ICES Journal of
Marine Science

ICES Journal of Marine Science (2021), 78(8), 2983–2998. doi:10.1093/icesjms/fsab053

Assessing the state of the Barents Sea using indicators: how, when, and where?

Cecilie Hansen [1,*], Gro I. van der Meeren[2], Harald Loeng[1], and Morten D. Skogen[1]

[1] *Institute of Marine Research, Bergen, Pb.1870, N-5817, Norway*
[2] *Institute of Marine Research, Austevoll Research Station, Sauganeset 16, Storebø N-5392, Norway*

*Correspondingauthor: tel: +47 984 31 016; *e-mail:* cecilie.hansen@hi.no

Hansen, C., van der Meeren, G. I., Loeng, H., and Skogen, M. D. Assessing the state of the Barents Sea using indicators: how, when, and where?. – ICES Journal of Marine Science, 78: 2983–2998.

Received 3 July 2020; revised 1 January 2021; accepted 15 February 2021; advance access publication 31 May 2021.

Two end-to-end ecosystem models, NORWECOM.E2E and NoBa Atlantis, have been used to explore a selection of indicators from the Barents Sea Management plans (BSMP). The indicators included in the BSMP are a combination of simple (e.g. temperature, biomass, and abundance) and complex (e.g. trophic level and biomass of functional groups). The abiotic indicators are found to serve more as a tool to report on climate trends rather than being ecological indicators. It is shown that the selected indicators give a good overview of the ecosystem state, but that overarching management targets and lack of connection between indicators and management actions makes it questionable if the indicator system is suitable for direct use in management as such. The lack of socio-economic and economic indicators prevents a holistic view of the system, and an inclusion of these in future management plans is recommended. The evaluated indicators perform well as an assessment of the ecosystem, but consistency and representativeness are extremely dependent on the time and in what area they are sampled. This conclusion strongly supports the inclusion of an observing system simulation experiment in management plans, to make sure that the observations represent the properties that the indicators need.

Keywords: Atlantis, Barents Sea, ecosystem model, indicator, monitoring, NORWECOM.E2E

Introduction

Assessing the state and predicting the ecosystem responses to multiple stressors is of great importance (Garcia *et al.*, 2003; Shin *et al.*, 2010), and ecosystem-based management is developed to consider the impact on the ecosystem from cumulative stressors and drivers (Frank *et al.*, 2005; Fu *et al.*, 2019). A sound management should engage scientists, stakeholders, and managers to integrate all components of an ecosystem into decision-making processes such that managers can balance trade-offs and determine what is more likely to achieve their desired goals (Link *et al.*, 2002; Levin *et al.*, 2009; Fulton *et al.*, 2014; Hornborg *et al.*, 2019). To assess the ecosystem, indicators that capture the state and trends of key ecosystem components are widely used. Here, an indicator will be understood as: *a quantity based on calculating trends and changes in ecological key species or processes by a selection of one or more single parameters with known or perceived relationship*, where a parameter is an observation or model value of one particular physical or biological component (Siwertson and Arneberg, 2019). An indicator should be representative for an individual component or relationship within an ecosystem, while at the same time reflecting the condition and trend of the whole ecosystem in question. A range of indicators have been suggested, defined, calculated, and evaluated, to track ecosystem status and inform managements (Shin and Shannon, 2010; Butchart *et al.*, 2010; Coll *et al.*, 2016; Lockerbie *et al.*, 2020).

In 2006, an integrated management plan for the Barents Sea–Lofoten area was endorsed by the Norwegian Parliament. This was updated in 2011 (Anon., 2006, 2011) and later revised in 2020 (Anon., 2020). The Barents Sea Management Plan (BSMP) includes by 2020 70 different indicators with a different degree of covariance, a majority being simple ecosystem indicators describing the temperature, primary production, biomasses, and distributions of a selection of species (Olsen *et al.*, 2011; Anon., 2015).

While being one of the shallow shelf seas that form the Arctic continental shelf, the Barents Sea is a productive area, hosting among other one of the world's largest cod stocks (Kjesbu *et al.*, 2014) in addition to a range of other commercially important stocks. Its western boundary is defined by the shelf break towards the Norwegian Sea, the eastern boundary by Novaya Zemlya, the southern boundary by Norway and Russia, and the northern boundary by the continental shelf break towards the deep Arctic Ocean. Stretching from 70°N to over 80°N, it is subject to large seasonal variations in light levels as well as seasonal sea ice. There is ample evidence of the effects of climate variability on the marine ecosystems of the Barents Sea, and the many possible pathways by which climate may affect ecological processes can vary across a broad range of temporal and spatial scales (Ottersen *et al.*, 2010). Climate affects fish both directly through physiology, including metabolic and reproductive processes, as well as through affecting their biotic (predators, prey, and species interactions) and abiotic (habitat type and structure) environment (see e.g. Hollowed *et al.*, 2013a, 2018). The Barents Sea is facing fast and large climate change impacts, and large changes have already been observed (Fossheim *et al.*, 2015; Lind *et al.*, 2018).

