line, measured from when the trawl enters till it is hauled out of the sea, and catch (blue line) from Norwegian trawlers in the Barents Sea from 1987 to 2021.

Climate change is the most recent driver with industrial scale impact. Anthropogenic climate change is commonly compared to pre-industrial (1850-1900) time (e.g., IPCC (2022); World Meteorological Organization (WMO) (2022)), and paleo-oceanographic records show a rapid warming that commenced in the early 20th century (Tesi et al., 2021). Observational time series from the Sub-Arctic Barents Sea confirm a long-term warming of the region through the 20th century (Boitsov et al., 2012; Yashayaev and Seidov, 2015). However, the warming has strengthened since 2000 (Ingvaldsen et al., 2021), and based on the description of the phenomena (chapters 5.1 and 5.2), it now appears to be the main driver of change in the Arctic part of the Barents Sea. The impact is pervasive and, for the Arctic part, includes loss of sea ice as an important component of the physical environment and as habitat, increased primary production, substantial changes in the zooplankton community, northward expansion of boreal species and an increasingly connected food web (Kortsch et al., 2015; Ingvaldsen et al., 2021; Mueter et al., 2021). It is important to acknowledge that on top of climate change there is considerable natural variation, with oscillations in temperature occurring on a multidecadal scale, apparently driven by similar oscillations in global volcanic activity (Mann et al., 2021). The impact on the ecosystem from climate change is expected to be influenced by this interannual variation, accelerating in periods of intense temperature increases and, at least for ecosystem elements that respond quickly to warming, reversing in periods of cooling. Relevant to this is the decline in temperature seen for the last four years covered by this assessment, which seems to have affected several of the biological indicators, causing the response seen to the warming that occurred in the first part of the period covered by most of these indicators (the years after 2004) to be reversed in recent years.

Pollution in the Barents Sea originates mainly from outside the area. Bioaccumulating persistent organic pollutants can affect high trophic level predators in particular, such as glaucous gull, polar bears and white whales (Dietz et al., 2019). Transport of pollutants into the area has decreased since monitoring started around 1990, but the decline has levelled off in recent years (Frantzen et al., 2022).

Observed deviations from the reference condition

Both the Arctic and sub-Arctic ecosystems showed **substantial** changes for the ecosystem characteristic "*Abiotic factors*", which encompasses the climate indicators. Temperature has increased in both ecosystems, and this is linked to anthropogenic climate change. For the same reason, winter sea-ice extent and freshwater content have decreased strongly in the Arctic part. Stratification has decreased in the Arctic and increased in the Sub-Arctic ecosystem. It is important to note that a decision had been made before the assessment to consider the period 1961-1990 representative for a "pristine" climate (i.e., climate largely unimpacted by anthropogenic climate change). The assessment was therefore based on comparisons with this period. However, climate was likely already impacted before the period 1961-1990, and the anthropogenic impact on temperature, sea-ice, and other climate indicators of the ecosystem characteristic *Abiotic factors* may potentially be larger than suggested by this assessment. As a major driver of the ecosystems in both parts of the Norwegian sector of the Barents Sea, climate change is likely to have caused transformations in ecosystem structure and functioning, especially in the Arctic part. Thermal niches defined by water mass areas, both in the water column and along the bottom, and ice habitats, for example, have been **substantially** affected, as assessed for the ecosystem condition *Landscape-ecological patterns* for both ecosystems. There is also **limited** evidence for an increase in annual primary production and an earlier start of the spring bloom in the Arctic ecosystem. For the ecosystem characteristic *Biomass distribution across trophic levels*, there is evidence that past over-harvesting and climate change have contributed to **limited** change in the overall shape of the trophic pyramid through declines of top predators. This is likely influencing trophic controls in the Arctic food web. Because of the negative impact of climate change on arctic fish, bird, and marine mammal species, the ecosystem characteristic *Biological diversity* of the Arctic ecosystem was assessed as showing evidence of **limited** deviation from the reference conditions. Some phenomena would indicate that this loss of Arctic biodiversity has impacted the ecosystem characteristic *Functional groups within trophic levels*, but important functions seem to have been maintained. Here, it is important to recall that functions lost by declines in Arctic species may be replaced by boreal species spreading into Arctic areas, as boreal communities usually harbour greater functional diversity and redundancy than Arctic ones. Other ecosystem characteristics in the Arctic are not showing any evidence for deviation from the reference condition. However, it should be emphasised that temporal coverage of the data is often an issue. In particular, in contrast to the long period covered by data on climate (from 1970 to 2020) the biological ecosystem characteristics are mainly assessed with data from 2004 to 2020, a period dominated by natural variability rather than long-term climate trends.

