PANEL-BASED ASSESSMENT OF ECOSYSTEM CONDITION OF THE NORWEGIAN SEA PELAGIC ECOSYSTEM

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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 last 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 pelagic ecosystem in the Norwegian Sea. The first report focused on the Arctic and sub-Arctic parts of the Barents Sea (Siwertsson et al., 2023) and the second on the shelf ecosystem in the Norwegian sector of the North Sea (Arneberg et al., 2023).

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 forms the basis for a structured, consolidated, evidence-based assessment of the ecological condition of an ecosystem (Jepsen et al., 2019; Jepsen et al., 2020; Jepsen et al., submitted). 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 Norwegian Sea has been led by the Institute of Marine Research (IMR) and been conducted by a panel consisting of 15 scientists from IMR and one other institution: Norwegian Institute for Nature Research (NINA). The work has been led by Per Arneberg in close cooperation with Bérengère Husson and Anna Siwertsson (all IMR). The work has been conducted in the period from 1 June 2022 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 is written up according to the PAEC protocol.

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

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 activities. An ecosystem in good ecological condition does not deviate substantially from this reference condition in structure, functions or productivity. This report describes the first operational assessment of the ecological condition of the pelagic ecosystem in the Norwegian 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 Norwegian Sea pelagic ecosystem deviates from the reference condition[2] by evaluating change in trajectories.

Key conclusions from the assessment of the Norwegian Sea pelagic ecosystem

The scientific panel concludes that there is evidence of limited impact of human pressures on the Norwegian Sea pelagic ecosystem. There are large uncertainties about whether this means that the impact is indeed limited or that more substantial impact is not detected because important indicators are lacking and many time series are too short. The most clear evidence for climate change is the observed temperature increase, which is seen with a 70 year long time series. There are also signs of increased ocean acidification. While climate change has the potential to affect primary production and zooplankton communities, time series available for these groups are too short to assess this. Fishing above recommended quotas over several years have contributed to declines in the herring and mackerel stocks, and there are also strong signals of decline in seabird populations. With projected further climate change and possibly overfishing, it is anticipated that stronger evidence of anthropogenic impacts will emerge.

Assessment method

The assessment was done by a scientific panel of 15 experts of the Norwegian Sea. In a first phase of scoping, the experts selected sets of indicators relevant to describe temporal changes in seven ecosystem characteristics for each of the ecosystem: *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 based on developing time series of the indicators and assessing whether there is a trend that indicates a deviation away from the reference condition. First, the experts assigned a *phenomenon* for each indicator, which contains a description of the indicator under the reference condition (i.e., when largely unimpacted by human activities) and of how the indicator is expected to change with increasing human pressure. Different time periods were considered descriptive for the reference condition for different parts of the ecosystem, and as data for these periods are unavailable for most indicators (except for e.g., 1961-1990 for climate[3]), the reference condition is generally described qualitatively. The phenomena are assessed as having a high, intermediate or low *validity* depending on the scientific basis supporting i) the link between changes in the indicator and the drivers and ii) consequences of the changes in the indicator’s value for the ecosystem. In the second phase of analysis, the data collected allow to build time series of the indicators in predefined geographical regions, and based on those, the *evidence* for the phenomena (i.e., whether the expected development away from the reference condition caused by increasing human pressure has occurred) are assessed. Next, the overall condition of each ecosystem characteristic is assessed as belonging to one of three categories with increasing deviation from the reference condition — from no to substantial deviation. Finally, it was assessed at the scale of the Norwegian Sea pelagic ecosystem. This report will be peer-reviewed to ensure the validity and robustness of its conclusions.

Datasets and indicators

The assessment of the condition of the Norwegian Sea pelagic ecosystem is based on 15 datasets (ch.3) supporting 22 indicators. Data to produce the ecosystem time series were collected from stock assessments and population models, satellites, and survey data.

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. Stratification and indicators of blue whiting stock size and recruitment were assessed as having only “intermediate” or “poor” data coverage because of missing information on seasonality and poor spatial coverage.

The indicator coverage was assessed as adequate for *Abiotic factors*, for which the selected indicators cover the important features of abiotic conditions in the ecosystem. The indicator coverage was only partially adequate for

Primary production, *Biomass distribution among trophic levels*, and *Functionally important species and biophysical structures,* as some important indicators are lacking. The lack of information on *Biological diversity* and *Functional groups within trophic levels* is such that the panel believes it might affect the assessment, and their indicator coverage was assessed as inadequate. There were no indicators selected for the ecosystem characteristic *Landscape ecological patterns.*

The condition of ecosystem characteristics

Some ecosystem characteristics show signs of human impact. However, many short time series and lack of information hinder an exhaustive assessment of the main human impacts. For two ecosystem characteristics (*Functionally important species and biophysical structures* and *Abiotic factors*) there is evidence of limited deviation anthropogenic impact, due to strong changes in temperature in the water column, signs of increased ocean acidification and declines in fish stock biomass partly caused by overfishing. There is some uncertainty associated with the assessment of the former ecosystem characteristic but considerable uncertainty about the assessment of the characteristic *Abiotic factors* due to short time series for many indicators. Some ecosystem characteristics could not be assessed because the data was considered insufficient (*Functional groups within trophic levels* and *Biological diversity*) and two were assessed as showing no evidence of anthropogenic impact (*Primary productivity* and *Biomass distribution among trophic levels*) but with large uncertainties because of short time series.

Ecosystem characteristic	Assessment of the Norwegian sea ecosystem
Primary productivity	The ecosystem characteristic was assessed as showing **no evidence of deviation** from the reference conditions. It is based on 2 indicators, of which one has well-known link to the drivers and well understood consequences on the ecosystem. There are no signs of change in annual primary production or date of start of spring bloom. The main driver of these indicators is climate change. The main uncertainty resides in the length of the time series for both indicators, which do not cover a period of change in the main driver, climate change.
Biomass distribution among trophic levels	The ecosystem characteristic was assessed as showing **no evidence of deviation** from the reference conditions. It is based on 3 indicators, two of which have well-known link to the drivers and well understood consequences on the ecosystem. There are no signs of change in annual primary production or date of start of spring bloom. The main driver of these indicators are fisheries and climate change. The main uncertainty resides in the length of the time series for both indicators, which do not cover a period of change in the main driver, climate change.
Functional groups within trophic levels	Data were **insufficient** to assess this ecosystem characteristic
Functionally important species and biophysical structures	The ecosystem characteristic was assessed as showing **evidence of limited deviation** from the reference conditions. It is based on 7 indicators, for most of which the links to the drivers and the impact on the ecosystem are not well understood. Strong declines in herring and mackerel stocks can be linked to the strong fishing pressure, above recommended quotas, that is applied since 2013. However, there is some uncertainty as some other indicators show no evidence of impact.
Landscape-ecological patterns	There were **no indicators identified** for this ecosystem characteristic
Biological diversity	Data were **insufficient** to assess this ecosystem characteristic
Abiotic factors	The ecosystem characteristic was assessed as showing **evidence of limited deviation** from the reference conditions. It is based on 8 indicators, which links to the drivers and to the ecosystem are mostly well understood. There is clear evidence of change in heat content and ocean acidification, in link with climate change. Short time series of the other indicators limit our understanding of the extent to which abiotic condition are affected by climate change. This introduces considerable uncertainty to the assessment of this ecosystem characteristic.

Future trajectories for ecosystem condition

Climate change is expected to further impact the Norwegian Sea pelagic ecosystem unless greenhouse gas emissions are cut immediately and severely. With climate change, the frequency, duration and severity of extreme climatic events such as storms and heatwaves are expected to increase. These are likely to increase the uncertainties around the ecosystems' future conditions. If problems related to overfishing are not resolved, this might cause large changes for the ecosystem.

Research and monitoring recommendations

This assessment relies on international, long term monitoring efforts that need continued funding to support future assessments. Long time series from observational data or models need to be available to conduct robust assessments. In particular, continued monitoring of zooplankton, with better identification of species involved, and in situ measurements of primary production are important improvements for future assessments. Mesopelagic species and their link to the ecosystem are still poorly know and require more regular monitoring and dedicated studies. Overall, further research is needed on ecosystem mechanisms and cascading impacts of anthropogenic pressures.

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.

3 In the first phase of the work with establishing a framework for assessing condition of Norwegian ecosystems, a joint decision was made for assessments that the climatic normal period 1961-1990 should be considered descriptive for climate under the reference condition (Nybø and Evju 2017, Fagsystem for fastsetting av god økologisk tilstand. Forslag fra et ekspertråd (in Norwegian)). Thus, this was done before the establishment of the Norwegian Sea scientific panel, which noted during the current assessment that climate in the 1961-1990 period cannot be considered unimpacted by anthropogenic emissions of greenhouse gases.

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 den norske delen av det pelagiske økosystemet i Norskehavet. 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.

Hovedkonklusjon fra vurderingen av det pelagiske økosystemet i Norskehavet

Forskerpanelet har konkludert med at det er evidens for begrenset menneskeskapt påvirkning på det pelagiske økosystemet i Norskehavet. Det er stor usikkerhet knyttet til om dette betyr at påvirkningen virkelig er begrenset eller at mer omfattende påvirkning ikke er påvist fordi viktige indikatorer mangler i vurderingen og mange tidsserier er for korte. Den tydeligste evidensen for klimaendringer er en observert stigning i temperatur, som er sett med en 70 år lang tidsserie. Det er også tegn på økt havforsuring. Klimaendringer har potensial til å påvirke primærproduksjon og dyreplanktonsamfunn, men tidsseriene for disse gruppene er for korte til å vurdere dette. Fiske over anbefalte kvoter over mange år bidrar til nedgang i bestandene av makrell og norsk vårgytende sild, og det er også tydelig observerte nedganger i bestander av sjøfugl. Med fortsatte klimaendringer og muligens overfiske, er det forventet at ytterligere evidens for menneskeskapt påvirkning vil bli observert.

Vurderingsmetode

Vurderingen ble gjort av et fagpanel på 15 eksperter på Norskehavet. I en første fase valgte ekspertene ut et sett av indikatorer som er relevant for å beskrive endringer i tid for syv økosystemegenskaper: 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. Metoden er basert på å utvikle tidsserier for indikatorene og vurdere om det er en trend i dataene som indikerer en utvikling bort fra referansetilstanden. Først utarbeider ekspertene et fenomen for hver indikator. Det inneholder en beskrivelse av indikatoren under referansetilstanden (dvs. når den i stor grad er upåvirket av menneskeskapte aktiviteter) og av hvordan indikatoren er forventet å endres under økende menneskeskapt påvirkning. Ulike tidsperioder ble ansett som beskrivende for referansetilstanden for ulike deler av økosystemet, og fordi det ikke finnes data for disse periodene for de fleste indikatorene (unntatt for for eksempel 1961-1990 for klima) er referanseperioden i stor grad beskrevet kvalitativt. Fenomenene er vurdert til å ha høy, middels eller lav gyldighet avhengig av i hvilken grad det vitenskapelige grunnlaget gir kunnskap om i) forbindelsen mellom endringer i indikatoren og påvirkningsfaktorene, og ii) konsekvenser av endringer i indikatorverdiene for økosystemet. I den neste fasen, som dreier seg om analyser, blir data samlet inn fra det relevante området slik at tidsserier kan bygges. Basert på disse, blir evidensen for fenomenene vurdert (dvs om det har vært en utvikling bort fra referansetilstanden som kan tilskrives menneskeskapt påvirkning). Til slutt blir tilstanden for hver økosystemegenskap vurdert til en av tre kategorier, fra ingen til betydelig avvik fra referansetilstanden. Basert på dette blir det gjort en vurdering for økosystemet som helhet. Rapporten vil bli underlagt fagfellevurdering for å sikre at konklusjonene er gyldige og robuste.

Datasett og indikatorer

Vurderingen av det pelagiske økosystemet i Nordsjøen er basert på 15 datasett (kap. 3) som støtter 22 indikatorer. Dataene som er brukt til å opparbeide tidsseriene ble samlet inn fra bestandsvurderinger og populasjonsmodeller, satellitter og toktdata.

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» for de fleste indikatorene. For indikatorene for stratifisering og bestandsstørrelse av kolmule ble datadekning vurdert som «intermediær» eller «dårlig» på grunn av henholdsvis manglende informasjon om sesongvariasjon og dårlig romlig dekning.

Indikatordekning ble vurdert som adekvat for Abiotiske forhold, hvor de valgte indikatorene dekker de viktige trekkene ved abiotiske forhold i økosystemet. For økosystemegenskapene primærproduksjon, Fordeling av biomasse mellom trofiske nivå og Funksjonelt viktige arter og biofysiske strukturer er indikatordekningen vurdert som delvis adekvat, i og med at noen viktige indikatorer mangler. Mangel på informasjon for Biologisk mangfold og Funksjonelle grupper innen trofiske nivå er slik at fagpanelet tenker det kan påvirke vurderingen, og indikatordekning for disse er vurdert som inadekvat. Ingen indikatorer var valgt ut for økosystemegenskapen Landskapsøkologiske mønstre.

Tilstanden til økosystemegenskapene

Noen økosystemegenskaper viser tegn på menneskeskapt påvirkning (Tabell S.2). De mange korte tidsseriene og mangel på informasjon hindrer imidlertid en utfyllende vurdering av menneskeskapt påvirkning. For to økosystemegenskaper (Funksjonelt viktige arter og biofysiske strukturer og Abiotiske forhold) er det evidens for begrenset menneskeskapt påvirkning på grunn av betydelig økning i temperatur i vannsøylen, tegn på økt havforsuring og nedgang i biomasse av fiskebestander delvis forårsaket av fiske over anbefalte kvoter gjennom mange år. Det er noe usikkerhet knyttet til vurderingen av den førstnevnte økosystemegenskapen, men betydelig usikkerhet knyttet til vurderingen av egenskapen Abiotiske forhold på grunn av korte tidsserier for mange indikatorer. Noen økosystemegenskaper kunne ikke vurderes fordi dataene ble vurdert som ikke tilstrekkelige (Funksjonelle grupper innen trofiske nivå og Biologisk mangfold) og for to ble det vurdert at det ikke er vist evidens for menneskeskapt påvirkning (Primærproduksjon og Fordeling av biomasse mellom trofiske nivå). Det var betydelig usikkerhet knyttet til vurderingen av de to sistnevnte egenskapene.

Tabell S.2 Sammendrag av vurderingen for de syv økosystemegenskapene for det pelagiske økosystemet i Norskehavet.

Økosystemegenskap	Vurdering av det pelagiske økosystemet i Norskehavet
Primærproduksjon	Økosystemegenskapen ble vurdert til å vise **ingen evidens for avvik** fra referansetilstanden. Dette er basert på 2 indikatorer, hvor kunnskapen om forbindelse til påvirkningsfaktor og konsekvenser for økosystemet er vurdert som god for en av dem. Det er ingen tegn til endringer i årlig primærproduksjon eller tidspunkt for start av våroppblomstringen. Den viktigste påvirkningsfaktoren er klimaendringer. Den viktigste usikkerheten er knyttet til lengden på tidsseriene for begge indikatorene, som ikke dekker en periode med endring i den viktigste påvirkningsfaktoren, klimaendringer.
Fordeling av biomasse mellom trofiske nivå	Økosystemegenskapen ble vurdert til å vise **ingen evidens for avvik** fra referansetilstanden. Vurderingen er basert på 3 indikatorer, hvor kunnskapen om forbindelse til påvirkningsfaktor og konsekvenser for økosystemet er vurdert som god for to av dem. Det er ingen tegn til endringer for relativ biomasse av pelagisk fisk og dyreplankton, men betydelig evidens for nedgang i bestander av sjøfugl fra høye trofiske nivå. Det er betydelig usikkerhet knyttet til vurderingen på grunn av manglende informasjon for viktige grupper som mesopelagisk fisk og sjøpattedyr. Basert på informasjonen som ble brukt i vurderingen var fagpanelet usikker på om vurderingskategorien burde være «ingen evidens for avvik» eller «evidens for begrenset avvik». Den betydelige nedgangen for sjøfugl var et argument forevidens for begrenset avvik.
Funksjonelle grupper innen trofiske nivå	Det var **ikke tilstrekkelig data** til å vurdere denne økosystemegenskapen.
Funksjonelt viktige arter og biofysiske strukturer	Økosystemegenskapen ble vurdert til å vise **evidens for begrenset avvik** fra referansetilstanden. Vurderingen er basert på 7 indikatorer, hvor forbindelse til påvirkningsfaktorer og konsekvenser for økosystemet ikke er godt forstått for de fleste. Betydelig nedgang i bestandene av sild og makrell kan knyttes til et høyt fisketrykk, over anbefalt kvoter og som har blitt anvendt siden 2013. Det er imidlertid noe usikkerhet knyttet til vurderingen siden andre indikatorer ikke viser noen endring.
Landskapsøkologiske mønstre	**Ingen indikatorer ble identifisert** for denne økosystemegenskapen.
Biologisk mangfold	Det var **ikke tilstrekkelig data** til å vurdere denne økosystemegenskapen.
Abiotiske forhold	Økosystemegenskapen ble **vurdert til å vise evidens** for begrenset avvik fra referansetilstanden. Vurderingen er basert på 8 indikatorer, hvor kunnskapen om forbindelse til påvirkningsfaktorer og konsekvenser for økosystemet er i stor grad vurdert som god. Det er tydelig evidens for endring i varmeinnhold og havforsuring, knyttet til klimaendringer. Korte tidsserier for de andre indikatorene begrenser vår forståelse av hvilken grad de abiotiske forholdene er påvirket av klimaendringer. Dette bidrar til betydelig usikkerhet i vurderingen av denne økosystemegenskapen.

Endringer i fremtiden for økosystemet

Klimaendringer er forventet å påvirke det pelagiske økosystemet i Norskehavet ytterligere med mindre det gjøres omfattende og umiddelbare kutt i utslipp av drivhusgasser. På grunn av klimaendringer forventes frekvens og varighet av ekstreme hendelser som stormer og varmebølger å øke. Dette vil sannsynligvis føre til økt usikkerhet om hva forholdene i økosystemet vil være i fremtiden. Hvis problemene knyttet til fiske over anbefalte kvoter ikke blir løst, kan dette føre til store endringer i økosystemet.

Anbefalinger for forskning og overvåkning

Denne vurderingen baserer seg på internasjonal og langvarig overvåking som trenger kontinuerlig finansiering for å kunne støtte fremtidige vurderinger. Det er behov for lange tidsserier fra observasjoner eller modeller for å kunne gjøre robuste vurderinger. Det er særlig behov for fortsatt overvåking av dyreplankton med bedre artsidentifisering og in situ målinger av primærproduksjon for å kunne forbedre fremtidige vurderinger. Mesopelagiske arter og deres forbindelse til økosystemet er fortsatt dårlig forstått og krever mer regulær overvåking og dedikerte studier. Generelt er det behov for videre forskning på økosystemprosesser og kaskadevirkinger fra menneskeskapt påvirkning.

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.

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Content

Introduction

Based on a mandate from the Norwegian Ministry of Climate and Environment, the System for Assessment of Ecological condition was developed with the aim — for each of the major terrestrial and marine ecosystems not covered by the EU Water Framework Directive in Norway — 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). 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; Jepsen et al., submitted). 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, 2021), 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 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, statistical modelling and ecosystem modelling). However, PAEC is also envisioned to be a tool for adaptive management of ecosystems, or specific ecosystem components. Thus, the protocol allows for the integration of a stakeholder group (consisting for instance of representatives from management agencies responsible for the specific ecosystem) into the assessment process (Fig. 1). This is not mandatory but may serve to broaden PAEC, from a purely scientific assessment to an operational and policy-relevant tool for developing management goals and adaptive management strategies for the implementation and assessments of specific management actions. Depending on the type of process in which the protocol is used, the level of stakeholder involvement in the assessment phase may vary across the different phases. For the assessments of marine ecosystems, the Advisory Group on Monitoring at IMR (“Overvåkingsgruppen” in Norwegian, The Royal Norwegian Ministry of the Environment (2006)), which is established to support the ocean management plans, has been informed about the work regularly (4 times yearly), throughout all phases of the work, with possibilities to provide feedback.

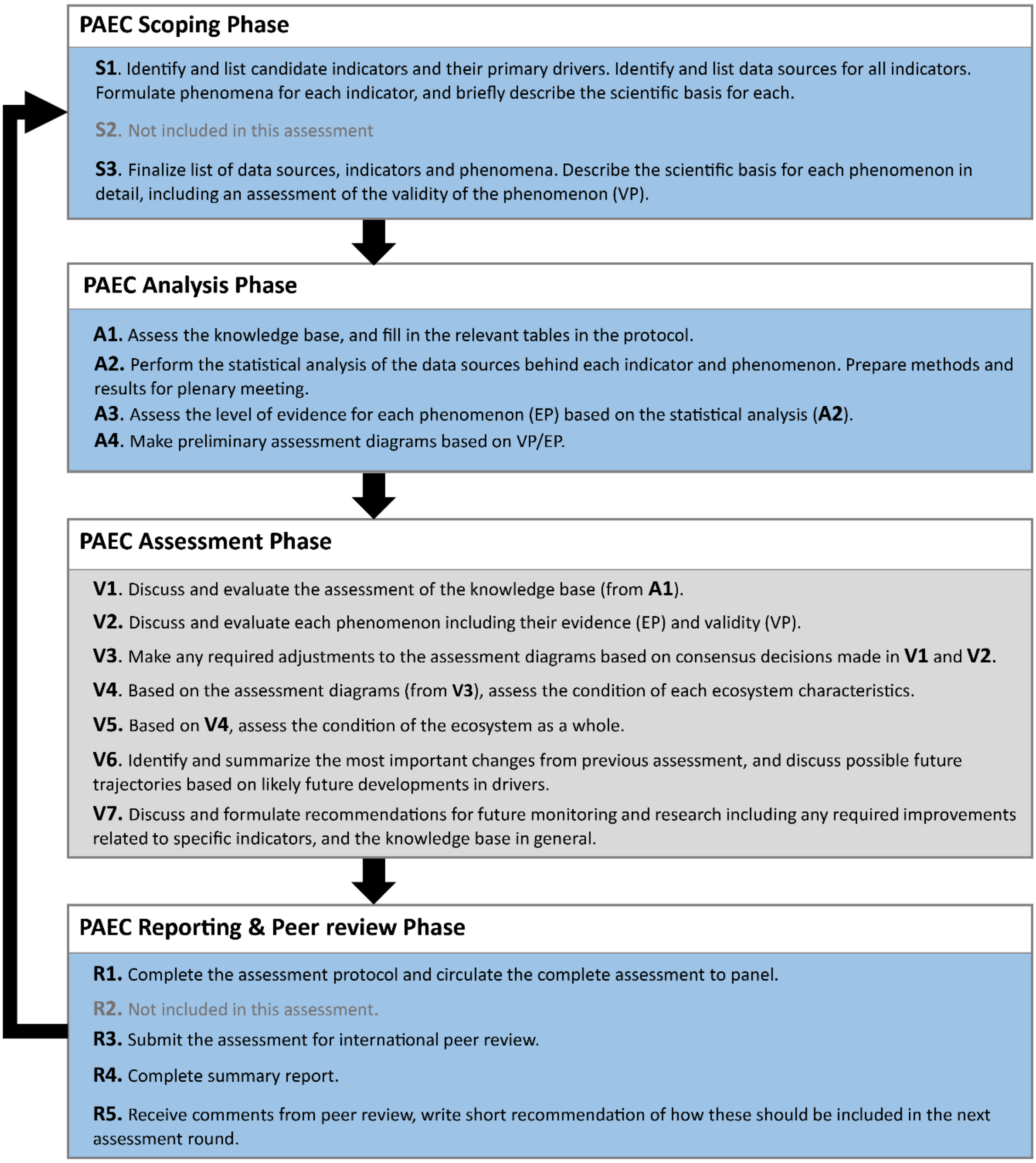


Figure 1: Summary of the four phases of ecosystem condition assessment according to PAEC, and the main tasks involved in each phase. PAEC allows non-mandatory involvement of a stakeholder group in the assessment panel in addition to the scientific panel. In such cases, the stakeholder group would provide 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. Revised from (Jepsen et al., 2020).

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

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

Table 1.1. The composition of the scientific panel with definitions of roles and expertise. The list is sorted alphabetically on last name, except for panel leader listed first.

Name, institution, email	Role	Expertise	Expert on single indicators
Per Arneberg, IMR [1], per.arneberg@hi.no	Project manager, leader of the scientific panel, expert	Ecosystem overview/ understanding	
Knut Yngve Børsheim, IMR[1], yngve.borsheim@hi.no	Expert, participant in scientific panel	Primary production	*Annual primary production, Timing of spring bloom*
Per Fauchald, NINA [2], per.fauchald@nina.no	Expert, participant in scientific panel	Seabirds, Ecosystem overview/understanding	*High trophic level seabirds*
Solfrid Sætre Hjøllo, IMR[1], solfrid.hjollo@hi.no	Expert, participant in scientific panel	Ecosystem modelling, oceanography, zooplankton	*Calanus finmarchicus productivity*
Bérengère Husson, IMR [1], Berengere.Husson@hi.no	Expert, participant in scientific panel, data management	Ecosystem data and models	
Åge Høines, IMR[1], aage.hoines@hi.no	Expert, participant in scientific panel	Pelagic fish	*Blue whiting stock size and blue whiting recruitment*
Elizabeth Jones, IMR [1], elizabeth.jones@hi.no	Expert, participant in scientific panel	Ocean acidification	*pH, Aragonite saturation*
Webjørn Melle, IMR[1], webjoern.melle@hi.no	Expert, participant in scientific panel	Zooplankton	*Mesozooplankton biomass relative to pelagic fish biomass, Copepod body size, Copepod species vulnerable to higher temperature, Copepod species benefitting from higher temperature*
Leif Nøttestad, IMR[1], leif.noettestad@hi.no	Expert, participant in scientific panel	Pelagic fish	*Mackerel stock size and mackerel recruitment*
Benjamin Planque, IMR [1], benjamin.planque@hi.no	Expert, participant in scientific panel	Ecosystem overview/ understanding	*Mesozooplankton biomass relative to pelagic fish biomass*
Anna Siwertsson, IMR [1], anna.siwertsson@hi.no	Expert, participant in scientific panel	Ecosystem overview/ understanding	
Øystein Skagseth, IMR[1], oystein.skagseth@hi.no	Expert, participant in scientific panel	Oceanography	*Heat content, Freshwater content, Inflow of Arctic water, Stratification, Inflow of Atlantic water, Nutrients*
Aril Slotte, IMR[1], aril.slotte@hi.no	Expert, participant in scientific panel	Pelagic fish	*Mackerel stock size and mackerel recruitment*
Hiroko Solvang, IMR [1], hiroko.solvang@hi.no	Statistical analyses	Statistical analyses	
Erling Kåre Stenevik, IMR[1], erling.stenevik@hi.no	Expert, participant in scientific panel	Pelagic fish	*Herring stock size and herring recruitment*

[1] IMR - Institute for Marine Research, [2] NINA - Norwegian Institute of Nature Research,

2 - Definition of the reference condition

All assessments of ecological condition done to follow up Norway's national biodiversity action plan (Minstry of Climate and Environment, 2015) apply the methodological framework described in the System for Assessment of Ecological Condition (Nybø and Evju, 2017). Note that this includes both marine and terrestrial ecosystems. The reference condition in this framework is defined as “intact ecosystems”, 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 Nybø and Evju (2017) of what constitutes “intact ecosystems” is 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)).*the list of drivers for abiotic factors should also include anthropogenic climate change*

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 conditions (physical and chemical) do 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 Norwegian Sea pelagic ecosystem are as follows:

- Human influence, under the definition of the reference condition, can be present but not pervasive or dominating. The current assessment focuses on the extent to which an ecosystem deviates from a condition that is under little or no influence from anthropogenic pressures. When operationalising this, an obvious question is how human pressures have historically changed the Norwegian Sea pelagic ecosystem, and related to this, how the recent time periods for which we have data from systematic monitoring can be considered descriptive for the reference condition.
- Industrial scale fisheries in the Norwegian Sea developed after the Second World War as a consequence of development of more efficient gear. This resulted in over-fishing of the stock of Norwegian spring spawning herring, leading to collapse of the stock in the early 1970s (Toresen and Østvedt, 2000). Thus, the conditions from the second half of the 20 th century and onwards may not be considered descriptive for the reference condition for fish.
- Whaling and seal hunting have a long history in the Norwegian Sea (Rørvik and Jonsgård, 1981). Thus, any recent period may not be considered descriptive for the reference condition for the marine mammal community. It should be noted that data on marine mammals were not used in the current assessment for capacity reasons.
- Pollution probably has a long history in the Norwegian Sea. Mass production of persistent organic pollutants such as PCB started in the 1930s (Markowitz, 2018) and pollution through local and long range transport of these substances became widespread in the subsequent decades.
- For climate, the period that should be considered descriptive for the reference condition has been pre-set to 1961-1990 for all assessments of ecological condition in Norway (Nybø and Evju (2017), Box 1). It should be noted that this period is already part of the strong increase in global temperatures after 1950 (IPCC, 2021) and therefore is not pre-industrial, i.e., it is already and increasingly impacted anthropogenically. IPCC AR6 (IPCC, 2021) 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.
- Systematic monitoring of the Norwegian Sea shelf ecosystem used for this assessment generally started after the periods that can be considered descriptive for the reference condition, with monitoring of the herring stock as an exception (Toresen and Østvedt, 2000). This has two important implications for how the assessment is done (Jepsen et al., submitted). First, it is not possible to describe the reference condition quantitatively, and this has here therefore been done qualitatively to the extent possible from literature sources. Second, the assessment is based on *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 with 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). Descriptions of the reference condition for each indicator are found in the phenomena descriptions (chapter 5).
- 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 (Fig. 7.1, Tab 7.1) 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.

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

3.1 Delineation of the ecosystem

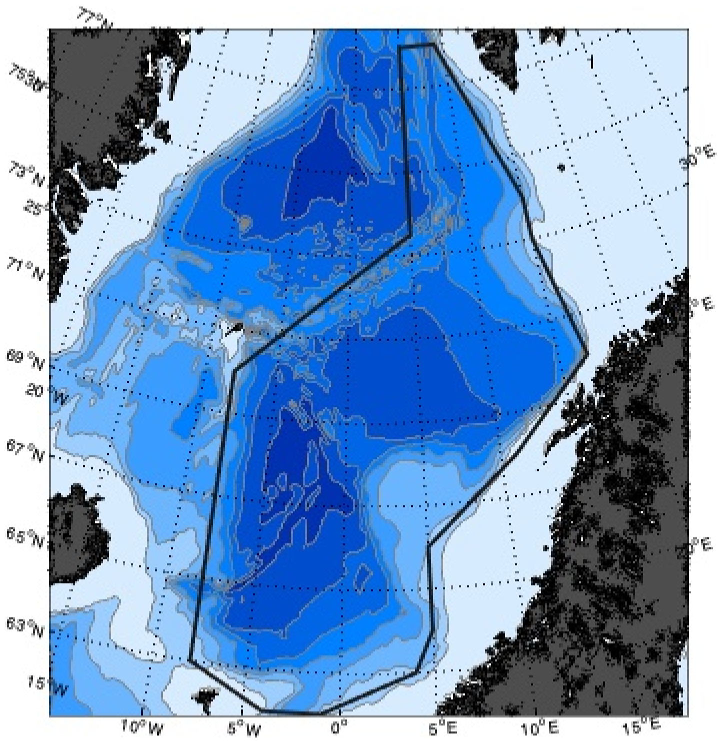


Figure 3.1: Map of the horizontal extent of the panel-based assessment of ecosystem condition of the Norwegian Sea pelagic ecosystem.

Vertically, the assessment of the pelagic ecosystem in the Norwegian Sea is limited to the upper 800 meters of the deeper parts of the Norwegian Sea. Horizontally, the area is limited to the east by the 1000 meters isobath, and as the assessment focuses mainly on areas dominated by Atlantic water masses, the delineation to the north-west follows Mohn’s ridge and in the west and south the Norwegian basin (Fig. 3.1)

3.2 General considerations regarding data sources

The main data sources for the current assessment are the international ecosystem survey in the Nordic seas (ICES (2021a), hereafter IESNS) and the international ecosystem summer survey in the Nordic seas (Nøttestad et al. (2021), hereafter IESSNS). These provide data on mesozooplankton biomass and contributes with data for the assessments of the large pelagic commercial fish stocks and estimation of oceanographic parameters (ICES, 2019a). Data from Argo buoys have also contributed to estimation of oceanographic parameters. Satellite monitoring of ocean colour from which chlorophyll a concentration is inferred has contributed with data for estimation of net primary production (Behrenfeld and Falkowski, 1997). Monitoring of seabird colonies along the Norwegian mainland coast through the SEAPOP programme has contributed with data on seabird abundance (SEAPOP, 2022) and dedicated monitoring for estimation of pH and aragonite saturation with data for indicators related to ocean acidification (Jones et al., 2020). The continuous plankton recorder survey (hereafter CPR), which provides estimates of relative abundance of a large number of zooplankton and phytoplankton taxa (Richardson et al., 2006) has been extended into the Norwegian Sea in recent years, and has provided data for estimation of changes in biological diversity. There are also data on marine mammals from the Norwegian Sea (Øien, 2009; Leonard and Øien, 2020b; Leonard and Øien, 2020a), but due to capacity constraints, these have not been used in the current assessment.

It should be noted that the Norwegian Sea is less data rich than the Barents Sea (see Siwertsson et al. (2023)) and the North Sea (see Arneberg et al. (2023)), as there are no ecosystem cruises that produces both biomass data and taxonomic information for large groups of ecosystem components, like the ecosystem survey in the Barents Sea (Eriksen et al., 2018) and the international bottom trawl survey in the North Sea (ICES, 2020). Also, the time series from CPR are much shorter than in the North Sea and other core areas for the CPR.

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 the ecosystem’s key components and functions. Researchers have based their selection of indicators on a compromise between parsimony in the number of indicators and their relevance and importance, supported by the scientific literature.

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 for phytoplankton and seabirds and have developed an indicator for the relative biomass of mesozooplankton and pelagic fish. 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 further combine different indicators to describe the overall variation in biomass across trophic levels. For “Functional groups within trophic levels”, important functions performed by each ecosystem component are identified by experts. Finally, for “Biological diversity”, classical biodiversity indices were difficult to link to anthropogenic drivers. Instead, the selected indicators represent species or groups of species that are known to be sensitive to, or to benefit from, certain anthropogenic pressures and can thus act as “indicator” species. For “Functional groups within trophic levels” and “Biological diversity”, indicators are only available for copepods, thus severely limiting the assessment.

We also attempted to identify important parameters of the ecosystem that are currently missing from the monitoring programs. Thus, issues of data availability or 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. This also includes indicators that were attempted to include in the assessment, but where it was realized that the quality was not sufficient. The indicators that were finally used were those for which direct measurements or proxies with sufficient quality were available.

Table 3.1 Description of data sources for assessment of ecological condition in the Norwegian Sea.

Dataset name	ID	Dataset DOI/URL/storage	Owner institution	Contact person for data	Content and methods	Temporal coverage
Chlorophyll, MODIS	D01	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 IESNS	D02	Norsk Marint Datasenter (NMD)	IMR [1]	Cecilie Broms, IMR [1]	WP2 nets from the IESNS in May (ICES, 2021a). For mesozooplankton. Only biomass of size fractions is considered, not taxonomy.	1995-2021
Mackerel	D03	http://doi.org/10.17895/ices.pub.8298	ICES	Leif Nøttestad, IMR [1]	Assessment of spawning stock biomass and recruitment of mackerel (*Scomber scombrus*) in the North-east Atlantic (ICES, 2021d)	1980-2021
NSS herring stock	D04	http://doi.org/10.17895/ices.pub.8298	ICES	Erling Kåre Stenevik, IMR [1]	Assessment of spawning stock biomass of Norwegian spring-spawning herring (ICES, 2021d	1907-2021
Herring recruitment	D05	http://doi.org/10.17895/ices.pub.8298	ICES	Erling Kåre Stenevik, IMR [1]	Assessment of Norwegian spring-spawning herring recruitment (ICES, 2021d)	1988-2021
Blue whiting	D06	http://doi.org/10.17895/ices.pub.8298	ICES	Åge Høines, IMR [1]	Assessment of blue whiting spawning stock biomass and recruitment (ICES, 2021d)	1981-2021
Seabirds	D07		NINA	Per Fauchald, NINA [2]		
Continuous plankton recorder (CPR)	D08	https://www.cprsurvey.org/services/the-continuous-plankton-recorder/	SAHFOS [4]	Espen Strand, IMR [1]	The CPR survey gives data on relative abundance of plankton species collected on ship routes covering a portion part of the Norwegian Sea. The method is described in Richardson et al. (2006)	
Calanus finmarchicus productivity	D09		IMR	Solfrid Hjøllo, IMR [1]		
Temperature	D10		IMR	Øystein Skagseth, IMR [1]	Data from CTD profiles from ship surveys (mainly IESNS), repeated sections (Svinøy and Gimsøy sections) supplemented with data from Argo buoys	1951-2021
Freshwater content	D11		IMR	Øystein Skagseth, IMR [1]	Data from CTD profiles from ship surveys (mainly IESNS), repeated sections (Svinøy and Gimsøy sections) supplemented with data from Argo buoys	1951-2021
Arctic water and stratification	D12		IMR	Øystein Skagseth, IMR [1]	Data from CTD profiles from ship surveys (mainly IESNS), repeated sections (Svinøy and Gimsøy sections) supplemented with data from Argo buoys	1995-2021
Nutrients	D13		IMR	Øystein Skagseth, IMR [1]	Data from repeated profiles at the Svinøy section	1995-2019
Inflow of Atlantic water	D14		IMR	Øystein Skagseth, IMR [1]	Data from current meter at the Svinøy section	1996-2021
pH and aragonite saturation	D15		IMR	Elizabeth Jones, IMR [1]	Data from measurements in the core of the Atlantic Water at the Svinøy section	2011-2021

IMR[1] – Institute for Marine Research, NINA [2] Norwegian institute for nature research

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 dataset from the Continuous Plankton Recorder Survey (CPR) (Continuous Plankton Recorder Survey, 2022) has 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 4.1. Additional descriptions of the methods are given in appendix 8.1, which also includes graphical representation of all indicator values and results from statistical analyses. Statistical analyses were conducted in R (R Core Team, 2019).

4.1 General considerations

The CPR is operated using ships of opportunity and data has been collected for a portion of the Norwegian Sea (figure 4.1). Some of the observations occur outside the assessment area, and all these data were used here.

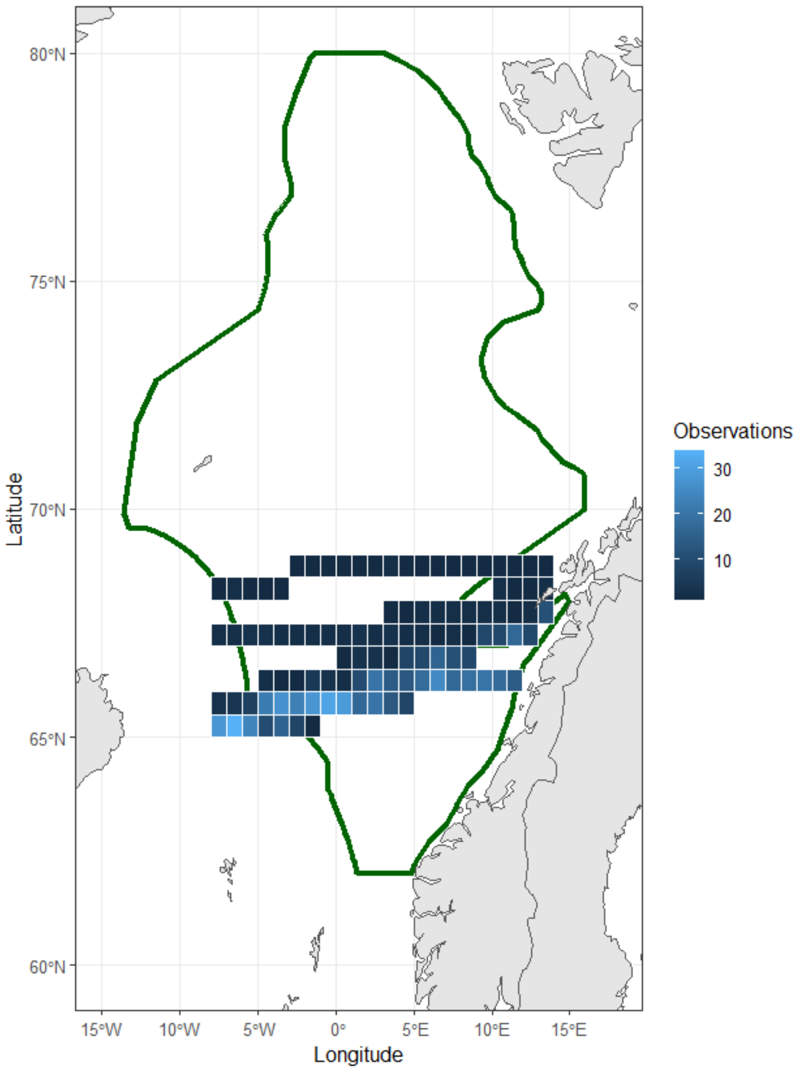


Figure 4.1. Location of grid cells from which CPR data have been used for the assessment and number of data points for each cell. The assessed area is indicated by the solid line.