The indicators for BSMP were selected through scientific workshops assessing the quality of observations for each suggested indicator, the length of existing time series, and the access to systematic updates. The indicators were chosen to show the development of the entire ecosystem, including physical and chemical oceanography, phytoplankton and zooplankton, and fish populations. The same process was later done in a joint Russian–Norwegian report describing the species and functional groups of the Barents Sea and suggesting indicators to be used in a future Russian ecosystem-based management plan for the Russian sector of the Barents Sea (McBride *et al.*, 2016). The indicators are not used for fisheries management.

Although the indicators used in the BSMP are science based, they are restricted due to the fact that they were selected based on existing monitoring programs and the likelihood of these to be continued. While they are representative for the individual components, they will not necessarily reflect the condition and trends in the whole ecosystem. The selection of indicators to best assess the state of an ecosystem together with the sensitivity and resilience to various natural and human pressures should *a priori* be done founded on the best science-based ecosystem knowledge not hampered by existing monitoring programs (Skogen *et al.*, 2021). A management system should then be defined as a trade-off between what information that are needed to achieve the objective of the BSMP, and the available resources. This allows for more informed and (possibly) new indicators to better identify the ecological and social processes that influence the ecosystem state, and to better identify management actions to minimize ecosystem risk. Although reference points and thresholds already are implemented in most of the biological indicators of the BSMP, no actual suggestions for management-actions to be introduced if the indicator crosses the thresholds are included. This responsibility is placed within each of the management bodies, to govern and regulate the different human activities.

Despite the growing number of observation activities, oceanic observations are still scarce in time and space. Observations give an incomplete access to a natural phenomenon, while ecosystem models on the other hand offer an incomplete representation of processes and components of a natural system (Oreskes *et al.*, 1994). Ecosystem models are probably the best tool to project and understand the consequences of anthropogenic stressors, estimate what is hard or even impossible to measure, and to do a full investigation of system-wide cause–effect relationships (Skogen *et al.*, 2021). The use of models and observations together therefore allows for a better assessment of the system state and impact of cumulative stressors and drivers (Tett *et al.*, 2013; Marshall *et al.*, 2016), and through e.g. the validation of sampling schemes and observations, ecosystem models can contribute to ecosystem management.

In the present work, the main focus has been to evaluate the appropriateness and significance of the proposed indicators in the BSMP. Using two different end-to-end ecosystem models in the Barents Sea, NORWECOM.E2E and NoBa Atlantis, a set of these indicators have been estimated using the suggested methodology in the plan, and modelled time series are presented under a future climate projection. As the proposed indicators are purely based on observations, they are limited by existing monitoring programs which sampling schemes will largely affect their quality. Numerical models can contribute to the efficient design and optimization of observing systems, and through an Observing System Simulation Experiment (OSSE, e.g. Arnold and Dey, 1986) this has been investigated, and the design of a minimum cost monitoring program has been suggested. Finally, thresholds, reference points, and management actions are discussed, and suggestions for additional indicators that better reflect the condition, the trends, and the sensitivity and resilience to various natural and human pressures of the whole Barents Sea, are put forward.

Material and methods

Indicators and the sub-areas applied in the Barents Sea management report

The datasets used for indicators in the existing management plans consist mainly of simple time series (Arneberg *et al.*, 2020). However, to develop indicators to measure changes that are expected to be sensitive to human impact and climate change and variation, more complex time series are being developed (Jepsen *et al.*, 2019; Siwertson and Arneberg, 2019). The indicators cover a large part of the ecosystem from ocean physics to plankton, fish, and marine mammals. Some of the suggested indicators are spatial, with a focus on a particular ecosystem type. The Barents Sea is a shelf sea dominated by Atlantic water in the south and Arctic in the north. Due to this, it is suggested to divide the Barents Sea into four different areas based on ecosystem-type: Atlantic, Arctic, Atlantic edge, and Arctic edge. The four areas cover ∼800000, 712000, 32000, and 76000 km^2, respectively. Further, as these areas are large and some processes might only occur in parts of, or to different times within, each area, a further division into sub-areas has been suggested (see Figure 1). Some of the indicators can be estimated for each sub-area, but it is suggested that the ecological conditions be reported for the whole ecosystem-type area. The NoBa Atlantis polygons (Hansen *et al.*, 2016) are suggested as sub-areas. More details on the indicators, areas, and sub-areas can be found in Jepsen *et al.* (2019).

As the list of indicators is comprehensive, we focus on the selection listed in Table 1. The functional relationship indicator is a composite indicator, which represents the relationship between total biomass of the benthic group and the total biomass of the pelagic and bentho-pelagic group. The BSMP is intended for management of all sectors, which is a recent development from including all sectors apart from fisheries. In the BSMP, representing the fisheries is the difference between the precautionary fisheries mortality and the actual mortality. In the model simulations, this comparison would not necessarily make much sense, as the precautionary level is not exactly the same as in the real system. Therefore, we chose to add indicators on the trophic levels in the catches, and the relationship between the benthic catch and the pelagic and bentho-pelagic catches.