Similarly, in the sub-Arctic ecosystem, the time series used for most of the biological indicators such as fish, benthos, and zooplankton are short and only cover the recent decades (Appendix 8.5). In line with this, it was assessed that no evidence of anthropogenic impact for any of the biological ecosystem characteristics could be detected based on this limited data (i.e., all except *Abiotic factors* and *Landscape-ecological patterns*). However, uncertainties for this assessment are larger than for the Arctic ecosystem, because there are more anthropogenic drivers in the sub-Arctic system. Thus, while sea-ice loss is a single dominant driver in the Arctic part (with long-term effects of past over-harvesting of marine mammals also playing a role), there are no single drivers with similarly strong influence in the sub-Arctic ecosystem. For the sub-Arctic part, cumulative impact of several drivers must typically be considered, which is more complex and tends to give more uncertain conclusions.

A summary of the assessments of deviation from the reference condition and assessed indicator coverage for the ecosystem characteristics in the two ecosystems are given in tables 7.3.1a for the Arctic part and 7.3.1b for the sub-Arctic part.

Table 7.3.1a *Graphical summary of the assessment of ecological condition for all ecosystem characteristics in Arctic Barents Sea.*

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

Table 7.3.1b*. Graphical summary of the assessment of ecological condition for all ecosystem characteristics in Sub-Arctic Barents Sea.*

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

Uncertainties to the overall assessment and methodological issues

Three main aspects of the protocol are driving large uncertainties in the assessment. The first one concerns the reference condition, defined in the mandate as “intact nature” (see chapter 2). The reference condition is a key concept as it is what the current ecosystem condition is compared with. As an historically important shelf sea impacted by human activities, mainly intense fisheries and harvesting, and as a region strongly impacted by climate change, reference periods with no or limited impact from human activities were difficult to identify. As describe above, observations from time-periods representing the reference condition (reference values) were consequently lacking. Reference conditions were thus described qualitatively for most of the phenomena, often as states that would conceptually allow to maintain past known structure and functioning. When assessing the evidence for the phenomena, it was for some indicators uncertain whether the observed changes were driving the system *away* or *towards* the reference condition, which affects the certainty of the ecosystem condition assessment. For example, suspensivorous megabenthos biomass is expected to decrease because of increasing fishing pressure, and climate change (SP05). We observed an increase of that biomass in the Sub-Arctic ecosystem, yet it is unknown whether this change drives the indicator towards or away from the reference conditions. Future improvements to the assessment method should include guidance on how to deal with this issue.

A second obstacle to a robust assessment of the ecosystem conditions is related to the differences in time-series lengths and the approach used to assess the deviation from reference condition. There is an apparent difference in the assessment between the observed trends in the climate indicators and the biological indicators. The climate indicators cover a longer time-period from the 1970s and show substantial directional change. Several of the biological indicators, of which many are considered climate sensitive, cover only the period from 2004 and show no directional changes. The background for the difference then lies in the observation that there is no significant trend in climate over the recent period 2004-2020, from which the biological data originate (Appendix 8.6). Thus, variation in climate is not expected to generate any directional change in climate sensitive biological indicators monitored only from 2004. This lack of directional change in climate sensitive indicators does not mean they have returned to the reference condition and are not impacted by anthropogenic drivers. Rather, the point to be taken is that due to short time series, we do not have the data to assess how they have changed following the strong warming after the 1970s. Based on the literature described in chapter 5, a likely hypothesis is that there has indeed been considerable biological change as a response to the warming. This strong expectation, combined with the lack of long time series, means that there is large uncertainty about the conclusion from the assessment. It should also be noted that there was a warming from 2004 till 2016 followed by a slight cooling of similar magnitude for the most recent years, and that, interestingly, many of the biological indicators follow the same bell shape climate trend. Thus, this supports the hypothesis that the indicators have indeed changed as a response to warming before 2004, and, more importantly, that additional change may be expected with future warming.