4.2 Framework for trend estimation – TREC

The objective of the method used to assess deviation from the reference conditions is to fit a trend to each indicator's data and to compare it to the phenomena stated by the experts (see chapter 5.1) and development of relevant anthropogenic drivers (see Appendix 8.2). Depending on the length of the indicator's time series, two types of trend analyses were done:

- For time series with at least 50 data points, four autoregressive linear models taking into account effects of autocorrelation in time series data were fitted (without autocorrelation or with autocorrelation from first to third order, see Pedersen et al. (2021) for an example of application of such models in PAEC), and the best fitted model was selected based on the AIC criteria. Then, to highlight potential nonlinear trends, the first step of a TREC analysis (Solvang and Planque, 2020; Solvang and Ohishi, 2022) was applied to the standardized time series to compare the fit of polynomial models (from degree 1 to 3). The best fitted model was also selected based on AIC criteria.

- For time series with less than 50 data points, autoregressive models are not robust (Hardison et al., 2019), and only the TREC analysis was applied then. As support information, a linear trend without autocorrelation in the residuals was applied to give an idea of the direction of the trend, but the interpretation should be done carefully as the trend coefficients and confidence interval may be erroneous. For supplementary information, we also applied a moving average smoother. All plots are available in Appendix 8.1.

Table 4.1. Methods for estimating indicator values from datasets for the Norwegian Sea

Ecosystem characteristic	**Indicator [ID]**	**Dataset ID**	**Methods**
Primary productivity	Annual primary productivity [NwI01]	D01	The indicator is represented by a time series on annual net primary production (gram carbon per m^2 per year) based on satellite data on ocean colour (from which chlorophyll concentration is inferred) and estimated from a vertically generalized production model (Behrenfeld and Falkowski, 1997).
Primary productivity	Timing of the spring bloom [NwI02]	D01	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 primary productivity [NwI01]	D01	See above
Biomass distribution among trophic levels	Mesozooplankton biomass relative to pelagic fish biomass [NwI03]	D02, D03, D04, D06	The indicator is represented by a time series on the ratio between estimated mesozooplankton biomass and the sum of estimated spawning stock biomass of herring, mackerel and blue whiting
Biomass distribution among trophic levels	High trophic level seabirds [NwI04]	D07	The indicator is represented by time series of total breeding colony sizes for black-legged kittiwake (*Rissa tridactyla*), common murre (*Uria aalga*) and Atlantic puffin (*Fratercula arctica*) on the Norwegian mainland Norwegian Sea coast.
Functional groups within trophic levels	Copepod body size [NwI05]	D08	The indicator is represented by a time series based on CPR abundance values (annual means in March-September from selected grids with high sampling effort within or in the vicinity of the Norwegian sector) of copepods assigned as small or large (UK Pelagic Habitats Expert Group, 2021). The time series itself is then calculated as the proportion of large copepod species.
Functionally important species and biophysical structures	Mackerel stock size [NwI06]	D03	The indictor is represented by the estimated spawning stock biomass (ICES, 2021b)
Functionally important species and biophysical structures	Mackerel recruitment [NwI07]	D03	The indicator is represented by the estimated recruitment represented by the age 0 estimated abundance (ICES, 2021b)
Functionally important species and biophysical structures	Herring stock size [NwI08]	D04	The indictor is represented by the estimated spawning stock biomass (ICES, 2022b)
Functionally important species and biophysical structures	Herring recruitment [NwI09]	D05	The indicator is represented by the estimated recruitment represented by the abundance of age 2 recruits (ICES, 2022b)
Functionally important species and biophysical structures	Blue whiting stock size [NwI10]	D06	The indictor is represented by the estimated spawning stock biomass (ICES, 2022a)
Functionally important species and biophysical structures	Blue whiting recruitment [NwI11]	D06	The indicator is represented by the estimated recruit abundance (age 1v, ICES, 2022a)
Functionally important species and biophysical structures	*Calanus finmarchicus* production [NwI12]	D09	The indicator is represented by the sum of C. finmarchicus production generated by the NORWECOM.E2E model (Hjøllo et al, 2021) for the assessment area over a year (Hjøllo et al., 2021).
Biological diversity	Copepod species vulnerable to higher temperature [Nw13]	D08	The indicator is represented by a time series on the average number of copepod species, per CPR-sample, that are assumed to be vulnerable to higher temperatures.

Biological diversity	Copepod species benefitting from higher temperature [NwI14]	D08	The indicator is represented by a time series on the average number of copepod species, per CPR-sample, assumed to benefit from higher temperatures.
Abiotic factors	Heat content [NwI15]	D10	The indicator is represented by a time series on heat content in the Atlantic layer in the Norwegian Sea.
Abiotic factors	Freshwater content [NwI16]	D11	The indicator is represented by a time series on freshwater content (salinity) in the Atlantic layer in the Norwegian Sea.
Abiotic factors	Inflow of Arctic water [NwI17]	D12	The indicator is represented by a time series on the volume of water with salinity < 34.9.
Abiotic factors	Stratification [NwI18]	D12	The indicator is represented by a time series on the density at 200m depth minus density at 10m depth.
Abiotic factors	Inflow of Atlantic water [NwI19]	D14	The indicator is represented by a time series on volume transport in the Norwegian Atlantic slope current.
Abiotic factors	Nutrients [NwI20]	D13	The indicator is represented by time series on nitrogen and silicate at 10-15m depth and 150-200m depth.
Abiotic factors	pH [NwI21]	D15	The indicator is represented by estimates from the core of Atlantic Water along the Svinøy transect. Indicator values are mean of observation (± sd).
Abiotic factors	Aragonite saturation [NwI22]	D15	The indicator is represented by estimates from the core of Atlantic Water along the Svinøy transect. Indicator values are mean of observation (± sd).

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 Table 5.1 and full descriptions in section 5.1) 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 (see Appendix 8.2), then there is evidence for deviation from the reference condition.

Table 5.1 List of phenomena including overall approach used to determine the extent to which each phenomenon has occurred in the pelagic ecosystem in the Norwegian 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 (category not used in the current assessment) (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)

Indicator [ID]	**Phenomenon [ID]**	**Anthropogenic drivers**	**Approach**
Annual primary productivity [NwI01]	Decreasing primary production [NwP01]	Climate change	2) and 3)
Timing of the spring bloom [NwI02]	Change in timing of spring bloom [NwP02]	Climate change	2) and 3)
Mesozooplankton biomass relative to pelagic fish biomass [NwI03]	Change in relative biomass of mesozooplankton to pelagic fish OR change in biomass ratio of mesozooplankton and pelagic fish [NwP03]	Fisheries and climate change	2) and 3)
High trophic level seabirds [NwI04]	Decreasing populations of pelagic high TL seabirds [NwP04]	Fisheries and climate change	2) and 3)
Copepod body size [NwI05]	Decreasing average copepod body size [NwP05]	Climate change	2) and 3)
Mackerel stock size [NwI06]	Decreasing mackerel stock size [NwP06]	Fisheries and climate change	2) and 3)
Mackerel recruitment [NwI07]	Change in mackerel recruitment [NwP07]	Fisheries and climate change	2) and 3)
Herring stock size [NwI08]	Decreasing herring stock size [NwP08]	Fisheries	2) and 3)
Herring recruitment [NwI09]	Decreasing herring recruitment [NwP09]	Fisheries	2) and 3)
Blue whiting stock size [NwI10]	Decreasing blue whiting stock size [NwP10]	Fisheries	2) and 3)
Blue whiting recruitment [NwI11]	Decreasing blue whiting recruitment [NwP11]	Fisheries	2) and 3)
Calanus finmarchicus productivity [NwI12]	Decreasing *Calanus finmarchicus* production [NwP12]	Climate change	2) and 3)
Copepod species vulnerable to climate warming [Nw13]	Decreasing number of copepod species sensitive to higher temperatures [NwP13]	Climate change	2) and 3)
Copepod species benefitting from climate warming [NwI14]	Increasing number of copepod species benefitting from higher temperatures [NwP14]	Climate change	2) and 3)
Heat content [NwI15]	Increasing heat content [NwP15]	Climate change	2) and 3)
Freshwater content [NwI16]	Increasing freshwater content [NwP16]	Climate change	2) and 3)
Inflow of Arctic water [NwI17]	Change in volume of Arctic Water [NwP17]	Climate change	2) and 3)
Stratification [NwI18]	Increasing stratification [NwP18]	Climate change	2) and 3)
Inflow of Atlantic water [NwI19]	Decreasing inflow of Atlantic Water [NwP19]	Climate change	2) and 3)
Nutrients [NwI20]	Change in concentrations of nutrients [NwP20]	Climate change	2) and 3)
pH [NwI21]	Decreasing pH [NwP21]	Global increase in CO_2	2) and 3)
Aragonite saturation [NwI22]	Decreasing aragonite saturation [NwP22]	Global increase in CO_2	2) and 3)

5.1 Scientific evidence base for the phenomena in the Norwegian Sea

Annual primary productivity [NwI01]

Phenomenon: Decreasing primary production [NwP01]

Ecosystem characteristic: Primary productivity

Under the reference condition annual primary production is high enough to sustain a food web of naturally occurring species. I n winter the surface water mixing is 100 to 200 meters deep in the Norwegian Sea. As insolation increases in spring, primary production increases accordingly, while thermal stratification develops. As described below, climate change is the main driver. In the Norwegian Sea, the mean surface temperature has not increased during the last 100 years, because the region is dominated by circulation and advection of Arctic waters versus Atlantic Waters (Xu et al., 2021). The present situation in this respect can therefore be assumed to mirror the reference condition.

The most important anthropogenic driver of change in the indicator is climate change. Global warming of surface waters has resulted in a worldwide increased stabilization of stratification and reduction of vertical advection of mineral nutrients to the euphotic zone (Yamaguchi and Suga, 2019; Kwiatkowski et al., 2020). As described above, mean surface temperature has not increased in the Norwegian Sea during the last 100 years (Xu et al., 2021). Future warming is expected to result in higher surface temperature, increased stratification and reduced primary production (Moore et al., 2018). While modelling work for the Norwegian Sea has suggested warming may give a weak increase in primary production (Kjesbu et al., 2022), the understanding of the link between climate change and change in the indicator is still rated as 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.

Knowledge gaps include a need for 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 biogeochemical models with high-quality atmospheric forcing which can consider changes in species composition.

Timing of the spring bloom [NwI02]

Phenomenon: Change in timing of spring bloom [NwP02]

Ecosystem characteristic: Primary productivity

In winter the surface water mixing is 100 to 200 meters deep in the Norwegian Sea and insolation is very low. As insolation increases in spring, primary production increases accordingly, while thermal stratification develops. Spring bloom dynamics are governed by a variety of factors and has been thoroughly reviewed and discussed by Lindemann and St. John (2014). Insolation, stratification, and grazing are recognized as main drivers of variability, and light and surface water mixing are influenced by cloudiness and storms. Thus, good weather in April and early May is conducive to early spring bloom, but a successful population of grazers may slow the accumulation of phytoplankton biomass. In the literature, the start of the spring bloom has been defined as the point in time when phytoplankton biomass reaches a certain threshold (Siegel et al., 2002). The biomass accumulation will be a function of both phytoplankton growth and water column stratification, which are influenced by temperature.

The most important anthropogenic driver of change in the indicator is climate change. Increasing sea surface temperature is predicted to stabilize stratification, but on the other hand climate change may increase storminess and influence timing of storms (Landgren et al., 2019). As the development of future storminess may be harder to predict, the understanding of the link between climate change and the indicator is rated as less certain.

The spring bloom is a major event in temperate marine ecosystems, and the success of many grazers depends on the high food availability at the height of the bloom. Many species have synchronized their spawning with the expected bloom for optimized food conditions. Changes in the timing of spring bloom may have negative consequences for these grazers (Edwards and Richardson, 2004; Durant et al., 2019; Yamaguchi et al., 2022). In temperate regions of the ocean, global warming has been shown to have influenced the onset of the bloom to earlier dates (Racault et al., 2012), and this prolongs the growing season. The effect of global warming on temperature has been detectable since the late 1980s, but the start spring bloom in the open ocean can only be precisely determined from the global ocean color satellite programs which started in 1996. The understanding of the importance of changes in the indicator for the ecosystem is rated as less good.

Research is needed to understand and quantify temporal changes and variability in the start of the spring bloom, as well as studies on the impact of climate change on the multiple controls at work (Lindemann and St. John, 2014). Other knowledge gaps include a need for more in situ measurements, high spatial resolution biogeochemical models, and analysis and interpretation of remote sensing data. 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.

Mesozooplankton biomass relative to pelagic fish biomass [NwI03]
Phenomenon: Change in relative biomass of pelagic fish [NwP03]

Ecosystem characteristic: Biomass distribution among trophic levels

Mesozooplankton and pelagic fish are dominant components of the Norwegian Sea pelagic ecosystem (Skjoldal, 2004). Mesozooplankton make up a large part of the diet of the three pelagic fish stocks; mackerel, Norwegian spring-spawning herring and blue whiting (Dalpadado et al., 2000; Langøy et al., 2012; Bachiller et al., 2016; Mousing et al., Submitted). Thus, important aspects of the overall distribution in biomass among trophic levels in the ecosystem can be observed by looking at the biomass of these two groups. While there is limited information about zooplankton and pelagic fish biomass variation under the reference condition in the Norwegian Sea, information do exist for one of the stocks, Norwegian spring-spawning herring (see phenomenon for herring stock size [NwP08]), showing that the size of the stock may vary over nearly an order of magnitude for periods that can be considered descriptive for the reference condition for this stock (i.e., pre WWII, Toresen and Østvedt (2000)). Large variation in stock size has been observed also for mackerel and blue whiting for more recent periods, and although some of this variation can be attributed to fishing, large parts of it is clearly due to variation in recruitment (ICES, 2021d; ICES, 2021c; ICES, 2022d), which may be more loosely linked to anthropogenic drivers and thus possibly to a large extent represent natural variation (see phenomena on herring recruitment [NwP09], mackerel recruitment [NwP07] and blue whiting recruitment [NwP11]). Related to this, it should be noted that several orders of magnitude variation in stock size has been demonstrated for pelagic fish stocks in other systems under periods of little anthropogenic impact (Baumgartner et al., 1992). Thus, pelagic fish biomass should be considered to be highly variable under the reference condition. Information on mesozooplankton biomass is more limited compared with what we know about pelagic fish, but estimates from 1995 and onwards from the Norwegian Sea shows that there was a drop of about a third from the mid-2000s to around 2010 linked to reduced inflow of Arctic water and an increase of a similar magnitude linked to increased inflow of Arctic water a decade later (Skagseth et al., 2022). This suggests that there is considerable natural variation also in mesozooplankton biomass under the reference condition.

The indicator is represented by an index on the ratio of overall biomass of the three pelagic fish stocks to mesozooplankton biomass. The most important anthropogenic driver of change in this indicator is fisheries, with climate change also having a possible role. The link between these drivers and biomass of the three pelagic fish stocks is described in the phenomena for these stocks (phenomena for mackerel stock size [NwP06], herring stock size [NwP08] and blue whiting stock size [NwP10]). In short, fisheries have the potential to cause declines in biomass of all the three stocks, whereas links to climate change are more uncertain. In addition, it should be noted that predation by marine mammals is estimated to be 3 times greater than removals from the fisheries (Skern-Mauritzen et al., 2022), thus having a potential for introducing considerable natural variation in the indicator. For mesozooplankton biomass, there are indications of a link to inflow of Arctic water to the ecosystem, with increasing inflow causing increased biomass (Skagseth et al., 2022). While there is a possible link between Arctic water inflow and climate change, there are large uncertainties associated with this (phenomena #Arctic water). There is also a fishery on mesozooplankton, but the quota is small and the effect on the stock is considered to be negligible (Broms et al., 2016; Hansen et al., 2021a). Although the understanding of the link between fisheries and pelagic fish stock biomass is rated as certain (see phenomena for fish stocks, NwP06, NwP08 and NwP10, i.e., capturing the effects on both pelagic fish and mesozooplankton biomass), is rated as less certain.

The extent to which mesozooplankton affects pelagic fish biomass or vice versa has been subject of several studies. For example, based on negative relationships between fish individual growth and biomass, Huse et al. (2012) suggested that there are clear indications of intra- and interspecific competition over food, that the biomass of pelagic planktivorous fish had been above the carrying capacity in the years preceding the study and that reduction in zooplankton biomass seen in the early 2000s was caused by fish predation. Similarly, based on a study of herring abundance, herring feeding and mesozooplankton abundance, Olsen et al. (2007) suggested that there was a top-down effect from herring on mesozooplankton biomass acting in the western part of the Norwegian Sea. Planque et al. (2022), on the other hand, quantified trophic interactions in the Norwegian Sea pelagic ecosystem using inverse modelling and found no support for top-down control on planktonic prey biomass and little support for the hypothesised competition for resources between the three small pelagic species. Thus, the knowledge about consequences of change in the indicator for the ecosystem as a whole is rated as less good.

High trophic level seabirds [NwI04]

Phenomenon: Decreasing populations of pelagic seabirds [NwP04]

Ecosystem characteristic: Biomass distribution among trophic levels

Under the reference condition, large breeding colonies hosting around 1.8 million breeding pairs of pelagic seabirds are found along the outer Norwegian coast bordering the Norwegian Sea. This rich pelagic seabird community is dominated by Atlantic puffin (*Fratercula arctica*) followed by black-legged kittiwake (*Rissa tridactyla*) and common guillemot (*Uria aalge*) (Brun, 1979). Fauchald et al. (2015) estimated the total population of these species to about 1.8 mill. pairs in 1980. The populations of puffin and common murre declined while the population of kittiwake increased during the 1970s (Brun, 1979), and assuming that populations of other pelagic seabirds is negligible, a conservative reference abundance (“pre-industrial” level) of pelagic seabirds in the eastern Norwegian Sea is about 1.8 - 2 mill. breeding pairs. Other pelagic seabirds that breed in the area include Northern fulmar (*Fulmarus glacialis*), European storm petrel (*Hydrobates pelagicus*), Leach's storm petrel (*Hydrobates leucorhous*), Northern gannet (*Morus bassanus*), great skua (*Stercorarius skua*), Arctic skua (*Stercorarius parasiticus*) and razorbill (*Alca torda*). Combined, these species counted around 20,000 breeding pairs, or about 3% of the pelagic seabirds in the eastern Norwegian Sea in an estimate from 2015 (Anker-Nilssen et al., 2015). Due to lack of monitoring they are excluded from the present analyses. The major food resource supporting the large colonies of pelagic seabirds in the eastern Norwegian Sea is juvenile fish drifting and residing in the Norwegian coastal current in an area from the spawning sites along the coast to the nursery and feeding areas in the Norwegian and Barents Seas (Anker-Nilssen, 1992; Sætre et al., 2002; Durant et al., 2003; Sandvik et al., 2016). Most notably, the pelagic seabirds prey upon juveniles of the large pelagic fish stocks inhabiting the Norwegian and Barents Seas, including the Norwegian spring spawning (NSS) herring stock (*Clupea harengus*) and the stocks of Northeast Arctic (NEA) saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*) (Anker-Nilssen, 1987; Anker-Nilssen and Øyan, 1995; Barrett et al., 2002; Anker-Nilssen and Aarvak, 2006). In addition, local stocks of sandeels (*Ammodytes* spp.) are important (Anker-Nilssen and Aarvak, 2006; Christensen-Dalsgaard et al., 2018). These food resources are seasonal with a peak in availability during spring and summer. Accordingly, pelagic seabirds are mainly present in the eastern part of the Norwegian Sea during pre-breeding and breeding (March-July), while they are mostly absent during autumn and winter (Fauchald et al., 2021).

The most important anthropogenic drivers of change in this indicator are fisheries and climate change. Following overfishing in the 1960s, the collapse of the NSS herring in 1970 (Dragesund et al., 2008) resulted in a series of years with low spawning output, low abundance of 0-group herring, and as a consequence, breeding failures and subsequent population declines in Atlantic puffin as well as other pelagic seabirds (Anker-Nilssen and Øyan, 1995; Sætre et al., 2002; Anker-Nilssen and Aarvak, 2006; Cury et al., 2011). The link between overfishing and the indicator is well documented in the Norwegian Sea (ibid.) and similar impacts have been described elsewhere (Cury et al., 2011; Grémillet et al., 2018). In addition to overfishing, climate change affects the seabird populations in a number of more indirect and subtle ways. Importantly, climate change impacts the timing and location of fish spawning and the subsequent production, distribution and survival of juvenile fish. As a result, the fine-tuned interrelationship between the availability of 0-group fish and the breeding cycle of seabirds is disrupted, causing a mismatch between prey availability and seabird reproduction (Durant et al., 2003; Durant et al., 2004). Rapid climate change does therefore negatively affect the productivity of pelagic seabirds breeding in colonies bordering the Norwegian Sea, and this mechanism is partly responsible for the current decline in the populations (Durant et al., 2003). The link between climate change and the indicator is well documented in the Norwegian Sea (ibid.) and similar impacts have been described elsewhere (see e.g., Piatt et al. (2020); Hansen et al. (2021b)). The understanding of the link between the indicator and fisheries and climate change is assessed as certain.

Atlantic puffin, black-legged kittiwake and common guillemot are, together with marine mammals and predatory fish, important predators on juvenile and pelagic fish and constitute a significant part of the top predator guild in the eastern part of the Norwegian Sea (Sætre et al., 2002; Skjoldal, 2004). 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. The understanding of the importance of changes in the abundance of pelagic seabirds is assessed as good.

Decreasing abundance of pelagic seabirds can be considered of ecosystem significance if, for example i) there is a sudden drop in the populations caused by a mass die-off of birds following a collapse in the availability of prey due to climate extremes or overfishing, ii) there is a significant gradual long-term (> 10 years) decrease in the populations associated with climate warming and/or decrease in the availability of prey.

Monitoring and research have highlighted the impacts of overfishing and climate change on seabird populations dynamics in the eastern Norwegian Sea. It is, however, difficult to discern the relative importance of the different drivers. Moreover, the negative impact of predation from a growing population of white-tailed eagles has probably also contributed to the decline in the populations of black-legged kittiwakes and common guillemots in the eastern Norwegian Sea (Hipfner et al., 2012).

Copepod body size [NwI05]

Phenomenon: Decreasing average copepod body size [NwP05]

Ecosystem characteristic: Functional groups within trophic levels

Under the reference condition, copepod body size is considered as a key trait in zooplankton as it is related to numerous physiological and ecological processes, e.g., individual growth, metabolic rates, feeding behavior and life history strategies (Pope et al., 1995; Kiørboe, 2011; McGinty et al., 2021). In planktonic communities, body size is of particular importance, because food webs are comprised of regular and progressively increasing size spectra (Sheldon et al., 1972). Copepod b ody size is affecting grazing efficiency, predator prey interactions, and trophic energy transfer and thereby determining the trophic structure and dynamics of pelagic communities (Gorokhova et al., 2013). Zooplankton body size varies with latitude and species tend to be larger in colder, higher latitudes compared to its congeners found in warmer regions (Bergmann's temperature-size rule).

The most important anthropogenic driver of change in zooplankton body size is climate change, in terms of increasing temperature. Higher temperatures cause elevated metabolic rates and energy costs, resulting in smaller body sizes both within species (Record et al., 2012) as well as at the community level (Beaugrand et al., 2002b). Ecological theory and observations suggest that climate warming is expected to favor small copepods over large copepods (Daufresne et al., 2009). This suggests that an increase in temperature should result in a decrease in the proportion of larger-sized individuals and species in a community.

As ocean temperatures increase over the next century, these changes are likely to shift communities into states where smaller phytoplankton and zooplankton species dominate. Significant shifts in zooplankton community structure and size-spectra towards the dominance of the small-sized copepod *Oithona similis* relative to large-bodied calanoid copepods have already been observed across the global ocean such as in the Arctic (Balazy et al., 2021), the North Sea (Nielsen and Sabatini, 1996; Bedford et al., 2018), the North Atlantic and the Mediterranean Sea (Beaugrand et al., 2003; Goberville et al., 2014; Castellani et al., 2015).

The replacement of large copepods with small ones has also been suggested as an indicator of eutrophication in the Baltic region (Gorokhova et al., 2013; HELCOM, 2018) but in marine systems the causal link between eutrophication and body size is ambiguous (Ndah et al., 2022).

Given the solid evidence described above the understanding of the link between temperature and zooplankton body size is rated as certain.

Changes in the average copepod body size are expected to alter the food web structure and the carbon transfer between trophic levels. Zooplankton communities composed of large-bodied copepods have a higher capacity for transfer of energy from primary producers (phytoplankton) to fish, i.e., higher energy transfer efficiency. By contrast, a dominance of small-bodied copepods is usually associated with lower energy transfer efficiency, due to higher losses (Lewandowska and Sommer, 2010). Thus, a reduction in the mean copepod body size represents unfavorable fish feeding conditions and less efficient utilization of primary production. According to ecological theories, this would represent a less efficient food web (HELCOM, 2018).

As ocean temperatures increase over the next century, these changes are likely to shift communities into states where smaller phytoplankton and zooplankton species dominate. This will result in a less productive system, with decreased trophic efficiency and reduced fecal carbon flux (Hébert et al., 2016).

A reduction in the zooplankton body size will have direct negative impact on fish feeding conditions, fish larval survival and recruitment (Beaugrand, 2005; Pitois et al., 2012). Pitois et al. (2021) found strong correlations between herring distribution and larger copepod mean sizes rather than high copepod abundances, confirming that copepod mean size has the potential to reflect food web and ecosystem health status as well as highlight climatic impacts on marine ecosystems. In the Norwegian Sea the herring selected the larger copepodite stages and adults of *C. finmarchicus* and *C. hyperboreus* during its feeding migration (Dalpapado et al. 2000).

Given the substantial evidence described above the understanding of the importance of change in the indicator for other parts of the ecosystem is rated as good.

Decreasing zooplankton body size can be considered of ecosystem significance if i) it causes massive declines in the production and recruitment of fish stocks, and ii) it causes reduced vertical carbon flux (carbon pump).

Knowledge gaps in monitoring and research: In the CPR data set, copepods are classified into two size groups: as Small" (< 2 mm) and "Large" (2> mm). However, dataset including species specific copepod sizes are available (Razouls et al., 2005-2022; Brun et al., 2017).

The interpretation of this phenomenon may be demanding due to top-down effects. Size-selective predation on zooplankton by predators (top-down) will affect the size composition of zooplankton and may counteract climate - induced effects (bottom-up). Future studies should try to disentangle the interaction between top-down and bottom-up control.

Alternative metrics related to copepod size should be investigated further, e.g., "Copepod community body size" as the abundance weighted mean prosome length (Evans et al., 2020). R elative metrics, including both size and abundance may be more informative, e.g. Normalized Biomass Size-Spectra (NBSS) and the Abundance-Size Spectrum of zooplankton, referring to the relative abundance or biomass of zooplankton organisms of different size classes (Thompson et al., 2013).

The MSTS (Zooplankton Mean Size and Total Stock) is a core indicator in the Baltic region, where the lengths of individuals are measured for each species (HELCOM, 2018). A similar indicator exists in the OSPAR area (FW6; Ndah et al. (2022)). However, a major limitation is that zooplankton sizes are not regularly measured in marine monitoring and are usually estimated using mean values from the literature. The lack of in-situ size information will mask any potential long-term change in species-specific size structure. Future monitoring should aim at including size measurements of zooplankton, by the use of laboratory image analyzing methods (e.g., FlowCam) or, preferably, by *in situ* methods (e.g., VPR).

Mackerel stock size [NwI06]

Phenomenon: Decreasing mackerel stock size [NwP06]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, the mackerel stock is one of the largest pelagic stocks in the Norwegian Sea, which is its main feeding area. Over the last 100 years, the perception of the NEA mackerel stock structure and migration patterns has changed considerably (Iversen, 2002). For a long time, the stock was assumed to consist of three populations with distinct migration patterns: Southern, Western and North Sea (Iversen, 2002). However, recent studies indicated no clear evidence of structuring within the populations (Jansen, 2013; Jansen and Gislason, 2013; Gíslason et al., 2020), but rather suggested that the stock is a single population with a dynamic migration pattern, spawning over a large area from the coast of Portugal to the North Sea (Brunel et al., 2017; ICES, 2019b); feeding in North-Sea, Norwegian Sea and adjacent areas (Nøttestad et al., 2016) and wintering around Shetland (Jansen et al., 2012). Since around 2005, the stock has experienced changes in growth, condition, and distribution pattern associated with an increase in recruitment and spawning stock biomass (Jansen et al., 2015; Olafsdottir et al., 2015; Nøttestad et al., 2016; ICES, 2021b). Such dynamics in the distribution of a commercially important stock extending over different exclusive economic zones (EEZs) is clearly a challenge for an effective management (Baudron et al., 2020). Hence, considerable research efforts have been put into understanding the reasons behind observed changes, both regarding the spawning (Bruge et al., 2016; Brunel et al., 2017; dos Santos Schmidt et al., In prep.), feeding (Astthorsson et al., 2012; Jansen et al., 2016; Pacariz et al., 2016; Nikolioudakis et al., 2018; Olafsdottir et al., 2019), and wintering distribution (Jansen et al., 2012). This includes attempts to develop new modeling approaches to study mackerel migrations (Heinänen et al., 2018; Boyd et al., 2020; Payne et al., 2022). The general conclusion from these studies is that the observed changes in distributions are driven by both the density dependent effects of changes in size of the stock as well as oceanographic, environmental, and ecological dynamics. In addition, recent research reveal that the NEA mackerel is highly dependent on its energetic status and feed heavily during the spawning period (Jansen et al., 2021), which ultimately may have significant influence on migration choices during spawning, and between spawning and feeding areas, for a large population under strict competition for prey. Furthermore, a new large scale tagging program have shown that the mackerel undertake size dependent spawning and feeding migrations with the wintering area in Northern North Sea as basis, and that recruits growing up in the North Sea migrates out of the area to feed far west into Icelandic Waters and spawn west of British Isles and farther south as they grow older and larger (ICES, 2021b; Ono et al., 2022). This suggest that any fidelity for a mackerel growing up in the North Sea or other nursery areas to maintain spawning there is low. Furthermore, one should expect that any dynamics in growth and condition, which typically fluctuates with stock size (Olafsdottir et al., 2015), may be an important driver for the migration and distribution of the stock.

The most important anthropogenic drivers of change in abundance of mackerel as a whole, and therefore also for the abundance in the Norwegian Sea feeding area, are fisheries and climate change. Under the recent condition with warming of NEA waters from 2000 onwards (Asbjørnsen et al., 2020; ICES, 2021c; Kjesbu et al., 2022), the NEA mackerel has had series of large year classes leading to high stock levels (ICES, 2021b), but at the same time the fishing pressure has been high with overshooting quotas around 40% since 2010. Under the continuous high fishing pressure with no large recent year classes this has ultimately led to the decreasing stock size after 2014. Our understanding of the link between fisheries and changes in the stock size inside the Norwegian Sea is therefore rated as certain, whereas the link to climate change and recruitment variation leading to more mackerel in the Norwegian Sea as well as the actual dynamics in distribution inside the area is less certain, i.e. although, as described above, scientists do agree that there are climate effects, there is still need for more research to understand actual underlying processes.

Decreasing stock size of mackerel feeding in the Norwegian Sea area would potentially affect the ecosystem. The diet and consumption of mackerel in the area is well known to overlap with the other larger fish stocks in the area Norwegian spring spawning herring and blue whiting (Bachiller et al., 2016; Bachiller et al., 2018), and it has been proposed that mackerel may interact with the other two stocks due to competition for prey, and that there may be top-down effects on zooplankton levels (Huse et al., 2012). Still, it is not confirmed yet that decreasing mackerel stock may have positive effects on the other pelagic fish stocks, or if bottom-up effects are more important for the dynamics. Salmon is another species proposed to potentially suffer from competition with mackerel overlapping during feeding in Norwegian Sea, but recent research have concluded that there is little evidence for this hypothesis (Utne et al., 2021). Instead it is suggested that the salmon is suffering from bottom-up effects and ecological regime shifts leading to changes in zooplankton availability (Utne et al., 2021; Vollset et al., 2022). In the North Sea region mackerel has been proved to feed heavily on 0-1 group of various fishes (ICES, 1997), whereas fish is a minor part of the diet in the Norwegian Sea as a whole as this is not a nursery area for fish in general (Bachiller 2016). However, when mackerel enters the more coastal areas off Norway it demonstrated that it potentially may wipe out local abundance of herring larvae when overlapping in time and space, but the effect on total recruitment is not known (Skaret et al., 2015; Allan et al., 2021). To sum up, our understanding of the importance of change in the indicator for other parts of the system is therefore rated as less good.

Mackerel recruitment [NwI07]

Phenomenon: Change in mackerel recruitment [NwP07]

Ecosystem characteristic: Functionally important species and biophysical structures

Following the argumentation for decreasing stock size above, decreasing recruitment of mackerel into the Norwegian Sea is also directly linked to the changes in the total stock.

The most important anthropogenic drivers in the indicator are fisheries and climate change. The effect of fisheries as a whole is reduced stock, and there is a relation between stock size and recruitment. More spawners produce more eggs, but also expanding distribution that ultimately may affect survival of progeny (ICES, 2019b; ICES, 2021b), so drivers affecting the stock size also indirectly affect the recruitment. Under the recent condition with warming of NEA waters from 2000 onwards (Asbjørnsen et al., 2020; ICES, 2021c; Kjesbu et al., 2022), the NEA mackerel has had series of large year classes. This has happened simultaneously with a north and westward shift in spawning (Brunel et al., 2017; ICES, 2019b; dos Santos Schmidt et al., In prep.) towards Iceland and the Norwegian Sea respectively, which ultimately also has led to more progeny ending up in the Norwegian Sea area visible as 1-2 year olds in the international trawl survey (Nøttestad et al., 2021). It is uncertain whether the shift in spawning areas is related to temperature (Brunel et al., 2017), or more related to migration potential following the size structure and condition of the stock as such and the need for feeding while spawning (Jansen et al., 2012). Both factors may play a role. It is also uncertain whether the more north-western spawning also has resulted in higher survival due to improved environmental conditions for progeny, which indirectly leads to more recruits in the Norwegian Sea area. In conclusion the knowledge about effects of fisheries and climate change for recruitment of mackerel into the Norwegian Sea is regarded less certain.

When interpreting potential ecosystem effects of decreasing recruitment into the Norwegian Sea, i.e., fewer young fish ages 1-2, the geographic distribution is to be taken into account. Here it is evident that the youngest fish is found more south and centrally or closer to Norwegian coast than the older fish (Nøttestad et al., 2021; Bjørdal et al., 2022), presumably due to reduced migration potential (Ono et al., 2022) and the fact that recruits feed closer to their nursery areas (Bjørdal et al., 2022). So, any ecosystem effect of large new year classes in the area would not have an impact over large areas prior to reaching the adult stages. With regard to diet and consumption the knowledge for recruits relative to adults is that they have similar diet (ICES, 1997; Bjørdal et al., 2022). So, the knowledge on potential effects on the ecosystem is similar described above for the total stock. The conclusion is that there is no quantitative evidence of actual ecosystem effects of decreasing abundance of recruits in the area, although this potentially may be the case. Hence, the impact of the indicator recruitment in the Norwegian Sea is rated as less good**.**

NSS herring stock size [NwI08]

Phenomenon: Decreasing herring stock size [NwP08]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, Norwegian spring spawning herring (NSSH, *Clupea harengus*) is one of the large pelagic fish stocks in the Norwegian Sea (Skjoldal, 2004). Spawning occurs along the Norwegian coast and larvae drift with the Norwegian coastal current into the Barents Sea where they stay till age 3-4 years, before migrating to the Norwegian Sea and join the adult stock there. After spawning in spring, the adult stock migrates into the Norwegian Sea to feed. Overwintering occurs in fjords or close to the coast in northern Norway. NSSH is an important predator of zooplankton, with the calanoid copepods (especially *Calanus finmarchicus*) as a dominant prey item (Dalpadado et al., 2000; Bachiller et al., 2016). It is itself an important prey species for marine mammals (Skern-Mauritzen et al., 2022), cod, saithe and other demersal species, in addition to seabirds (Holst et al., 2004). The population dynamics of the NSSH is highly influenced by the recruitment dynamics which is characterized by infrequent strong year classes (Fiksen and Slotte, 2002; Sætre et al., 2002; Skagseth et al., 2015; Huse, 2016). NSSH is one of the few species across all Norwegian ecosystems for which there are robust data on population size and variation under the reference condition. The period prior to 1945 can be considered representative for the reference condition as fishing mortality was at a low level and likely not significantly influencing stock size (Toresen and Østvedt, 2000). Data on the stock has been collected since 1907, and virtual population analyses suggests that stock size varied between 2 and 16 million tons between 1907 and 1945 (Toresen and Østvedt, 2000).

The most important anthropogenic driver of change in this indicator is fisheries. Because of implementation of new fishing technology, fishing mortality increased to high levels in the 20 years following 1945, resulting in serious overfishing and collapse of the stock in the late 1960'ies, when the estimated stock size had declined to 0.05 million tons (Dragesund, 1970; Toresen and Østvedt, 2000). Thus, without proper management, fisheries have a potential to cause serious declines in the NSSH stock. Climate change is another anthropogenic driver that should be discussed. An assessment looking at how sensitive NSHH is to impact from climate change based on general life history and ecological interactions as well as climate projections up to 2041, suggests that NSSH will be positively affected by climate change for this period (Kjesbu et al., 2022). It should be noted that the latter study has not addressed directly climate induced changes in herring prey or predators, such as for example changes in zooplankton species composition, which has been shown to be important for fish stock dynamics in the North Sea (Beaugrand et al., 2003). This contributes to uncertainty associated with the assessment of a positive impact of near future climate change on NSHH. In addition, several studies indicate that recruitment is affected by temperature, with a dome shaped relationship between the two variables, suggesting an optimal temperature below and above which recruitment is negatively affected (Toresen and Østvedt, 2000; Toresen et al., 2019), although there are uncertainties with this result (Garcia et al., 2020). A possible negative effect on NSSH recruitment from future temperature increases would contribute further to the uncertainty of the assessment of a positive effect on the stock, and climate change is therefore not considered as an important driver for near future changes in NSHH stock size here. The understanding of the link between fisheries and NSS herring stock size is rated as certain.

Several studies have addressed the ecological interactions between herring and other components of the Norwegian Sea pelagic ecosystem. The influence of interspecific competition as well as competition with the two other large plankton-feeding pelagic fish stocks, mackerel (*Scomber scombrus*) and blue whiting (*Micromesistius poutassou*) has been studied by looking at the relationship between length at age and intraspecific and interspecific biomass of these species. While some evidence of intraspecific competition was found for mackerel, no evidence was seen for competition with the other species, suggesting variation in herring biomass do not have strong effects on mackerel. For blue whiting, strong evidence for interspecific competition was found and the vertical distribution between herring and blue whiting appears to be linked so that herring occurs shallower when the abundance of blue whiting is high, indicating interaction between these species (Huse et al., 2012). Based on these findings and observations of a decline in zooplankton biomass concurrent with an increase in pelagic fish biomass, it has also been speculated that the reduction in zooplankton biomass was caused by pelagic fish and that the system is subject to top-down control (Huse et al., 2012). Subsequent modelling work based on the principle of chance and necessity, which allows reconstruction of a large number of possible ecosystem trajectories (Planque and Mullon, 2020) suggest on the other hand that there is some support for bottom-up control, no support of top-down control and weak support for competition between pelagic fish species (Planque et al., 2022). Results related to mackerel are associated with high degree of uncertainty (ibid.). Based on these partly conflicting results, the understanding of importance of change in NSS herring stock size for other parts of the ecosystem is rated as less good.

While the collapse in the herring stock probably allowed high levels of capelin to be sustained in the Barents Sea for many years (Gjøsæter and Bogstad, 1998; Hjermann et al., 2004; Gjøsæter et al., 2009), there is no evidence of similarly strong effects on components of the Norwegian Sea ecosystem.