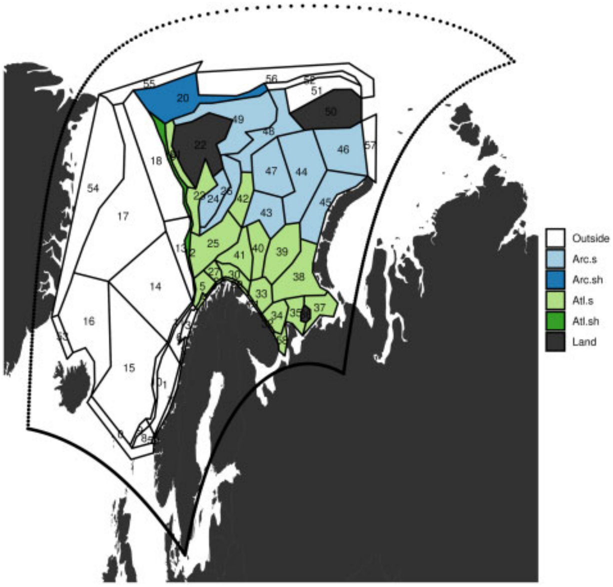

Figure 1. The horizontal extent of the two model grids in the study. The NORWECOM.e2e provided as black dots, the polygons in NoBa as solid black lines. The NoBa polygons are used in the calculations of the spatial indicators, the six different categories are marked as white: outside of Barents Sea, dark grey: land, light blue: Arctic shelf, darker blue: Arctic shelf edge, light green: Atlantic shelf and darker green: Atlantic shelf edge. These domains were used for calculation of all the spatial indicators in both end-to-end ecosystem models.

For the calculation of total biomass in functional groups and at trophic level, we have followed the categories defined by the assessment tool development project (Jepsen *et al.*, 2019), and converted the components included in NoBa and NORWECOM.e2e correspondingly to these.

The trophic levels of the different components are collected from MacKenzie *et al.* (2021) and are listed in Table 2.

Physical forcing and set-up

Physical forcing was taken from a downscaling of the Norwegian Earth System Model (NorESM1-ME) with the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams, 2005). The Norwegian Earth System Model (NorESM1-ME) is a fully coupled climate carbon cycle model developed in Norway in collaboration with researchers from the National Center for Atmospheric Research in the United States. The ocean physical circulation is based on the Miami Isopycnic Coordinate Ocean Model (MICOM), coupled with the Hamburg Oceanic Carbon Cycle (HAMOCC5) model (Maier-Reimer *et al.*, 2005; Tjiputra *et al.*, 2013). In this study, we applied the standard coupled RCP4.5 projection, following the standard CMIP5 (Coupled Model Intercomparison Project phase 5) protocol (Taylor *et al.*, 2012). The RCP4.5 represents a future scenario where the global mean atmospheric radiative forcing approach 4.5 W m^{-2} by year 2100. Under this scenario, the atmospheric CO_2 concentration pathway reaches 538 ppm at 2100. For the comparison with the regional model, we focused on analysing results from the period from 2006 to 2070.

The ROMS model set-up is initialized from the NorESM1-ME model, and this model is also used at the open boundaries and as atmospheric forcing 2. A weak relaxation towards NorESM1-ME sea surface salinity with a time scale of 360 days was also applied. The model domain for the ROMS downscaling covers the North Atlantic, the Nordic and Barents Seas, and the Arctic Ocean from 30°N to the Bering Strait, with a horizontal model resolution of $\sim 10 \times 10$ km. The ROMS model on this grid has previously been evaluated in a hindcast study in Melsom *et al.* (2009) and Sandø *et al.* (2014). Here, it was shown that downscaling reduced the biases in the Barents Sea projected by the global model, and that

Table 1. Selected indicators included in the BSMP, which are evaluated by using NORWECOM.e2e and NoBa Atlantis.

Indicator	Explanation	Comments
Temperature	Annual (mean) temperature	Per area
Freshwater height	Reference salinity 35	Per area
Ice cover	Annual mean ice concentration	Per area
Net primary production	gC m^{-2} $year^{-1}$	Per area
Diatom:flagellate ratio	Diatoms to flagellates NPP ratio	Per area
pH		Per area
Herring abundance	Abundance of juvenile herring in the Barents Sea	Age class 1–4
Population size NEA cod	Total biomass of NEA cod in the Barents Sea	Includes whole stock
Abundance, Greenland halibut	Abundance, total population, in the Barents sea	Includes whole stock
Biomass at trophic level	Total biomass at trophic level 2, 3, and 4	See Table 2 for details
Biomass in functional groups	Fraction of biomass at the three levels	See Table 2 for details
Catch at trophic level	Total catch in the three functional groups	See Table 2 for details
Relationship between biomass of functional groups	Development between total biomass in the functional groups	See Table 2 for details
Relationship between catch of functional groups	Development between total catch in the functional groups	See Table 2 for details

Two fisheries indicators (catch at trophic level and in functional groups) are added to the list.

Table 2. Components included in each of the functional groups used in the Barents Sea management plan.