The third and last point concerns the weighting of the different phenomena during the final assessment phase of ecosystem characteristics. This assessment is currently based on discussions between the members of the panel aiming at integrating the information from the various phenomena in each ecosystem characteristic. It implies a weighting of the phenomena based on their importance in the ecosystem structure and functioning. To avoid this weighting to be biased during the assessment phase, future iterations of this work should include a step of phenomena weighting prior to the assessment phase.

7.3.3 Future trajectories for ecosystem condition

As climate change and fisheries are the two main anthropogenic drivers, scenarios for these are considered here. Comments are also given on recovery of marine mammals from previous overharvesting. While quantitative model projections are available for climate development, fisheries and their management is harder to predict (Planque et al., 2019). Climate scenarios are therefore elaborated further than fisheries scenarios here.

On a long time-scale, warming and sea-ice decline are expected to continue in the Barents Sea, unless global CO_2 emissions are cut immediately and severely. If emissions remain high, large changes in climate are expected by the end of the century (Fig. 7.3.4). From what we know about climate change as a driver in both the Arctic and Sub-Arctic part of the Norwegian sector of the Barents Sea shelf (see sections 7.3.2, 5.1 and 5.2), it is reasonable to expect that substantial future changes in climate will cause large ecological changes. In both ecosystems this includes northward expansion of species, resulting in, among other things, changes in the zooplankton community which may set off cascading effects in other parts of the ecosystems. While declines in lipid-rich and large zooplankton are expected with moderate warming (Mueter et al., 2021), predictions of effects from strong warming are more speculative but may involve changes in zooplankton phenology which may cause recruitment failure in fish stocks, as has been observed in the North Sea (Beaugrand and Kirby, 2010; Clausen et al., 2018). Relevant for the latter is that spawning of many key fish species occurs along the Norwegian mainland coast south of the Barents Sea, where possible changes in zooplankton phenology may occur earlier than in the Barents Sea itself. In the Arctic part of the Barents Sea, increased primary production, increasingly connected food webs and declines or loss of sea-ice dependent and Arctic species, such as polar cod are other clear expectations from warming (Ingvaldsen et al., 2021). In the Sub-Arctic, northward shifts of spawning and feeding grounds, and of important fish stocks distribution are also forecasted towards 2050 (RCP4.5, (Kjesbu et al., 2022). These incoming species are generally large and long-lived and will likely transform the trophic links and functional diversities, also in the Norwegian sector (Pécuchet et al., 2020; Frainer et al., 2021).

Some species, and in particular Arctic endemic marine mammals, are also expected to be negatively impacted by climate change, while currently recovering from past over-harvesting. One key question is therefore how the carrying capacity of these species may decline because of climate change and how fast the recovery will be towards these declining carrying capacities. Marine mammals consume a significant part of the production at different trophic levels in the ecosystems in the northeast Atlantic region (Skern-Mauritzen et al., 2022), and another key question is therefore how the growth in the mammal populations will affect other parts of these two ecosystems.

How the changes from climate change will play out in the near future will likely depend on how natural multidecadal climate oscillations (Mann et al., 2021) are manifested in the coming decades.

With climate change, the frequency, duration and intensity of extreme events (heatwaves, low ice extent) will increase (Frölicher et al., 2018; Oliver et al., 2018; Laufkötter et al., 2020; Perkins-Kirkpatrick and Lewis, 2020; Fox-Kemper et al., 2021). Important heatwaves have already been detected in the Barents Sea (Mohamed et al., 2022), with very diverse and unpredictable responses observed in the ecosystem (Husson et al., 2022). This, with the unknown effects of the combined impacts of climate and fisheries, and the legacy effects of past overfishing and over-harvesting, are limiting our capacity to forecast near-future changes in the ecosystem condition. More complex statistical models linking the indicators dynamic to those different spatial and temporal scales of pressure could help develop these forecasts although knowledge gaps and stochastic events will always be part of the uncertainties and risks.