Knowledge gaps: There are several surveys covering the stock at different times of the year, in addition to a tagging program. However, there is no coverage of the stock during the autumn. It has been shown that there is an extension of the feeding into autumn in later years (Homrum et al., 2022). This study was based on data from the fishery, and a survey coverage of herring and its prey in the Norwegian Sea during autumn would fill an important knowledge gap.

NSS herring recruitment [NwI09]

Phenomenon: Decreasing herring recruitment [NwP09]

Ecosystem characteristic: Functionally important species and biophysical structures

Key aspects of the NSS herring stock under the reference condition are described above for the indicator for stock size. Analyses using data from 1907 suggest that recruitment of the stock is highly variable between years for a period that can be considered descriptive for the reference condition (1907-1945, (Fiksen and Slotte, 2002)).

The most important anthropogenic driver of change in this indicator is fisheries in the sense that high fishing pressure causing severe depletion in stock size can impair recruitment (Fiksen and Slotte, 2002). As described in the phenomenon for NSSH stock size above, future temperature increase may affect recruitment negatively (Toresen et al., 2019), but there are considerable uncertainties associated with this (Garcia et al., 2020), and climate change is therefore not considered as an important anthropogenic driver here. The understanding of the link between fisheries and NSS herring recruitment is rated as less certain, as clear effects can be assumed only after long periods of unsustainable fishing.

As herring larvae and younger age stages reside outside the Norwegian Sea, as described in the phenomena for herring stock size, changes in recruitment does not have other effects on the Norwegian Sea ecosystem than the indirect effects acting through herring stock size. As described above, we have a poor understanding of the consequences of changes in herring stock size for the ecosystem, and consequently the understanding of importance of change in NSS herring recruitment for other parts of the ecosystem is rated as less good.

Knowledge gaps: Investigate how climate variability impacts top-down processes (predation) during the early life stages of NSSH.

Blue whiting stock size [NwI10]

Phenomenon: Decreasing blue whiting stock size [NwP10]

Ecosystem characteristic: Functionally important species and biophysical structures

Under the reference condition, blue whiting is one of the large pelagic fish stocks in the Norwegian Sea (Skjoldal, 2004). The species is most common at 100–600 m depth but is also found close to the surface in parts of the day and close to the bottom in shallow waters. It is observed as deep as 900 meters. Adult blue whiting migrates every winter to the spawning areas west of the British Isles. Eggs and larvae are transported by currents, and the drift pattern varies from year to year. Larvae from the spawning west of Ireland can end both in the Norwegian Sea and in Bay of Biscay. The most important feeding and nursery area is the Norwegian Sea. The food of blue whiting consists mainly of euphausiids, amphipods and copepods (Pinnegar et al., 2015; Bachiller et al., 2016) and they are prey for piscivorous fish (Dolgov et al., 2009) and cetaceans (Hátún et al., 2009). Stock size is strongly influenced by variation in recruitment.

The most important anthropogenic driver of change in this indicator is fisheries. Around year 2000, there was considerable overfishing of the stock (Standal, 2006), causing worries about stock collapse, illustrating the potential of fisheries to cause decline in stock size. The understanding of the link between fisheries and blue whiting stock size is rated as certain.

Adult blue whiting carries out active feeding and spawning migrations in the same area as herring. Blue whiting consequently has an important role in the pelagic ecosystems of the area, both by consuming zooplankton and small fish, and by providing a food resource for larger fish and marine mammals (ICES, 2009a). Several studies have addressed the ecological interactions between blue whiting and other components of the Norwegian Sea pelagic ecosystem. The influence of interspecific competition as well as competition with the two other large plankton-feeding pelagic fish stocks, mackerel (*Scomber scombrus*) and Norwegian spring spawning herring (*Clupea harengus*) has been studied by looking at the relationship between length at age and intraspecific and interspecific biomass of these species. While some evidence of intraspecific competition was found for mackerel, no evidence was seen for competition with the other species, suggesting variation in blue whiting biomass do not have strong effects on mackerel. For herring, strong evidence for interspecific competition was found and the vertical distribution between herring and blue whiting appears to be linked so that herring occurs shallower when the abundance of blue whiting is high, indicating interaction between these species (Huse et al., 2012). Based on these findings and observations of a decline in zooplankton biomass concurrent with an increase in pelagic fish biomass, it has also been speculated that the reduction in zooplankton biomass was caused by pelagic fish and that the system is subject to top-down control (Huse et al., 2012). Subsequent modelling work based on the principle of chance and necessity, which allows reconstruction of a large number of possible ecosystem trajectories (Planque and Mullon, 2020) suggests on the other hand that there is some support for bottom-up control, no support of top-down control and weak support for competition between pelagic fish species. Results related to mackerel are associated with high degree of uncertainty (Planque et al., 2022). Based on these partly conflicting results, the understanding of importance of change in blue whiting stock size for other parts of the ecosystem is rated as less good.

Knowledge gaps: In 2014 the ICES Stock Identification Methods Working Group (SIMWG) reviewed the evidence of separate stocks based on the new scientific evidence (ICES, 2014b) and concluded that the perception of blue whiting in the NE Atlantic as a single-stock unit is not supported by the best available science. SIMWG further recommended that blue whiting be considered as two units. However, there is currently no information available that can be used as the basis for generating advice on the status of the individual stocks. There is still a need for more information regarding population structure in these stocks.

Blue whiting recruitment [NwI11]

Phenomenon: Decreasing blue whiting recruitment [NwP11]

Ecosystem characteristic: Functionally important species and biophysical structures

Key aspects of the blue whiting stock under the reference condition are described above for the indicator for stock size. Recruitment of the stock is highly variable between years. However, there have been periods with different recruitment regimes; a period with low recruitment before 1996, a high level regime in the period 1996-2005, low for 2006-2009 and variable thereafter (ICES, 2021d), but even rather low spawning stock biomasses have resulted in good recruiting year-classes. Spatial distribution of spawning varies between years due to variation in oceanographic conditions, with spawning under fresher and colder conditions in the spawning region occurring mainly along the European Continental Shelf edge west of Ireland, in particular on Porcupine Bank, while during more saline and warmer conditions, spawning expands further westward across Rockall Trough onto Rockall Plateau and shifts northward along the European Continental Shelf Spawning (Miesner and Payne, 2018). Shifts in oceanographic conditions between warm/saline and cold/fresh is linked to variation in the sub-polar gyre, with a stronger gyre producing colder and fresher conditions (Hatun et al., 2009). The eggs and larvae spawned on the Porcupine Bank area (west of Ireland) can drift both towards the south and towards the north, depending on the spawning location, oceanographic conditions, and the effects from wind force, while the spawning products from the northern spawning area west of the Hebrides always drift northwards. The northward drift spreads a major part of the juvenile blue whiting to the Norwegian Sea and adjacent areas from Iceland, Faroes and North Sea to the Barents Sea. The larvae usually settle on the deeper areas of the various shelf edges in autumn and stay more or less associated with bottom the first winter or more, gradually becoming part of the mature stock after two or three years.

The most important anthropogenic driver of change in the indicator is fisheries in the sense that high fishing pressure causing severe depletion in stock size can impair recruitment. While there was a considerable fishery on 0 group on the beginning of the 2000s, thus directly affecting recruitment, fisheries are now performed in the first and second quarter on the spawning grounds, i.e., mainly on mature fish, and thus having a potential to affect recruitment only indirectly through the size of the spawning stock. Although spawning distribution is clearly influenced by variations in the physical environment (Hatun et al., 2009; Miesner and Payne, 2018), this does not give reason to assume a link to climate change as an important driver, as this is connected to variation in the sub-polar gyre (Hatun et al., 2009) and not long term changes in temperature or other parameters that are projected to change as a consequence of anthropogenic impact on the climate. Thus, climate change is not considered an important anthropogenic driver for near future changes in blue whiting recruitment. The understanding of the link between fisheries and blue whiting recruitment is rated as less certain, as clear effects can be assumed only after long periods of unsustainable fishing on the spawning stock.

The understanding of importance of change in blue whiting recruitment for other parts of the ecosystem is rated as less good.

Knowledge gaps: Focus on potential mechanisms that may account for the hypothesized links between the oceanographic climate and the recruitment dynamics.

1. The predation hypothesis

This hypothesis examines the role of mackerel predation and changes in the spawning distribution of blue whiting. Changes in the spawning distribution leads to changes in the mackerel–blue whiting larvae overlap, and therefore the degree of predation.

1. The food hypothesis

This hypothesis is based on the amount and availability of food to the larvae and juveniles. Changes in the oceanographic conditions may change the food availability and ultimately impact larval/juvenile growth, survival and recruitment. More research is required to examine these topics (ICES, 2009b).

Calanus finmarchicus production [NwI12]

Phenomenon: Decreasing Calanus finmarchicus production [NwP12]

Ecosystem characteristic: *Functionally important species and biophysical structures*

Calanus finmarchicus is a key species in the Norwegian Sea. It is the dominant herbivore in Atlantic water masses, but it also occurs in high numbers on the cold side of the Arctic front (Broms and Melle, 2007; Broms et al., 2009; Melle et al., 2014; Kristiansen et al., 2019). It is the main food of herring, mackerel and young blue whiting, and the main initial prey for larvae of cod, herring, saith and haddock (e.g. Ellertsen et al. (1977); Dalpadado et al. (2000); Gislason and Astthorsson (2002); Dommasnes et al. (2004); Broms et al. (2012); Langøy et al. (2012); Bachiller et al. (2016)).

The most important anthropogenic driver of change in the indicator is climate change. Temperature affects the abundance, distribution and phenology of plankton populations. Rising temperatures are causing species to expand at the northern edge of their distribution and retreat at the southern edge (Beaugrand et al., 2009). It may be difficult to disentangle the effect of temperature and advection, as species assemblages are typically associated to a given water-mass (e.g. Melle et al. (2004)). During times with increasing temperature, the abundances of *C. finmarchicus* and other Sub-Arctic zooplankton species are expected to decrease (see phenomenon for copepod species vulnerable to higher temperature [NwP13]). To the extent that water temperature rise is associated with reduced transport of Arctic water into the Norwegian Sea, this will probably have the most instantaneous effect. Other studies have shown a negative development of mesozooplankton biomass in the Norwegian Sea since about year 2000 (Kristiansen et al., 2019; ICES, 2022d; Skagseth et al., 2022; Utne et al., 2022), but we do not know which species being part of the biomass, are responsible for the decrease. In the waters west of the British Isles, (Planque and Fromentin, 1996) showed a negative relationship between the abundance of *C. finmarchicus* and temperature, while the opposite was the case for the more temperate species *C. helgolandicus*. Although these waters are not part of the Norwegian Sea it is worth mentioning since it indicates that in the southern range of its distribution *C. finmarchicus* will respond negatively to a temperature increase. The Svinøy Standard Section, heading NW from the Svinøy Island off the coast at Møre has been sampled with vertical WP2 nets from 200m depth to the surface. The abundance of *C. finmarchicus* in the Atlantic region showed a decline from 1996 to 2012. In this study they made no attempts linking the changes in abundance to environmental factors (Dupont et al., 2017), but others have reported an increase in water temperatures in the section over the same time period (Skagseth and Mork, 2012). Given the lack of scientific studies, the understanding of the link between climate change and the indicator is rated as less certain.

C. finmarchicus is the major prey of pelagic fish species like herring, mackerel, and to some extent blue whiting and salmon (Dalpadado et al., 2000; Langøy et al., 2012; Bachiller et al., 2016; Melle et al., 2020; Utne et al., 2022). Eggs and nauplii of *C. finmarchicus* are also the major prey for fish larvae, especially herring and cod. Therefore, decreased abundance of *C. finmarchicus* likely will have adverse effect on the individual growth, recruitment, production and distribution and phenology of key commercial fish stocks. Given the mostly circumstantial evidence described above the understanding of the consequences from change in the indicator for the rest of the ecosystem is rated as less good.

Knowledge gaps: There is a lack of knowledge about the effect of increased temperature on the abundance of cold-water species themselves and the processes involved in the numerical regulations of the populations. The effect of reduced abundance of cold-water species on key pelagic fish stocks and carbon sequestration await quantification. Combined time-series analyses and process studies based on data sampled on the same temporal and spatial scale across trophic levels probably are the way forward.

Copepod species vulnerable to higher temperature [NwI13]

Phenomenon: Decreasing number of species sensitive to higher temperatures [NwP13]

Ecosystem characteristic: Biological diversity

The Norwegian Sea contains two main water masses (e.g., Blindheim 2004). In the central and eastern Norwegian Sea, surface waters down to approximately 500 m is dominated by relatively warm and saline Atlantic water. In the west, the East Icelandic Current brings cold and less saline water of Arctic origin into the basin. Towards east this water mass dives under the Atlantic water and forms what Blindheim (2004) referred to as intermediate Arctic water. The Arctic and Atlantic water masses are separated by the Arctic front and the whole region is characterised as Sub-Arctic by Longhurst (1998) and later by Beaugrand et al. (2002a). Arctic and Atlantic water masses contain unique collections of zooplankton species as described by Wiborg (1954), Østvedt (1955), Hirche (1991), Dalpadado et al. (1998), Aßmus et al. (2009), Melle et al. (2004)(and references therein), and Strand et al. (2020). A sampling line for CPR (Continuous Plankton Recorder) was operated during the years from 1948 to 1982, going from the Norwegian coast to Weather Station Mike. Over the years copepods with smaller body size showed great variability in abundance while larger species like *C. finmarchicus* and *Metridia longa* varied far less, showing no long-term trend (Aßmus et al., 2009). Only wind conditions showed any relationship to the variations in abundance (Aßmus et al., 2009). A key species in the Norwegian Sea is the copepod *Calanus finmarchicus*. Being an Atlantic species, it is the dominant herbivore in Atlantic water masses, but it also occurs in high numbers on the cold side of the Arctic front (Broms and Melle, 2007; Broms et al., 2009; Melle et al., 2014; Kristiansen et al., 2019). It is the main food of herring, mackerel and young blue whiting, and the main initial prey for larvae of cod, herring, saith and haddock (e.g. Ellertsen et al. (1977); Dalpadado et al. (2000); Gislason and Astthorsson (2002); Dommasnes et al. (2004); Broms et al. (2012); Langøy et al. (2012); Bachiller et al. (2016)). An Arctic complement to *C. finmarchicus* is *Calanus hyperboreus* (Hirche, 1991). While *C. finmarchicus* typically feature a one-year lifecycle, spawning at the surface closely linked to the phytoplankton spring bloom, *C. hyperboreus* spawn at several hundred meters during winter while the nauplii move to the surface to feed when the phytoplankton bloom occurs, a behaviour developed in response to unpredictable Arctic blooms (Hirche, 1991). Melle et al. (2004) gives an overview of species common to the Atlantic and Arctic water masses of the Norwegian Sea. The Atlantic copepod community: *Calanus finmarchicus*, *Metridia longa, Paraeuchaeta norvegica*. Their Arctic equivalents often from the same genus: *Calanus hyperboreus* and *Paraeuchaeta glacialis.* By statistical analyses of the CPR data from 1958-1999, Beaugrand et al. (2002a) grouped copepod species into 9 species assemblages ranging from Subtropical and warm-temperate assemblage to Arctic assemblage with their associated geographical distribution (Table 5.2).

The most important anthropogenic driver of change in the indicator is temperature increase. Temperature affects the abundance, distribution and phenology of plankton populations. Rising temperatures are causing species to expand at the northern edge of their distribution, while they are retreating at the southern edge (Beaugrand et al., 2009). It may be difficult to disentangle the effect of temperature and advection, as species assemblages are typically associated to a given water mass (e.g. Melle et al. (2004)). During times with increasing temperature the abundances of copepods, being members of the Sub-Arctic and Arctic species assemblages (Table 5.2), are expected to decrease. To the extent that water temperature rise is associated with reduced transport of Arctic water into the Norwegian Sea, this will probably have the most instantaneous effect. Other studies have shown a negative development of mesozooplankton biomass in the Norwegian Sea since about year 2000 (Kristiansen et al., 2019; ICES, 2022d; Skagseth et al., 2022; Utne et al., 2022), but we do not know which species being part of the biomass, are responsible for the decrease. During years with elevated advection of cold Arctic water into the system there is an increase in the abundance of the Arctic species, *C. hyperboreus* (Kristiansen et al., 2019; Skagseth et al., 2022). In the waters west of the British Isles, (Planque and Fromentin, 1996) showed a negative relationship between the abundance of *C. finmarchicus* and temperature, while the opposite was the case for the more temperate species *C. helgolandicus*. Although these waters are not part of the Norwegian Sea it is worth mentioning since it indicates that in the southern range of its distribution *C. finmarchicus* will respond negatively to a temperature increase. The Svinøy Standard Section, heading NW from the Svinøy Island off the coast at Møre has been sampled with vertical WP2 nets from 200m depth to the surface. The abundance of *C. finmarchicus* in the Atlantic region showed a decline from 1996 to 2012. In this study no attempts were made to link the changes in abundance to environmental factors (Dupont et al., 2017), but others have reported an increase in water temperatures in the section over the same time period (Skagseth and Mork, 2012). Given the lack of scientific studies, the understanding of the link between temperature and the indicator is rated as less certain.

The cold water species denoted above are representing the major preys of pelagic fish species like herring, mackerel, and to some extent blue whiting and salmon (Dalpadado et al., 2000; Langøy et al., 2012; Bachiller et al., 2016; Melle et al., 2020; Utne et al., 2022). Eggs and nauplii of *C. finmarchicus* are also the major prey for fish larvae, especially herring and cod. Therefore, decreased abundance of the cold-water copepods likely will have adverse effect on the individual growth, recruitment, production and distribution and phenology of key commercial fish stocks. Given the mostly circumstantial evidence described above the understanding of the consequences from change in the indicator for the rest of the ecosystem is rated as less good

There is a lack of knowledge about the effect of increased temperature on the abundance of cold-water species themselves and the processes involved in the numerical regulations of the populations. The effect of reduced abundance of cold-water species on key pelagic fish stocks and carbon sequestration await quantification. Combined time-series analyses, ecosystem modelling and process studies probably is the way forward.

Table 5.2 Biological composition of species assemblages and their ecological preferendum. From Beaugrand et al. 2002a. The time period considered in the analyses was 1958–1999. The names of some species assemblages have been slightly modified in comparison to those used in Beaugrand et al. (ibid.).

Name of the assemblage	**Species or taxa**	**Ecological preferendum**
1. Subtropical and warm-temperate species assemblage	*Undeuchaeta major, Acartia danae, Paracandacia bispinosa, Euchaeta media, Temora stylifera, Scolecithrix danae, Euchaeta marina, Candacia ethiopica, Eucalanus attenuatus, Lucicutia spp., Eucalanus elongatus, Candacia pachydactyla, Rhincalanus cornutus, Euchaeta pubera, Centropages violaceus*	Oceanic and pseudo-oceanic species generally found near shelf edges and in the northward extension of the Gulf Stream
2. Warm-temperate oceanic species assemblages	*Euchaeta acuta, Undeuchaeta plumosa, Euchirella rostrata, Neocalanus gracilis, Clausocalanus spp., Nannocalanus minor, Pleuromamma borealis, P. gracilis, P. abdominalis, P. xiphias, P. piseki, Calocalanus spp., Mesocalanus tenuicornis, Heterorhabdus papilliger, Centropages bradyi, Mecynocera clausi*	Oceanic warm water species, generally south of 52°N but concentration associated with the path of the North Atlantic Current above 521N east of the mid-Atlantic ridge
3. Warm-temperate pseudo-oceanic species assemblage	*Euchaeta gracilis, Euchaeta hebes, Ctenocalanus vanus, Calanoides carinatus*	Warm water shelf-edge species found south of about 50°N along the European shelf edge for years prior to the 1980s
4. Temperate pseudo-oceanic species assemblage	*Rhincalanus nasutus, Eucalanus crassus, Centropages typicus, Candacia armata, Calanus helgolandicus*	Species can be found in oceanic and neritic water, but their abundance is higher along shelf edges until about 55°N before the 1980s
5. Shallow-water species assemblage	*Isias clavipes, Anomalocera patersoni, Labidocera wollastoni*	Species generally found above the continental shelf but mainly abundant in shallow coastal regions
6. Continental shelf species assemblage	*Centropages hamatus, Temora longicornis, Pseudocalanus adult, Para-Pseudocalanus spp.*	Species generally found above the continental shelf
7. Cold-temperate mixed-water species assemblage	*Aetideus armatus, Pleuromamma robusta, Acartia spp., Metridia lucens*	Species indicative of mixed water more usually found at the boundary between warm water and subarctic water
8. Subarctic species assemblage	*Heterorhabdus norvegicus, Scolecithricella spp., Euchaeta norvegica, Calanus finmarchicus*	Species indicative of subarctic water
9. Arctic species assemblage	*Calanus hyperboreus, Metridia longa, Calanus glacialis*	Species indicative of arctic water

Copepod species benefitting from higher temperature [NwI14]

Phenomenon: Increasing number of copepod species benefitting from higher temperatures [NwP14]

Ecosystem characteristic: Biological diversity

The Norwegian part of the Norwegian Sea contains two main water masses (e.g. Blindheim (2004)). In the central and eastern Norwegian Sea, surface waters down to approximately 500 m is dominated by relatively warm and saline Atlantic water. In the west, the East Icelandic Current brings cold and less saline water of Arctic origin into the basin. Towards east this water mass dives under the Atlantic water and forms what Blindheim (2004) referred to as intermediate Arctic water. The Arctic and Atlantic water masses are separated by the Arctic front and the whole region is characterised as Sub-Arctic by Longhurst (1998) and later by Beaugrand et al. (2002a). Arctic and Atlantic water masses contain unique collections of zooplankton species as described by Wiborg (1954), Østvedt (1955), Hirche (1991), Dalpadado et al. (1998), Aßmus et al. (2009), Melle et al. (2004)(and references therein), and Strand et al. (2020). A sampling line for CPR (Continuous Plankton Recorder) was operated during the years from 1948 to 1982, going from the Norwegian coast to Weather Station Mike. Over the years copepods with smaller body size showed great variability in abundance while larger species like *C. finmarchicus* and *Metridia longa* varied far less, showing no long-term trend (Aßmus et al., 2009). Only wind conditions showed any relationship to the variations in abundance (Aßmus et al., 2009). A key species in the Norwegian Sea is the copepod *Calanus finmarchicus*. Being an Atlantic species, it is the dominant herbivore in Atlantic water masses, but it also occurs in high numbers on the cold side of the Arctic front (Broms and Melle, 2007; Broms et al., 2009; Melle et al., 2014; Kristiansen et al., 2019). It is the main food of herring, mackerel and young blue whiting, and the main initial prey for larvae of cod, herring, saith and haddock (e.g. Ellertsen et al. (1977); Dalpadado et al. (2000); Gislason and Astthorsson (2002); Dommasnes et al. (2004); Broms et al. (2012); Langøy et al. (2012); Bachiller et al. (2016)). An Arctic complement to *C. finmarchicus* is *Calanus hyperboreus* (Hirche, 1991). While *C. finmarchicus* typically feature a one-year lifecycle, spawning at the surface closely linked to the phytoplankton spring bloom, *C. hyperboreus* spawn at several hundred meters during winter while the nauplii move to the surface to feed when the phytoplankton bloom occurs, a behaviour developed in response to unpredictable Arctic blooms (Hirche, 1991). Melle et al. (2004) gives an overview of species common to the Atlantic and Arctic water masses of the Norwegian Sea. The Atlantic copepod community: *Calanus finmarchicus*, *Metridia longa, Paraeuchaeta norvegica*. Their Arctic equivalents often from the same genus: *Calanus hyperboreus* and *Paraeuchaeta glacialis.* By statistical analyses of the CPR data from 1958-1999, Beaugrand et al. (2002a) grouped copepod species into 9 species assemblages ranging from Subtropical and warm-temperate assemblage to Arctic assemblage with their associated geographical distribution (Table 5.2).

The most important anthropogenic driver of change in the indicator is temperature increase. Temperature affects the abundance, distribution and phenology of plankton populations. Rising temperatures are causing species to expand at the northern edge of their distribution, while they are retreating at the southern edge (Beaugrand et al., 2009). It may be difficult to disentangle the effect of temperature and advection, as species assemblages are typically associated to a given water mass (e.g. Melle et al. (2004)). During times with increasing temperature the abundances of copepods being members of the oceanic warm-temperate species assemblages (Table 5.2) are expected to increase. To the extent that water temperature rise is associated with increased transport of Atlantic water in the extension of the North-Atlantic current into the Norwegian Sea, this will probably have the most instantaneous effect. Strand et al. (2020) analysed spatial and seasonal occurrences of four Calanus species in CPR data from the Northern North Sea, the Norwegian Sea and western Barents Sea. The warm water representative of the four, *C. helgolandicus*, prevailed in the North Sea while diminishing abundances were found northwards towards the Barents Sea. With increasing temperature, the ratio of *C. helgolandicus* to *C. finmarchicus* is expected to increase (Strand et al., 2020). In the waters west of the British Isles, Planque and Fromentin (1996) showed a negative relationship between the abundance of *C. finmarchicus* and temperature, while the opposite was the case for the more temperate species *C. helgolandicus*. Although these waters are not part of the Norwegian Sea it is worth mentioning since it indicates positive effect on *C. helgolandicus* abundance from temperature increase, in waters up-stream to the Norwegian Sea. Given the lack of scientific studies, the understanding of the link between temperature and the indicator is rated as less certain.

Many of the warm-water species listed by Beaugrand et al. (2002a) are smaller and store fat for overwintering to a lesser degree than *C. finmarchicus*, which dominate copepod biomass today. Thus, we can expect deprived feeding conditions for pelagic fish species like herring, mackerel, and to some extent blue whiting and salmon if a switch towards smaller species occurs following a temperature rise (Dalpadado et al., 2000; Langøy et al., 2012; Bachiller et al., 2016; Utne et al., 2022). Eggs and nauplii of *C. finmarchicus* are also the major prey for fish larvae, especially herring and cod. *C. helgolandicus,* being an autumn spawner, at least in the North Sea, may not provide nauplii and eggs during spring to the same extent that *C. finmarchicus*. Therefore, increased abundance of the warm-water copepods likely will have adverse effect on the individual growth, recruitment and production of key commercial fish stocks. Given the mostly circumstantial evidence described above the understanding of the consequences from change in the indicator for the rest of the ecosystem is rated as less good

There is a lack of knowledge about the effect of increased temperature on the abundance of warm-water species and the processes involved in the numerical regulations of the populations. The effect of reduced abundance of warm-water species on key pelagic fish stocks and carbon sequestration await quantification. Combined time-series analyses and process studies probably is the way forward.

Heat content [NwI15]

Phenomenon: Increasing heat content [NwP15]

Ecosystem characteristic: Abiotic factors

Under the reference condition, which for abiotic factors is defined as the climate for 1961-1990 period, the Heat Content (HC) was generally low but with pronounced decadal variability. The number of observations going into the HC estimate were infrequent from the 1950s and has increased over time through the initiation of the fixed repeated sections in the 1970-80s, start of annual spring spatial surveys from 1995, and finally the implementation of the ARGO buoy program in the early 2000s. Based on this, estimates from the 1961-1990 period, especially the first half, are less certain.

The most important anthropogenic driver of heat content is anthropogenic greenhouse warming (Pörtner et al., 2019). Further, due to the northward amplification of global warming we expect higher increase in the heat content of the Norwegian Sea ecoregion compared with marine areas at lower latitudes (Skagseth and Mork, 2012; Mork et al., 2014; Mork et al., 2019). Based on the estimated record of heat content starting in 1951 (Mork et al., 2014), natural variability is likely to dominate over an anthropogenic signal on annual to multi-decadal scale. The understanding of the link between anthropogenic impact on the climate and the indicator is still rated as certain.

Changes in heat content can affect the Norwegian Sea ecosystem across different trophic levels (Skjoldal, 2004). Species composition of zooplankton is expected to be affected, with possible significant effects on higher trophic levels (see phenomena for NwI15 and NwI16). Migration of the major pelagic fish stocks may also be affected by changes in heat content, although it should be noted that this can also be strongly influenced by other factors, such as stock size. For example, geographical expansion of mackerel in the Norwegian sea between 2007 and 2016 has been attributed to increases in stock size, with temperature determining the direction of the changes in expansion (Olafsdottir et al., 2019). Nikolioudakis et al. (2018), looking at changes for the years 2011-2017 and using a different statistical framework than Olafsdottir et al. (2019), found no role of stock size but a clear role of temperature in driving changes in mackerel geographic distribution. The understanding of the consequences from change in the heat content for the rest of the ecosystem is rated as good.

Warming of the Atlantic water masses depend on the inflow of Atlantic Water, surface heating during summer and cooling during winter, and inflow of Arctic Water from the Iceland and Greenland Seas. More research supported by sustained observation through Argo buoys and other observation platforms is needed to better understand the relative contribution from these sources.

Freshwater content [NwI16]

Phenomenon: Increasing freshwater content [NwP16]

Ecosystem characteristic: Abiotic factors

Under the reference condition, which for abiotic factors is defined as the climate for 1961-1990 period, the freshwater content shows a general increase and prominent decadal variability on top of this trend (Dickson et al., 1988; Blindheim et al., 2000; Mork and Blindheim, 2000; Häkkinen and Rhines, 2004; Skagseth et al., 2008; Mork et al., 2014; Mork et al., 2019). The number of observations going into the estimation of freshwater content were low from the 1950s and increased with the initiation of fixed repeated sections in the 1970-80s and further with the start of annual spring spatial surveys from 1995, and finally with the implementation of the ARGO buoy program in the early 2000s. Based on this, estimates from the reference period, especially the first half, are less certain.

The most important anthropogenic driver of freshwater content is anthropogenic climate warming (Pörtner et al., 2019). With high certainty anthropogenic impact on the climate will lead to an increased hydrological cycle with increased evaporation in subtropics, and increased precipitation at mid-latitude. The integrated effect of this on the freshwater content is uncertain. The Greenland Ice cap has melted at a rate of 279 billion tonnes/year since 1990 (NASA, 2022). The faith of the Greenland ice cap meltwater, even expected to accelerate in future, is uncertain but have the potential to drastically increase the amount of freshwater and change the conditions in the Norwegian Sea ecoregion. Arctic sea ice melt also has the potential to contribute with freshwater (Kacimi and Kwok, 2022), and events of freshwater from the Arctic are previously reported to freshen the Atlantic layer of the Norwegian Sea (Dickson et al., 1988). The understanding of the link between anthropogenic impact on the climate and the indicator is rated as certain.

Increased amount of freshwater will contribute to increased stratification, which may affect phytoplankton dynamics (see phenomena NwP01 and NwP02). In addition, Freshwater Content has for the most recent decades been an indicator of the overall influence of sub-artic waters entrained into the Atlantic Water entering the Norwegian Sea (Hatun et al., 2005). Freshwater content is positively correlated to silicate in the Atlantic water (Rey, 2012). High levels of silicate favor diatom growth until ambient levels are depleted below 1-2 mol m^{-3} (Egge and Aksnes, 1992; Brown et al., 2003). Freshwater content is also positively correlated to overall zooplankton biomass and abundance of the large Arctic zooplankton species *Calanus hyperboreus* (Skagseth et al., 2022). The understanding of the consequences of changes in the indicator for other parts of the ecosystem is rated as good.

Freshwater Content have proven to be a very powerful indicator for the Norwegian Sea pelagic ecosystem. To take full advantage of this indicator, better understanding of the mechanistic relations is required.

Inflow of Arctic Water [NwI17]

Phenomenon: Change in volume of Arctic water [NwP17]

Ecosystem characteristic: Abiotic factors

Arctic Water is here defined as water with salinity < 34.9 at depth range 150-300m in Norwegian Basin. These data are based on similar hydrographic data as for HC and FC for the period 1995-2021. We do not have estimates for the reference period (1961-1990).

The most important anthropogenic driver of change in the indicator is climate change. The characteristics of the Arctic Water, produced in the Greenland – and Iceland Seas, depend on the source waters, the Polar - and Atlantic Water, as well as their modification by the local atmospheric forcing (Helland-Hansen and Nansen, 1909). Anthropogenic glacier- and sea ice melt may lead to fresher Arctic Water. In the end this could increase the Arctic influence in the Norwegian Sea under the assumption of similar flux into the Norwegian ecoregion. The exchange between the Iceland and Greenland Seas with the Norwegian Sea is in part wind driven (Spall et al., 2021), but knowledge of how the wind pattern may develop under climate change is uncertain. Overall, the understanding of the link between the driver and change in the indicator is rated as less certain.

The amount of Artic Water is an index of advection of Arctic Water to the Norwegian Sea ecoregion. It is characterized by elevations in levels of nutrients, total abundance of zooplankton and abundance of large zooplankton (Kristiansen et al., 2016; Kristiansen et al., 2019; Skagseth et al., 2022). Wild salmon feeding is found to improve in periods of increased amount of Arctic Water (Utne et al., 2022; Vollset et al., 2022). The understanding of the consequences of change in the indicator for the rest of the ecosystem needs to be further challenged but is still rated as good.

There is lack of data to resolve the mechanistic driving of Arctic Waters from the west into the Norwegian Sea ecoregion. Given the recent studies pointing the importance of the Arctic Water (Kristiansen et al., 2016; Kristiansen et al., 2019; Skagseth et al., 2022; Vollset et al., 2022), high priority should be given to improve the mechanistic understanding of this driver and its biological implication.

Stratification [NwI18]

Phenomenon: Increasing stratification [NwP18]

Ecosystem characteristic: Abiotic factors

Stratification is here defined as the density difference between 10m and 200m in the Norwegian and Lofoten basins. The indicator is based on the same hydrographic data as for Heat content and Freshwater content for the period 1995-2021. We do not have estimates for the reference period that has been set for climate (1961-1990). As the upper layer warms in the spring, vertical circulation of the upper water column changes from a deep winter to a shallow mixed layer. This is closely linked to the onset of the spring bloom (Sverdrup, 1953; Skjoldal, 2004). Storms will break down stratification and contribute to input of nutrients to the upper water column. Intensity of storms in winter will influence the amount of nutrients available at the onset of the spring bloom while the frequency of storms during summer will contribute to renewed input of nutrients and increased primary production (Lasker, 1981).

The most important anthropogenic driver of change in the indicator is climate change. Warming of the upper layer will increase the stability of the upper water column (Li et al., 2020). Climate change is also causing increased atmospheric humidity which may cause stronger winds and thus more energy for ocean mixing (Makarieva et al., 2013), in effect causing a deeper less stratified mixed layer. In addition, increased freshwater input due to an increased hydrological cycle that with high certainty is linked to climate change (see phenomenon NwP16), will contribute to increased stratification. The overall effect of these processes is an increase in stratification (Pörtner et al., 2019). Although the understanding of the links between climate change and each of these processes is rated as certain, the understanding of the link between the climate change and their combined impact on the indicator is rated as less certain.

As the onset of the spring bloom is closely linked to the transition from a deep winter – to a shallow mixed layer, change in the indicator may have consequences for primary production, affecting both timing and overall production. Such effects may propagate to the zooplankton community, affecting both overall production and match or mismatch between new primary production and zooplankton reproduction and growth (see phenomena NwP01 and NwP02). The understanding of the consequences of changes in the indicator for other parts of the ecosystem is rated as good.

Stratification can be estimated in numerous ways. Further work is underway to evaluate how the stratification parameter should be defined especially utilizing ARGO data providing that provide depth-time hydrographic profiles.

Inflow of Atlantic water [Nw19]

Phenomenon: Decreasing inflow of Atlantic water [NwP19]

Ecosystem characteristic: Abiotic factors

The Norwegian Atlantic Current (NwAC) is the poleward extension of the Gulf Stream and serves as a conduit of warm and saline Atlantic water from the North Atlantic to the Arctic Ocean. The inflow of Atlantic water is an important determinant of the local climate in the Norwegian Sea (Mork et al., 2014; Skagseth et al., 2022). Here we include an index of the Atlantic inflow to the Nordic Seas, based on moored current and temperature measurements in the NwAC (Orvik and Skagseth, 2003) over the 25-year period 1995–2022. Thus, this does not overlap with the period that has been defined as descriptive for the reference condition for climate.

The NwAC is both thermohaline and wind driven, and the influence these two factors are likely time scale dependent (Skagseth et al., 2008). There are likely two opposing effects. On seasonal to annual time scale increased winds assumably will amplify the NwAC (Skagseth et al., 2004; Bringedal et al., 2018; Orvik, 2022). On longer time scales thermohaline forcing (mainly a weaker cooling) may reduce and in effect weaken the NwAC (Spall, 2010; Bringedal et al., 2018). Overall, the Atlantic inflow is likely to show moderate reduction as a consequence of climate change. While the understanding of the link between climate change and each of the two processes described above (wind driven strengthening and thermohaline driven weakening of the inflow) is rated as certain, the understanding of their combined impact on the indicator is rated as less certain.

The Atlantic Inflow with the NwAC carries an enormous amount of heat (Orvik and Skagseth, 2003), salt and nutrients and thus in a broad sense have the potential to affect all trophic levels in the Norwegian Sea ecoregion. Changes in this indicator may lead to large changes in the ecosystem functioning. Processes that are expected to be affected include primary production, organism metabolism (increasing with temperature), zooplankton species composition (see phenomena NwP13 and NwP14) and area of habitat suitable for the main pelagic fish species (Skjoldal, 2004). This indicator representing the variability in the strength of the Atlantic inflow is assumed to be important not only for the Norwegian Sea but also for the downstream Barents Sea and the Arctic Ocean. The understanding of the consequences of changes in the indicator for other parts of the ecosystem is rated as good.

The processes governing the Inflow of Atlantic Water is still not fully resolved and further observations are needed to advance this understanding.

Nutrients [NwI20]

Phenomenon: Change in concentration of nutrients [NwP20]

Ecosystem characteristic: Abiotic factors

Concentrations of nitrate is important for determining the level of total primary production while silicate is the single most essential element for sustained diatom growth and thus determines whether the phytoplankton community is dominated by diatoms or other groups of phytoplankton. Limitations in access to silicate and other macronutrients in the Norwegian Sea may shorten the spring diatom bloom period and hamper zooplankton growth, which in turn may have consequences for growth and development of commercially important fish stocks (Egge and Aksnes, 1992; Gundersen, 2020). Ocean circulation changes are shown to have a major influence on the amount and composition of nutrients in the Norwegian Sea (Garcia and Levitus, 2006; Rey, 2012; Hatun et al., 2017; Gundersen, 2020). In addition, the stratification and thus the vertical mixing determines the amount of nutrients in the photic zone that are made available for primary production (see phenomenon NwP18).

The most important anthropogenic driver of change in the indicator is climate change. Greenland Ice Cap melt is expected to add nutrient rich meltwater to the Norwegian Sea. The relative strength of Atlantic and Arctic inflow influences nutrient concentrations in the Norwegian sea, with increasing Arctic inflow contributing to higher nutrient levels (see phenomenon NwP17). As the understanding of the link between climate change and the inflow of Arctic water is rated as less certain (ibid.), understanding of the link between climate change and the indicator nutrients is also rated as less certain. Given this uncertainty, there is no clear expectation of either an increase or decrease in nutrient concentrations as a consequence of climate change.

As the seasonal growth of copepods (*Calanus* spp.) is tightly coupled to the diatom spring bloom (Egge and Aksnes, 1992), a reduction in silicate could have a strong effect on their production. Silicate uptake by diatoms diminishes strongly below ambient silicate concentrations of 1–2 mol m^{-3} (Egge and Aksnes, 1992; Brown et al., 2003). This means that the main growth of diatoms is expected to take place above this concentration level. A decrease in diatom biomass due to the silicate reduction during the spring bloom would leave larger concentrations of unused nitrate that would be utilized by other phytoplankton forms leading to other routes for channeling the produced energy to higher trophic levels. Thus, a reduction in silicate could have a strong effect on copepod production, and further affect the major fish stocks in the Norwegian Sea.

Between 2000 and 2010, there was a reduction in zooplankton biomass in the Norwegian Sea. It has been suggested that the main reason was a strong increase in the biomass of several pelagic fish stocks such as herring, blue whiting, and mackerel (Gjøsæter et al., 2011). Based on this, it has been hypothesized that the ecosystem in the Norwegian Sea is under top–down control. However, the 20% decrease in silicate concentrations in the same period may also have had an impact on the reduction in zooplankton biomass. Hence, the possibility that bottom–up control is also present cannot be excluded (Rey, 2012). In addition, due to their large size and rapid sinking rate, diatoms also play a key role in the export of biological material to deeper waters and therefore in the biogeochemical cycles in the ocean. Overall, the understanding of consequences from changes in the indicator for other parts of the ecosystem is rated as good.