Functional group	Components included
Pelagic	Mammals and seabirds (3.4–4.5)
	Large pelagic fish (4.4)
	Mesopelagic fish (3)
	Mackerel (3.7)
	Blue whiting (4)
	NSS herring (3.2)
	Capelin (3.2)
	Squid (3.7)
	Zooplankton (2)
Benthic	Demersal fish (3.2)
	Flatfish (3.7*)
	Long rough dab (3.7)
	Skates and rays (4)
	Haddock (4.1)
	Crabs (4*)
Bentho-pelagic	Sharks (4.3)
	Small pelagic fish (3.9)
	Redfish (Beaked 3.7, Golden 4)
	Greenland halibut (4.5)
	Saithe (4.4)
	NEA cod (3.7)
	Polar cod (3.1)
	Prawns (3)

Trophic level (TL) is provided for each group. If species listed in the BSMP were represented by functional components in the model, the whole biomass in the functional component was added. For snow crab and flatfish, no information on TL was available. These were therefore assumed to be similar to red king crab and long rough dab, respectively.

the downscaled results generally were closer to observations. For the present study, the regional ROMS model was run for the period 2006–2070. More details on the set-up and performance of the downscaling can be found in Sandø *et al.* (2018).

Observing system simulation experiment

When estimating the value of an index, one is often limited to available observations from existing monitoring programs. Regarding the validity of an index this is not necessarily the best approach. Given an acceptable level of precision, one should always ask how many observations are needed, and where and when are the best points to observe, to achieve this. Such efforts will increase the value of observations and enable new applications by connecting and synthesizing sparse observations. To do such an investigation for the BSMP, a minimum cost monitoring program for some of the simple indicators has been designed using an OSSE (Arnold and Dey, 1986) approach. The exercise has been done using monthly mean outputs from the NORWECOM.E2E model asking the following question: *which polygon in which month is the best one to approximate the inter-annual variability in the full regional index*. The answer to this question has been approximated by comparing modelled detrended annual mean time series of the chosen indicator for each of the four Barents Sea sub-areas, to modelled detrended monthly time series from each polygon within a region. The best combination of month and polygon to estimate the regional mean inter-annual variability has then been found using the Spearman correlation.

NORWECOM.E2E

The NORWegian ECOlogical Model system End-To-End (NORWECOM.E2E), a coupled physical, chemical, biological model system (Aksnes *et al.*, 1995; Skogen *et al.*, 1995; Skogen and Søiland, 1998), was developed to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model has been validated by comparison with field data in the Nordic and Barents seas (Skogen *et al.*, 2007; Hjøllo *et al.*, 2012; Skaret *et al.*, 2014). The model is extended with a module to project ocean acidification (Skogen *et al.*, 2014).

In the present study, the model is run in offline mode. Physical ocean fields (velocities, salinity, temperature, water level, and sea ice) from the ROMS downscaling (Physical forcing and set-up section, Figure 2) have been interpolated from 5-day means and used as forcing together with daily atmospheric (wind and short wave radiation) fields from the NorESM1-ME simulation. The horizontal grid used (Figure 3) is identical to a subdomain of the original ROMS grid. The simulation started on 1 January 2006. After a 12 year spin-up (running the first year 12 times) the full model period (2006–2070) was run sequentially with a time step of 1 h.

The biochemical model is coupled to the physical model through the light, the hydrography and the horizontal and vertical movements of the water masses. The prognostic variables are dissolved inorganic nitrogen, phosphorous, and silicate (SI), two different types of phytoplankton (diatoms and flagellates), two detritus (dead organic matter) pools (N and P), diatom skeletal (biogenic silica), and oxygen. Two types of zooplankton (meso- and micro-zooplankton) are included based on a module taken from the ECOHAM4 model (Moll and Stegert, 2007; Pätsch *et al.*, 2009; Stegert *et al.*, 2009). The processes included are primary and secondary production, grazing by zooplankton on phytoplankton and detritus, respiration, algae death, remineralization of inorganic nutrients from dead organic matter, self-shading, turbidity, sedimentation, resuspension, sedimental burial, and denitrification. Ocean acidification is modelled using a module for the carbonate system (Blackford and Gilbert, 2007; Skogen *et al.*, 2014, 2018). To allow the integration of the carbon system, three prognostic state variables are added [detritus C pool, dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC)]. Remineralization takes place both in the water column and in the sediments. Particulate matter has a sinking speed relative to the water and may accumulate on the bottom if the bottom stress is below a certain threshold value, and resuspended if the bottom stress is above a limit. Parameterization of the biochemical processes is taken from literature based on experiments in laboratories and mesocosms, or deduced from field measurements (Aksnes *et al.*, 1995; Pohlmann and Puls, 1994; Mayer, 1995; Gehlen *et al.*, 1995; Lohse *et al.*, 1995, 1996; Bode *et al.*, 2004; Garber, 1984).