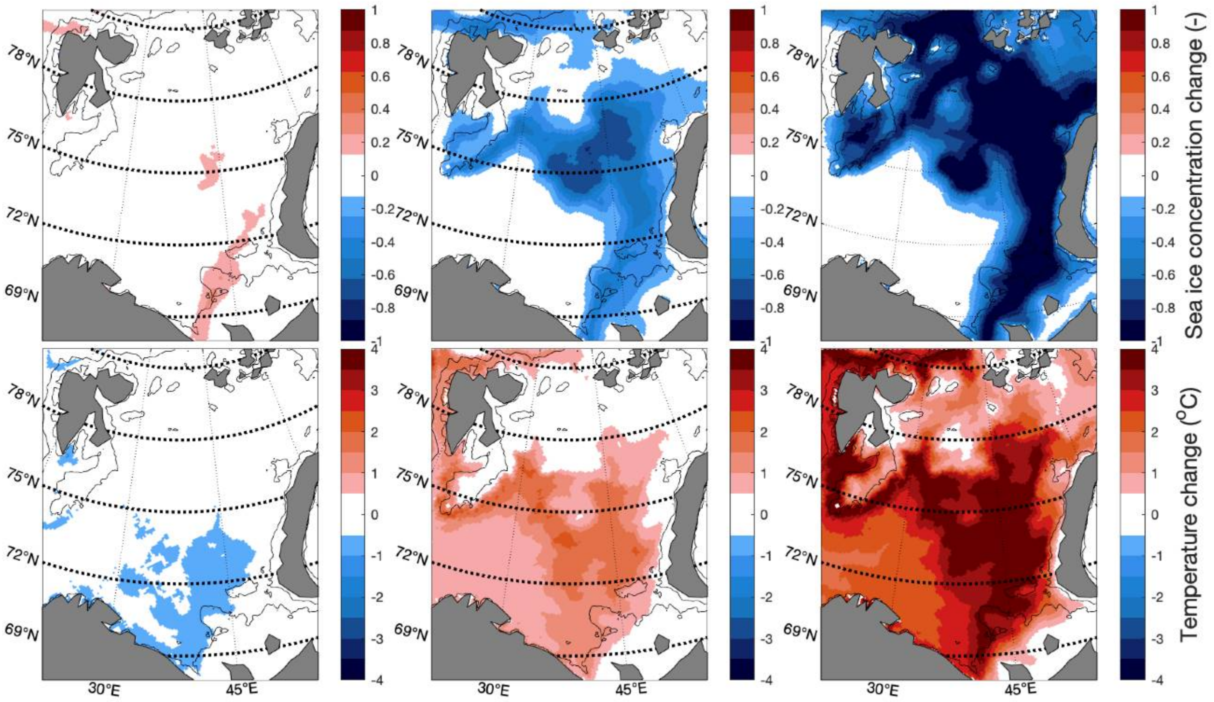


Figure 7.3.4 The upper row showing projected change in sea ice concentration from 2015 to the period 2081-2100 (shown as proprotional change of area with more than 15% ice cover from 2015 to an average for 2081-2100) under three different emission scenarios, SSP1-2.6 (left panel) SSP2-4.5 (middle panel) and SSP5-8.5 (right panel). The bottom row showing projected change in temperature from 2015 to 2100 for the same emission scenarios. Projections are downscaled from the model NorESM2 using the ocean model NEMO NAA10km. Source: Anne Britt Sandø, Institute of Marine Research, personal communication.

Fisheries management in the Barents Sea has developed in a more sustainable direction during the last two decades with no signs of setbacks. Here we therefore consider a scenario where this is continued. This would not only include sustainable harvesting of the target species, but also development of measures to protect the rest of the ecosystem from side effects of fishing, such as by-catch and impact on benthic fauna from bottom trawling (Jørgensen et al., 2020). Under this scenario, and in the near future, the signs of decreasing impact from fisheries, which has been found in this assessment, are likely to develop further.

Recommendations for monitoring and research

This assessment of the shelf ecosystems in the Norwegian sector of the Barents Sea is based on data from the Ecosystem survey of the Barents Sea and precursor surveys, fish stock assessments from the Arctic Fisheries Working Group under ICES, satellite-based monitoring of sea ice and primary production, monitoring of seabird breeding colonies in the SEAPOP program, monitoring of marine mammals through the MOSJ program (and a variety of research programmes) and monitoring of zooplankton in the Fugløya-Bjørnøya section and of ocean acidification parameters at selected sites. The assessment has been made possible through the investment in these long-term monitoring initiatives, and continued investment in them, and expansion of them, is a prime priority for future assessments.