Winter silicate concentrations in the Norwegian and Barents Seas is controlled by the dynamics of the North Atlantic Subpolar Gyre, and its subsequent effect on the inflow into the Norwegian Sea, should be considered when attempting to make realistic ecosystem predictions. Continuous long and regular time-series observations of nutrients is needed to get a better understanding of the natural variability in marine ecosystems.

pH [NwI21]

Phenomenon: Decreasing pH [NwP21]

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. Oceanic uptake of excess atmospheric CO_2 released by human activities, such as burning of fossil fuels and industrialisation, have increased the amount of CO_2 in the oceans. Since 1985, observations of the global ocean show that pH in surface water has decreased by about 0.002 per year (Copernicus Marine Services, 2021). This corresponds to an increase in hydrogen ions (less basic ocean). For the Nordic Seas region, surface water pH has decreased at a slightly faster rate relative to the global ocean by 0.002-0.003 per year in the period 1981-2019 (Fransner et al., 2022). Continued pH decrease is rated as highly likely (Pörtner et al., 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 pumps and other redox reactions. Changes in pH may also affect the availability and toxicity of vital metals, potentially changing 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 (e.g., 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 of the effect of reduced pH directly on marine organisms and ecosystems. The effects need to be related to studies of adaptive capacity and multi-stressors. This also requires multi-disciplinary, observational long-term data sets in relevant areas (Browman, 2016).

Aragonite saturation [NwI22]

Phenomenon: Decreasing aragonite saturation [NwP22]

Ecosystem characteristic: Abiotic factors

Under the reference condition, aragonite saturation is high enough for calcifying organisms with aragonitic shells and skeletons to occur with biomasses high enough to sustain food webs in the Norwegian Sea and ecological processes characterising this regional ecosystem.

The most important anthropogenic driver of change in the indicator is climate change. Oceanic uptake of excess atmospheric CO_2 released by human activities, such as burning of fossil fuels and industrialisation, has increased the amount of CO_2 in the oceans over a relatively short time period. The oceanic carbonate ion concentration (CO_3^{2-}) is driving the saturation of calcium carbonate ($CaCO_3$) biominerals, including aragonite, and the chemical dissolution of the $CaCO_3$ biominerals. Decreasing pH (from increasing ocean CO_2) has resulted in a decrease in the calcium carbonate saturation state (Ω), with consequences for the dissolution potential and calcification process. Aragonite is the most labile form of $CaCO_3$ in the ocean and the Nordic Seas region has shown decreased Ω of 0.012 per year in the period 1981-2019 and $CaCO_3$ undersaturation in the depth layer of 1000–2000 m (Fransner et al., 2022). Continued decrease of Ω is rated as highly likely (Pörtner et al., 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 impacts $CaCO_3$ 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<1) in the ocean, which will continue and has consequences for cold water corals and their ability to withstand erosion and continue to grow (ICES, 2014a). At Ω<1 more energy is required by organisms to produce $CaCO_3$ (e.g., Comeau et al. (2013)). Climate-driven changes such as ocean warming enhance 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).

Several economically important shellfish species can be weakened by ocean acidification (e.g. Agnalt et al. (2013); Andersen et al. (2013)), and this could also be the case for cold-water coral reefs that are found along the Norwegian coast (Turley et al., 2007). Cold-water corals build their structures out of aragonite and have compensation mechanisms to be able to calcify when ΩAr <1. However, the calcification rates and strength of the structures is reduced under low ΩAr (Hennige et al., 2015). Cold-water coral reefs and their ecosystems are therefore likely to be adversely affected if seawater becomes undersaturated with respect to aragonite. The cold-water coral sites in the Nordic Seas are generally located between 0 and 500 m depth and currently the aragonite saturation horizon is located at greater depths. However, model projections show that shoaling of the horizon may expose cold-water reefs to corrosive waters by the end of this century (Fransner et al., 2022). Further, some non-calcareous organisms have shown to be adversely affected by changes in CO_2 or low pH, and other organisms even respond positively to high CO_2 content and low pH (Dupont and Pörtner, 2013).

There are large knowledge gaps about the thresholds and adaptive capacity of organisms to perform calcification at low saturation states in the ocean. The effect on the marine ecosystem is little understood and the effects need to be related to studies of adaptive capacity and influence of several different environmental stressors (Rastrick et al., 2018). This also requires multi-disciplinary, observational long-term data sets in relevant areas. Overall, the understanding of the importance of changes in the indicator for the ecosystem is rated as less good.

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 a Table 6.1.

Table 6.1. Description of the indicators per ecosystem characteristic in the Norwegian 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 [NwI01] Timing of the spring bloom [NwI02]	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 impacts on other parts of the ecosystem, in particular the type of herbivorous zooplankton that dominates. There is also a lack of **direct (in situ) measurements** of primary production with the aim of calibrating satellite-based estimates. Given these gaps, the indicator coverage for this ecosystem characteristic is rated as **partially adequate**.
Biomass distribution among trophic levels	Annual primary productivity [NwI01]	This indicator represents the producers (phytoplankton) in the ecosystem, making photosynthetically fixed carbon available for consumers.	Indicators on biomass **marine mammals**, **carnivorous zooplankton** (e.g., krill, amphipods, chaetognaths and gelatinous zooplankton) and **mesopelagic species**, respectively, are lacking in the assessment. This is an important gap in the indicator coverage, as these groups constitute a considerable part of the biomass at the trophic levels of secondary consumers and above. Indicators on **microbes** are lacking altogether, meaning that there is no information on an important process such as the microbial loop. 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 between groups to allow for robust comparisons of biomass trends. However, indicators included here cover several of 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	Mesozooplankton biomass relative to pelagic fish biomass [NwI03]	This indicator represents the trophic balance between mesozooplankton prey and pelagic fish biomass. Together, these two groups represent a large part of the biomass of primary and secondary consumers in the ecosystem.	
Biomass distribution among trophic levels	High trophic level seabirds [NwI04]	F ish eating seabirds are a significant part of the top predator guild in the Norwegian Sea. 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.	
Functional groups within trophic levels	Mesozooplankton body size [NwI05]	Changes in the average copepod body size is expected to alter the food web structure and the carbon transfer between trophic levels.	Indicators are lacking for functions related to fish, seabirds, marine mammals, invertebrate mesopelagic species, other zooplankton species than copepods as well as microbes and parasites. Given these large gaps, the indicator coverage for this ecosystem characteristic is rated as **inadequate**.
Functionally important species and biophysical structures	Mackerel stock size [NwI06] Mackerel recruitment [NwI07]	Mackerel, herring and blue whiting constitute the three major fish stocks in the ecosystem and are important as both predators and prey. Important prey groups are zooplankton and partly fish larvae. For example, mackerel is a potentially important predator on herring larvae. Recruitment is an important ecological process that help characterize the stock itself.	There are no indicators for marine mammals, important mesopelagic species, microbes and important groups of larger zooplankton such as krill and amphipods. However, the three pelagic fish stocks and *C. finmarchicus* are dominant species in the ecosystem, and the indicator coverage is therefore rated as **partially adequate**.
Functionally important species and biophysical structures	Herring stock size [NwI08] Herring recruitment [NwI09]		
Functionally important species and biophysical structures	Blue whiting stock size [NwI10] Blue whiting recruitment [NwI11]		
Functionally important species and biophysical structures	*Calanus finmarchicus* production [NwI12]	The stock constitutes a major food source for the three major pelagic fish stocks (mackerel, herring and blue whiting) and thus forms an important link between the primary producers and upper trophic levels.	

Landscape-ecological patterns	There are no indicators for this ecosystem characteristic		Indicators included in other marine PAEC assessments (Arneberg et al., 2023; Siwertsson et al., 2023) were not considered relevant for the current assessment. For example, the indicator on area unaffected by bottom trawling, used in the North Sea, was not relevant, as the current assessment focuses on the pelagic ecosystem and does not include benthic habitats. For the Barents Sea, indicators for area of habitats defined by, respectively, sea ice and Arctic Water were used. Similar indicators were not relevant for the current assessment, as it focuses on areas that don't have seasonal ice cover. For the next round of assessment, work should be done to identify other habitat defining parameters, such as area with temperature suitable for different pelagic fish species.
Biological diversity	Copepod species vulnerable to climate warming [Nw13]	The role of the two indicators is to assess changes in species diversity of copepods, which constitute an important component in the ecosystem	Indicators on biological diversity are lacking for all other groups than copepods, and the indicator coverage is therefore rated as **inadequate**.
Biological diversity	Copepod species benefitting from climate warming [NwI14]		
Abiotic factors	Heat content [NwI15]	The role of the indicator is to assess and quantify changes in temperature over the period with available hydrographic observations.	The set of indicators are covering the key aspects of the abiotic part of the ecosystem, and the indicator coverage for this ecosystem characteristic is therefore rated as **adequate**.
Abiotic factors	Freshwater content [NwI16]	Freshwater content is linked to degree of stratification in the water column, which may in turn be linked to dynamics if primary producers. Freshwater Content has for the most recent decades also been an indicator of the overall influence of sub-artic waters entrained into the Atlantic Water entering the Norwegian Sea (Hatun et al., 2005) and is correlated to silicate concentration in the Atlantic Water (Rey, 2012).	
Abiotic factors	Arctic Water [NwI17]	The amount of Arctic Water is an indicator of advection of Arctic Water to the Norwegian Sea, which is related to concentration of nutrients and biomass and species composition of zooplankton (Skagseth et al., 2022).	
Abiotic factors	Stratification [NwI18]	Variation in degree of stratification of the water column can have significant impact on the dynamics of primary producers.	
Abiotic factors	Inflow of Atlantic Water [NwI19]	Atlantic inflow constitutes the main transport of heat into the ecosystem.	
Abiotic factors	Nutrients [NwI20]	Availability of nutrients is typically a limiting factor for primary producers.	
Abiotic factors	pH [NwI21]	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 [NwI22]	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 7.1). 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). For TRyr we interpret that the time series should cover a time period with reference condition (intact nature) for the indicator to be assessed as adequate.
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.

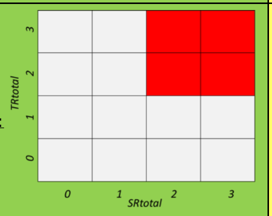
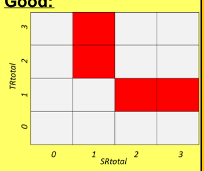
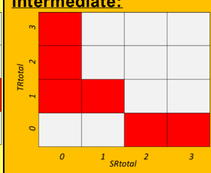
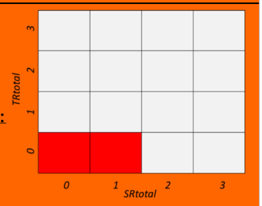
		Categories			
Spatial Representativity (SR)	SRd1	**Fulfilled** : Design-based sampling where the entire sampling population has a possibility of being included.		**Not fulfilled** : Design-based sampling where only a SUBSET of the sampling population has a possibility of being included.	
	SRd2	**Fulfilled** : 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. See section for definition of terms in the beginning of the report for definitions of the terms "design-based sampling" and "model-based sampling".

Table 7.1. Assessment of the knowledge base for the datasets, indicators and ecosystem characteristics for the Norwegian sea. Numbers are footnotes given 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**
	1	2	3	4		5	6		Annual primary productivity [NwI01]	Primary production 7
	1	2	3	4		5	6		Timing of the spring bloom [NwI02]	Primary production 7
	1	2	3	4		5	6		Annual primary productivity [NwI01]	Biomass distribution among trophic levels 20
	8	9	10	11		12	13		Mesozooplankton biomass relative to pelagic fish biomass [NwI03]	Biomass distribution among trophic levels 20
	14	15	16	17		18	19		High trophic level seabirds [NwI04]	Biomass distribution among trophic levels 20
	21	22	23	24		25	26		Copepod body size [NwI05]	Functional groups within trophic levels 27
	28	29	30	31		32	33		Mackerel stock size [NwI06]	Functionally important species and biophysical structures 70
	34	35	36	37		38	39		Mackerel recruitment [NwI07]	Functionally important species and biophysical structures 70
	40	41	42	43		44	45		Herring stock size [NwI08]	Functionally important species and biophysical structures 70
	46	47	48	49		50	51		Herring recruitment [NwI09]	Functionally important species and biophysical structures 70
	52	53	54	55		56	57		Blue whiting stock size [NwI10]	Functionally important species and biophysical structures 70
	58	59	60	61		62	63		Blue whiting recruitment [NwI11]	Functionally important species and biophysical structures 70
	64	65	66	67		68	69		*Calanus finmarchicus* productivity [NwI12]	Functionally important species and biophysical structures 70
	71	72	73	74		75	76		Copepod species vulnerable to higher temperature [Nw13]	Biological diversity 83
	77	78	79	80		81	82		Copepod species benefitting from higher temperature [NwI14]	Biological diversity 83
	84	85	86	87		88	89		Heat content [NwI15]	Abiotic factors
	90	91	92	93		94	95		Freshwater content [NwI16]	Abiotic factors
	96	97	98	99		100	101		Arctic water [NwI17]	Abiotic factors
	102	103	104	105		106	107		Stratification [NwI18]	Abiotic factors
	108	109	110	111		112	113		Inflow of Atlantic water [NwI19]	Abiotic factors
	114	115	116	117		118	119		Nutrients [NwI20]	Abiotic factors
	120	121	122	123		124	125		pH [NwI21]	Abiotic factors
	126	127	128	129		130	131		Aragonite saturation [NwI22]	Abiotic factors

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 (**Figure 7.2**) and presented in a table (**Table 7.2**). 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.

<table>
<tr><th>Validity of Phenomenon (VP)</th><th>Evidence for Phenomenon (EP)</th></tr>
<tr><td>High : A CERTAIN link to relevant drivers, and a GOOD understanding of the role of the indicator in the ecosystem.</td><td>High : High level of evidence that the expected changes in the indicator have occurred. High (expected or observed) ecosystem significance of observed changes.</td></tr>
<tr><td rowspan="2">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.</td><td>Intermediate : High level of evidence that the expected changes in the indicator have occurred. Limited (expected or observed) ecosystem significance of observed changes.</td></tr>
<tr><td>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.</td></tr>
<tr><td rowspan="2">Low : A LESS CERTAIN link to relevant drivers, and a LESS GOOD understanding of the role of the indicator in the ecosystem.</td><td>None : No evidence that the expected changes in the indicator have occurred (sufficient data).</td></tr>
<tr><td>Insufficient : No evidence that the expected changes in the indicator have occurred (insufficient data).</td></tr>
</table>

Figure 7.2 The criteria and color coding used in the assessment of the phenomena (Table 7.2).

Table 7.2. Assessment of the phenomena in the Norwegian Sea. For definitions of categories and criteria see Figure 7.2. The assessment of the evidence of the phenomenon, EP, can vary in different areas of the ecosystem being assessed and therefore two columns are presented. Details on VP are found under the phenomena description for each indicator in section 5.1.

Ecosystem characteristic	Indicator	Phenomenon [ID]	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)	Comments EP
Primary productivity	Annual primary productivity [NwI01]	Decreasing primary production [NwP01]	High	None	There is no evidence of a decreasing trend in the variable and thus no evidence of this phenomenon.
Primary productivity	Timing of the spring bloom [NwI02]	Change in timing of spring bloom [NwP02]	Low	None	There is no evidence of a decreasing or increasing trend in the variable and thus no evidence of this phenomenon.
Biomass distribution among trophic levels	Annual primary productivity [NwI01]	Decreasing primary production [NwP01]	High	None	There is no evidence of a decreasing trend in the variable and thus no evidence of this phenomenon.
Biomass distribution among trophic levels	Mesozooplankton biomass relative to pelagic fish biomass [NwI03]	Change in relative biomass of mesozooplankton to pelagic fish OR change in biomass ratio of mesozooplankton and pelagic fish [NwP03]	Low	None	Based on the linear model, there is a declining trend in the biomass of mesozooplankton relative to biomass of pelagic fish over the entire length of the time series. However, this trend cannot be clearly attributed to anthropogenic drivers. As noted for the assessment of the mackerel (NwI06) and herring (NwI08) stock sizes, fishing above recommended levels after 2013 has contributed to declines in these stocks. Based on the Bayesian trend analysis, a non-linear model is suggested as the best fit for the variable (i.e., mesozooplankton biomass relative to pelagic fish biomass), exhibiting a decline in the first part followed by an increase in the latter part. Thus, the fisheries driven declines in mackerel and herring stocks contributes to the increase on the latter part of the time series, towards values in the beginning. Overall, the declining trend cannot be attributed to impact from anthropogenic drivers with any reasonable confidence, and it is therefore assessed that there is no evidence for the phenomenon.
Biomass distribution among trophic levels	High trophic level seabirds [NwI04]	Decreasing populations of pelagic high TL seabirds [NwP04]	High	High	The data show a strong long-term (40 years) decline (>70%) in the populations of pelagic seabirds. In several studies this decline has been linked to overfishing and climate change. It is therefore concluded that there is high evidence that the phenomenon has occurred.
Functional groups within trophic levels	Copepod body size [NwI05]	Decreasing average copepod body size [NwP05]	High	Data insufficient	The time series is too short (8 years) to assess whether there has been a change in variable that can be attributed to effects of climate change
Functionally important species and biophysical structures	Mackerel stock size [NwI06]	Decreasing mackerel stock size [NwP06]	Low	Intermediate	The early decline is likely linked to fishing above recommended quotas. Effects of fishing above reccomended quotas in the recent years is hidden by good recruitment and year classes, but the stock size should be higher with less fishing (ICES, 2021d). There is thus intermediate evidence for this phenomenon
Functionally important species and biophysical structures	Mackerel recruitment [NwI07]	Change in mackerel recruitment [NwP07]	Low	Low	After the 2000s, recruitment has improved, maybe because of climate change, but the processes are uncertain. The evidence of the phenomenon is thus assessed as low.
Functionally important species and biophysical structures	Herring stock size [NwI08]	Decreasing herring stock size [NwP08]	Intermediate	Intermediate	The development of the stock is highly influenced by variation in recruitment. Recruitment is highly variable, with low recruitment in most years and high recruitment approximately once a decade. Last year with high recruitment was 2016. Looking at the most recent years, there has been a decline in stock size after 2008. A part of this decline is due to low recruitment for most of these years. Another part of the decline is caused by fishing about 30% above recommended levels since 2013, due to a lack of quota sharing agreement between the countries involved in the fisheries after this year. The latter has resulted in an accumulated 1.5 million tonnes catch above recommended levels since 2013. Thus, while fisheries have clearly contributed to the decline in the stock, there are uncertainties about the consequences of this for other parts of the ecosystem, and the evidence of the phenomenon is therefore set to intermediate.

Ecosystem characteristic	Indicator	Phenomenon [ID]	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)	Comments EP
Functionally important species and biophysical structures	Herring recruitment [NwI09]	Decreasing herring recruitment [NwP09]	Low	None	There is no trend in the time series, and thus no evidence of a lowered recruitment due to fisheries. Rather, other factors, such as temperature and size of the mackerel stock may be influencing recruitment (Garcia et al., 2020).
Functionally important species and biophysical structures	Blue whiting stock size [NwI10]	Decreasing blue whiting stock size [NwP10]	Intermediate	None	There is an increasing trend when looking over the whole length of the time series. As for herring, the size of the stock is strongly influenced by recruitment. Recruitment show a different pattern of variation than for herring, with high or low recruitment occurring over consecutive years rather than high recruitment in single years, possibly as a result of similar between year variation in the strength of the sub-polar gyre (Hatun et al., 2009; Payne et al., 2012; Miesner and Payne, 2018). While there has been a lack of a quota sharing agreement after 2013 and consequently a considerable fishing above the recommended total allowable catch, this has not generated a decline in the stock size for the period that has followed. It is therefore assessed that there is no evidence of the phenomenon.
Functionally important species and biophysical structures	Blue whiting recruitment [NWI11]	Decreasing blue whiting recruitment [NwP11]	Low	None	There is no evidence of a decline in the time series. As described above, there is evidence that recruitment is driven by oceanographic processes. It is therefore assessed that there is no evidence of the phenomenon.
Functionally important species and biophysical structures	*Calanus finmarchicus* production [NwI12]	Decreasing *Calanus finmarchicus* production [NwP12]	Low	None	There is no evidence of a decline in the variable. Thus, it is assessed that there is no evidence of the phenomenon.
Biological diversity	Copepod species vulnerable to climate warming [Nw13]	Decreasing number of copepod species sensitive to higher temperatures [NwP13]	Low	Data insufficient	The time series is too short (8 years) to assess whether there has been a change in variable that can be attributed to effects of climate change
Biological diversity	Copepod species benefitting from climate warming [NwI14]	Increasing number of copepod species benefitting from higher temperatures [NwP14]	Low	Data insufficient	The time series is too short (8 years) to assess whether there has been a change in variable that can be attributed to effects of climate change
Abiotic factors	Heat content [NwI15]	Increasing heat content [NwP15]	High	High	There is a clear increase in temperature that is attributed to anthropogenic impact on climate. In particular, reduced levels of cooling of Atlantic water due to a warmer atmosphere, is important. The changes are expected to have significant impact on other parts of the ecosystem. The evidence for the phenomenon is thus rated as high.
Abiotic factors	Freshwater content [NwI16]	Increasing freshwater content [NwP16]	High	None	There is large natural variation in the indicator. Therefore, it is hard to assess whether the indicator has changed as a consequence of anthropogenic impact. It is therefore assessed that there is no evidence that the phenomenon has occurred, but there is considerable uncertainty associated with this due to the high natural variability.
Abiotic factors	Inflow of Arctic water [NwI17]	Change in volume of Arctic Water [NwP17]	Intermediate	Data insufficient	The time series is too short to assess whether there is a long-term trend that may be linked to anthropogenic climate change on top of natural variation.
Abiotic factors	Stratification [NwI18]	Increasing stratification [NwP18]	Intermediate	Data insufficient	The time series is too short assess whether there is a long-term trend that may be linked to anthropogenic climate change on top of natural variation. The slightly decreasing trend seen for this time series, indicating weaker stratification, is thus hard to attribute to anthropogenic climate change. It should also be noted that this weak trend is mainly driven by the two last years of the series, when stratification was lower than during the previous years. These low values could be due to increased mixing of the upper water column due to increased winds, but further analyses would be required to confirm this.
Abiotic factors	Inflow of Atlantic water [NwI19]	Decreasing inflow of Atlantic Water [NwP19]	Intermediate	Data insufficient	The time series is too short assess whether there is a long-term trend that may be linked to anthropogenic climate change on top of natural variation. The time series shows high interannual variability and no trend, which is supported by a recent publication (Orvik, 2022).
Abiotic factors	Nutrients [NwI20]	Change in concentrations of nutrients [NwP20]	Intermediate	Data insufficient	The time series is too short assess whether there is a long-term trend that may be linked to anthropogenic climate change on top of natural variation. The time series show a strong declining trend for silicate concentrations. This is likely influenced by a weakened state of the sub-polar gyre index since the mid 1990's, which affects the inflow of nutrients into the Norwegian Sea (Hatun et al., 2017). The results are low levels of silicates in the whole water column and relatively higher ratio of nitrogen to silicate.

Ecosystem characteristic	Indicator	Phenomenon [ID]	Validity of Phenomenon (VP)	Evidence for Phenomenon (EP)	Comments EP
Abiotic factors	pH [NwI21]	Decreasing pH [NwP21]	Intermediate	Intermediate	Despite a short time-series, there is a clear decreasing trend in pH. As there are considerable uncertainties about the consequences of this for other parts of the ecosystem, the evidence for the phenomenon is rated as intermediate.
Abiotic factors	Aragonite saturation [NwI22]	Decreasing aragonite saturation [NwP22]	Intermediate	Intermediate	Despite a short time-series, there is a clear decreasing trend in aragonite saturation. As there are considerable uncertainties about the consequences of this for other parts of the ecosystem, the evidence for the phenomenon is rated as intermediate.

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, which provide time-series plots and trend analyses for each indicator, and 2) the PAEC assessment diagrams (Fig. 7.3.1). 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.

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

No deviation from the reference condition

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

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

Limited deviation from the reference condition

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

- Most or all of the phenomena should be in the orange cells in the PAEC assessment diagram (Fig. 7.3.1a, b)
- Most or all phenomena should have either low evidence (EP=Low) or intermediate evidence (EP=Intermediate) in combination with a low-intermediate validity (VP=Low or Intermediate)
- This category is often assigned with lower confidence than the other two categories, since it can include phenomena which both have low-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.

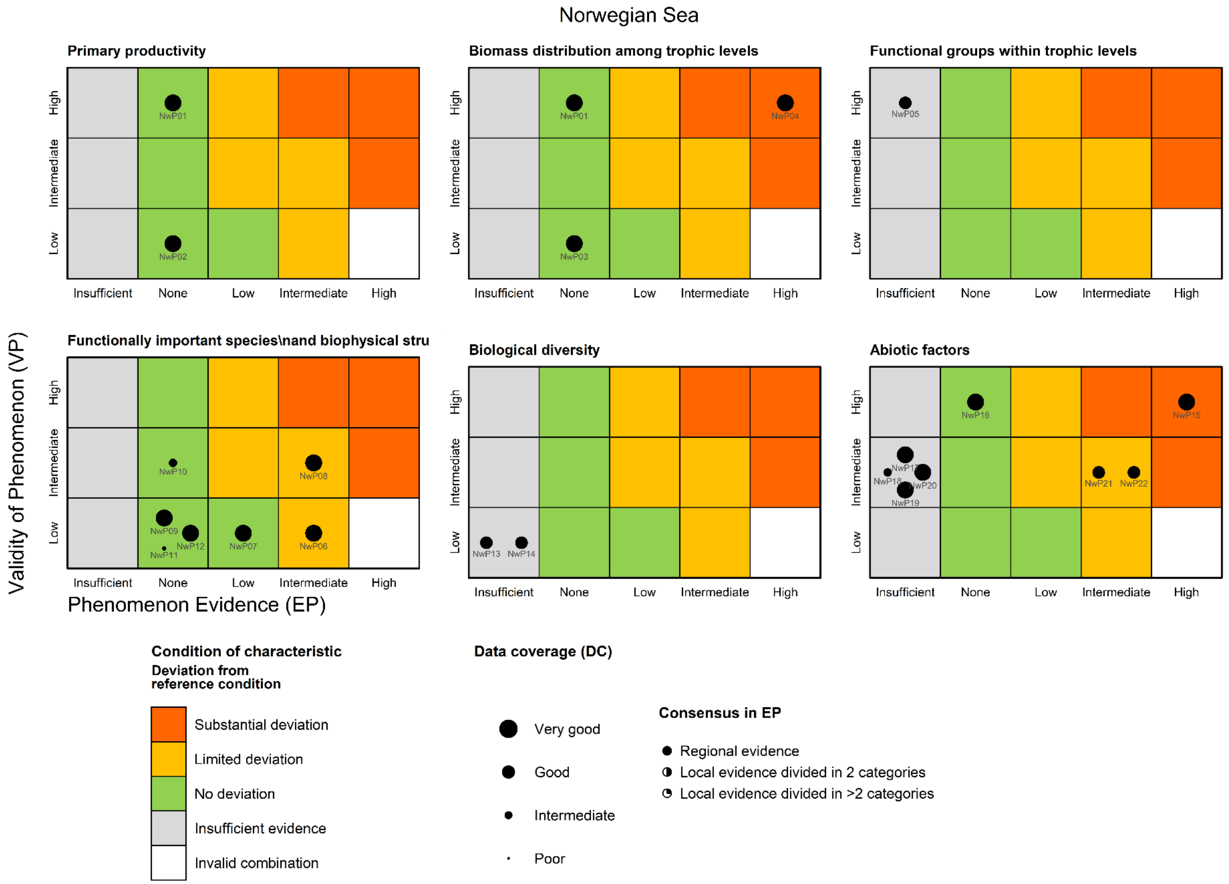
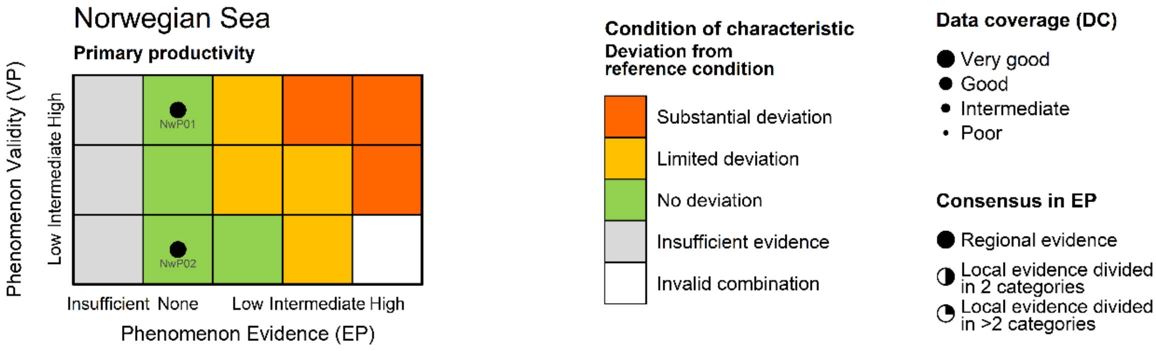


Figure 7.3.1. The PAEC assessment diagram provides an overview of all phenomena for all ecosystem characteristics. Each dot represents the assessment of a phenomenon with ID (from Table 5.1). The size of the dot indicates the data coverage (DC; larger symbols = better coverage, from Table 7.1). The placement of the dot shows the value for the validity (VP) of the phenomenon and the levels of evidence (EP) for the phenomenon (from Table 7.2). 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 colored boxes, within the diagrams for each of the ecosystem characteristics, indicate the condition of the respective characteristic

Norwegian Sea – Primary productivity



ID	Phenomenon	Time-period
NwP01	Decreasing primary production	2003-2020
NwP02	Change in timing of spring bloom	2003-2020

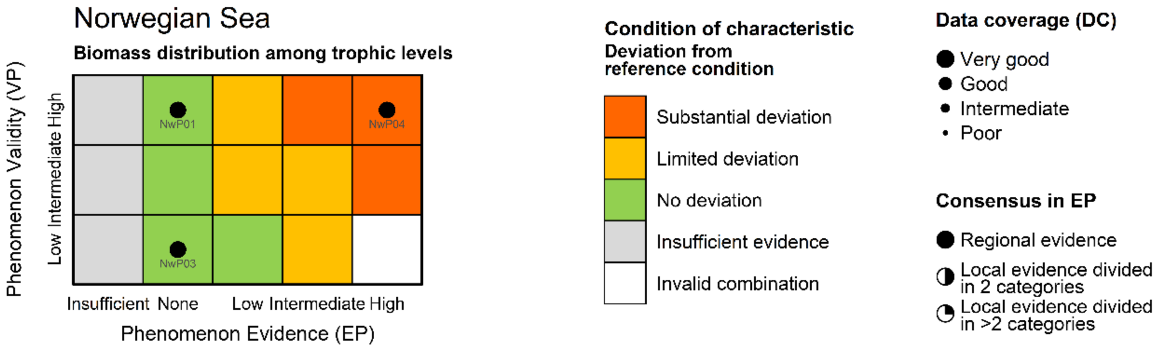
Figure 7.3.1 (i): The PAEC assessment diagram for the Primary productivity ecosystem characteristic of the Norwegian Sea. The table below list the indicators included in this ecosystem characteristic, their associated phenomenon, and the time period covered by the data used to assess the evidence for the phenomenon.

Assessment category: Based on the available indicators, the ecosystem characteristic *Primary productivity* for the Norwegian Sea was assessed as showing **no evidence of deviation** from the reference conditions.

Justification for choice of assessment category: This assessment is based on two indicators of low and high validity, respectively, and good data coverage. According to the data there is no detectable trend in annual primary productivity (NwI01) or date of start of the spring bloom (NwI02).

Uncertainties related to the choice of assessment category: The main uncertainty resides in the length of the time series for both indicators, which do not cover a period of change in the main driver, climate change. From the ICES working group WGINOR, it has also been shown that the peak in primary production is occurring 2 weeks earlier than 20 years ago, suggesting that choice of indicator can be of importance. Future iteration of this assessment could discuss the possibility of using the date of maximum productivity instead of the date of the start of the bloom. Contributing to the uncertainty is also that there is no information on the date of end of the autumn bloom and thus on the duration of the productive season.

Norwegian Sea – Biomass distribution among trophic levels



ID	Phenomenon	Time-period
NwP01	Decreasing primary production	2003-2020
NwP03	Change in relative biomass of pelagic fish	1995-2021
NwP04	Decreasing populations of pelagic seabirds	1980-2021

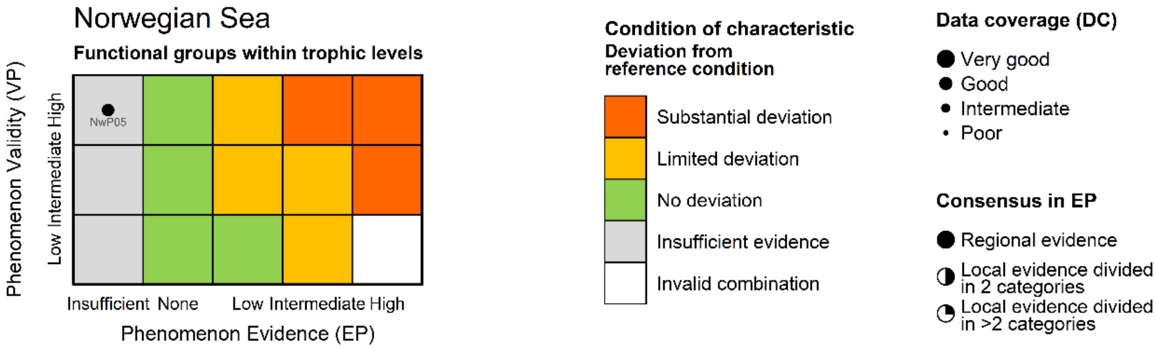
Figure 7.3.1 (ii): The PAEC assessment diagram for the Biomass among trophic levels ecosystem characteristic of the Norwegian Sea. The table below list the indicators included in this ecosystem characteristic, their associated phenomenon, and the time period covered by the data used to assess the evidence for the phenomenon.

Assessment category: Based on the available set of indicators, it was assessed that there is **no evidence of deviation** from reference condition for the ecosystem characteristic *Biomass distribution among trophic levels*.

Justification for choice of assessment category: This assessment is based on three phenomena of low and high validity. Annual primary productivity and mesozooplankton biomass show no evidence of deviation from the reference condition, as do the ratio of mesozooplankton to pelagic fish. Seabirds, however, showed strong signs of impacts, but this was not considered a strong enough incentive to conclude that the overall distribution of biomass among trophic levels has changed.

Uncertainties related to the choice of assessment category: there are major uncertainties associated with this assessment. The set of indicators is incomplete as it, partly due to capacity constraints, does not include important groups such as mesopelagic fish and marine mammals. Based on the information used in the assessment, the panel was uncertain as to whether the assessment category should be “no evidence of deviation” or “evidence of limited deviation”. The substantial decline observed for seabirds was an argument for evidence of limited deviation. In addition, having separate indicators for mesozooplankton and pelagic fish biomass, respectively, could have made it easier to understand assess changes in the trophic pyramid.

Norwegian Sea – Functional groups within trophic levels

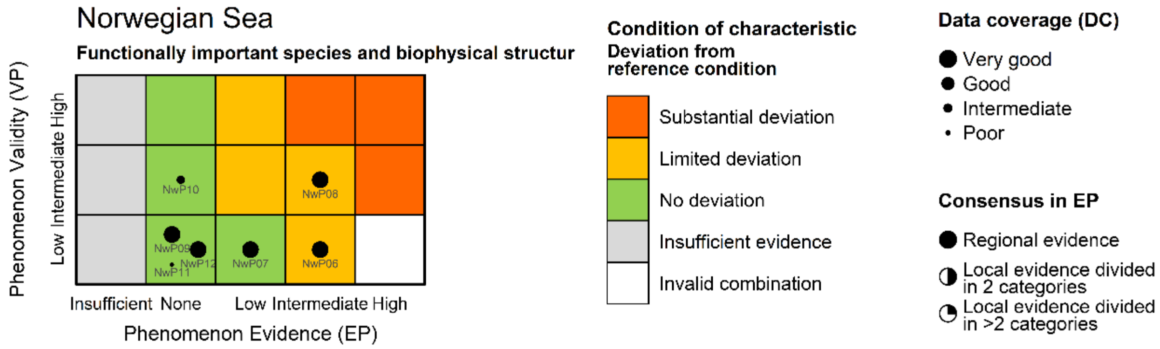


ID	Phenomenon	Time-period
NwP05	Decreasing average copepod body size	2009-2016

Figure 7.3.1 (iii): The PAEC assessment diagram for the Functional groups within trophic levels ecosystem characteristic of the Norwegian Sea. The table below list the indicators included in this ecosystem characteristic, their associated phenomenon, and the time period covered by the data used to assess the evidence for the phenomenon.

This ecosystem characteristic was not assessed as there was insufficient data to assess evidence of deviation for the only indicator for the characteristic.

Norwegian Sea – Functionally important species and biophysical structures



ID	Phenomenon	Time-period
NwP06	Decreasing mackerel stock size	1980-2021
NwP07	Change in mackerel recruitment	1980-2021
NwP08	Decreasing herring stock size	1907-2021
NwP09	Decreasing herring recruitment	1988-2021
NwP10	Decreasing blue whiting stock size	1981-2021
NwP11	Decreasing blue whiting recruitment	1981-2021
NwP12	Decreasing Calanus finmarchicus production	2000-2020

Figure 7.3.1 (iv): The PAEC assessment diagram for the Functionally important species and biophysical structures ecosystem characteristic of the Norwegian Sea. The table below list the indicators included in this ecosystem characteristic, their associated phenomenon, and the time period covered by the data used to assess the evidence for the phenomenon.

Assessment category: Based on the current set of indicators it is assessed that there is evidence for limited deviation from the reference condition for this ecosystem characteristic, as indicators for stock size of mackerel and herring are developing towards worsening condition that require attention.

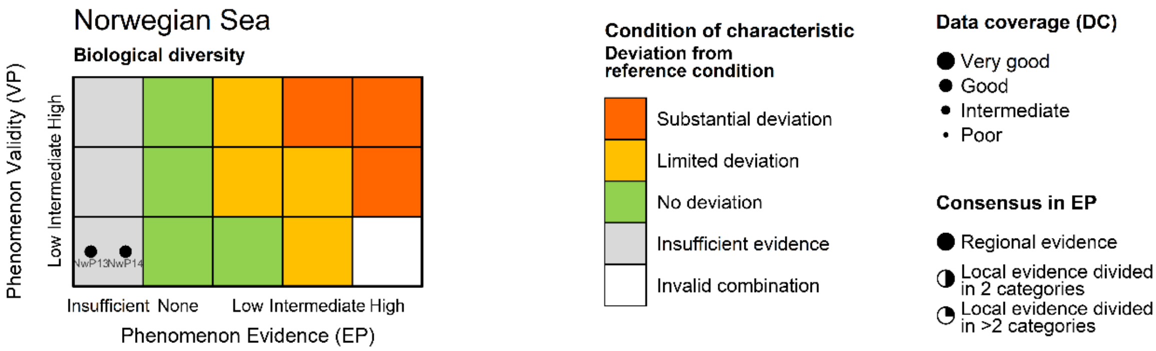
Justification for choice of assessment category: This assessment is based on a set of seven indicators associated with phenomena with low or intermediate validity. Data coverage is mostly assessed as very good, but substantially poorer for indicators related to blue whiting (NwI10 and NwI11). Three of the indicators address recruitment of pelagic fish stocks (NwI07, NwI09 and NwI11, recruitment of mackerel, herring and blue whiting, respectively), and these were given lower weight in the assessment than the others. This is because change in recruitment is not assessed to have major consequences for the rest of the ecosystem in addition to that on stock size, which is already captured by the other indicators in this ecosystem characteristic. Among the remaining four indicators, the indicators on stock size for herring (NwI08) and mackerel (NwI06) show evidence for intermediate deviation from the reference condition due to recent declines that is partly attributed to fishing substantially above recommended quotas since 2013. The indicators on blue whiting stock size (NwI10) and production in the *Calanus finmarchicus* stock (NwI12) are assessed to show no evidence for deviation from the reference condition. The assessment category of limited evidence for deviation from the reference condition for this ecosystem characteristic as a whole was chosen because the deviation for herring and mackerel stock is considered important for the ecosystem if it develops further, which may happen if action is not taken to reduce the fishing pressure. Also important for the choice of category is that the data coverage for blue whiting stock size is assessed as substantially poorer than for herring and mackerel stock size, thus weighing less than the two latter in the assessment.

Uncertainties related to the choice of assessment category: There is a considerable uncertainty associated with choice of assessment category as the majority of the indicators show no evidence of change from the reference condition. The lack of indicators for important groups such as marine mammals and mesopelagic fish also contributes to the uncertainty.