The incident irradiation used in the biochemical model is modelled using a formulation based on Skartveit and Olseth (1986, 1987) using short wave radiation outputs of the NorESM1-ME model, and corrected linearly at the sea surface using the modelled ice concentration. Initial fields for nutrients and DIC were interpolated from annual means of the NorESM1-ME simulation for the years 2001–2005 [except for silicate where typical winter values of Atlantic Water in the Norwegian Sea has been used ($SI = 5.5\ \mu M$, F.Rey, pers. comm.) as silicate has a large offset in the NorESM1-ME simulation], together with some small

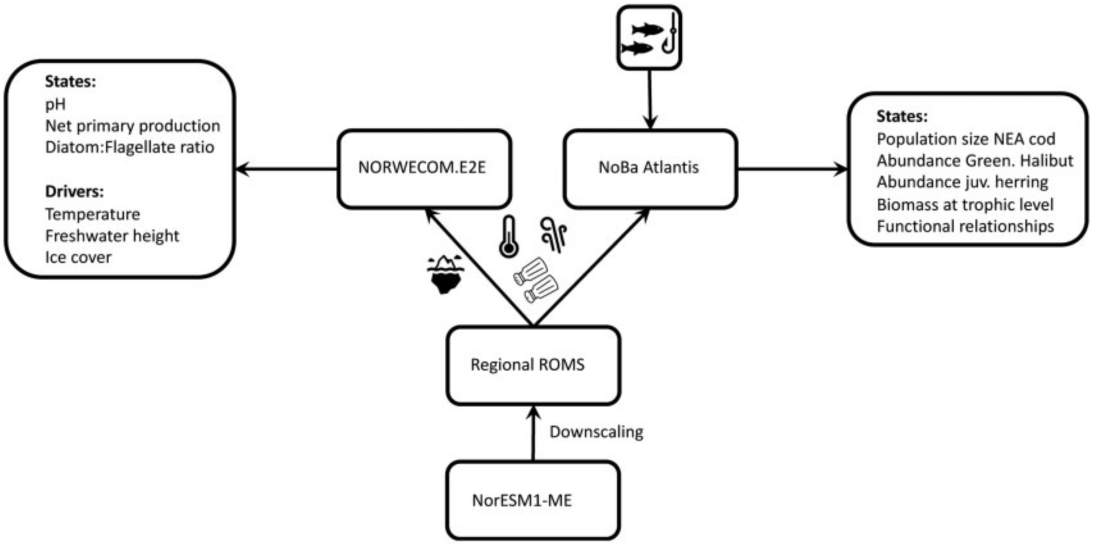

Figure 2. Conceptual figure of the forcing, downscaling, models and indicators calculated from the two end-to-end ecosystem models applied in this study.

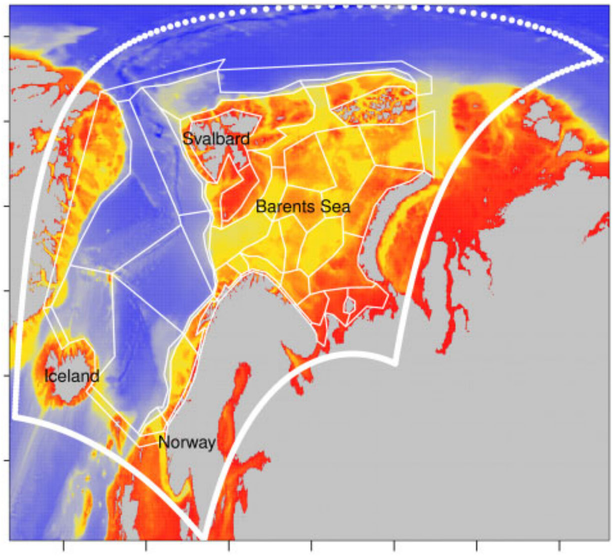

Figure 3. Model domain for NORWECOM.E2E and NoBa Atlantis with bathymetry. NORWECOM.E2E grid marked as white dots, NoBa Atlantis in solid white lines. Colours denote water depth in meters.

initial amounts of algae (0.10 mg Nm^{-3}) for both diatoms and flagellates. For DOC only the transient part is considered, and the initial value is therefore set to zero. These values are also used at the open boundaries. Inorganic nitrogen is added to the system from the atmosphere, while there are no river inputs of nutrients and carbon. To absorb inconsistencies between the forced boundary conditions and the model results, a 7 gridcell “Flow Relaxation Scheme” zone (Martinsen and Engedahl, 1987) is used around the open boundaries.

The Nordic and Barents Seas Atlantis model

The Nordic and Barents Seas Atlantis model (NoBa) is an application of the Atlantis framework (Fulton *et al.* 2011; Weijerman *et al*., 2016; Audzijonyte *et al.*, 2017), implemented for the Nordic and Barents seas (Hansen *et al.*, 2016, 2019a,b). Atlantis is an end-to-end model, including multiple modules depending on the complexity of the model. In this study, the harvest module was included in addition to physics and biology. NoBa used the same physical forcing as NORWECOM.e2e for the period from 2006 to 2068 (Figure 2). However, the model started with spin-up in 1981 (running the same year 24 times), using two other applications of the ROMS model to cover the period until 2006 (Hansen *et al*., 2019b). Contrary to NORWECOM.E2E, the version of NoBa included in this study did not take into account or calculate any effects of ocean acidification. The model grid covers 4 million km^2 by 60 polygons (Figure 1), which have one sediment layer and up to seven vertical layers depending on the mean depth of the polygon. The polygons are defined to be as homogeneous as possible with respect to bathymetry, hydrography and to avoid splitting natural boundaries. The version applied here included 53 functional groups and species, representing key components of the ecosystems in the Nordic and Barents Seas. These covered all trophic levels from phytoplankton, bacteria, zooplankton to fish, seabirds, and marine mammals. Commercially important groups such as Northeast Atlantic cod (*Gadus morhua*), mackerel (*Scomber scrombus*), Norwegian spring spawning herring (*Clupea harengus*), and saithe (*Pollachius virens*) were parameterized as separate components, whereas less commercially important species, e.g. mesopelagic fish, jellyfish, and small pelagic fish were grouped together in functional groups. The functional groups were constructed to be as similar as possible with respect to diet, longevity, and distribution (both horizontally and vertically)(Hansen *et al.*, 2016). The components are coupled through a somewhat flexible diet matrix, where the prey availability for the predator is defined (Audzijonyte *et al*., 2017).