During the assessment, the scientific panel has identified additional indicators which are recommended to be included in the next assessment. An overview of these is given in tables 7.3.2a (Arctic) and 7.3.2b (Sub-Arctic). In these tables there are also short evaluations of the possibility for inclusion of each indicator in the next assessment. In addition, several of the included indicators have shortcomings, and should be improved in the next assessment (Appendix 8.1 and 8.2). Future assessments would also benefit from harmonization of indicators used here and in assessments of the Northeast Atlantic done by OSPAR. Indicators used in OSPAR should be considered for the next assessment, however, the relevance of different indicators for the Barents Sea ecosystems needs to be investigated.

Several indicators were not included in the current assessment because of capacity and resource constraints. Data exist for these, and it should be prioritized to include them in the next assessment. This includes indicators for benthic fish biomass, benthic infauna biomass, seafloor stabilization from benthic invertebrates, fish feeding guilds, shrimp stock size and area affected by bottom trawling (tables 7.3.2a and 7.3.2b). Inclusion of these will require resources, such as funding to organise and analyse available data on benthic infauna. In addition, some of the included indicators need resources for development to decrease the uncertainty in the assessment, such as developing population estimates for mammal species in the Sub-Arctic ecosystem.

Other indicators are not included because data are lacking, and monitoring needs to be developed. An important monitoring gap is lack of taxonomic information for phytoplankton and zooplankton. Such data would allow development of indicators for several ecosystem characteristics (tables 7.3.2a and 7.3.2b) which could be important for detection of climate-driven ecological regime shifts (Beaugrand et al., 2014; Mueter et al., 2021). Some of this monitoring can be developed with more systematic taxonomic identification during the BESS survey, which could provide data for indicators on Arctic and Atlantic *Calanus* species as well as body size groups of low trophic level zooplankton. Another important monitoring gap is the lack of data related to the microbial loop (abundance and species composition of microbes), which can be an important source of carbon for some species depending on the season (De Laender et al., 2010) and which is relevant for several ecosystem characteristics (Tables 7.3.2a and 7.3.2b). That particular need, as well as for taxonomic information for phytoplankton, may require the employment of new technologies, such as automated sampling platforms and eDNA (Truelove et al., 2022). Lack of systematic monitoring and time-series of ice-associated algae and fauna (especially lower trophic levels) also prevent this important compartment of the Arctic ecosystem from being included in the current assessment. Also, the assessment of benthic invertebrates would benefit from more frequent sampling of microbenthic infauna, as the current assessment use by-catch data from bottom trawls, focusing on larger species.

Indicators related to marine mammal functions in the ecosystems are generally hard to estimate and could be the object of specific surveys and studies. At-sea observations of pelagic aggregation could occur during the BESS, while nutrient cycling would necessitate monitoring water chemistry in link with pelagic mammals' abundance, distribution and behaviour. Comparison of at-sea distributions and identified foraging areas for marine mammals should be explored in relation to known prey distributions (BESS data). Similarly, surveying the distribution of whale carcasses could give first indications on the frequency of such events in the region. Other opportunities on these topics could reside in population models, providing sufficient knowledge on individual's behaviour and mortality. Insights into top-down control by marine mammals should be a prioritised area for ecosystem models.

Specific to the PAEC approach and the ecosystem characteristics used, there is a need to consider the utility of biodiversity indices in the *Biological diversity* characteristic in addition to the current indicators focusing on population trends in species sensitive to specific pressures. The assessment of the characteristic *Biomass distribution among trophic levels* was based on several biomass trends, and possibilities to integrate this type of indicators in future assessments should also be explored.

Finally, a better understanding of the combined effects of multiple drivers on the ecosystem is necessary to improve the understanding of observed deviations from reference conditions under anthropogenic pressures and improve the certainty of the assessment. Mesocosm experiments and numerical and statistical modelling studies could help integrating the large existing knowledge and test hypotheses on potential combined effects, non-linear responses, synergies and legacy effects. In addition, such models on the relationship between (multiple) drivers and indicators will strengthen the assessment of evidence for the various phenomena. Statistical models with this aim already exist but are mainly applicable on longer time series. For short time series, more development is needed. One option could be to develop univariate and multivariate indicator-pressure statistical models on which the phenomena could be based. These models could then also be used for short-term predictions.