Norwegian Sea – Landscape-ecological patterns

There were no indicators for this ecosystem characteristic.

Norwegian Sea – Biological diversity

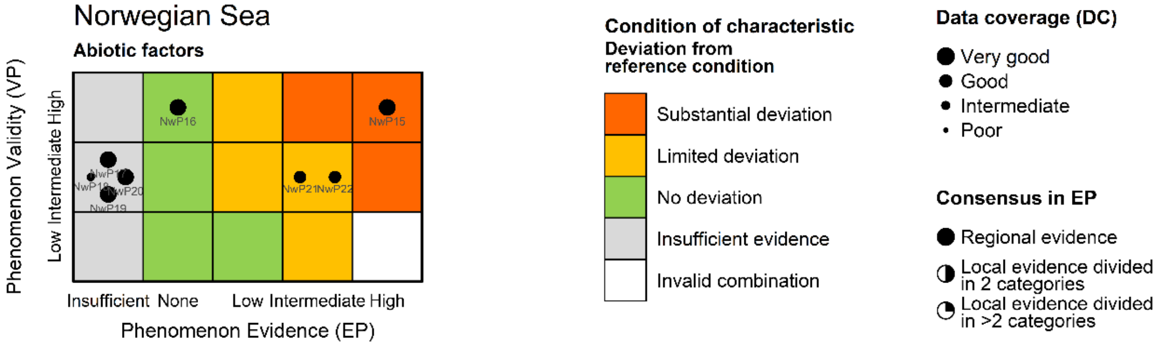


ID	Phenomenon	Time-period
NwP13	Decreasing number of copepod species sensitive to higher temperatures	2009-2016
NwP14	Increasing number of copepod species benefitting from higher temperatures	2009-2016

Figure 7.3.1 (v): The PAEC assessment diagram for the Biological diversity ecosystem characteristic of the Norwegian Sea. The table below list the indicators included in this ecosystem characteristic, their associated phenomenon, and the time period covered by the data used to assess the evidence for the phenomenon.

This ecosystem characteristic was not assessed as there was insufficient data to assess evidence of deviation for the two indicators for the characteristic.

Norwegian Sea – Abiotic factors



ID	Phenomenon	Time-period
NwP15	Increasing heat content	1951-2021
NwP16	Increasing freshwater content	1951-2021
NwP17	Change in volume of Arctic Water	1995-2021
NwP18	Change in stratification	1995-2021
NwP19	Decreasing inflow of Atlantic Water	1995-2021
NwP20	Change in concentrations of nutrients	1995-2019
NwP21	Decreasing pH	2011-2021
NwP22	Decreasing aragonite saturation	2011-2021

Figure 7.3.1 (vi): The PAEC assessment diagram for the Abiotic factors ecosystem characteristic of the Norwegian Sea. The table below list the indicators included in this ecosystem characteristic, their associated phenomenon, and the time period covered by the data used to assess the evidence for the phenomenon.

Assessment category: Based on the available set of indicators, the scientific panel concluded that there was evidence for limited deviation from the reference conditions for the ecosystem characteristic *Abiotic factors*. Heat content and indicators for ocean acidification suggest that the abiotic conditions are affected by climate change.

Justification for choice of assessment category: This assessment is based on eight indicators. For four of them, data were insufficient to assess change, and these were thus not considered in the assessment. Among the four indicators that were used, two have high validity and two have intermediate validity. Before seeing the diagram, the panel decided that nutrients (NwI20), heat content (NwI15) and freshwater content (NwI16) should have a more weight than the other indicators, based on their importance in describing abiotic conditions, but also their importance to assess the state of the ecosystem as a whole. One indicator (freshwater content NwI16) shows no evidence of deviation, two (ocean acidification indicators NwI21 and 22) show evidence of limited deviation and heat content (NwI15) shows evidence of substantial deviation from the reference conditions. Thus, the chosen assessment category “evidence for limited deviation”, is an average of the three categories indicated by the four indicators used.

Uncertainties related to the choice of assessment category: Although the indicator coverage is assessed as adequate for these time series, there are important uncertainties linked to the length of the time series relative to the drivers’ period of change and natural variability. In particular, some indicators (e.g., inflows from Arctic and Atlantic water NwI17 and 19) are known to display multidecadal variability. It is challenging to link the observed changes in these indicators unequivocally to human drivers as their time series are short relative to those multidecadal variations. Thus, the extent to which there are changes in these indicators due to anthropogenic climate change remains unknown, meaning four indicators were not used in the final assessment. Based on the indicators that were used, the panel was uncertain as to whether the assessment category should be “evidence of limited deviation” or “evidence of substantial deviation”. The strength and importance for the ecosystem of the warming trend shown by the heat content indicator was an argument for concluding that there was evidence for substantial deviation, while the patterns seen for the indicators for freshwater content and ocean acidification together provided arguments for concluding with evidence for limited deviation.

Figure 7.3.2. A graphical summary of the assessment of the Norwegian sector of the Norwegian Sea pelagic ecosystem. 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 concludes that there is evidence of limited impact of human pressures on the Norwegian Sea pelagic ecosystem. There are large uncertainties about whether this means that the impact is indeed limited or that more substantial impact is not detected because important indicators are lacking and many time series are too short. The most clear evidence for climate change is the observed temperature increase, which is seen with a 70 year long time series. There are also signs of increased ocean acidification. While climate change has the potential to affect primary production and zooplankton communities, time series available for these groups are too short to assess this. Fishing above recommended quotas over several years have contributed to declines in the herring and mackerel stocks, and there are also strong signals of decline in seabird populations. With projected further climate change and possibly overfishing, it is anticipated that stronger evidence of anthropogenic impacts will emerge.

Current state of knowledge of the reference condition

Systematic monitoring rarely stretches back to periods when climate was not affected by greenhouse gas emissions and when fishing and harvesting had negligeable effects on resources. Robust monitoring-based quantitative descriptions of the reference condition are therefore beyond reach and the evidence that can be used to define the reference condition is scarce. While there is good knowledge of the composition of the key species assemblages, i.e., the zooplankton and fish communities, some species groups are poorly known, such as free living microbes (virus, bacteria, fungi) and infectious organisms (Skjoldal, 2004). In general, the structure of the ecosystem is better described than are processes and interactions.

Given the above descriptions and following from the description of the phenomena (Ch. 5.1), the reference condition for the pelagic ecosystem in the Norwegian Sea should refer to an ocean cooler than the last two decades. This corresponds to a zooplankton community dominated by cold-water species, in particular *Calanus finmarchicus*, which contributed to favourable feeding conditions for pelagic fish stocks, in particular herring, mackerel and blue whiting.

Reconstructed variations in spawning stock biomass (SSB) of Norwegian spring-spawning herring back to 1907 (Toresen and Østvedt, 2000) show that the period before WWII was characterised by low fishing mortality. This is suitable to describe the reference condition for this species. During this period, estimated SSB varied between approximately 2 and 16 million tonnes, indicating that the variation in SSB under the reference condition is inherently large for this stock.

Under the reference condition, marine mammals were more abundant than in recent years (Rørvik and Jonsgård, 1981). Pollutants, such as heavy metals and persistent organic pollutants were absent or found in concentrations that were not significantly elevated above background levels.

Main drivers of change

Climate change and fisheries are the most important anthropogenic drivers of change in the Norwegian Sea pelagic ecosystem. From the 22 indicators included in this assessment (see chapter 5.1 and table 7.2), only these two drivers are identified as important drivers. Climate change is a potentially important driver of change for 82% of the indicators and fisheries for 37% (note that for some of the indicators, both drivers are identified). The ecosystem is possibly affected by pollution, from long-range transport and local origin (petroleum extraction activities). Underwater noise from seismic activities and ship traffic may also affect the ecosystem (see Hansen et al. (2022), where a complete list of all potential anthropogenic drivers are given).

Over the 70 years covered by monitoring, there has been an overall increase in temperature. During the period 1960-2000, the Norwegian Sea was in a consistent relative cold state but with prominent decadal variability. This was followed by a rather strong warming, peaking around 2005, and since then the Norwegian Sea has been in a relative warm state. (Figure 7.3.3).

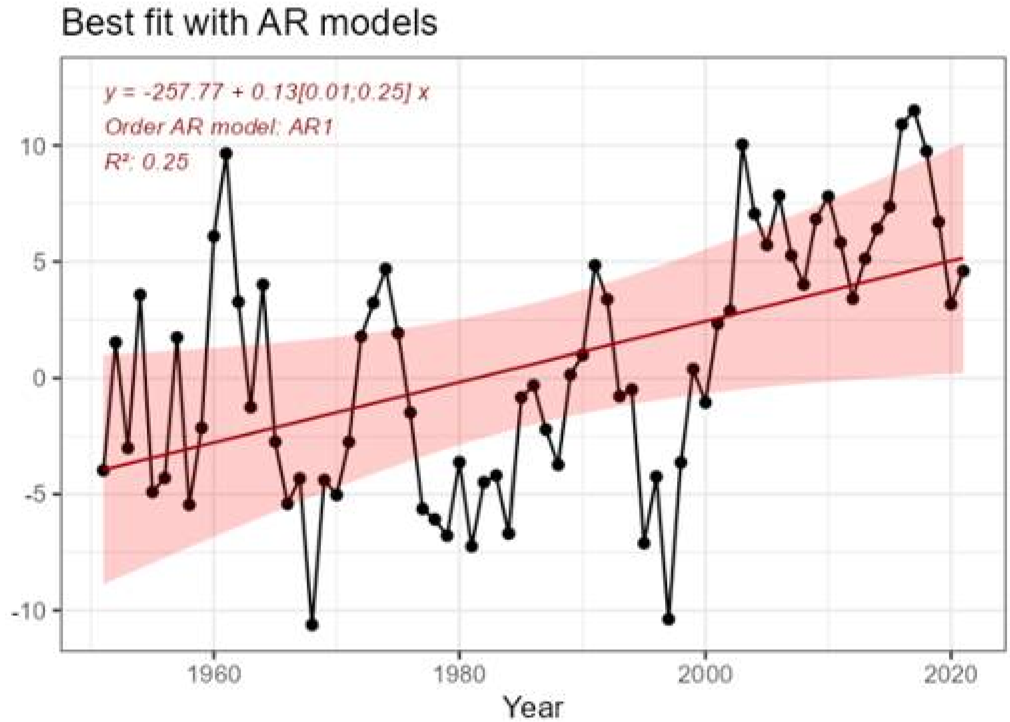


Figure 7.3.3. Estimated yearly means of heat content in the Norwegian Sea from 1951 to 2021. Linear trend fitted using a first order auto regressive model is indicated by the red line and equation with 95% CI shown in red.

Fishing mortality for mackerel, Norwegian spring spawning herring and blue whiting has varied considerably through time. Levels were exceptionally high for herring in the 1960s and led to collapse in the stock (Toresen and Østvedt, 2000). From the 1980s and onwards, fishing mortality for all three stocks has been well below levels where stock collapse is likely and thus at more sustainable levels (figures 7.3.4-6). After 2013 there has been no agreement on quota sharing among the nations participating in the fisheries, which has led to fishing about 30% above recommended total allowable catch (TAC). As described in table 7.2, this has contributed to declines in the stocks of herring and mackerel.

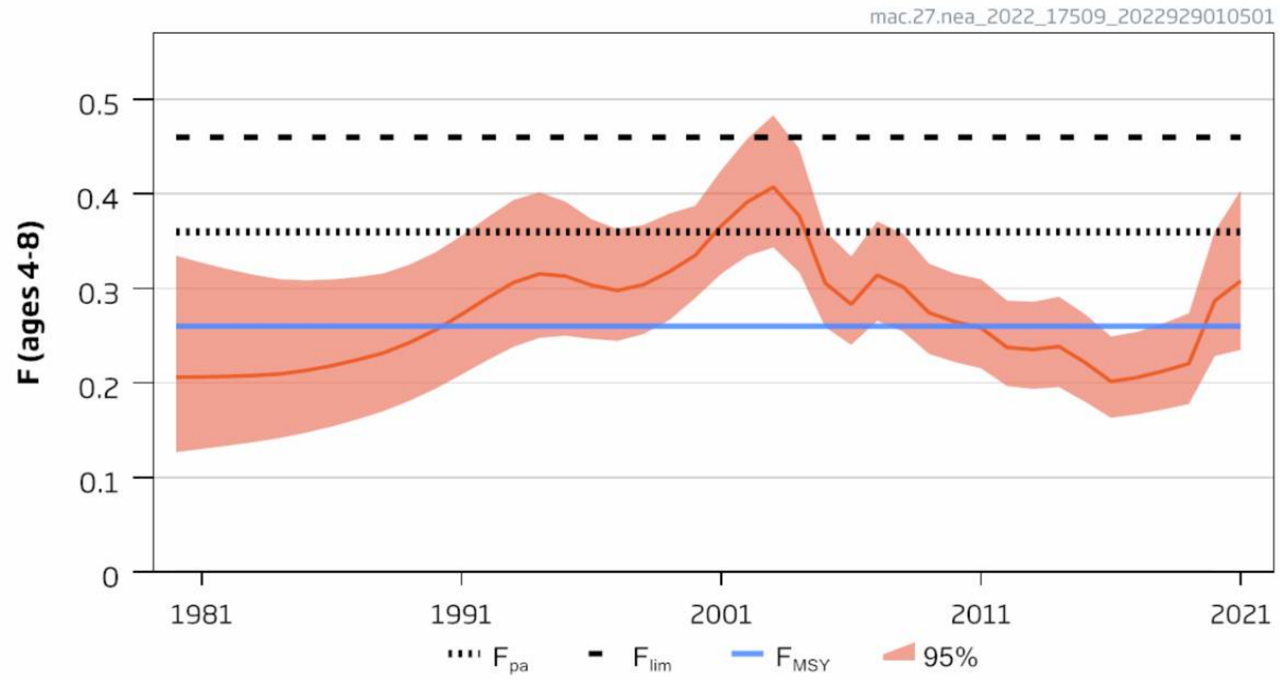


Figure 7.3.4 Fishing mortality of mackerel in the Northeast Atlantic and adjacent waters for ages 4-8 years indicated by the red line with 95% confidence intervals indicated by the red shaded area. The reference points F_{pa} (precautionary reference point for fishing mortality), F_{lim} (a critical threshold of fishing mortality, above which recruitment overfishing and stock collapse is possible) and F_{MSY} (fishing mortality consistent with achieving maximal sustainable yield) are indicated by horizontal lines. Source: ICES (2022c).

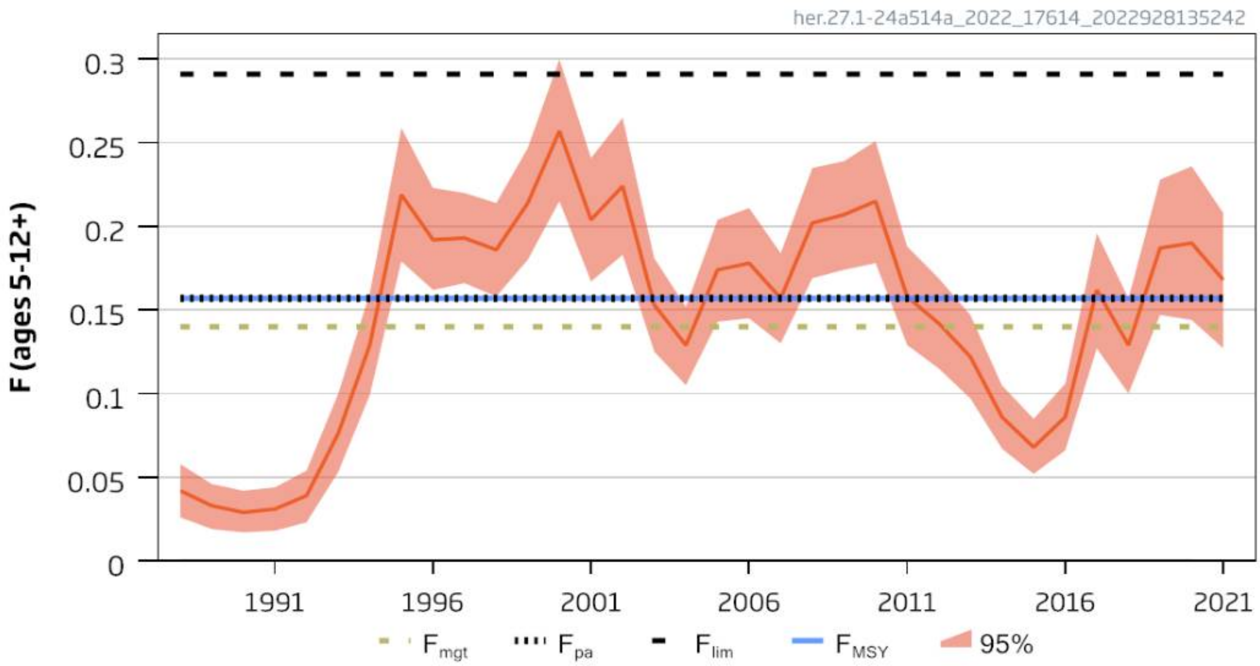


Figure 7.3.5 Fishing mortality of Norwegian Spring-Spawning Herring for ages from 5 years and above indicated by the red line with 95% confidence intervals indicated by the red shaded area. The reference points F pa (precautionary reference point for fishing mortality), F lim (a critical threshold of fishing mortality, above which recruitment overfishing and stock collapse is possible), F MSY (fishing mortality consistent with achieving maximal sustainable yield) and F mgt (fishing mortality for precautionary harvest control rule based on a management strategy evaluation) are indicated by horizontal lines. Source: ICES (2022b)

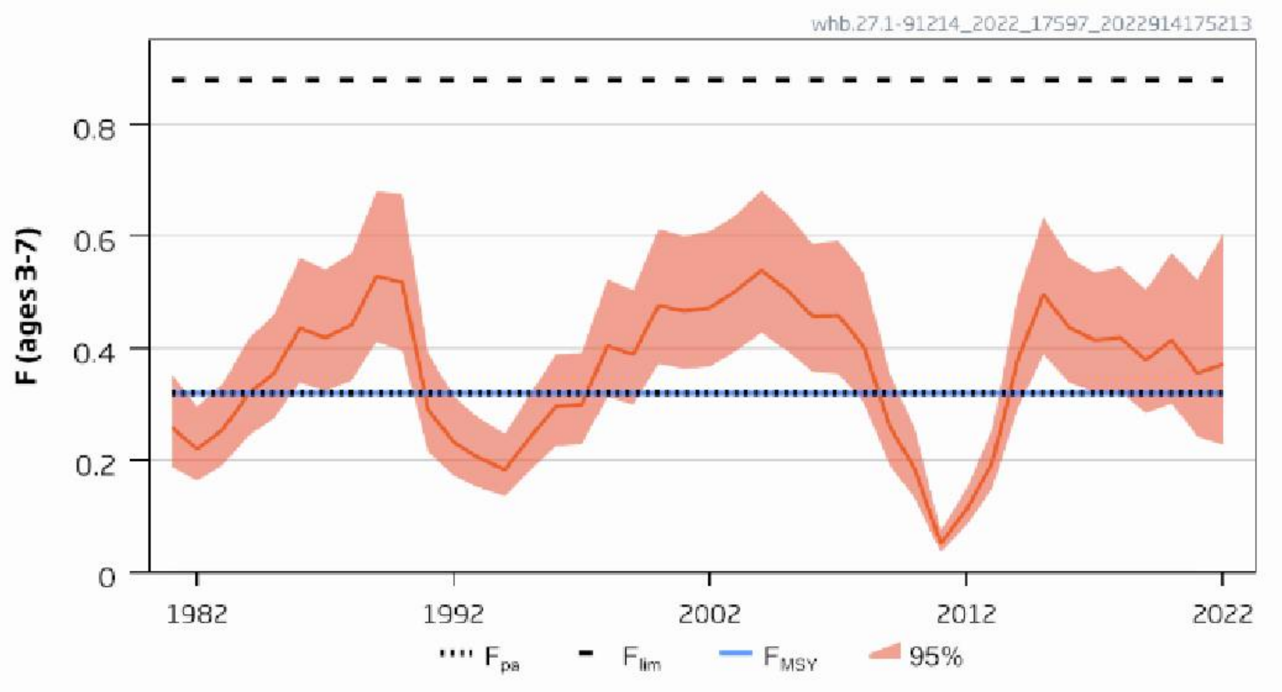


Figure 7.3.6 Fishing mortality of blue whiting in the Northeast Atlantic and adjacent waters for ages 4-8 years indicated by the red line with 95% confidence intervals indicated by the red shaded area. The reference points F pa (precautionary reference point for fishing mortality), F lim (a critical threshold of fishing mortality, above which recruitment overfishing and stock collapse is possible) and F MSY (fishing mortality consistent with achieving maximal sustainable yield) are indicated by horizontal lines. Source: ICES (2022a).

The Norwegian Sea is generally less polluted than the North Sea and Skagerrak and levels of contaminants in seafood originating from the Norwegian Sea are generally below maximum levels for food safety (Frantzen et al., 2022). Concentration of persistent organic pollutants and some other substances, such a mercury, typically increase with trophic level because of biomagnification (Michelangeli et al., 2022). Particularly high levels of persistent organic pollutants have been found in killer whales (*Orcinus orca*, Wolkers et al. (2007)). The main input of persistent organic pollutants and heavy metals to the Norwegian Sea is through atmospheric transport (Frantzen et al., 2022). Levels of these contaminants are measured in air on the North-Norwegian coast (Andøya), but the time series are too short (from 2010) to assess trends (Miljøstatus, 2022).

Routine and legal discharges of oil produced water constitute the largest discharges of oil from oil and gas production in the Norwegian Sea. Time series for level of these operational discharges have not been available for the current assessment.

Noise from seismic exploration, ship traffic and other anthropogenic activities can affect behaviour or induce stress in other ways in several groups of species, such marine mammals, fish and several types of invertebrates (Nowacek et al., 2007; Weilgart, 2018; Duarte et al., 2021). There is less information about whether this translates into effects on survival and reproduction at populations levels, but there is clearly a potential for such effects (Kvadsheim et al., 2017; Kvadsheim et al., 2020; Kvadsheim and Sivle, 2020; Duarte et al., 2021). On an intensity scale of five, anthropogenic noise levels in the Norwegian Sea have been assessed as intermediate (level 3) (Hansen et al., 2022).

Observed deviations from the reference condition

The indicators describing the ecosystem characteristic *Abiotic factors* show evidence for limited deviation from the reference condition. This is mainly driven by the increase in heat content observed from a 70 year long time series and attributed to anthropogenic climate change. Thermal changes are expected to have large consequences for the ecosystem. Signs of increased ocean acidification (reduced pH and aragonite saturation) are also detected from short time series, but there remain large uncertainties about the biological implications of this.

The substantial decreases in seabird populations seen in this assessment have been linked to the observed warming in the Norwegian Sea. Other changes in the reported indicators cannot be robustly attributed to climate change. This may be due to a mix of too few indicators for some ecosystem characteristics and too short time series for meaningful assessment of change for several indicators. For example, substantial changes in temperature are expected to cause significant changes in zooplankton communities. Such changes are indeed seen in the North Sea, were long zooplankton time series with high taxonomic resolution (69 years) are available. Similar time series are available for the Norwegian Sea, but they are too short (8 years) to allow meaningful assessment of changes due to anthropogenic climate warming.

There is evidence for limited deviation from the reference condition for the ecosystem characteristic *Functionally important species and biophysical structures*. This is due to declines in the sizes of the stocks of Norwegian spring-spawning herring and mackerel partially caused by a fishing pressure that has been substantially above the recommended TAC since the international agreement on quota sharing broke down in 2013. If the fishing pressure remains higher than recommended, the situation is anticipated to become severe, in particular for the herring stock, one of the key components of the ecosystem.

The ecosystem characteristics *Biological diversity* and *Functional groups within trophic levels* could not be assessed due to insufficient data support. The short time series for some of the zooplankton indicators discussed above contributed to this, as well as a lack of indicators for other ecological groups for these ecosystem characteristics.

A summary of the assessments of deviation from the reference condition and assessed indicator coverage for the ecosystem characteristics are given in table 7.3.1.

Table 7.3.1 Graphical summary of the assessment of ecological condition for all ecosystem characteristics in the Norwegian Sea

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

7.3.3 Future trajectories for ecosystem condition

As climate change and fisheries are the two main drivers of the Norwegian Sea ecosystem, scenarios for these are considered here. While quantitative model projections for different emission scenarios (which depend on development of politics and international relations) are available for climate development, fisheries and their management depend on regional politics and international relations in ways that are harder to predict (Planque et al., 2019).

In the long term, trends in Norwegian Sea temperatures will depend on the efforts to mitigate greenhouse gas emissions. Under the IPCC SSP1-4.5 scenario, a regional downscaling show projected changes in summer temperature at sea surface and 100m depth of the same order, 0.95°C and 0.8°C, respectively. For the SSP5-8.5 scenario the projected changes are 1.64°C and 0.99°C (Sandø et al., 2022)(Fig 7.3.6). Net primary production is projected to increase as a consequence of this warming, by 12% for the SSP1-4.5 scenario but limited to only 2% under the warmest climate scenario (Sandø et al., 2022). Better recruitment and feeding conditions should favor most of the commercially exploited stocks (Kjesbu et al. 2022). Related to climate change, ocean acidification is expected to remain limited in the region, with a projected decrease in pH by 0.1 by 2100 under the SSP5-8.5 "Business as usual" emission scenario (Fig.7.3.7). Oxygen concentration are expected to slightly decrease (up to -0.3 +- 0.1 ml l^{-1}, Fig 7.3.7, Sandø et al. (2022)). The extent to which these changes will affect the ecosystem is, however, poorly understood.

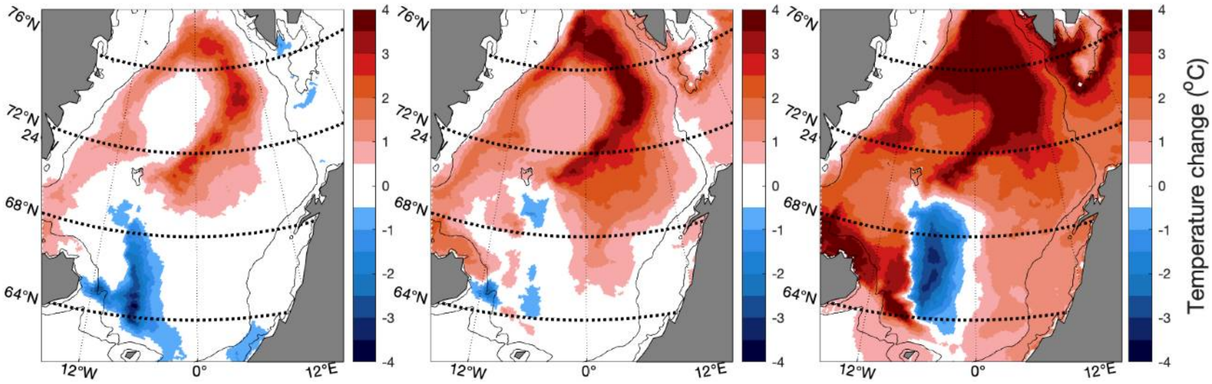


Figure 7.3.6 projected change in temperature from 2015 to 2100 in the Norwegian Sea under three different emission scenarios, SSP1-2.6 (left panel), SSP2-4.5 (middle panel) and SSP5-8.5 (right panel). Projections are downscaled from the model NorESM2 using the regional ocean model NEMO NAA10km. Source: Anne Britt Sandø, Institute of Marine Research, personal communication.

With climate change, the frequency, duration and intensity of extreme events (heatwaves or coldspells, storms) will increase (Frölicher et al., 2018; Oliver et al., 2018; Laufkötter et al., 2020; Perkins-Kirkpatrick and Lewis, 2020). There is little information about the impact of extreme climatic events in the Norwegian Sea. However, abundant literature has reported their impacts across the globe (Smale et al., 2019; Smith et al., 2023). More complex statistical models linking the indicator's dynamics to extreme events could help assessing the uncertainties and risks associated with increased frequencies and intensities of such events.

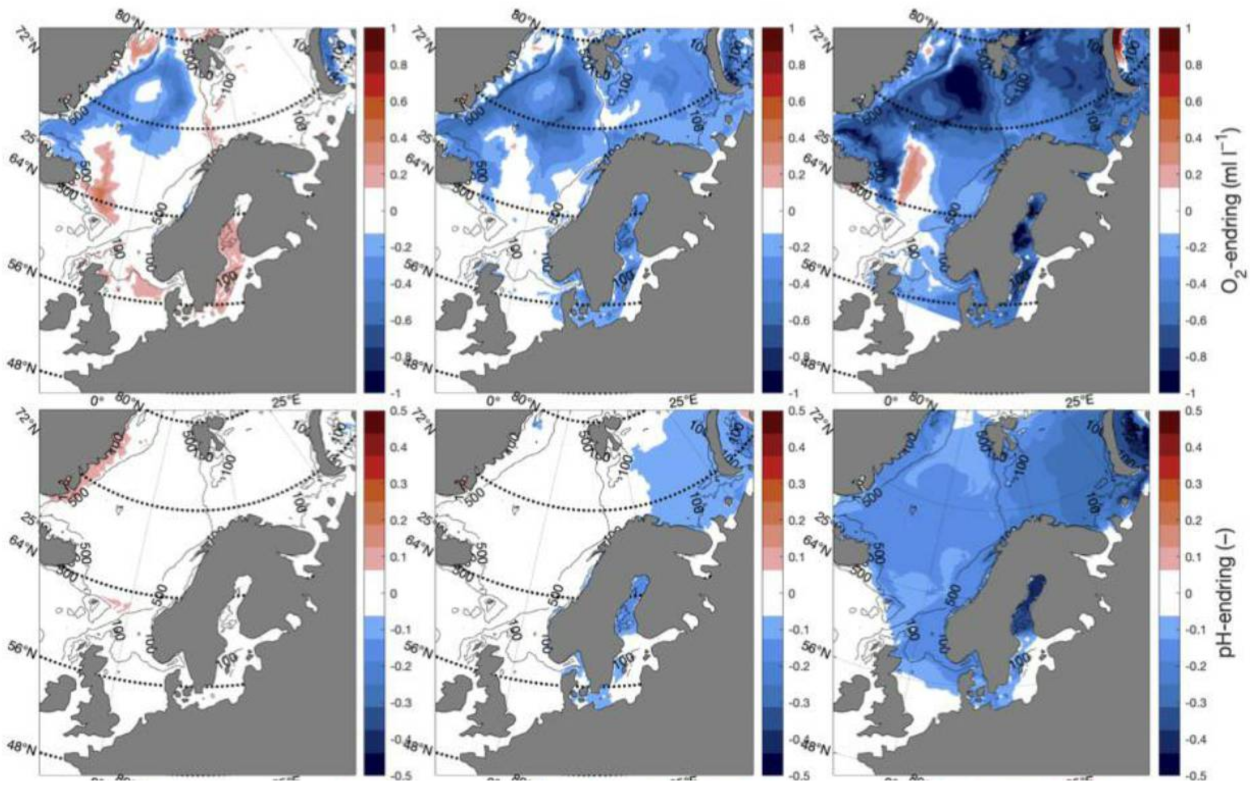


Figure 7.3.7. Spatial distribution of changes in oxygen (ml l^{-1}) and pH (-) for SSP1-2.6, SSP2-4.5, and SSP5-8.5 (left-right) for the period 2015-2100

Future fisheries management strategies are challenging to predict, but a key question for the condition of the Norwegian Sea ecosystem condition on a short-term is the lack of compliance of fishing effort with recommended quotas. If this problem is not addressed, there might be large changes also in the rest of the ecosystem.

The future state of the ecosystem will also depend on the development of pressures such as under-water noise from e.g., shipping and pressures from emerging industrial activities such as deep-sea mining (see Hansen et al., 2022 for a more comprehensive list of anthropogenic pressures).

7.3.4 Recommendations for monitoring and research

This assessment of the pelagic ecosystem in the Norwegian Sea is based on data from the two international spring and summer ecosystem surveys in the Nordic Seas (IESNS and IESSNS) and precursor surveys, additional monitoring of the physical environment with Argo boys and a program dedicated for monitoring of ocean acidification, fish stock assessments from the Working Group on Widely Distributed Stocks (WGWIDE) under ICES, satellite-based monitoring of primary production, monitoring of seabird breeding colonies in the SEAPOP program, simulations with the NORWECOM.E2E ecosystem model and monitoring of zooplankton through the Continuous Plankton Recorder Survey. 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. In addition, the use of models should be expanded with the aim of strengthening the use of both observations and models (Skogen et al., 2021).

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 table 7.3.2. In this table there are also short evaluations of the possibility for inclusion of each indicator in the next assessment. 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 Norwegian

Sea pelagic ecosystem needs to be investigated.

Data on zooplankton with high taxonomic resolution is required to assess key impacts of climate change on the ecosystem, in particular whether large changes in zooplankton communities with ecosystem wide impacts of the kind that has occurred in the North Sea, will develop in the Norwegian Sea. For the Norwegian Sea, short time series of the type used to reveal these changes in the North Sea (where monitoring has been done since 1958) are available through the Continuous Plankton Recorder Survey. A priority should be to continue this program in the Norwegian Sea to build longer time series. In addition, zooplankton data with high taxonomic resolution has been collected in the Svinøy section for long time periods but were not available to the current assessment due to needs for organization and quality assurance of the data. Doing this before the next round of this assessment should be a priority.

In addition, key zooplankton groups such as krill amphipods and gelatinous zooplankton, which are currently not monitored, should be included in the two ecosystem survey programs.

The level of annual primary production is the main determinant of the amount of energy coming into the ecosystem. Estimation of this for large ecosystems is typically done using satellite data, which relies on in situ measurements of production for calibration. Such estimates are scarce for high latitude ecosystems, and increased effort for primary production in situ measurement is therefore needed. There is also a potential for using data from profiles from biogeochemical Argo buoys (on nutrients, light etc.) to estimate primary production.

There is a need for better monitoring of the mesopelagic part of the ecosystem, including data with taxonomic resolution to assess changes in biodiversity. In addition, more research is needed on how this compartment interacts with the rest of the ecosystem.

Finally, research on the overall dynamics of the ecosystem (see e.g., Huse et al. (2012); Planque et al. (2022)) should continue to provide a better basis for understanding how the effects of anthropogenic impact may cascade through the ecosystem. This should include research on the mechanisms driving inflow of Arctic Water to the Norwegian Sea, as this might be a key oceanographic process influencing the Norwegian Sea ecosystem (Skagseth et al., 2022).

Table 7.3.2. Suggested important missing indicators for the Norwegian Sea. An indication of 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 Appendix 8.1.

Ecosystem characteristic	**Suggested indicator**	**Relevance to the ecosystem characteristic and obstacles to its inclusion in the current assessment**	**Possibility of inclusion for the next assessment**
Primary productivity	Phytoplankton species composition	Variation in species composition can have impacts on other parts of the ecosystem, in particular the type of herbivorous zooplankton that are successful grazers. In addition, diatoms may have toxic effects and negatively affect growth and development of copepods, and the relationship between diatoms and dinoflagellates may be a relevant indicator. Relevant data exist from CPR (Continuous Plankton Recorder Survey, 2022), but has not been included because of capacity constraints.	1
Biomass distribution among trophic levels	Biomass of high trophic level marine mammals	The group constitutes a significant part of the biomass in the ecosystem. Not included because of lack of capacity. Data exists from surveys of several whale species (Solvang et al., 2015; Leonard and Øien, 2020b; Leonard and Øien, 2020a).	1
Biomass distribution among trophic levels	Biomass of carnivorous zooplankton	The group constitutes a significant part of the biomass in the ecosystem (Skjoldal, 2004). Not included because of lack of data with sufficient quality. Although some carnivorous zooplankton are sampled by CPR, the group typically resides below the depth sampled by CPR (~ 7 m) (John et al., 2001). In addition, important carnivorous groups such as amphipods, euphausiids, amphipods and gelatinous zooplankton are too large to be sampled efficiently by the CPR.	2
Biomass distribution among trophic levels	Microbes	The amount of energy flowing through the microbial loop can significantly affect the overall flow of energy in the ecosystem and thus several important ecological processes. Not included because of lack of data.	3
Biomass distribution among trophic levels	Biomass of mesopelagic species	This group probably constitute a significant part of the biomass of at the trophic level of secondary consumers and above. Not included because of lack of data.	2
Functional groups within trophic levels	Gelatinous zooplankton	Variation in biomass or abundance of the group may have significant effects on energy flow and a substantial number of other species in the ecosystem (for a discussion, see phenomenon for NI10 in Arneberg et al. (2023)). Data is lacking.	2
Functional groups within trophic levels	Krill	Krill is important both as prey and predators. Not included because of lack of data.	2
Functional groups within trophic levels	Indicator(s) for functions performed by phytoplankton	An indicator for the relationship between diatoms and dinoflagellates, d iscussed for *Primary productivity* above, may be relevant here. Not included because of capacity constraints.	1
Functional groups within trophic levels	Indicator(s) for functions performed by microbes	It should be evaluated how different types of microbes contribute to different ecosystem functions and develop indicators according to this. Not included because of lack of capacity and data.	3
Functional groups within trophic levels	Indicators for function(s) performed by parasites	Parasites are here defined to include all types of infectious organisms, i.e., including viruses and bacteria. Parasites constitute a large part of the total biodiversity (suggested as e.g. around 40% Dobson et al. (2008)) and may significantly affect ecosystem structure and processes (Lafferty, 2008). Work is needed to identify relevant indicators. Not included because of lack of capacity and data.	3
Functional groups within trophic levels	Indicator(s) for functions performed by seabirds	Seabirds are important predators for parts of the ecosystem. Not included because of lack of capacity.	1

Functional groups within trophic levels	Indicator(s) for functions performed by marine mammals	Mammals are important predators in the ecosystem and change in functional groups may affect several ecological processes. Not included because of lack of capacity.	2
Functionally important species and biophysical structures	Indicator for microbes	Should be included to provide information on the microbial loop. Not included because of lack of capacity and data.	3
Landscape-ecological patterns	Indicators for habitat-defining biogenic or anthropogenic structures	Indicators included in other marine PAEC assessments (Arneberg et al., 2023; Siwertsson et al., 2023) were not considered relevant for the current assessment. For example, the indicator on area unaffected by bottom trawling, used in the North Sea, was not relevant, as the current assessment focuses on the pelagic ecosystem and does not include benthic habitats. For the Barents Sea, indicators for area of habitats defined by, respectively, sea ice and Arctic Water were used. Similar indicators were not relevant for the current assessment, as it focuses on areas that don’t have seasonal ice cover. For the next round of assessment, work should be done to identify other habitat defining parameters, such as area with temperature suitable for different pelagic fish species. This was not included here because of lack of capacity.	2
Biological diversity	Number of parasitic species sensitive to impact from climate change, fisheries and other anthropogenic drivers	Parasites (including virus and bacteria) may be more prone to extinctions from anthropogenic drivers than are other types of species (Lafferty and Kuris, 2009). As they constitute a major part of the total biodiversity (Dobson et al., 2008) and may profoundly affect ecosystem structure and processes (Lafferty, 2008), such indicators may have an important role in the assessment. Not included because of lack of capacity and data.	3
Biological diversity	Number/biomass of microbial species/groups sensitive to different anthropogenic drivers	Microbial species may be important for the overall flow of energy in the ecosystem through the microbial loop. Not included because of lack of capacity and data.	3
Biological diversity	Number of phytoplankton sensitive to climate change and nutrient levels	Changes in phytoplankton species composition can be important for processes and structure in the ecosystem (see above). Not included because of lack of capacity. Data exists through the CPR program (see above).	1
Biological diversity	Abundance of seabird species sensitive to fisheries, climate change and pollution.	Seabirds are important predators for parts of the ecosystem. Not included because of lack of capacity.	1
Biological diversity	Abundance of mammal species sensitive to fisheries (bycatch), climate change and pollution	Mammals are important predators in the ecosystem and change in species composition may affect several ecological processes. Not included because of lack of capacity.	1

8 - Appendices

Appendix 8.1 Scientific basis for the indicators used in the assessment

Indicator: Annual primary production [NwI01]

Ecosystem characteristic: Primary productivity

Phenomenon: Decreasing primary production [NwP01]

Main driver: Climate change

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

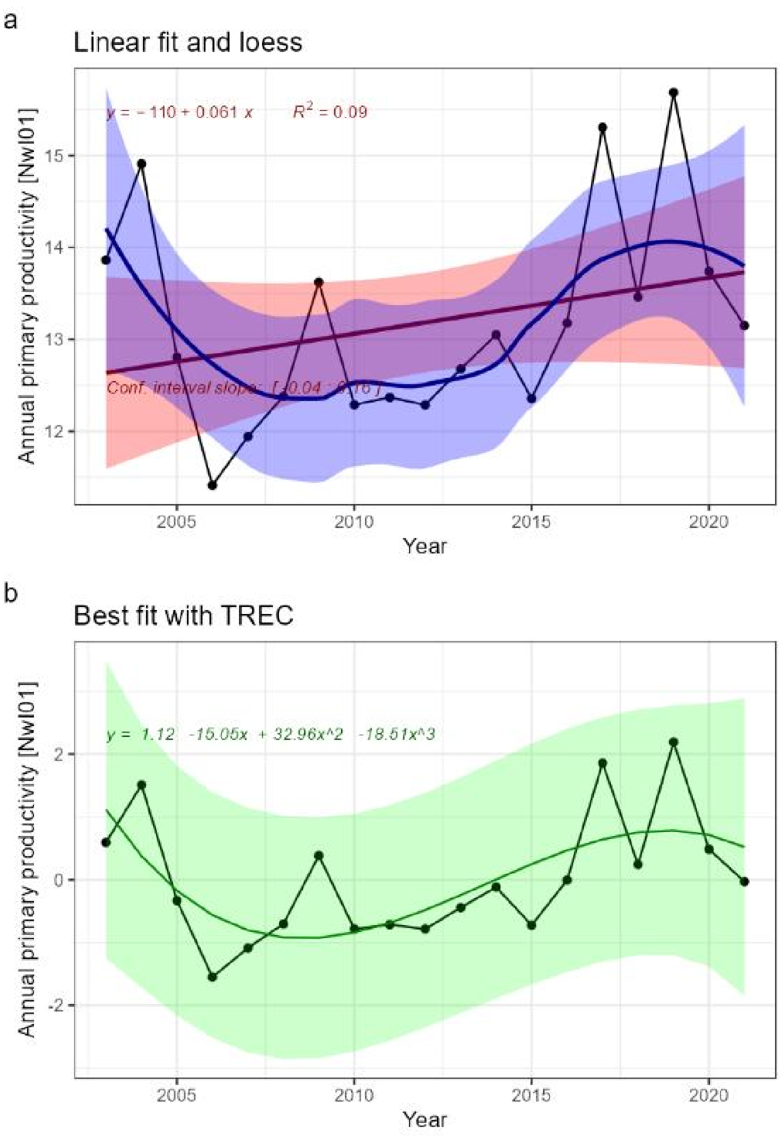


Fig.1.1: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon

There is no evidence of a decreasing trend in the variable and thus no evidence of this phenomenon.