Fisheries were implemented as time series of fisheries mortality for the period from 1981 to 2017. From 2017 and onward, the fisheries followed a flat maximum sustainable yield (MSY) fishery for a majority of the commercially important species, prawns, capelin, and snow crabs being the only ones excluded from this strategy. All in all, 12 components were harvested in the model

Table 3. Harvested components and their corresponding fishing mortality at maximum sustainable yield (Fmsy) in NoBa, NEA cod = Northeast Atlantic cod, NSS herring = Norwegian Spring spawning herring.

Harvested component	Fmsy
NEA cod	0.4
Mackerel	0.245
Saithe	0.065
Haddock	0.225
Golden redfish	0.15
Beaked redfish	0.13
NSS herring	0.15
Blue whiting	0.25
Greenland halibut	0.1
Other demersal fish	0.15
Large demersal fish	0.15
Small pelagic fish	0.15
Mesopelagic fish	0.15
Mesozooplankton	4.5

The last five are the additional species that are only harvested in half of the simulations ("all in"). The maximum sustainable yield level (Fmsy) was used as harvest level from 2017 and onwards.

(Table 3). Maximum sustainable yield was calculated by running multiple simulations, finding the point where the curve between catch and biomass reached its maximum point. The fishing mortality representing the maximum point was then used for the rest of the simulation (2018–2068).

In this study, 112 simulations were included (Hansen *et al.*, 2019b). These were divided into eight different scenarios, where each scenario included 14 replicates. As Atlantis is a deterministic model, we chose to add some variability for each scenario by forcing the growth rate of mesozooplankton (Hansen *et al.*, 2019b). The shape of the changes in the growth rate followed the shape of the mesozooplankton biomass in the Norwegian sea for the period 1995–2017 (Broms *et al.*, 2016). Between each replicate, the starting point was shifted 2 years, in addition to one simulation where an arbitrary time series based on the original data points was applied. The time series were repeated, such that they covered the whole simulation. The eight scenarios can be split into four categories, following a simplification of the Shared Socioeconomic pathways (SSPs; Riahi *et al.*, 2017). In short, this means that the fishing mortality for each of the harvested components was calculated by multiplying the fishing mortality at MSY level by a fraction (0.6, 0.8, 1.0, and 1.1). Each of the four fractions was then applied in a scenario including either only the currently commercially harvested components, or these in addition to five other components (Table 3). Among these five were mesozooplankton and mesopelagic fish, due to an increased interest in harvest of these components in the area. Both the additionally harvested and the currently commercial components were fished at Fmsy from 2017 and onward, to avoid changing the historical period from 1981 to 2017.

The reason for including all the simulations was that they provide us with the opportunity to evaluate if the indicators were able to pick up differences in the harvest level or in the number of components that are being harvested. We know from earlier studies (Hansen *et al.*, 2019b) that changes in harvest level and the number of components being harvested, in addition to the modest climate change seen in RCP4.5, do have a strong impact on the ecosystem.

Results

Long-term trends of simple indicators

Some of the indices from the proposed list can be directly estimated from the models. However, as the models differ in both state variables and processes the available modelled indices will differ between them, therefore only some examples of modelled indices from each model are given below.

In Figure 4, time series of annual (mean) temperature, freshwater height, ice cover, net primary production, diatom to flagellate ratio, and pH from the NORWECOM.E2E model are shown for all four areas (Arctic, Atlantic, Arctic edge, and Atlantic edge) of the Barents Sea. As ocean physics is an input to the NORWECOM.E2E system, temperature, fresh water height, and ice are from the ROMS downscaling (Sandø *et al.*, 2018). After an adjustment of the initial field for the first 10 years, an increase in temperature and freshwater height and a decrease in ice cover are seen. Except for the Atlantic edge area where there is no long-term trend in temperature, the modelled projected increase in temperature is almost 1°C from 2006 to 2070. Using the Fitting Generalised Linear Models routine in R (glm), the trend in annual mean SST is between 0.010 and 0.014°C pr year in the