Table 7.3.2a. *Indicators for the Arctic Norwegian sector of the Barents Sea, which are not included in this assessment. The priority is indicated and represents how easily the indicator can be included in future assessments: 1: data available, can be included in the next assessment; 2: monitoring can be included in current programs or modelling tools are available; 3: monitoring or models must be developed. For recommendations on further development of indicators included in the assessment, see Appendices 8.1 and 8.2.*

Ecosystem characteristic	Indicator	Possibility for inclusion in next assessment
Primary productivity	Species composition phytoplankton	3
Primary productivity	Ice algae	3
Primary productivity	*In situ* primary productivity	2
Biomass distribution among trophic levels	Low TL benthic fish	1
Biomass distribution among trophic levels	High TL benthic fish	1
Biomass distribution among trophic levels	Benthic infauna	1
Biomass distribution among trophic levels	Ice flora and fauna	3
Biomass distribution among trophic levels	Microbial loop species	3
Functional groups within trophic levels	Benthos seafloor stabilization	1
Functional groups within trophic levels	Mammal nutrient cycling	3
Functional groups within trophic levels	Mammal carcasses	3
Functional groups within trophic levels	Mammal top-down control	3
Functional groups within trophic levels	Low TL zooplankton body size	2
Functional groups within trophic levels	Fish feeding guilds	1
Functional groups within trophic levels	Phytoplankton functional groups	3
Functional groups within trophic levels	Ice flora and fauna functional groups	3
Functional groups within trophic levels	Microbial loop functions	3
Functionally important species and structures	Ice flora and fauna	3
Functionally important species and structures	Shrimp	1
Functionally important species and structures	Arctic *Calanus*	2
Functionally important species and structures	Atlantic *Calanus*	2
Functionally important species and structures	Snow crab	1
Functionally important species and structures	Microbial species	3
Landscape-ecological patterns	Area affected by bottom trawling	1
Landscape-ecological patterns	Spawning and nursery areas	1
Biological diversity	Arctic *Calanus*	2
Biological diversity	Sharks and rays	1
Biological diversity	Phytoplankton diversity	3
Biological diversity	Ice flora and fauna diversity	3
Biological diversity	Microbial diversity	3
Abiotic factors	Nutrients	1

Table 7.3.2b. *Indicators for the Sub-Arctic Norwegian sector of the Barents Sea, which are not included in this assessment. The priority is indicated and represents how easily the indicator can be included in future assessments: 1: data available, can be included in the next assessment; 2: monitoring can be included in current programs or modelling tools are available; 3: monitoring or models must be developed. For recommendations on further development of indicators included in the assessment, see Appendices 8.1 and 8.2.*

Ecosystem characteristic	**Indicator**	**Possibility for inclusion in next assessment**
Primary productivity	Species composition phytoplankton	3
Primary productivity	*In situ* primary productivity	2
Biomass distribution among trophic levels	Microbial loop species	3
Biomass distribution among trophic levels	Benthic infauna	1
Biomass distribution among trophic levels	Low TL benthic fish	1
Biomass distribution among trophic levels	High TL benthic fish	1
Functional groups within trophic levels	Phytoplankton functional groups	3
Functional groups within trophic levels	Microbial loop functions	3
Functional groups within trophic levels	Low TL zooplankton body size	2
Functional groups within trophic levels	Benthos seafloor stabilization	1
Functional groups within trophic levels	Fish feeding guilds	1
Functional groups within trophic levels	Mammal nutrient cycling	3
Functional groups within trophic levels	Pelagic prey aggregation by mammals	2
Functionally important species and structures	Microbial species	3
Functionally important species and structures	Shrimp	1
Functionally important species and structures	Snow crab	1
Landscape-ecological patterns	Area affected by bottom trawling	1
Landscape-ecological patterns	Spawning and nursery areas	1
Biological diversity	Phytoplankton diversity	3
Biological diversity	Microbial diversity	3
Biological diversity	Sharks and rays	1
Abiotic factors	Nutrients	1

8. Appendices

8.1 Scientific basis for indicators - Arctic Barents Sea

8.2 Scientific basis for indicators - Sub-Arctic Barents Sea

8.3 Footnotes to data coverage assessment (Table 7.1)

8.4 Phenomena for indicators not included in the current assessment

8.5 Data for indicators not included in the current assessment

8.6 Assessment for "Abiotic factors" for the period 2004-2019/2020

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HAVFORSKNINGSINSTITUTTET

Postboks 1870 Nordnes
5817 Bergen
Tlf: 55 23 85 00
E-post: post@hi.no
www.hi.no