Background data and supplementary analysis

Fig.1.2: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Recommendations for future development of the indicator

Indicator: Timing of the spring bloom [NwI02]

Ecosystem characteristic: Primary productivity

Phenomenon: Change in timing of spring bloom [NwP02]

Main driver: climate change

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

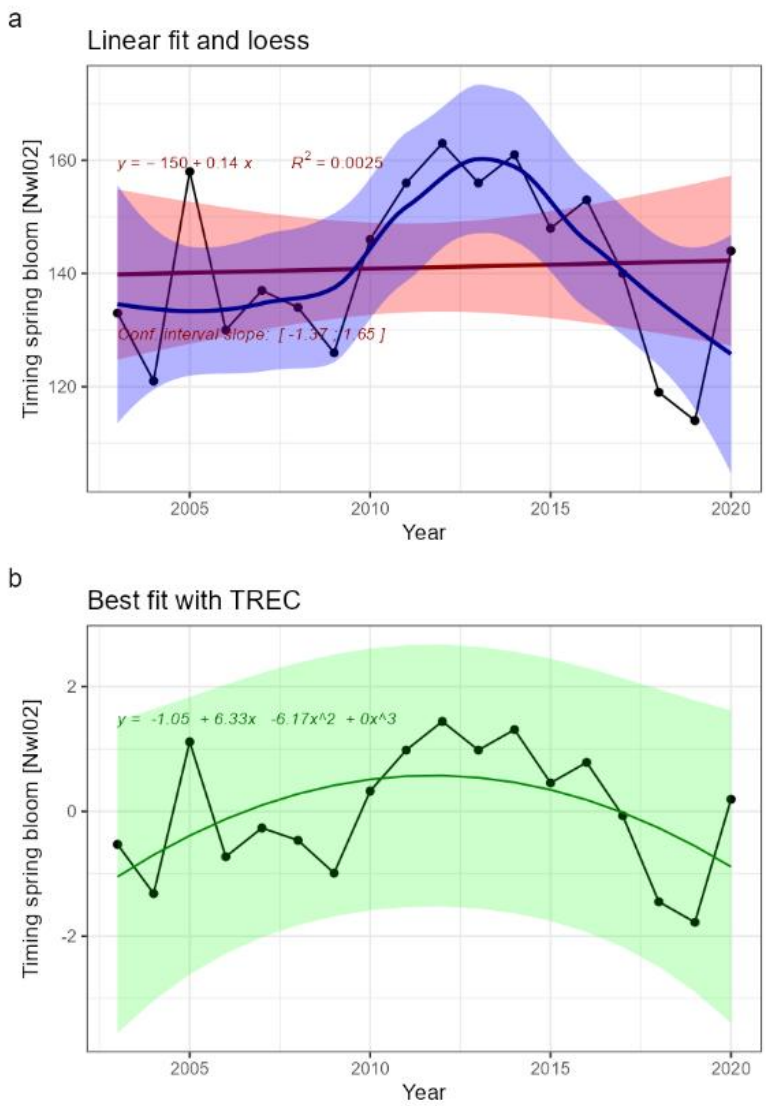


Fig.2: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

There is no evidence of a decreasing or increasing trend in the variable and thus no evidence of this phenomenon

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Mesozooplankton biomass relative to pelagic fish biomass [NwI03]

Ecosystem characteristic: Biomass distribution among trophic levels

Phenomenon: Change in relative biomass of pelagic fish [NwP03]

Main driver: Biomass distribution among trophic levels

Supplementary metadata

Not relevant

Supplementary methods

The indicator is represented by a time series on the ratio between estimated mesozooplankton biomass and the sum of estimated spawning stock biomass of herring, mackerel and blue whiting. The mesozooplankton biomass comes from CPR data and pelagic biomass is summed from stock evaluation.

Plots of indicator values

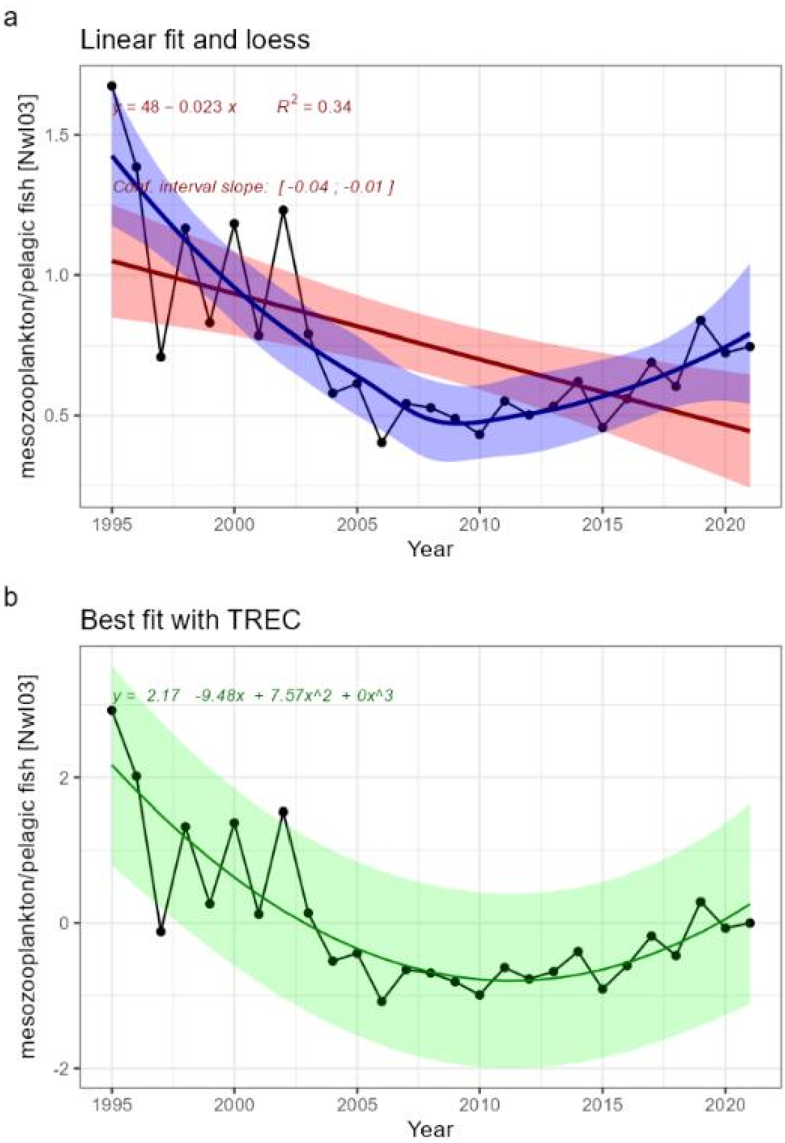


Fig.3.1: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

Based on the linear model, there is a declining trend in the biomass of mesozooplankton relative to biomass of pelagic fish over the entire length of the time series. However, this trend cannot be clearly attributed to anthropogenic drivers. As noted for the assessment of the mackerel (NwI06) and herring (NwI08) stock sizes, fishing above recommended levels after 2013 has contributed to declines in these stocks. Based on the Bayesian trend analysis, a non-linear model is suggested as the best fit for the variable (i.e., mesozooplankton biomass relative to pelagic fish biomass), exhibiting a decline in the first part followed by an increase in the latter part. Thus, the fisheries driven declines in mackerel and herring stocks contributes to the increase on the latter part of the time series, towards values in the beginning. Overall, the declining trend cannot be attributed to impact from anthropogenic drivers with any reasonable confidence, and it is therefore assessed that there is no evidence for the phenomenon.

Background data and supplementary analysis

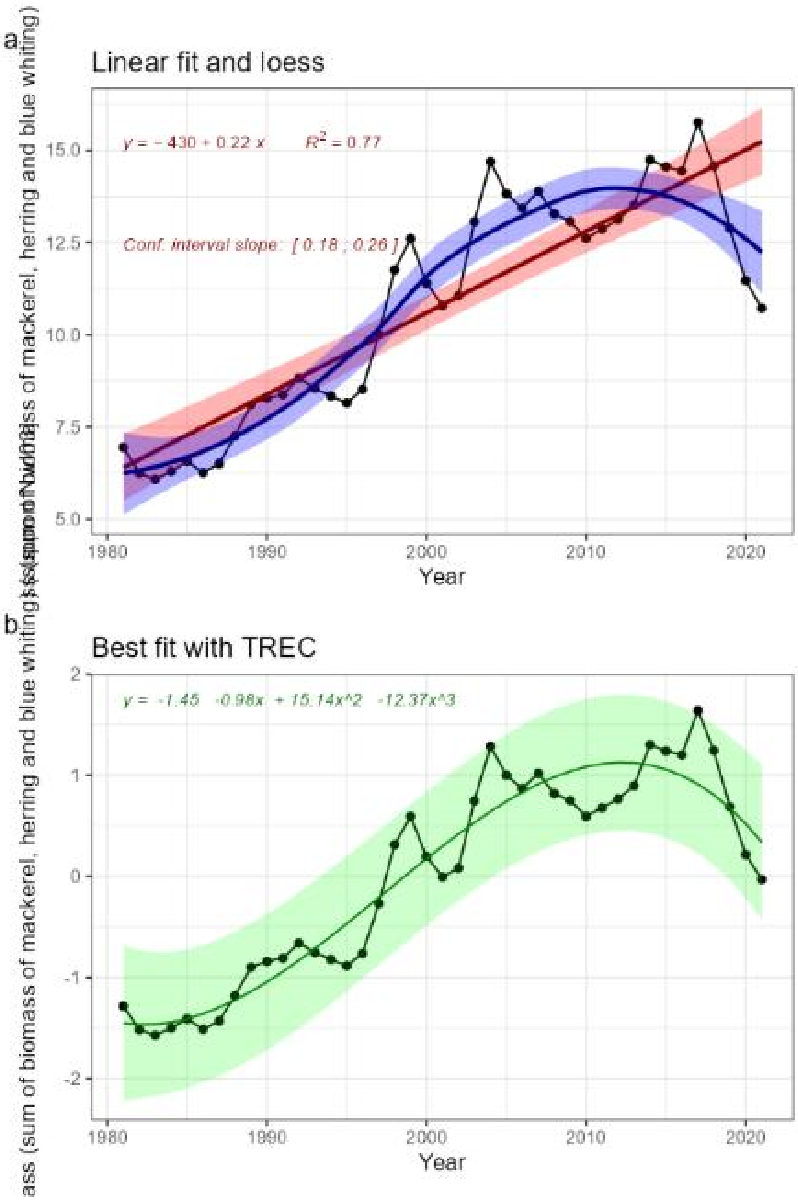


Fig. 3. 2: Sum of pelagic fish biomass. Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

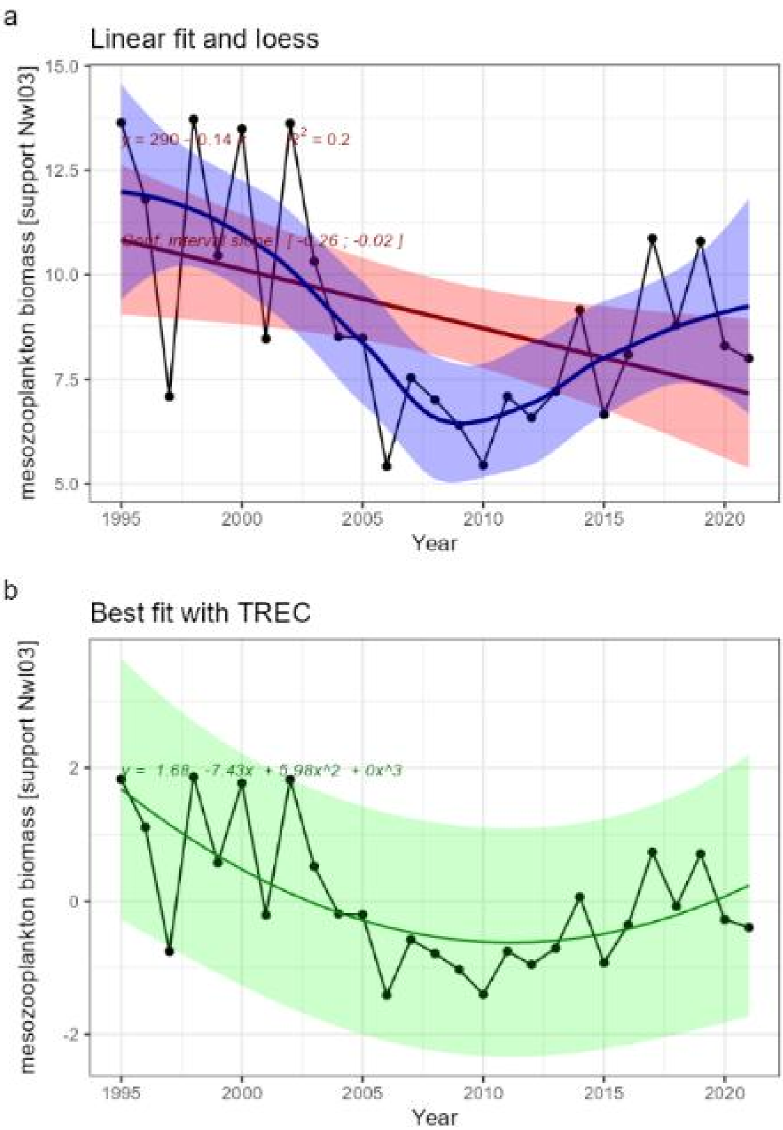


Fig. 3.3 : Mesozooplankton biomass. Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Recommendations for future development of the indicator

Indicator : High trophic level seabirds [NwI04]

Ecosystem characteristic: Biomass distribution among trophic levels

Phenomenon: Decreasing populations of pelagic seabirds [NwP04]

Main driver: fisheries and climate change

Supplementary metadata

Not relevant.

Supplementary methods

Data are from population monitoring of breeding colonies of common guillemot (*Uria aalge*), Atlantic puffin (*Fratercula arctica*) and black-legged kittiwake (*Rissa tridactyla*) from Runde (Møre og Romsdal, 62°24’N 005°37’E), Halten fyr (Trøndelag, 64°29’N 009°67’E), Sklinna (Trøndelag, 65°13’N, 10°58’E), Røst (Nordland, ca. 67°30’ N 12°00’ E) and Anda (Nordland, 69°03’59’’ N, 15°10’11’’ E). See www.seapop.no for details. Methods for monitoring are described in Walsh et al. (1995). Counting was done in fixed plots in the breeding colonies. Counting units represent the breeding population but varies between the time series. It includes number of individuals, number of eggs and number of apparently occupied/active nests. Indicators are given as the annual count in percentage of the average count over the duration of the monitoring period. In addition to colony specific data, estimates of the annual size of the breeding populations in the Norwegian part of the Norwegian Sea from 1980 to 2013 are shown (Fauchald et al., 2015). These time series estimates were based on a combination of the population monitoring at key sites and mapping of the breeding populations in all known breeding localities. The data series are presented as separate figures, but it should be noted that the series are partly based on the same monitoring data.

Data sources:

Dataset name	Dataset ID	Dataset DOI/URL/storage	Responsible institution	Contact person for data	Content and methods	Temporal coverage
Colony monitoring		www.seapop.no The National monitoring programme for breeding seabirds	NINA	Signe Christensen- Dalsgaard (Runde, Anda), Nina Dehnhard (Sklinna), Georg Bangjord, SNO (Halten) Tycho Anker-Nilssen (Røst)	Counts of active nests, eggs or adults in breeding colonies	Varies between colonies.
Regional population		w ww.seapop.no	NINA	Per Fauchald	Regional estimates of breeding population	1980-2013

Plots of indicator values

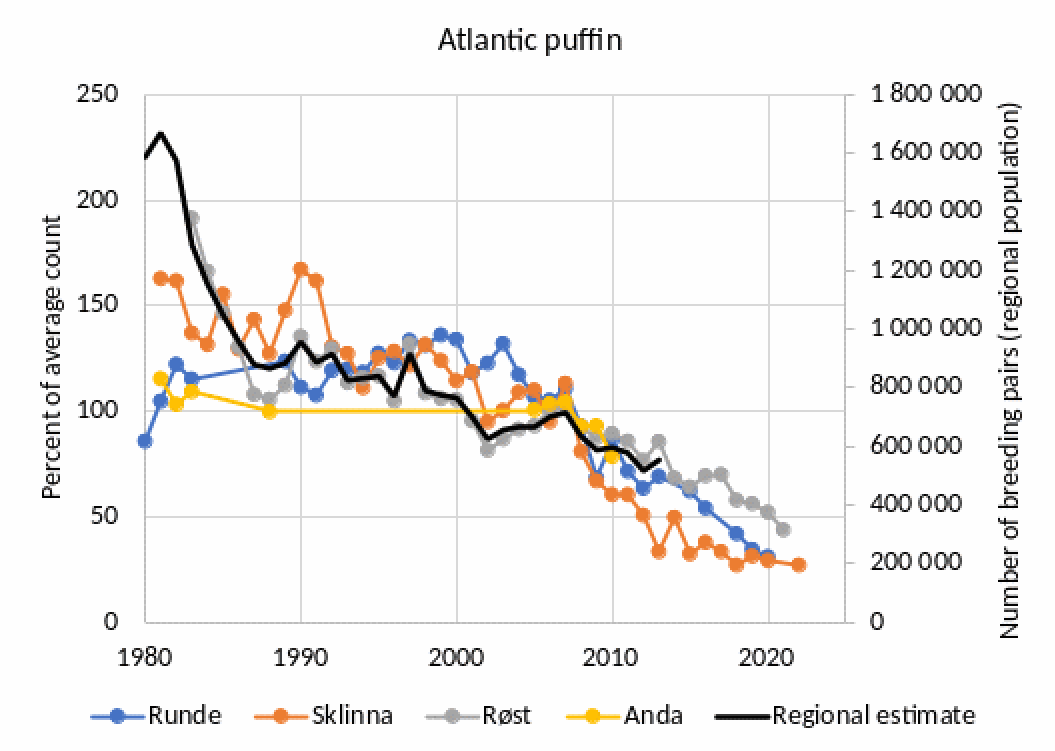


Fig.4.1: Plots of indicator values for Atlantic puffin

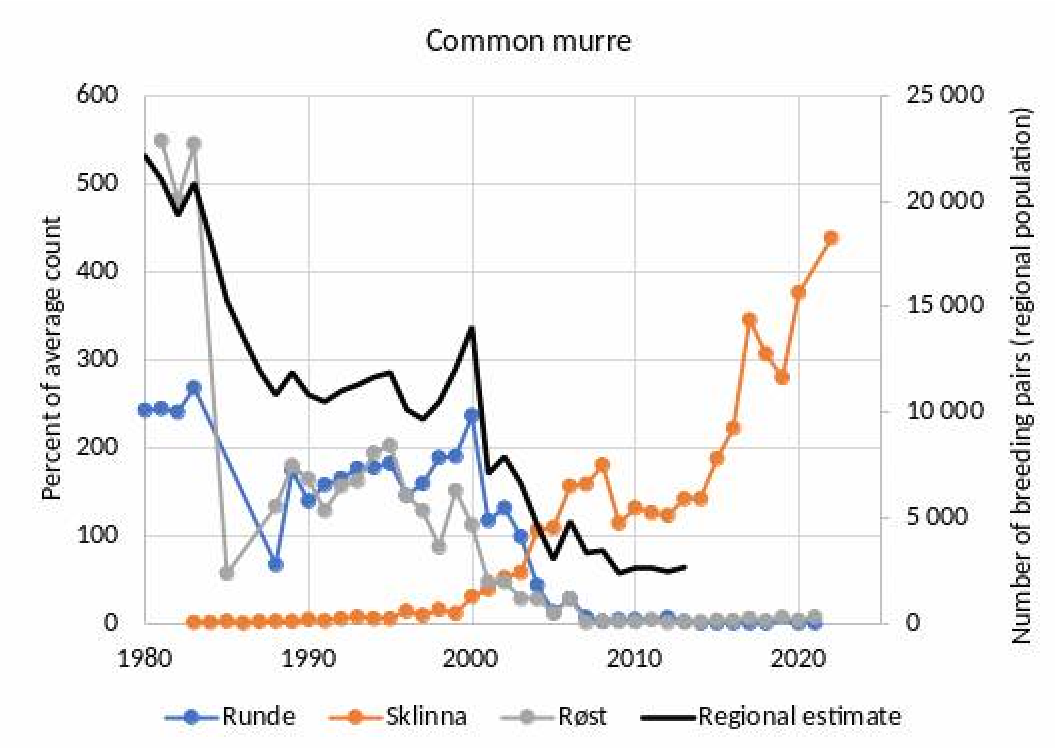


Fig.4.2: Plots of indicator values for Common murre

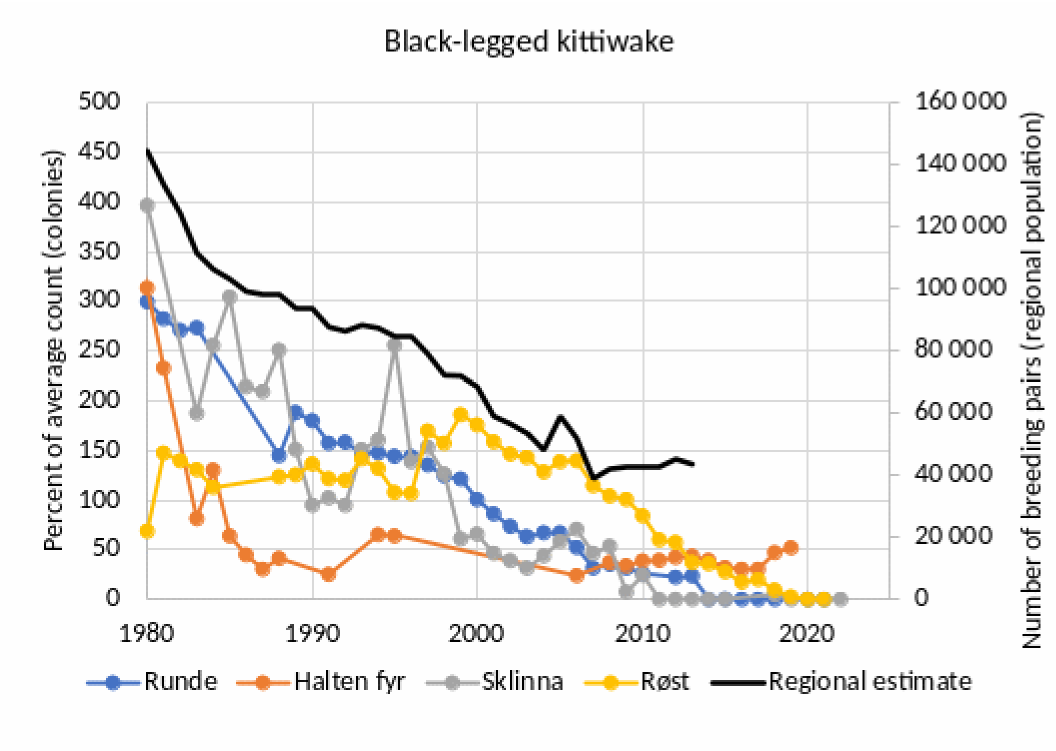


Fig.4.3: Plots of indicator values for Black-legged kittiwake

Assessment of the evidence for the phenomenon:

All monitored colonies of Atlantic puffin and black-legged kittiwake show a strong decline in the number of breeding birds the last 40 years. For common guillemot, one colony, Sklinna, show an increasing trend. However, this colony is relatively small, counting approximately 1500 breeding pairs in 2022. Sklinna is in other words still too small to compensate for the general decrease in the regional population from about 20000 pairs in 1980, not least the decline in the former colonies at Runde, Røst and Værøy (Brun, 1979).

The population of Atlantic puffin has declined by more than two thirds since 1980, a decline from 1.6 mill. pairs in 1980 to less than 500 000 pairs in 2020. The population of black-legged kittiwake has declined by more than 72% since 1980, a decline from 144000 pairs in 1980 to less than 40000 in 2020. Finally, the population of common murre has declined by about 75%, a decline from about 20000 pairs in 1980 to about 5000 pairs in 2020.

Conclusion:

The data show a strong long-term (40 years) decline (>70%) in the populations of pelagic seabirds. In several studies this decline has been linked to overfishing and climate change. We conclude that there is *high evidence that the phenomenon has occurred.*

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Copepod body size [NwI05]

Ecosystem characteristic: Functional groups within trophic levels

Phenomenon: Decreasing average copepod body size [NwP05]

Main driver: Climate change

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

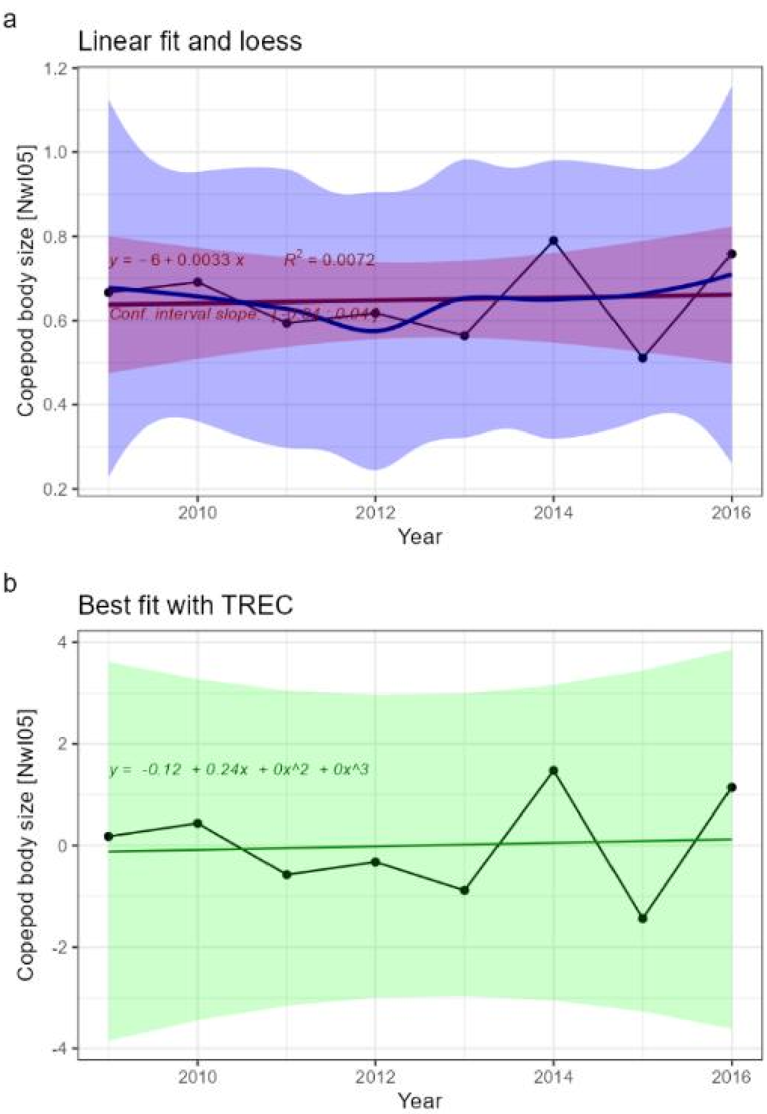


Fig.5: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

The time series is too short (8 years) to assess whether there has been a change in variable that can be attributed to effects of climate change

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Mackerel stock size [NwI06]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Decreasing mackerel stock size [NwP06]

Main driver: fisheries and climate

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

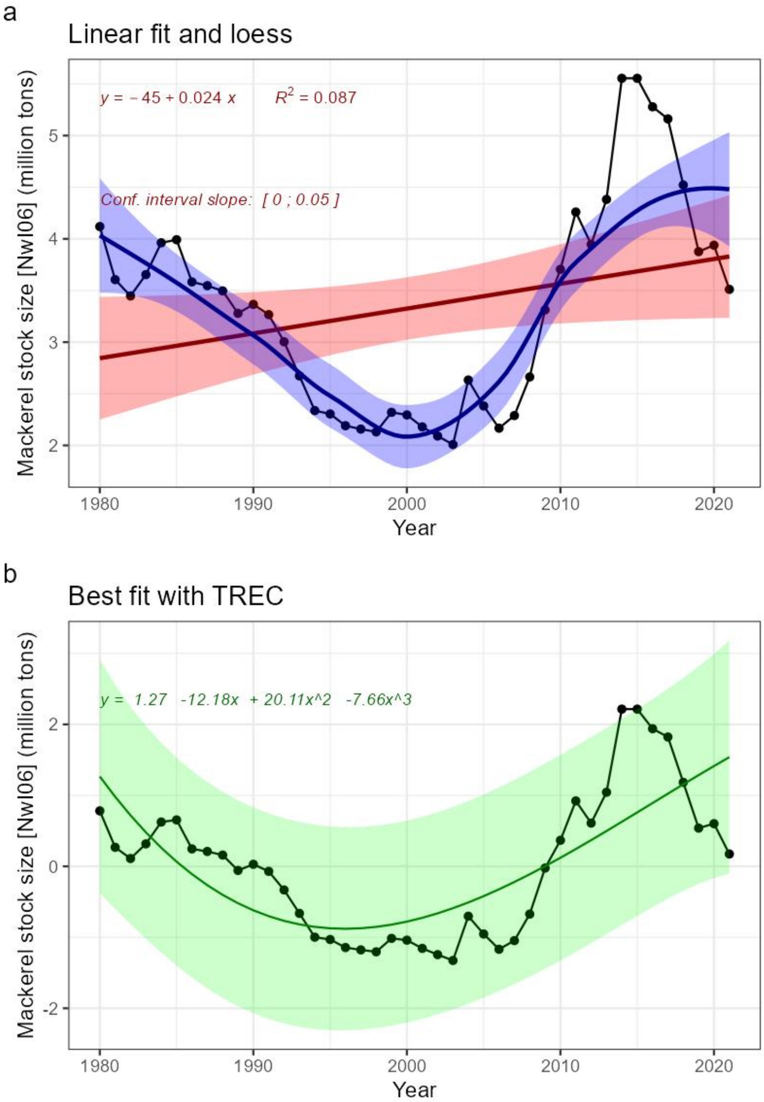


Fig.6: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Fig.6: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

The early decline is likely linked to overfishing. Prolonged overfishing in the recent years is hidden by good recruitment and year classes, but the stock size should be higher with less fishing (ICES, 2021d). There is thus intermediate evidence for this phenomenon

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Mackerel recruitment [NwI07]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Change in mackerel recruitment [NwP07]

Main driver: Climate and fisheries

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

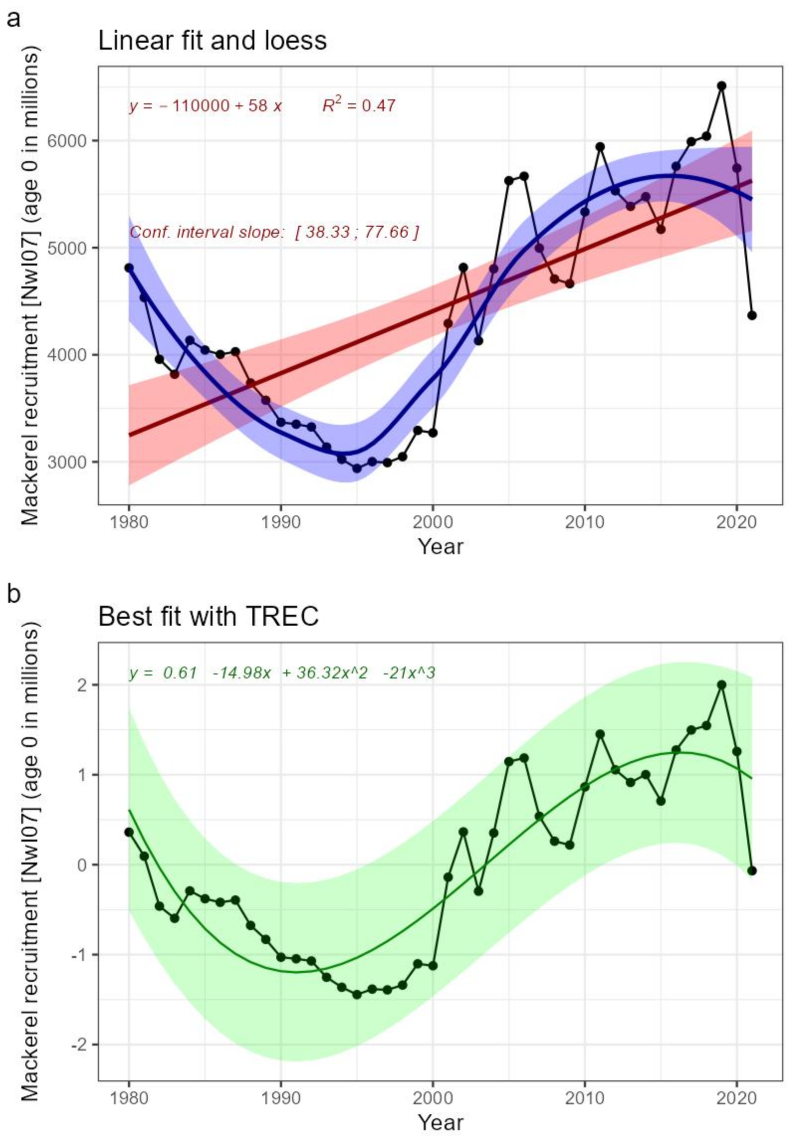


Fig.7.1: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

After the 2000s, recruitment has improved, maybe because of climate change, but the processes are uncertain. The evidence of the phenomenon is thus assessed as low.

Background data and supplementary analysis

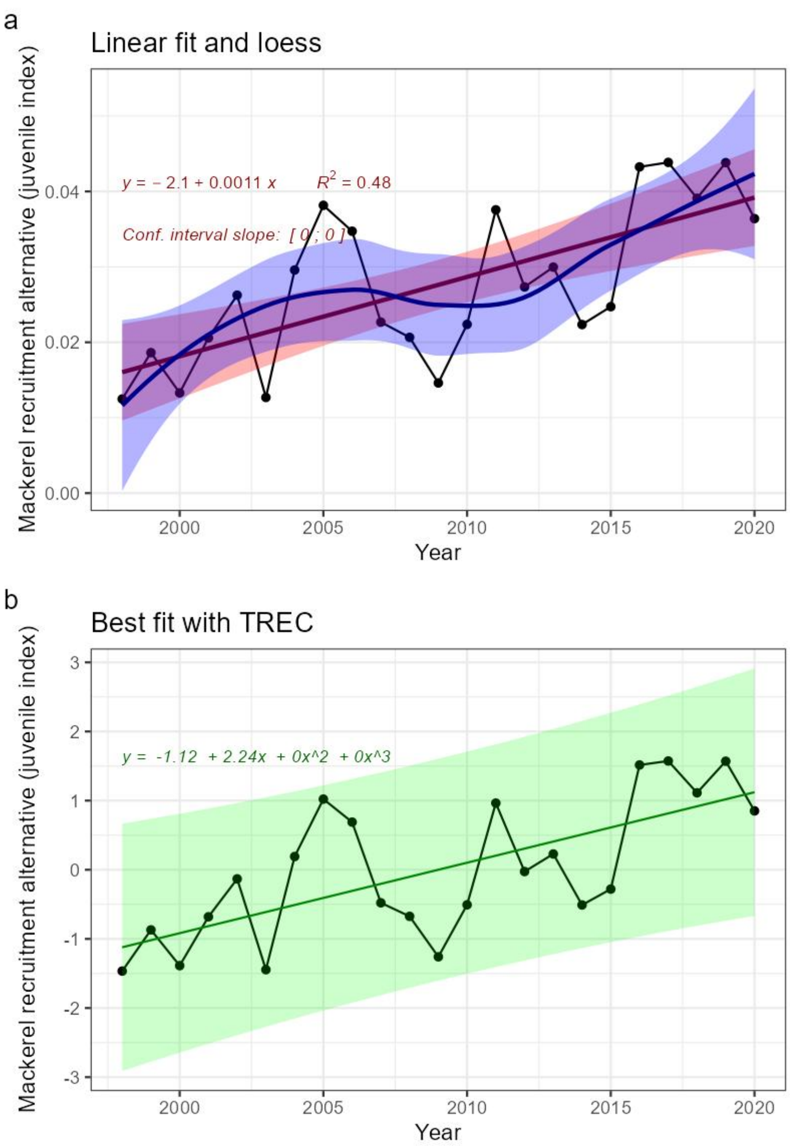


Fig.7.2: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Recommendations for future development of the indicator

Indicator: Herring stock size [NwI08]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Decreasing herring stock size [NwP08]

Main driver: Fisheries and climate

Supplementary metadata

Not relevant.