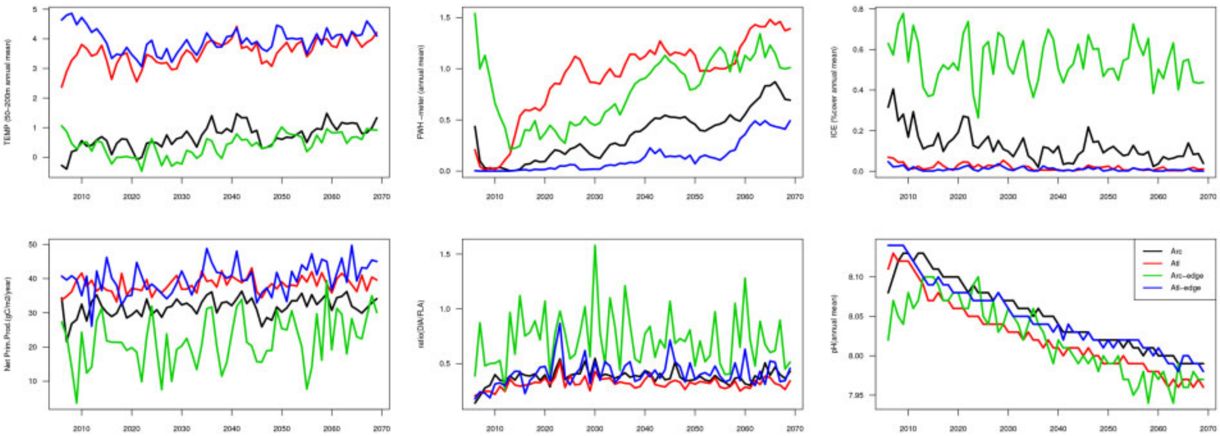

Figure 4. Time series for temperature (50–200 m), fresh water height, ice cover, net primary production, ratio diatoms: flagellates and pH for Arctic (black), Atlantic (red), Arctic edge (green), and Atlantic edge (blue) part of the Barents Sea from the NORWECOM.E2E model. All values are annual means, except net primary production which is annual depth integrated value (gC m^2 $year^{-1}$).

other areas. Comparing the detrended annual mean temperatures, there is a significant relationship ($p < 0.01$) between the Arctic and the Atlantic area ($r = 0.76$), Atlantic and Arctic edge ($r = 0.35$), Atlantic and Atlantic edge ($r = 0.47$) and Atlantic edge and Arctic edge ($r = 0.87$). Also all sub-areas are significantly correlated to the mean over the whole Barents Sea ($r = 0.97$ Atlantic, $r = 0.88$ Arctic, $r = 0.44$ Atlantic edge, $r = 0.35$ Arctic edge). The increase in freshwater height (see Table 1) is up to 1 m, with the highest value in the Atlantic and lowest in the Atlantic edge. The ice cover in the Arctic part shows a steady decline from 40% to around 5% during the first 30 years before it stabilize at that level with some inter-annual variability. For the Arctic edge, the ice cover does not show any clear trend.

The net primary production (NPP) shows an increase in all areas from the initial levels varying between 20 and 40 gC m^2 $year^{-1}$. The strongest increase is found in the two edge areas (0.12 and 0.09 gC m^2 $year^{-1}$ for Arctic and Atlantic edge, respectively), while the increase is only half that in the Atlantic and Arctic areas. Comparing the detrended annual NPP, there is a significant relationship ($p < 0.01$) between the Arctic and the Atlantic area ($r = 0.50$) and Arctic and Arctic edge ($r = 0.34$). Both the Arctic and Atlantic sub-area are significant correlated to the mean of the whole Barents Sea ($r = 0.86$ and $r = 0.84$, respectively). The ratio between flagellate and diatom production shows no clear trend, while there is a decline in the pH just above -0.002 $year^{-1}$ for all areas after an initial adjustment to a level just above 8.10.

Abundance of juvenile herring declined through the whole period, and in particular after 2040 (Figure 5). Towards the end of the simulation, the variability of herring juveniles in the scenario with the highest harvest level increased. This indicated a stronger dependency on the biomass level of mesozooplankton, and an increasing vulnerability in the stock. After 2017, when Fmsy harvest was introduced, the herring stock experienced a sharp decline in total biomass and was not able to recover due to the lack of a harvest control rule (not shown). Biomass of NEA cod showed a strong dependency on the management of the stock and less vulnerability to the moderate climate change (Figure 5). The narrow variability indicated a weaker connection to the mesozooplankton biomass levels compared to juvenile herring. The NEA cod diet consisted of, among others, capelin, juvenile herring, polar cod, and haddock. Being a top predator, it switched between prey when the abundance of one of them decreased (not shown). Abundance of Greenland halibut declined when the harvest was changed in 2017 (Figure 5). However, the difference between the four scenarios was not large, ∼15% between the lightest and strongest harvested scenario. Similar to the NEA cod, Greenland halibut showed a low response from the bottom-up variability forced by zooplankton growth rate.

In the suggested indicator list in the management plans, polar cod, capelin, beaked and golden redfish, and long rough dab were present. The biomass and/or abundance indicators for all these were also calculated (not shown). Polar cod showed less impact of the management scenarios, whereas long rough dab experienced an increase in total biomass linked to the commercially important stocks being increasingly harvested. The interaction between long rough dab biomass and level of the harvest was negatively correlated. Redfish (both golden and beaked) showed the same pattern of impact from the management scenarios as the cod. Capelin, due to the level of harvest and the problematic stock development which is difficult to recreate, showed less impact to changes in harvest level.

Complex indicators

Biomass and trophic level in functional groups

From Figure 6, there are only small changes in the mean trophic levels (TL) between the scenarios. Exploring the areas and the time series showed a different picture, with the TL varying between both seasons and areas.