Supplementary methods

Plots of indicator values

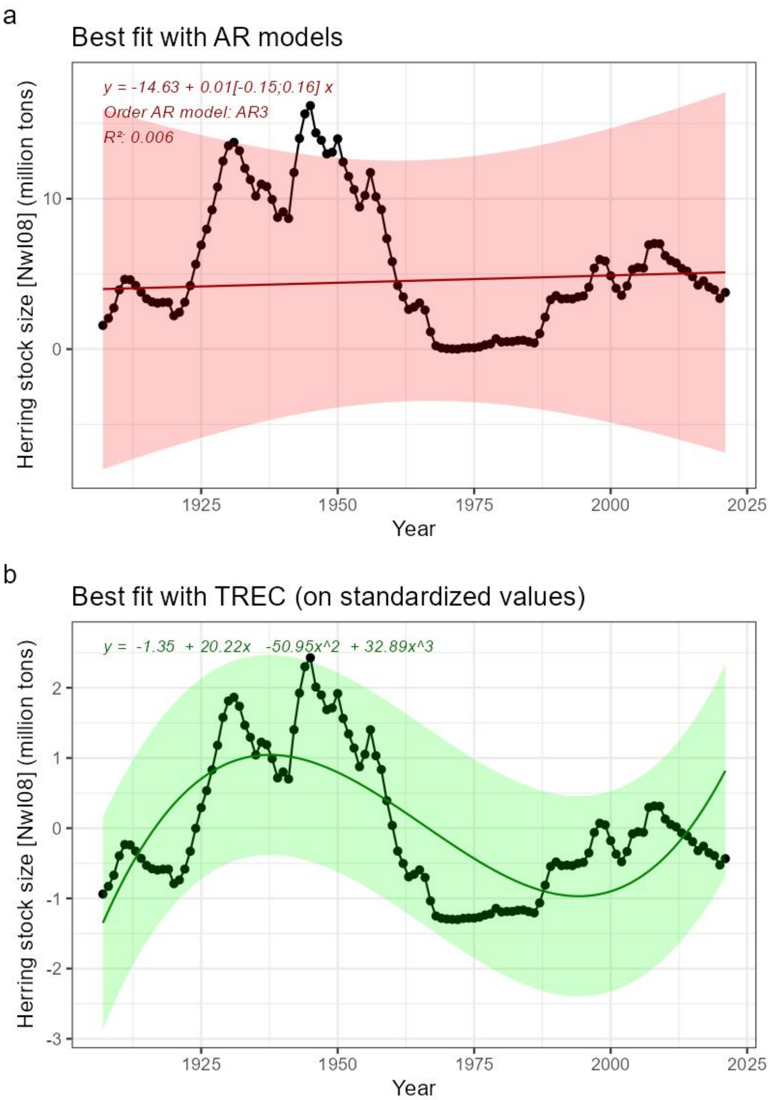


Fig.8: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon

The development of the stock is highly influenced by variation in recruitment. Recruitment is highly variable, with low recruitment in most years and high recruitment approximately once a decade. Last year with high recruitment was 2016. Looking at the most recent years, there has been a decline in stock size after 2008. A part of this decline is due to low recruitment for most of these years. Another part of the decline is caused by fishing about 30% above recommended levels since 2013, due to a lack of quota sharing agreement between the countries involved in the fisheries after this year. The latter has resulted in an accumulated 1.5 million tonnes catch above recommended levels since 2013. Thus, while fisheries have clearly contributed to the decline in the stock, there are uncertainties about the consequences of this for other parts of the ecosystem, and the evidence of the phenomenon is therefore set to intermediate.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Herring recruitment [NwI09]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Decreasing herring recruitment [NwP09]

Main driver: Fisheries

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

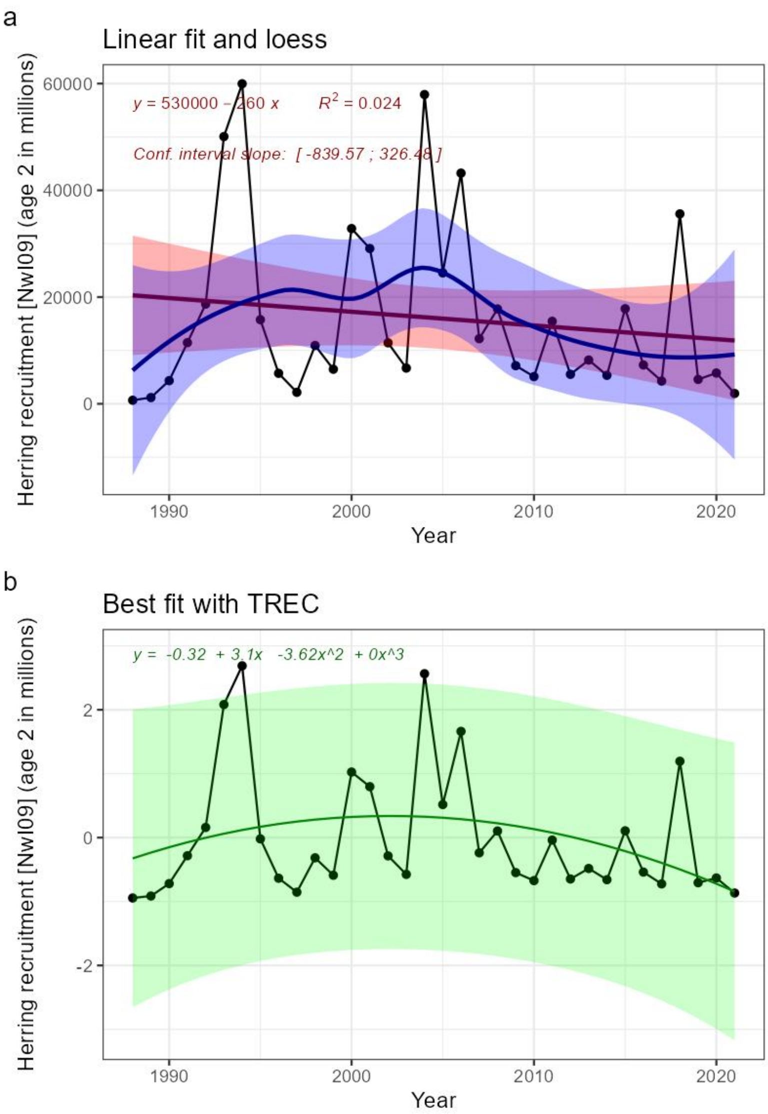


Fig.9: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

There is no trend in the time series, and thus no evidence of a lowered recruitment due to fisheries. Rather, other factors, such as temperature and size of the mackerel stock may be influencing recruitment (Garcia et al., 2020).

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Blue whiting stock size [NwI10]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Decreasing blue whiting stock size [NwP10]

Main driver: Fisheries

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

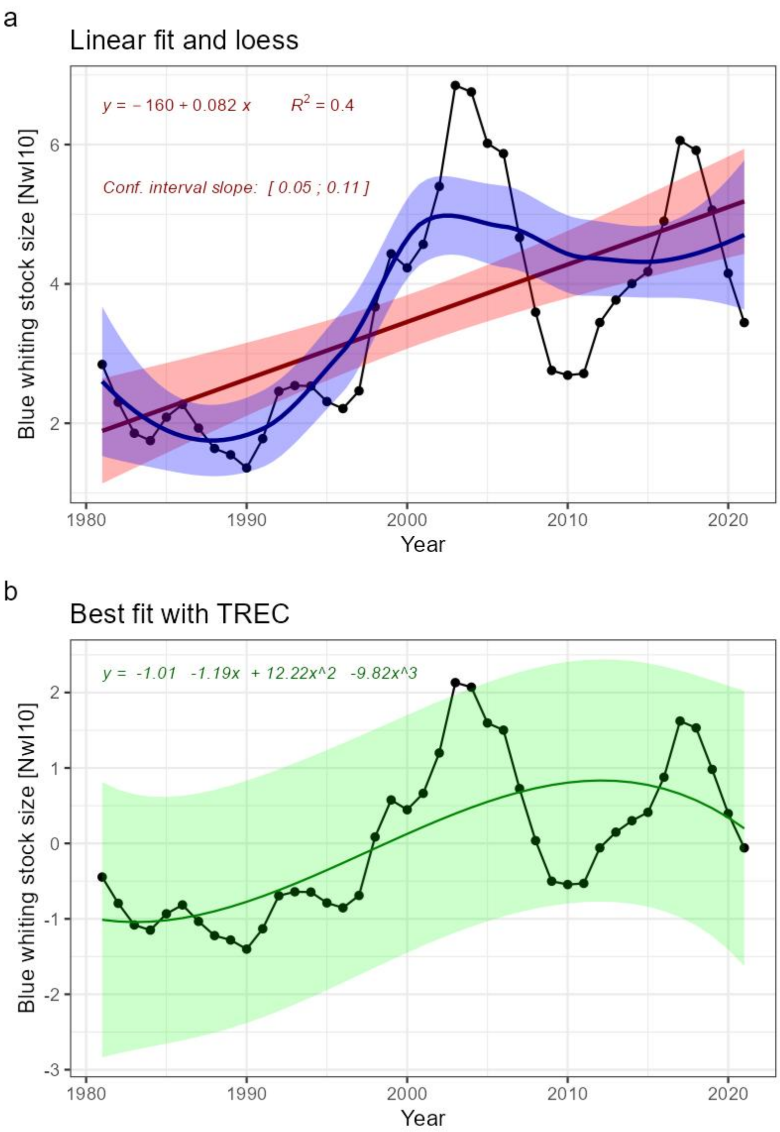


Fig.10: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon

There is an increasing trend when looking over the whole length of the time series. As for herring, the size of the stock is strongly influenced by recruitment. Recruitment show a different pattern of variation than for herring, with high or low recruitment occurring over consecutive years rather than high recruitment in single years, possibly as a result of similar between year variation in the strength of the sub-polar gyre (Hatun et al., 2009; Payne et al., 2012; Miesner and Payne, 2018). While there has been a lack of a quota sharing agreement after 2013 and consequently a considerable fishing above the recommended total allowable catch, this has not generated a decline in the stock size for the period that has followed. It is therefore assessed that there is no evidence of the phenomenon.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Blue whiting recruitment [NwI11]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Decreasing blue whiting recruitment [NwP11]

Main driver: Fisheries

Supplementary metadata

Not relevant.

Supplementary methods

Not relevant.

Plots of indicator values

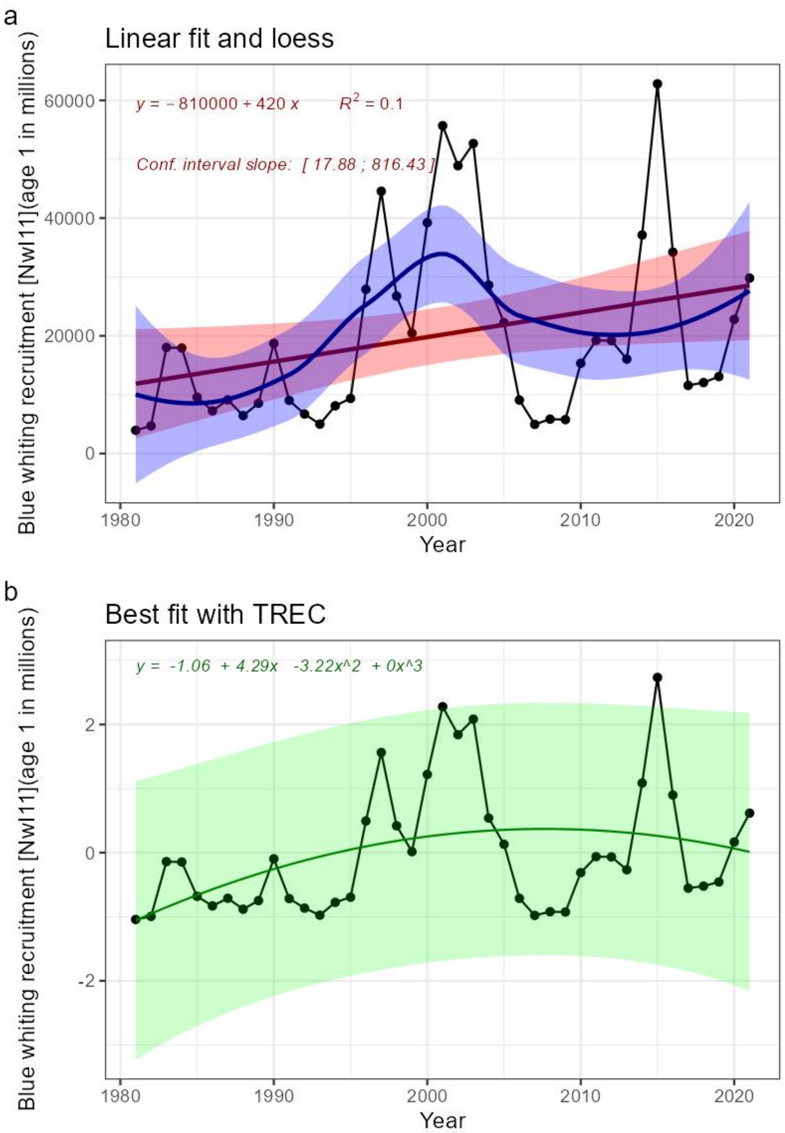


Fig.11: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

There is no evidence of a decline in the time series. As described above, there is evidence that recruitment is driven by oceanographic processes. It is therefore assessed that there is no evidence of the phenomenon.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Calanus finmarchicus stock size [NwI12]

Ecosystem characteristic: Functionally important species and biophysical structures

Phenomenon: Decreasing Calanus finmarchicus production [NwP12]

Main driver: Climate

Supplementary metadata

Supplementary methods

Plots of indicator values

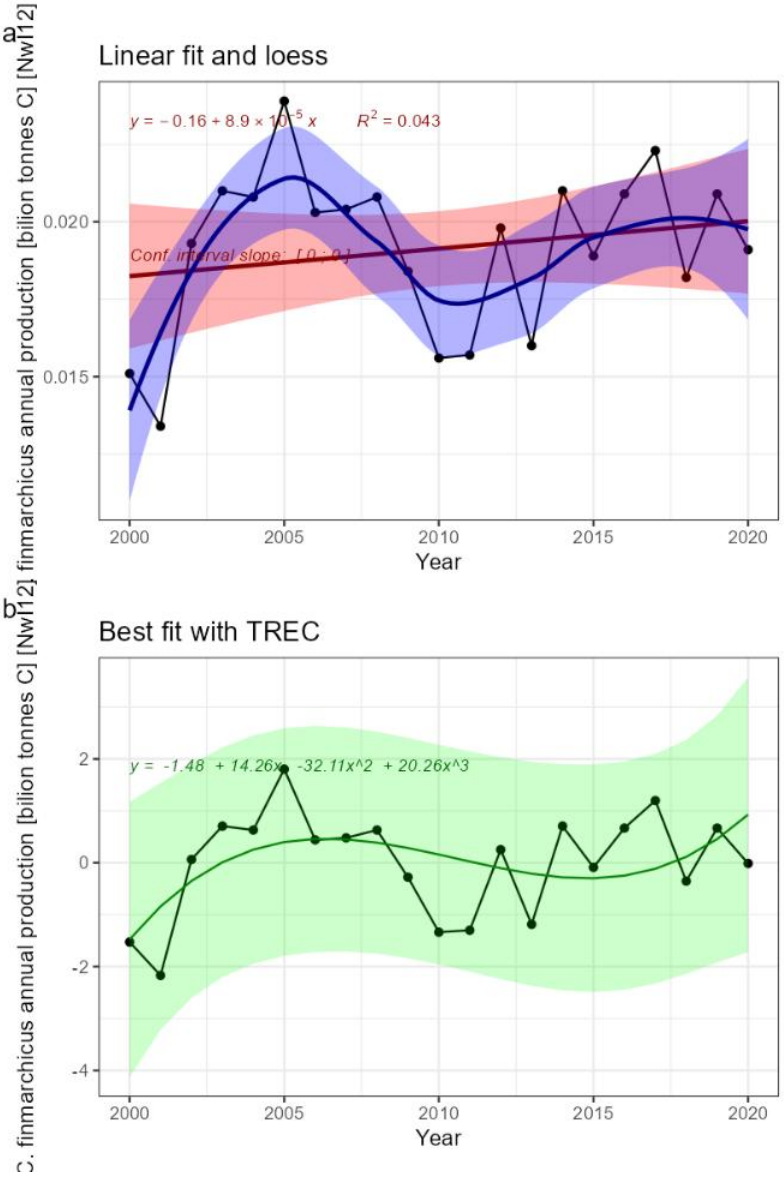


Fig.12: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon

There is no evidence of a decline in the variable. Thus, it is assessed that there is no evidence of the phenomenon.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Copepod species vulnerable to higher temperature [Nw13]

Ecosystem characteristic: Biological diversity

Phenomenon: Decreasing number of copepod species sensitive to higher temperatures [NwP13]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Not relevant

Plots of indicator values

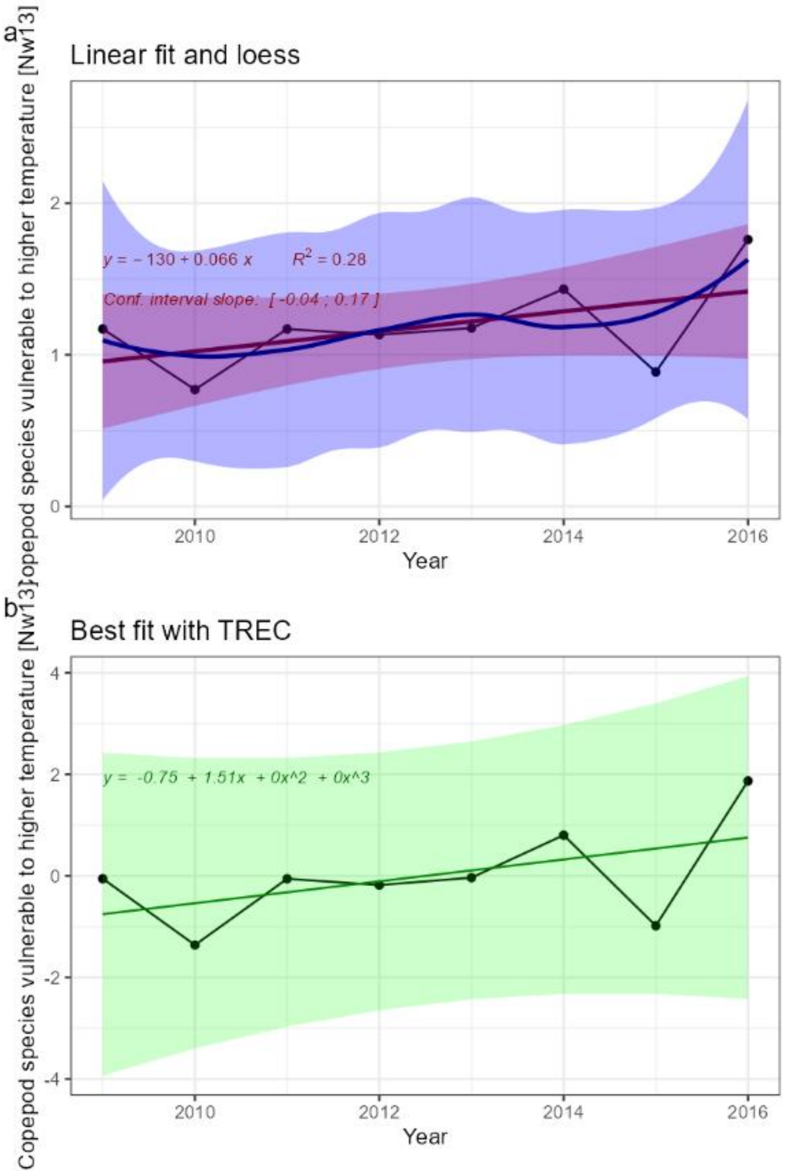


Fig.13: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon

The time series is too short (8 years) to assess whether there has been a change in variable that can be attributed to effects of climate change

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator : Copepod species benefitting from higher temperature [NwI14]

Ecosystem characteristic: Biological diversity

Phenomenon: Increasing number of copepod species benefitting from higher temperatures [NwP14]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Not relevant

Plots of indicator values

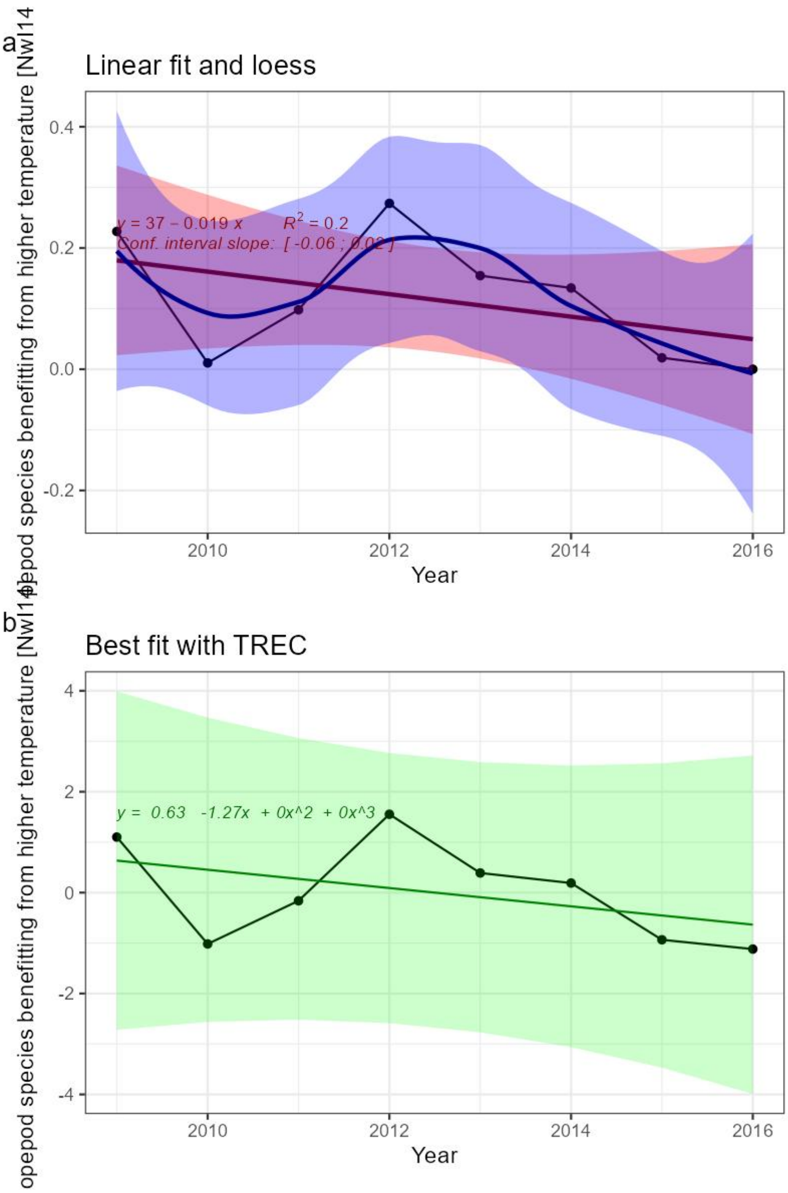


Fig.14: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time serie

Assessment of the evidence for the phenomenon

The time series is too short (8 years) to assess whether there has been a change in variable that can be attributed to effects of climate change

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Heat content [NwI15]

Ecosystem characteristic: Abiotic factors

Phenomenon: Increasing heat content [NwP15]

Main driver: Climate

Supplementary metadata

Not relevant.

Supplementary methods

Heat content is represented as anomalies calculated from removing the mean over the whole time series.

Plots of indicator values

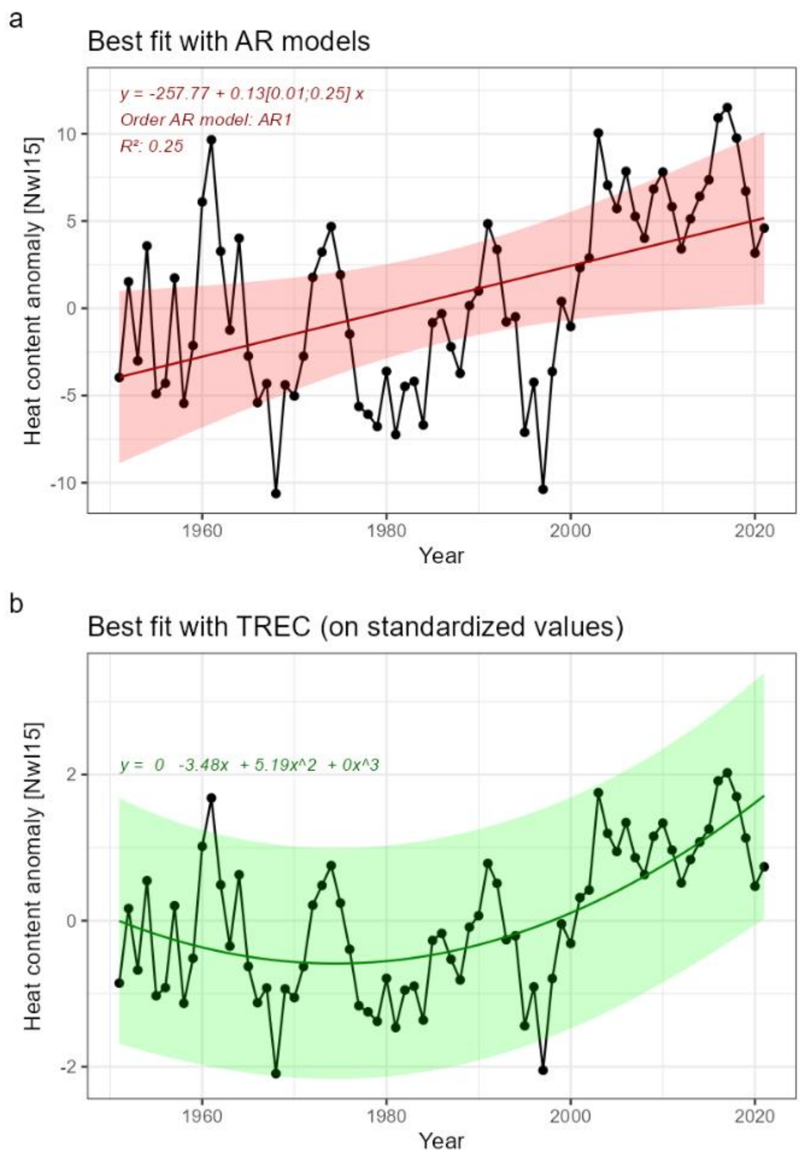


Fig.15: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

There is a clear increase in temperature that is attributed to anthropogenic impact on climate. In particular, reduced levels of cooling of Atlantic water due to a warmer atmosphere, is important. The changes are expected to have significant impact on other parts of the ecosystem. The evidence for the phenomenon is thus rated as high.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Freshwater content [NwI16]

Ecosystem characteristic: Abiotic factors

Phenomenon: Increasing freshwater content [NwP16]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Freshwater content is represented as anomalies calculated from removing the mean over the whole time series

Plots of indicator values

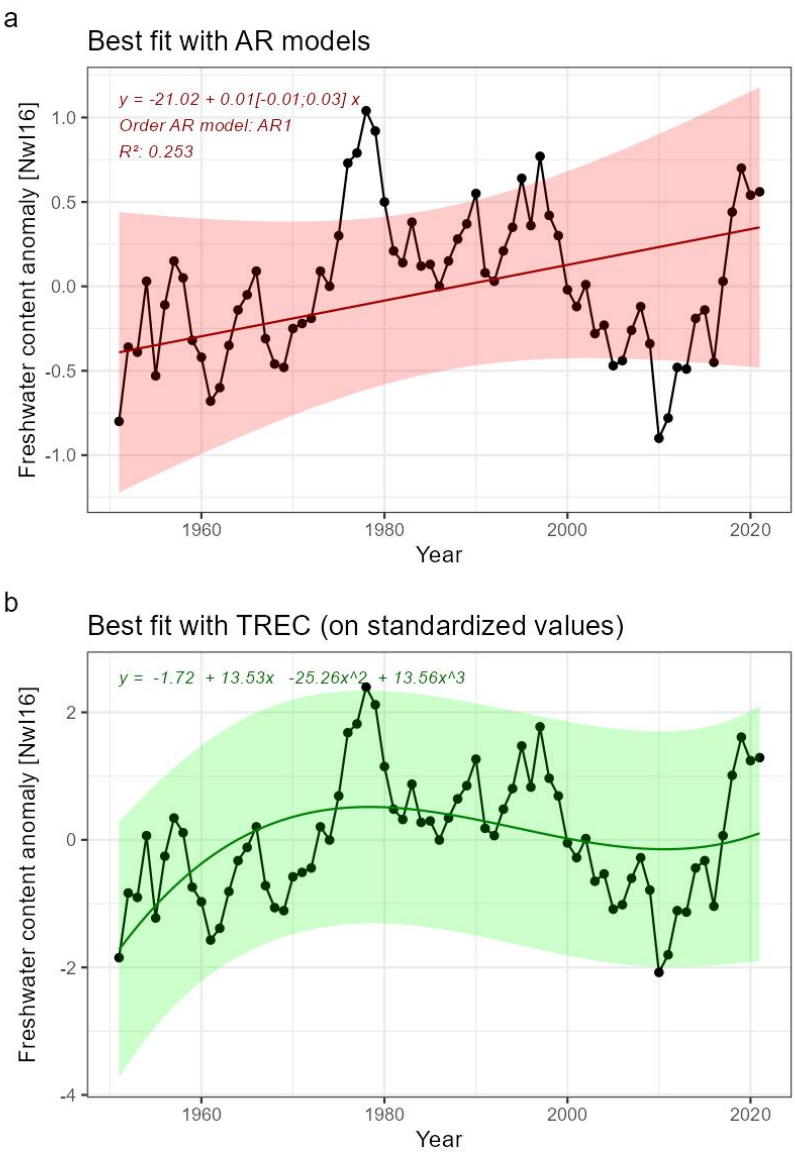


Fig.16: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Fig.16: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled

time series

Assessment of the evidence for the phenomenon:

There is large natural variation in the indicator. Therefore, it is hard to assess whether the indicator has changed as a consequence of anthropogenic impact. It is therefore assessed that there is no evidence that the phenomenon has occurred, but there is considerable uncertainty associated with this due to the high natural variability.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Inflow of Arctic water [NwI17]

Ecosystem characteristic: Abiotic factors

Phenomenon: Change in inflow of Arctic Water [NwP17]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Not relevant

Plots of indicator values

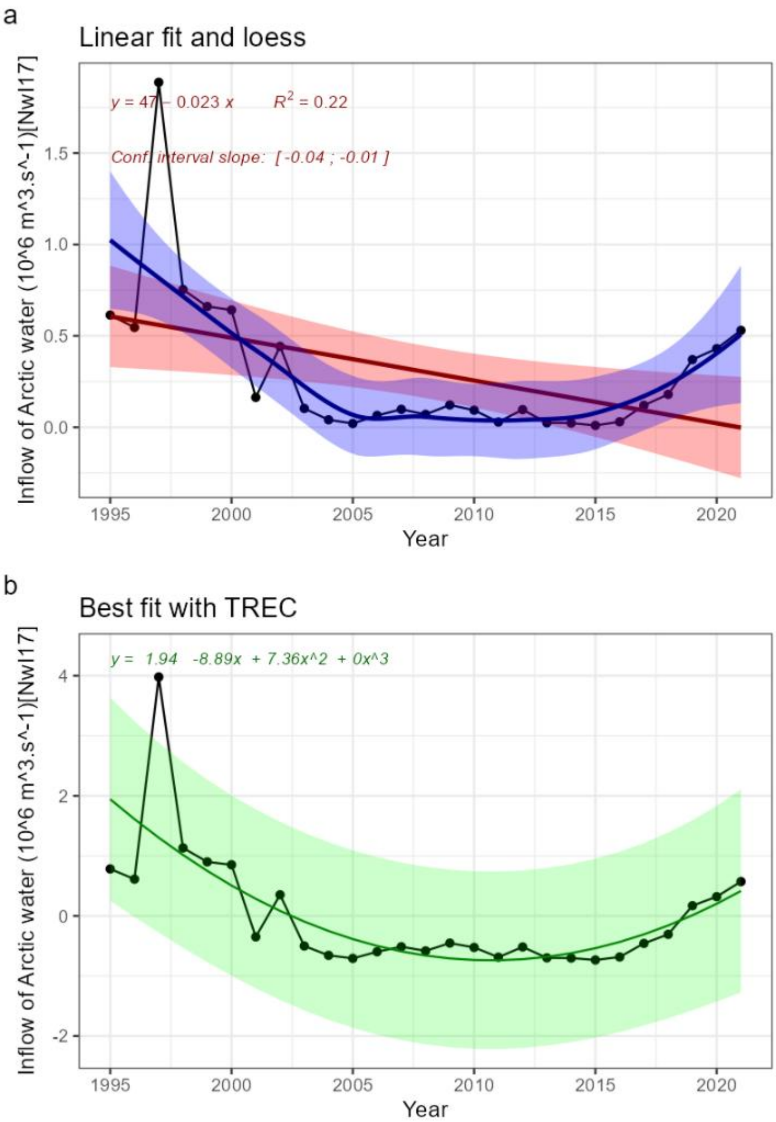


Fig.17: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

The time series is too short to assess whether there is a long-term trend that may be linked to anthropogenic climate change on top of natural variation.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Stratification [NwI18]

Ecosystem characteristic: Abiotic factors

Phenomenon: Increasing stratification [NwP18]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Stratification Drho is calculated as: Drho = rho(200m) – rho(10m)

Plots of indicator values

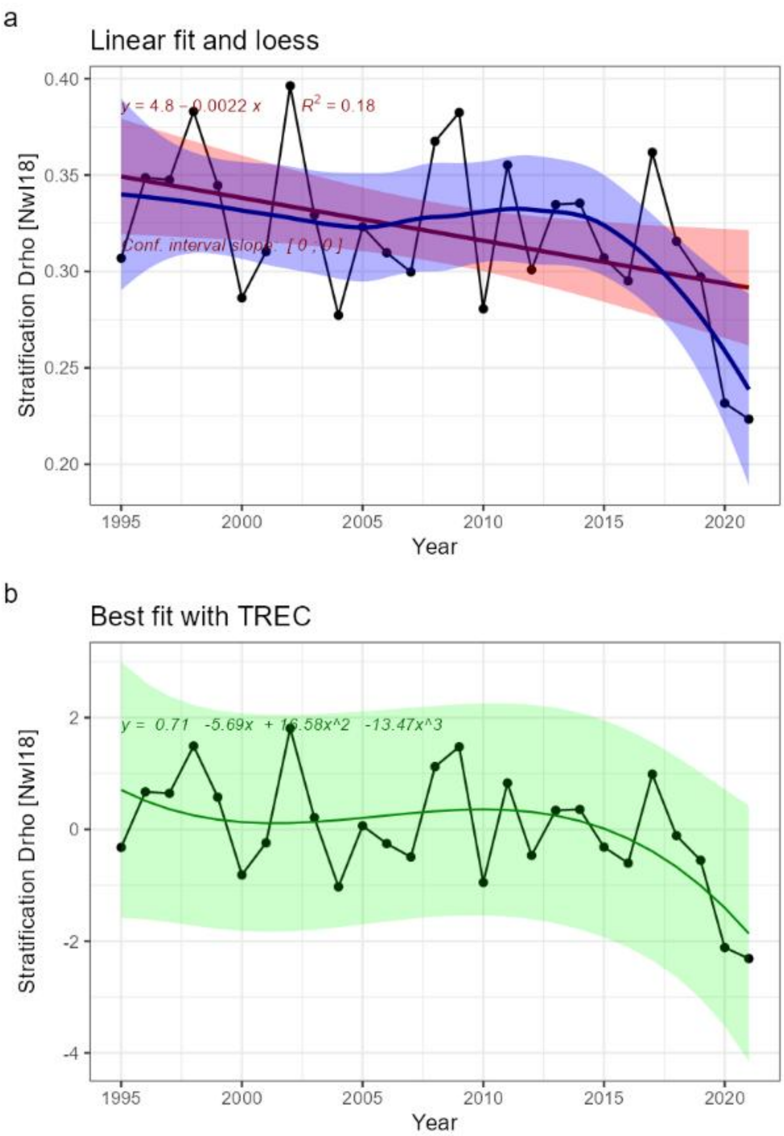


Fig.18: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

This time series shows a slightly decreasing trend, indicating weaker stratification. However, this trend is mainly driven by the two last years of the series, when stratification was lower than during the previous years. Stratification is driven by two opposite mechanisms that are well understood but which dominance regime are not well identified. The last two point in the series could be du to local processes, maybe due to mixing winds, but further analyses would be required to confirm this. The more large-scale patterns of increasing stratification are thus not evident in the North Sea. There is, in any case, not enough data to attribute the past changes to anthropogenic pressures.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Inflow of Atlantic water [NwI19]

Ecosystem characteristic: Abiotic factors

Phenomenon: Decreasing inflow of Atlantic Water [NwP19]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Date represented are annual mean from: Year^{-1} (May) – Year (April)

Plots of indicator values

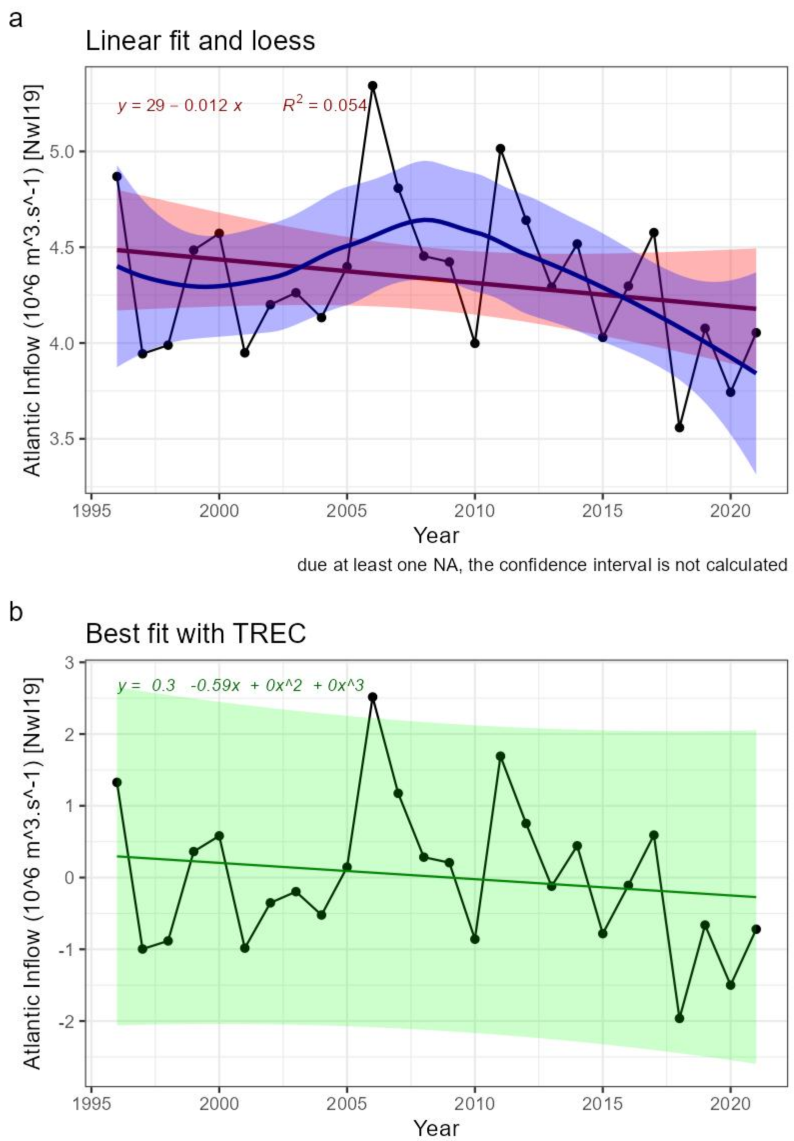


Fig.19: Indicator time series and fitted trends. A) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. B) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

This time series shows high interannual variability and no trend. This is supported by a recent publication (Orvik et al., 2022). However, it is too short to link it to anthropogenic drivers.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: Nutrients [NwI20]

Ecosystem characteristic: Abiotic factors

Phenomenon: Change in concentrations of nutrients [NwP20]

Main driver: Climate

Supplementary metadata

Not relevant

Supplementary methods

Indices of inorganic nutrients are mean winter values defined horizontally by 62-69^{o}N and 2^{o}W-16^{o}E, and in depth layers 10-50m and 100-200m following Gundersen (2020) of Silicate and Nitrate (SiO_4):Silicate (NO_3) ratio, but excluding the Norwegian Shelf

Plots of indicator values

The period is from 1995 to 2019 (need update). Silicate shows an order 1 µmol/l decrease in both depth layers from 1995-2005 and thereafter remains at low values. The last few years indicate a possible further decrease. The N:S ratio increased from 1995 to a relative maximum in 2003, thereafter intermediate levels with anomalous single years. After 2016 this ratio has been relatively high.

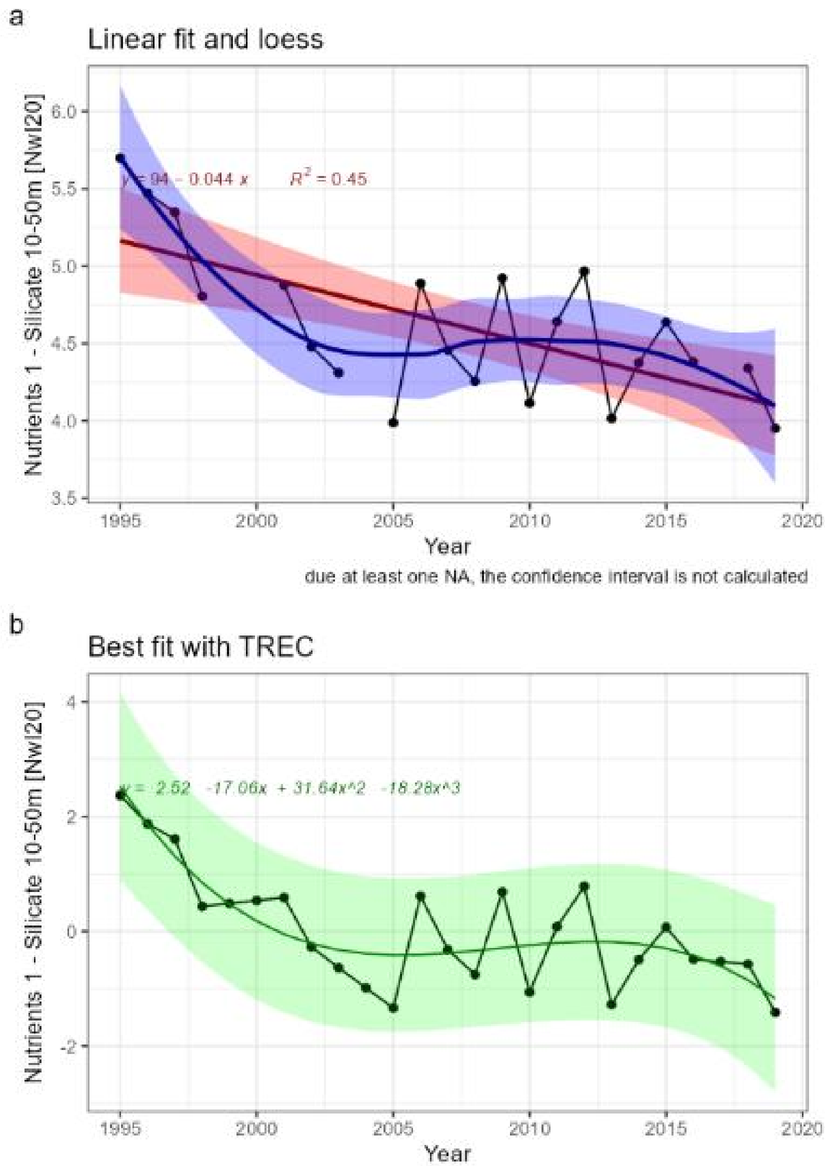


Fig. 20.1: Indicator time series and fitted trends. a) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. b) Best fitted trend using the first steps of a TREC analysis on scaled time series

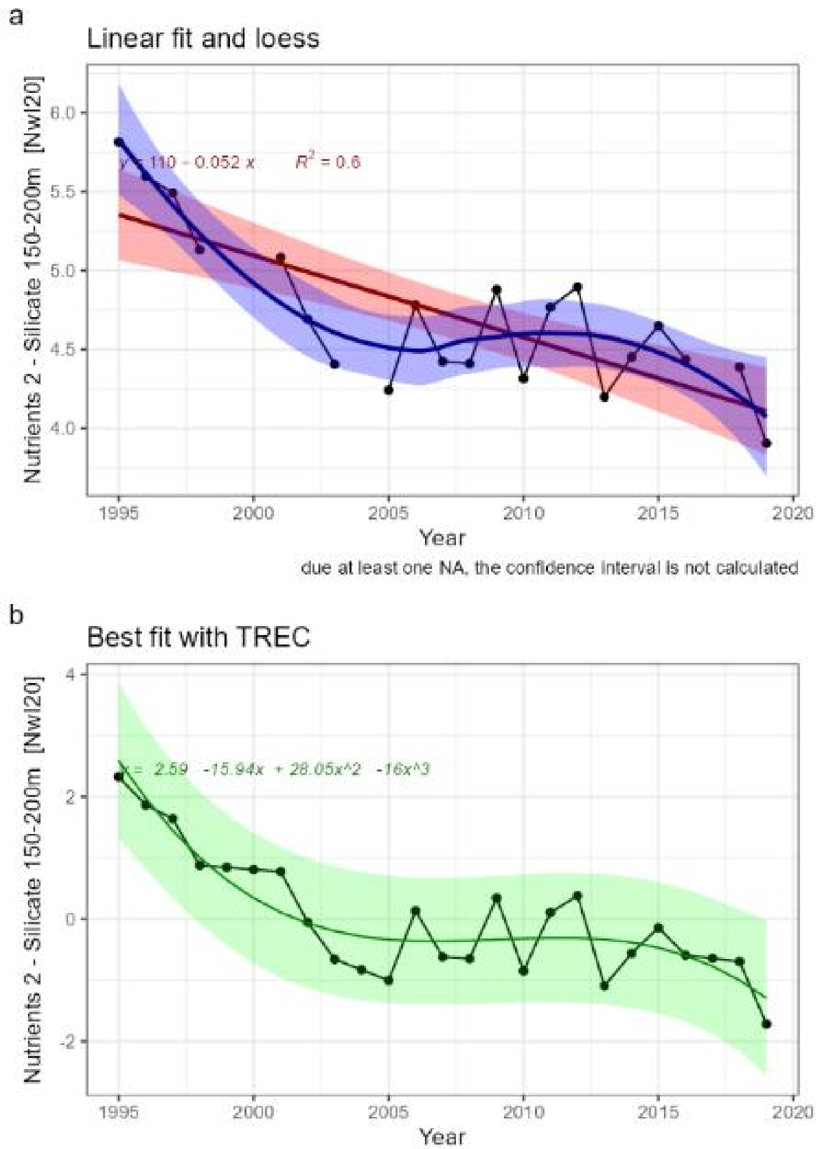


Fig. 20.2: Indicator time series and fitted trends. a) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. b) Best fitted trend using the first steps of a TREC analysis on scaled time series

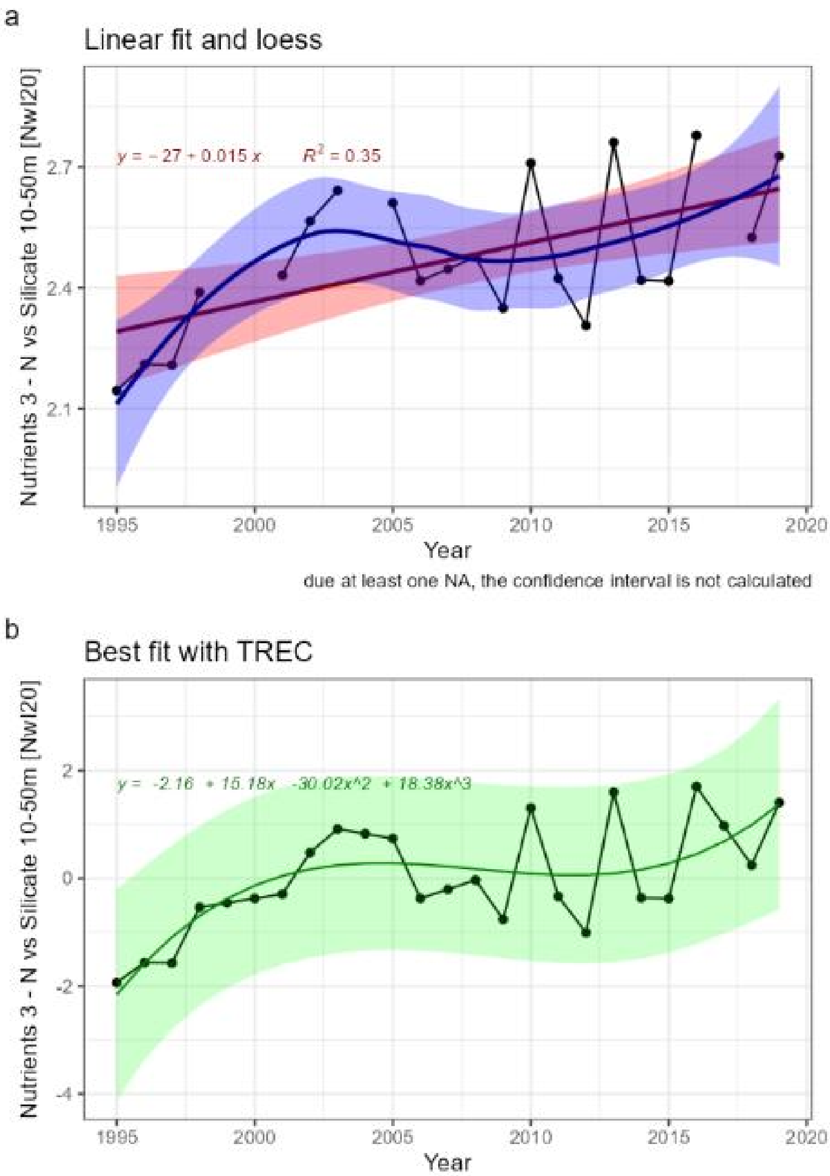


Fig. 20.3: Indicator time series and fitted trends. a) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. b) Best fitted trend using the first steps of a TREC analysis on scaled time series

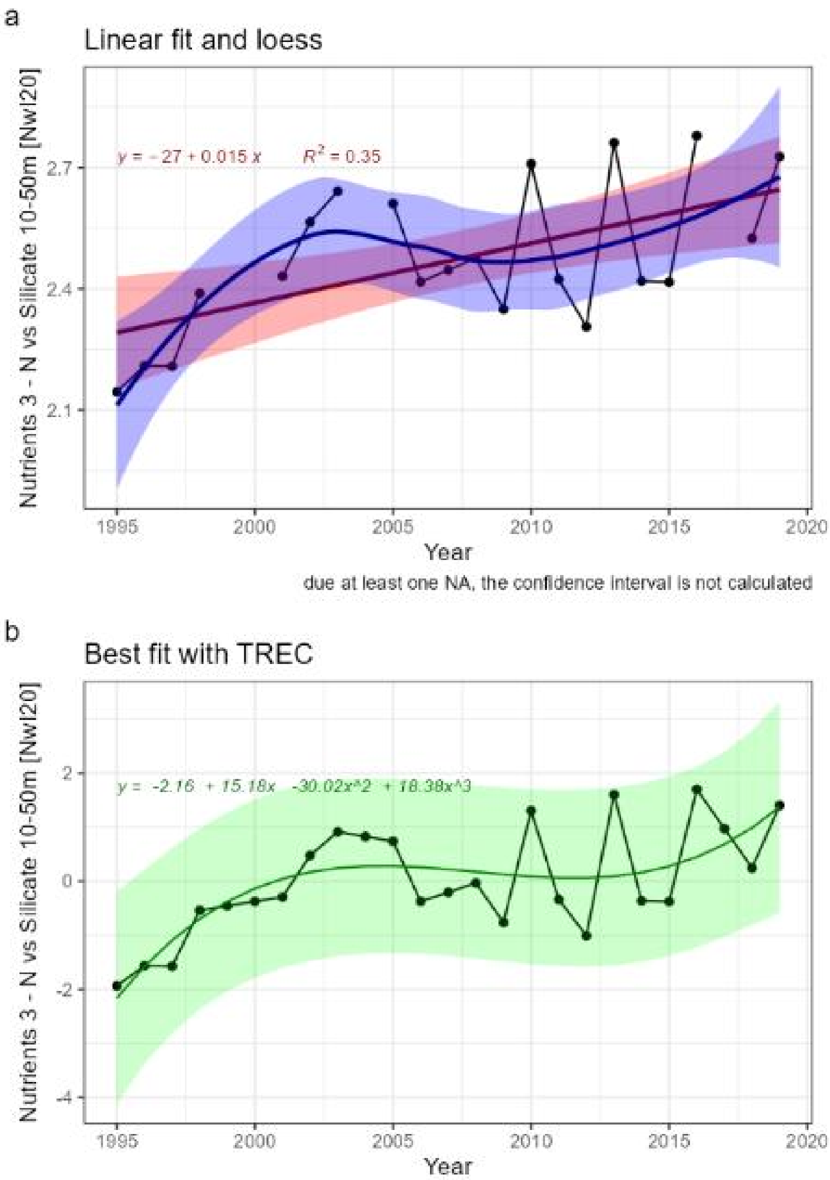


Fig. 20.4: Indicator time series and fitted trends. a) linear trend fitted with Least-square method (not adapted for short time series) in red, and loess in blue, for information. b) Best fitted trend using the first steps of a TREC analysis on scaled time series

Assessment of the evidence for the phenomenon:

The sub-polar gyre index indicates a weakened state since the mid 1990’s. This affected the inflow of nutrients into the Norwegian Sea. The results are low levels of silicates in the whole water column and relatively higher ratio of Nitrogen to Silicates. The time series is however too short to associate these changes to anthropogenic impacts.

Background data and supplementary analysis

Recommendations for future development of the indicator

Indicator: pH [NwI21]

Ecosystem characteristic: Abiotic factors

Phenomenon: Decreasing pH [NwP21]

Main driver: Climate

Supplementary metadata

The data for the Norwegian Sea are from the Norwegian ocean acidification monitoring program (2011-2012 Tilførselsprogrammet and 2013–2019 Havforsuringsprogrammet) are published in the database 'Vannmiljø' (www.vannmiljo.miljodirektoratet.no) of the Norwegian Environment Agency and are available in the Norwegian Marine Data Centre (NMDC) via https://doi.org/10.21335/NMDC-1939716216.

Supplementary methods

Mean values for the Atlantic Water (salinity ³ 34.9, temperature ³ 0 ° C, depth ³ 200 m) were calculated in the Norwegian Sea (Norwegian Basin) from observations of total alkalinity and total dissolved inorganic carbon between 2011 and 2021 obtained through the observational program "Monitoring ocean acidification in Norwegian waters", funded by the Norwegian Environment Agency. Details of the analytical methods and calculations for pH on a total scale are found in the annual reports for the above mentioned program in (Chierici et al., 2016; Chierici et al., 2017; Jones et al., 2018; Jones et al., 2019).

Plots of indicator values

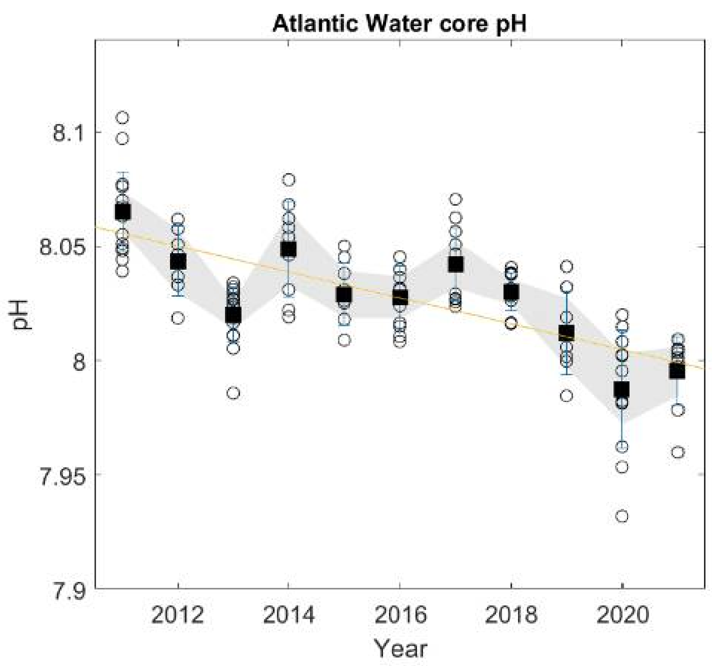


Fig.21: The time series of pH in the period 2011 to 2021 in the Atlantic Water (salinity □ 34.9, temperature □ 0, depth □ 200 m) in the Norwegian Sea. The linear regression fit (orange line; gradient = □ 0.0056 □ 0.0013, p = 0.0022, R2 = 0.67) is based on annual mean pH values (black squares) from observational data (circles). Bars are □ 1 standard deviation for each annual mean. The grey shaded area represents the 95% confidence limits.

Assessment of the evidence for the phenomenon:

Intermediate evidence that the phenomenon has occurred.

The linear fit in the relatively short time period from 2012 to 2020 shows a significant trend of decreasing pH of 0.0056 yr^{-1} in the Atlantic Waters in the Norwegian Sea. This is nearly three times faster than the rates of pH decrease determined for 200-1000 m depth in the Norwegian Sea (0.001-0.002 yr^{-1}; Fransner et al. 2022) and twice as fast the rates of pH decrease determined for the global ocean (0.002 yr^{-1}; Copernicus Marine). The rate differences likely result from variations in sampling period, different spatial coverage and length of the time series within the given region. From the time series in the Norwegian Sea, it is also obvious that minimum pH values decrease with increased frequency. Consequently, the observed trend is as expected and is caused by the increased atmospheric CO_2 due to human activities.

Background data and supplementary analysis

Not relevant

Recommendations for future development of the indicator

The observations are usually performed in winter (November-February) and should have small effects from biotic processes. However, some observations were collected in spring (April-May) and may be affected by biotic processes. This contributes to the interannual variability and spread within one year (shown as bars Fig. Nw.21.1), resulting in limitation for robust trend analysis. It is crucial to continue with long term observations and should cover seasonal variability and capture processes that may influence the region of different time scales, e.g. circulation features, to be able to follow the trends and develop regional models for prediction of pH trends in the Norwegian Sea.

Indicator: Aragonite saturation [NwI22]

Ecosystem characteristic: Abiotic factors

Phenomenon: Decreasing aragonite saturation [NwP22]

Main driver: Climate change

Supplementary metadata

The data for the Norwegian Sea are from the Norwegian ocean acidification monitoring program (2011-2012 Tilførselsprogrammet and 2013–2019 Havforsuringsprogrammet) are published in the database 'Vannmiljø' (www.vannmiljo.miljodirektoratet.no) of the Norwegian Environment Agency and are available in the Norwegian Marine Data Centre (NMDC) via https://doi.org/10.21335/NMDC-1939716216.

Supplementary methods

Mean values for the Atlantic Water (salinity ³ 34.9, temperature ³ 0 ° C, depth ³ 200 m) were calculated in the Norwegian Sea (Norwegian Basin) from observations of total alkalinity and total dissolved inorganic carbon between 2011 and 2021 obtained through the observational program "Monitoring ocean acidification in Norwegian waters", funded by the Norwegian Environment Agency. Details of the analytical methods and calculations for pH on a total scale are found in the annual reports for the above mentioned program in (Chierici et al., 2016; Chierici et al., 2017; Jones et al., 2018; Jones et al., 2019).

Plots of indicator values

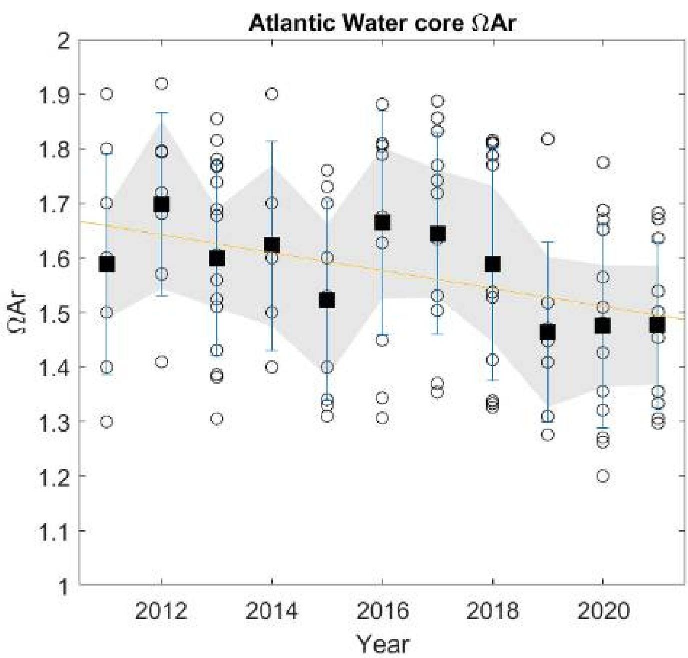


Fig.22: The time series of aragonite saturation (ΩAr) in the period 2011 to 2021 in the Atlantic Water (salinity ³ 34.9, temperature ³ 0°C, depth ³ 200 m) in the Norwegian Sea. The linear regression fit (orange line; gradient = - 0.0164 ± 0.0060, p = 0.0239, R2 = 0.45) is based on annual mean ΩAr values (black squares) from observational data (circles). Bars are ± 1 standard deviation for each annual mean. The grey shaded area represents the 95% confidence limits.

Assessment of the evidence for the phenomenon:

Intermediate evidence that the phenomenon has occurred.

The linear fit in the relatively short time period from 2012 to 2020 shows a significant trend of decreasing aragonite saturation of 0.0164 yr^{-1} in the Atlantic Waters in the Norwegian Sea. This is faster than the rates of ΩAr decrease determined for the similar 200-1000 m depth range in the Norwegian Sea (0.004-0.006 yr^{-1} ; Fransner et al. 2022). The rate differences likely result from variations in sampling period, different spatial coverage and length of the time series within the given region. From the time series in the Norwegian Sea, it can be seen that there is increased frequency of Ω_{Ar} <1.4, which results in negative effects for calcification for winged snails. Consequently, the observed trend is as expected and is caused by the increased atmospheric CO_2 due to human activities.

Background data and supplementary analysis

Recommendations for future development of the indicator

Appendix 8.2: Information about drivers –Norwegian Sea

Fisheries

Mackerel

Fishing pressure on the stock is above F_{MSY} but below F_{pa} and F_{lim}; spawning-stock size is above MSY $B_{trigger}$, B_{pa}, and B_{lim}.

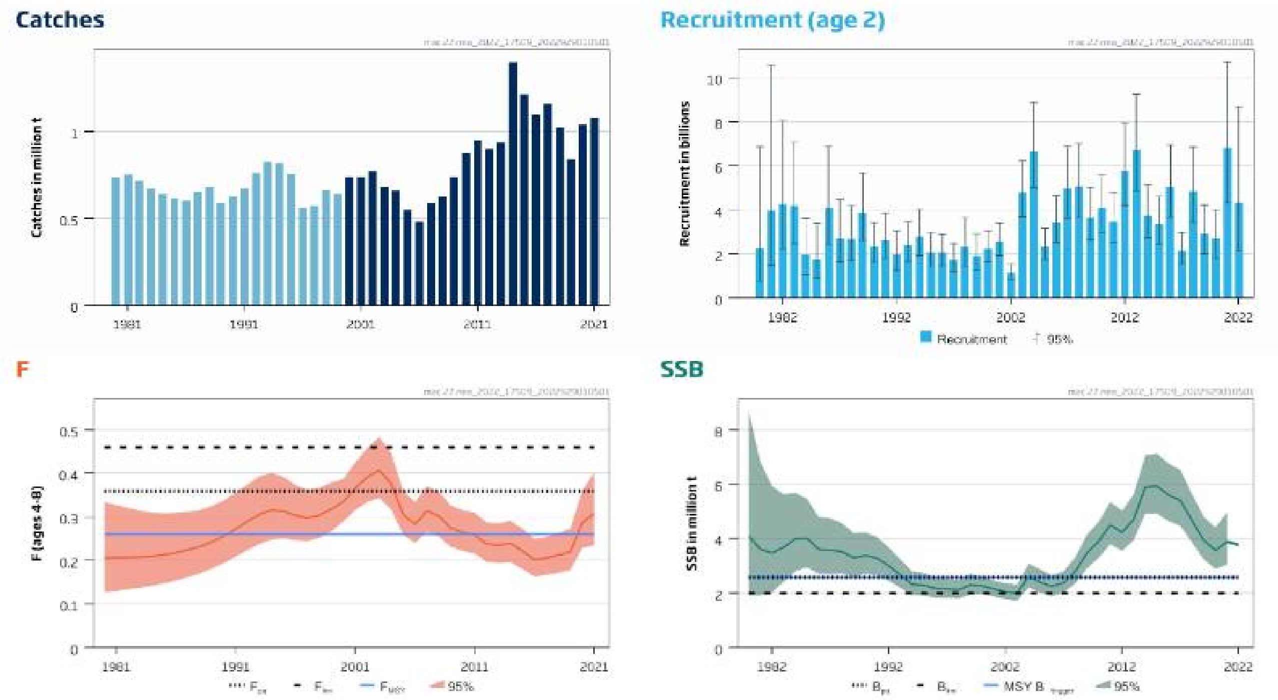


Figure D.1.1 Mackerel in subareas 1–8 and 14, and in Division 9.a. Summary of the stock assessment. Catches prior to 2000 have been down-weighted in the assessment because of the considerable underreporting suspected to have taken place in this period. Abundance estimates of age 0 and 1 from the assessment model poorly reflect year-class strength and therefore recruitment is shown at age 2. Source: ICES (2022c)

Norwegian Spring-Spawning Herring

Fishing pressure on the stock is above F_{MSY} and between F_{pa} and F_{lim}; spawning-stock size is above MSY B $_{trigger}$, B_{pa}, and B_{lim}.

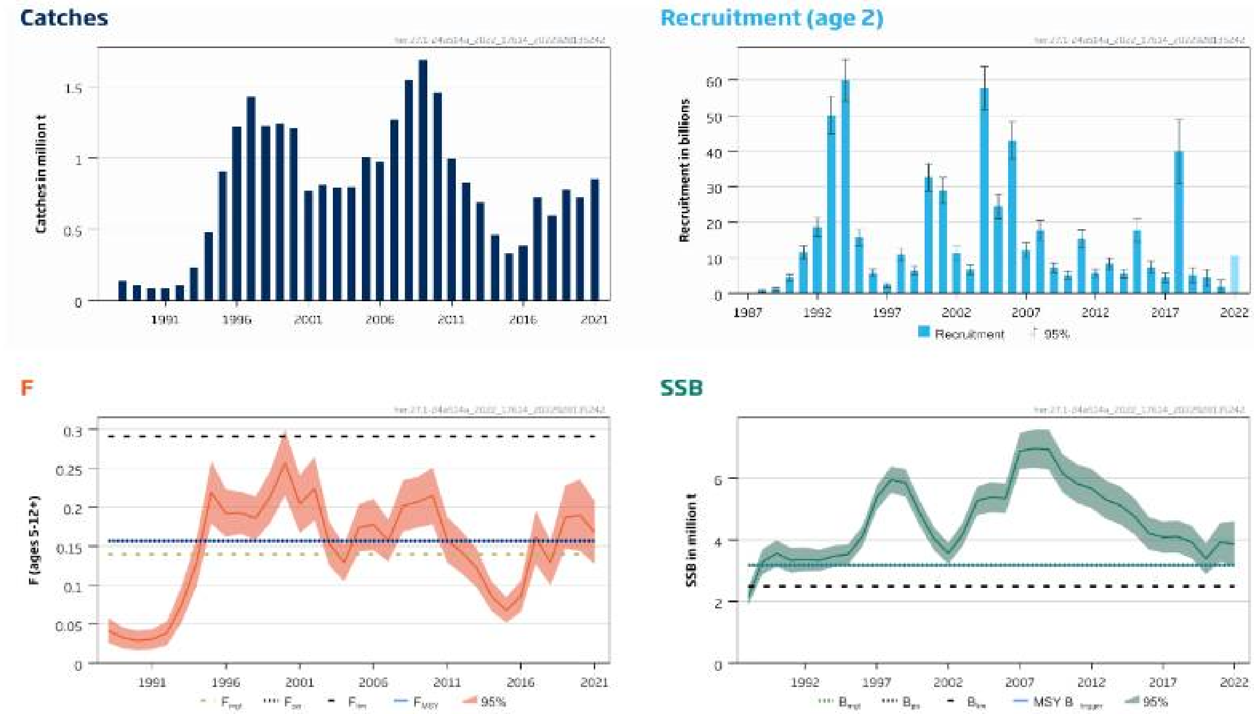


Figure D.1.2 Herring in subareas 1, 2, and 5, and in divisions 4.a and 14.a (Norwegian spring-spawning herring). Summary of the stock assessment. The assumed recruitment value for 2022 is shaded in a lighter colour. Source: ICES (2022b).

Blue whiting

Fishing pressure on the stock is above F_{MSY} and F_{pa} but below F_{lim}; spawning-stock size is above MSY $B_{trigger}$, B_{pa}, and B_{lim}.

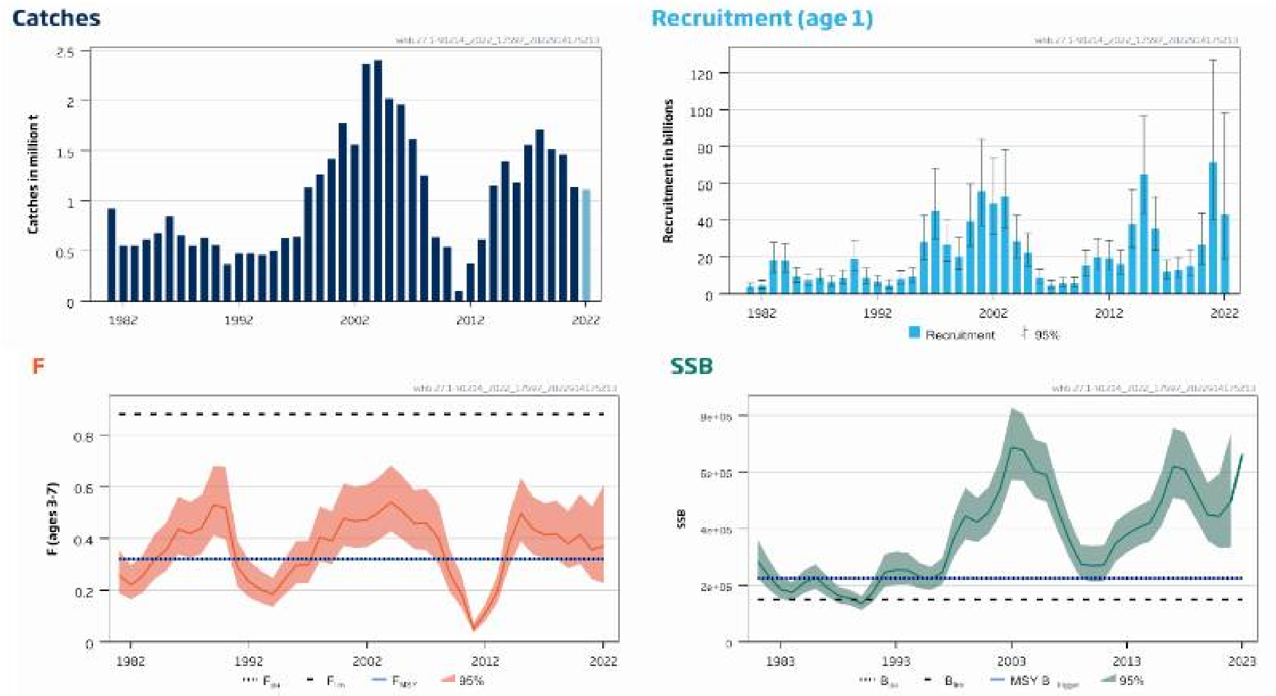


Figure D.1.3 Blue whiting in subareas 1–9, 12, and 14. Summary of the stock assessment. The catch estimate for 2022 is preliminary. The assumed recruitment value for 2023 is shaded in a lighter colour. ICES (2022a).

Appendix 8.3 Footnotes to data coverage assessment (Table 7.1)

Footnotes for table 7.1., data coverage assessment

Primary production

1. Fulfilled, satellite data coverage of entire population
2. Fulfilled, entire area covered by systematic sampling.
3. Not fulfilled, sampling can depend on cloud cover
4. Not fulfilled, sampling design is not model based
5. Partially adequate coverage, long time series, but does not overlap with the reference condition.
6. Adequate coverage, seasonal variation is very relevant and taken into account.
7. **Total indicator coverage for the characteristic “primary productivity” is considered adequate**

Biomass across trophic levels

8. May survey, covers norwegian sea, not continued since 2021
9. Stratified randomised sampling
10. All stations have the same probability to be sampled
11. Not a model-based model
12. Time series goes back to 1995, but there was changes of methods in this time series (e.g. depth of the sampling).
13. Seasonality important and not taken into account
14. Not a design-based sampling where the entire sampling population has possibility of being included.
15. Not a design-based sampling based on randomisation
16. Not a design-based sampling, with known probability of including each sampling unit.
17. Model-based sampling using a statistical model for taking into account variation in time and space of the sampling.
18. Long time series relative to relative dynamics but not overlapping with reference period.
19. Seasonality is not relevant.
20. **Total indicator coverage for the characteristic “Biomass across trophic levels indicator” is considered adequate**

Functional groups within trophic levels

21. CPR data: mainly the traffic linking Norway and Iceland. There was a change in the routes. Just a small part of the population is monitored.
22. CPR data can be considered a randomized design
23. There is known probability of sampling the route
24. not a model-based design
25. (Copepod body size) very short time series not easily linked to driver effect
26. (Copepod body size) Seasonality is important and covered from CPR data
27. **Total indicator coverage for the characteristic “Functional groups within trophic levels” is considered partially adequate**

Functionally important species and biophysical structures

28. Most of the data comes from catch data and tag studies. Others come from the IBTS trawl survey. Those data are suitable to estimate mackerel population
29. Trawl in IBTS survey, tagging of individual provide a randomized sampling. Catch data can be considered to be based on a model of fish distribution.

0. Each sampling unit has a known probability of being sampled
1. Not a model-based design
2. The time series is long enough to cover relevant dynamics. Trends in the stock are quite robust. More weight was put on the catch and tag data before the 2000s. Now it is more and more relying on the surveys.
3. The survey follows the stock. Aggregation in autumn make it easier for the fisherman to capture them. Trawl sampling is adapted to periods when it is known that they are more in surface.
4. Data comes from IBTS trawl survey and eggs survey. Those data are suitable to estimate mackerel recruitment
5. Trawl in IBTS survey follows a randomized sampling. Catch data can be considered to be based on a model of fish distribution.
6. Each sampling unit has a known probability of being sampled
7. Not a model-based design
8. The time series is long enough to cover relevant dynamics. Trends in the stock are quite robust. More weight was put on the catch and tag data before the 2000s. Now it is more and more relying on the surveys.
9. The survey follows the stock. Aggregation in autumn make it easier for the fisherman to capture them. Trawl sampling is adapted to periods when it is known that they are more in surface. Eggs surveys in winter allow a good recruitment estimation
0. Assessment based on 3 survey indices and fisheries data covering the whole population
1. Stratified random sampling for all surveys
2. Known probability of sampling each unit
3. Fisheries can be considered a model-based design and are suitable for the assessment
4. Data go back to pre-WWII, which can be considered as a period with limited impact.
5. Seasonality important and taken into account
6. Two surveys for recruitment: may + autumn in the Barents Sea. Cover the whole population
7. Stratified random or gridded sampling for all surveys
8. Known probability of sampling each unit
9. Not a model-based design
0. Data go back to pre-WWII, which can be considered as a period with limited impact.
1. Season important and taken into account
2. Different small surveys covering only part of the stocks. Mainly fisheries data, but they do not cover the whole stock (and considered model-based sampling)
3. Not design based sampling
4. Not design based sampling
5. Fisheries are the main data for the assessment and do not cover the SSB stock of blue whiting
6. Partially adequate: long enough for relevant dynamics but not covering the reference conditions
7. Seasonality not important
8. No survey for recruitment
9. No survey for recruitment
0. No survey for recruitment
1. Not a model-based design
2. Partially adequate: long enough for relevant dynamics but not covering the reference conditions
3. No survey for recruitment so seasonality not taken into account
4. The model Norwecom.E2E produces data over the whole assessment area
5. The data are sampled on a grid of ~4x4 km
6. All grid cells are used to estimate the production
7. Not a model-based sampling
8. But the time series is not covering a period with no climate change
9. The seasonality is important and taken into account
0. **Total indicator coverage for the characteristic "Functionally important species and biophysical structures" is considered partially adequate**

Biological diversity

1. CPR data: mainly the traffic linking Norway and Iceland. There was a change in the routes. Just a small part of the population is monitored.
2. CPR data can be considered a randomized design
3. There is known probability of sampling the route
4. Not a model-based design
5. Very short time series not easily linked to driver effect
6. Seasonality is important and taken into account
7. CPR data: mainly the traffic linking Norway and Iceland. There was a change in the routes. Just a small part of the population is monitored.
8. CPR data can be considered a randomized design
9. There is known probability of sampling the route
10. Not a model-based design
11. Very short time series not easily linked to drivers effect
12. Seasonality is important and taken into account
13. **<u>Total indicator coverage for the characteristic “Biological diversity” is considered partially adequate</u>**

Abiotic factors

14. Fulfilled, a design-based grid sampling where the entire population has a possibility of being included.
15. Fulfilled, sampling of stations in the grid covering the whole area
16. Fulfilled, all stations have the same probability of being included as there are no factors such as sea ice occurrence that could prevent it
17. Not fulfilled, not a model-based sampling
18. Adequate, along time series relative to relevant dynamic and overlapping with the 1961-1990 defined as the climate reference period.
19. Adequate, heat content has a “long memory” and between-year variation can be meaningfully estimated without coverage of all seasons
20. Fulfilled, a design-based grid sampling where the entire population has a possibility of being included.
21. Fulfilled, sampling of stations in the grid covering the whole area
22. Fulfilled, all stations have the same probability of being included as there are no factors such as sea ice occurrence that could prevent it
23. Not fulfilled, not a model-based sampling
24. Adequate, along time series relative to relevant dynamic and overlapping with the 1961-1990 defined as the climate reference period
25. Adequate, freshwater content has a “long memory” and between-year variation can be meaningfully estimated without coverage of all seasons
26. Fulfilled, a design-based grid sampling where the entire population has a possibility of being included.
27. Fulfilled, sampling of stations in the grid covering the whole area
28. Fulfilled, all stations have the same probability of being included as there are no factors such as sea ice occurrence that could prevent it
29. Not fulfilled, not a model-based sampling
30. Inadequate, the time series is long enough to assess relationships with other abiotic and biotic variables, but not overlapping with the reference period for climate and too short to be able to distinguish variation due to anthropogenic impact (climate change) from natural muti-decadal variation, which recent literature suggest may occur on a 50-70-year time scale, thus much longer than the 27 year long time series used here.
31. Adequate. Arctic Water content has a “long memory”, and between-year variation can be meaningfully estimated

without coverage of all seasons.

2. Fulfilled, a design-based grid sampling where the entire population has a possibility of being included.
3. Fulfilled, sampling of stations in the grid covering the whole area
4. Fulfilled, all stations have the same probability of being included as there are no factors such as sea ice occurrence that could prevent it
5. Not fulfilled, not a model-based sampling
6. Inadequate, the time series is long enough to assess relationships with other abiotic and biotic variables, but not overlapping with the reference period for climate and too short to be able to distinguish variation due to anthropogenic impact (climate change) from natural muti-decadal variation, which recent literature suggest may occur on a 50-70-year time scale, thus much longer than the 27 year long time series used here.
7. Inadequate, stratification varies through the year and this variation is large compared to between-year variation. This is not covered by the sampling.
8. Not fulfilled, not a grid-based sampling
9. Not fulfilled, not a grid-based sampling
0. Not fulfilled, not a grid-based sampling
1. Fulfilled, sampling is done in a section positioned across the inflow (Svinøy Inadequate, the time series is long enough to assess relationships with other abiotic and biotic variables, but not overlapping with the reference period for climate and too short to be able to distinguish variation due to anthropogenic impact (climate change) from natural muti-decadal variation, which recent literature suggest may)
2. Inadequate, the time series is long enough to assess relationships with other abiotic and biotic variables, but not overlapping with the reference period for climate and too short to be able to distinguish variation due to anthropogenic impact (climate change) from natural muti-decadal variation, which recent literature suggest may occur on a 50-70-year time scale, thus much longer than the 26 year long time series used here.
3. Adequate, sampling is done throughout the year
4. Fulfilled, a design-based grid sampling where the entire population has a possibility of being included.
5. Fulfilled, sampling of stations in the grid covering the whole area
6. Fulfilled, all stations have the same probability of being included as there are no factors such as sea ice occurrence that could prevent it
7. Not fulfilled, not a model-based sampling
8. Inadequate, the time series is long enough to assess relationships with other abiotic and biotic variables, but not overlapping with the reference period for climate and too short to be able to distinguish variation due to anthropogenic impact (climate change) from natural muti-decadal variation, which recent literature suggest may occur on a 50-70-year time scale, thus much longer than the 25 year long time series used here.
9. Adequate, samples are taken in winter and thus measures the amount of nutrients potentially available for primary production the following season
0. Not fulfilled, the sampling is not design based
1. Not fulfilled, the sampling is not design based
2. Not fulfilled, the sampling is not design based
3. Model- based sampling done in the Atlantic Water along the Svinøy transect. Indicator values are mean of observation
4. Inadequate, short time series relative to relevant dynamics as they start only in 2011, thus decades after CO_2 concentration in the atmosphere had started to increase significantly due to anthropogenic emissions
5. Adequate, sampling is done in winter when year to year variation can be best detected
6. Not fulfilled, the sampling is not design based
7. Not fulfilled, the sampling is not design based
8. Not fulfilled, the sampling is not design based
9. Model -based sampling done in the Atlantic Water along the Svinøy transect. Indicator values are mean of observation
0. Inadequate, short time series relative to relevant dynamics as they start only in 2011, thus decades after CO_2

concentration in the atmosphere had started to increase significantly due to anthropogenic emissions

1. Adequate, sampling is done in winter when year to year variation can be best detected
2. **Total indicator coverage for the characteristic “Abiotic factors” is considered partially adequate**

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