The TL of the pelagic group was best described by the Arctic shelf ($|r| > 0.8$), but this relationship was not found between any of the other areas and the whole Barents Sea. The TL of the benthic group experienced strong correlations between all the areas and the total value for the whole Barents Sea, and experienced significant ($p < 0.01$) and strong correlations ($|r| > 0.5$) internally between the four indicator areas. The TL of the

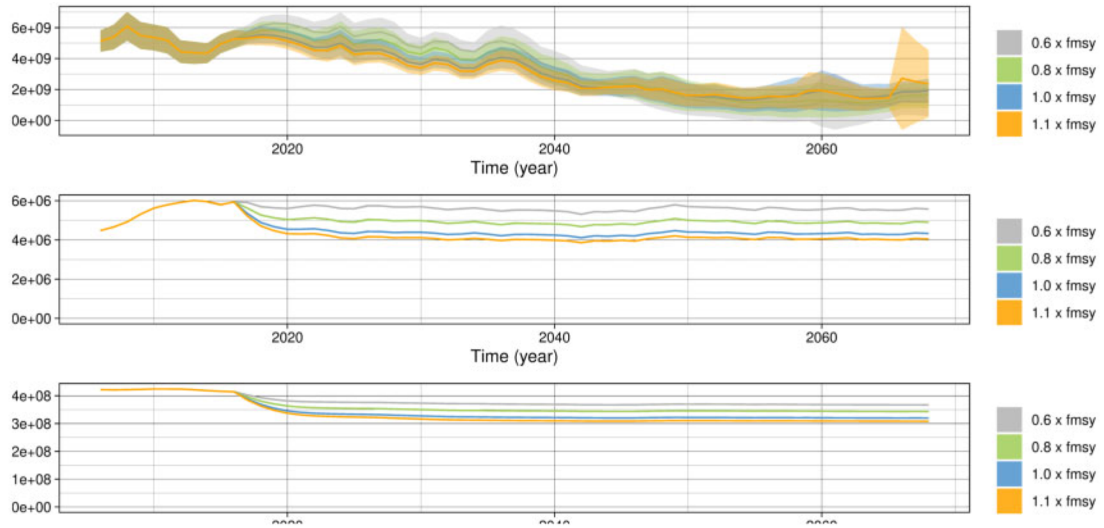

Figure 5. Time series from the NoBa model of abundance juvenile herring (top) and Greenland halibut (bottom) summed up over all polygons, and the biomass (tons wet weight) of Northeast Atlantic cod (middle) for the period from 2006 to 2068. Solid line represents mean values over the 14 replicates of each scenario, while the shaded area is one standard deviation.

bentho-pelagic group had relatively strong correlations for all indicator areas but the Atlantic shelf. The TL of the bentho-pelagic group experienced similar strong, significant correlations between the indicator areas but lacked any connections between the Atlantic shelf edge and the whole Barents Sea (Table 7). There were no differences in the relationships between the indicators for the different areas that picked up the changes in the management scenarios.

None of the seasons explained significantly changes in any of the other seasons for the TL of the three functional groups.

Relationship between different functional groups

For the whole Barents Sea, the changes in the biomass of the pelagic, benthic and bentho-pelagic group between the historic period (2006–2015) and the projected period (2056–2065) were not large. The pelagic groups experienced an increase of roughly 7% for all the scenarios. The bentho-pelagic group varied more, experiencing a change between 10 and −0.6%, decreasing with increasing fishing pressure. For the benthic group, there were low biomass changes in the "commercial only" scenarios (>3%), whereas in the "all in" scenario, it varied from −12 to −21%, with the largest change in the simulations experiencing the highest fishing pressure.

The functional relationship (FunctRelB; Figure 6) experienced low correlations between the indicator areas, except between the Arctic and Atlantic shelf edge. Compared to the whole area, the strongest connection was found between the Atlantic shelf and the Barents Sea, where it was a very good match between the two simulated time series ($|r| > 0.9$). For the other areas, no such strong relationships could be found (Table 8).

There were few differences between the scenarios including harvest on additional ecosystem components and those including the commercial components only (Figure 6).

Trophic level of catch in the functional groups

Across the two scenarios, the trophic level (TL) of the catch in the different functional groups (Figure 6 TLPC, TLPBC, TLBC) seem to change a lot from the historical period to the four different management scenarios, for both the "all in" and the "commercial only" scenario. However, as was the case for the TL in the biomass of the three different groups, this was only the case for the TL for the pelagic catch in the "all in" scenario. Here, the catch was composed of pelagic fish in the "commercial only" scenarios, but when the harvest on mesozooplankton was implemented in the "all in" scenario, the TL in the catch of this functional group fell from 3.5 to 2.0.

At functional group level, the bentho-pelagic component (PelBenC; Figure 6) was similar between catching commercial only and catching additional species. For both the benthic and the pelagic functional groups (Figure 6), there were large differences in total catch. This was caused by the additional species that were harvested in the "all components" scenario, resulting in much larger catches in these groups compared to the "commercial only" scenario.

Optimal sampling strategy

Based on results from the NORWECOM.E2E model, and OSSE exercise has been done to design a minimum cost observational system to estimate the inter-annual variability in two of the simple BSMP indicators. The results for temperature and NPP are

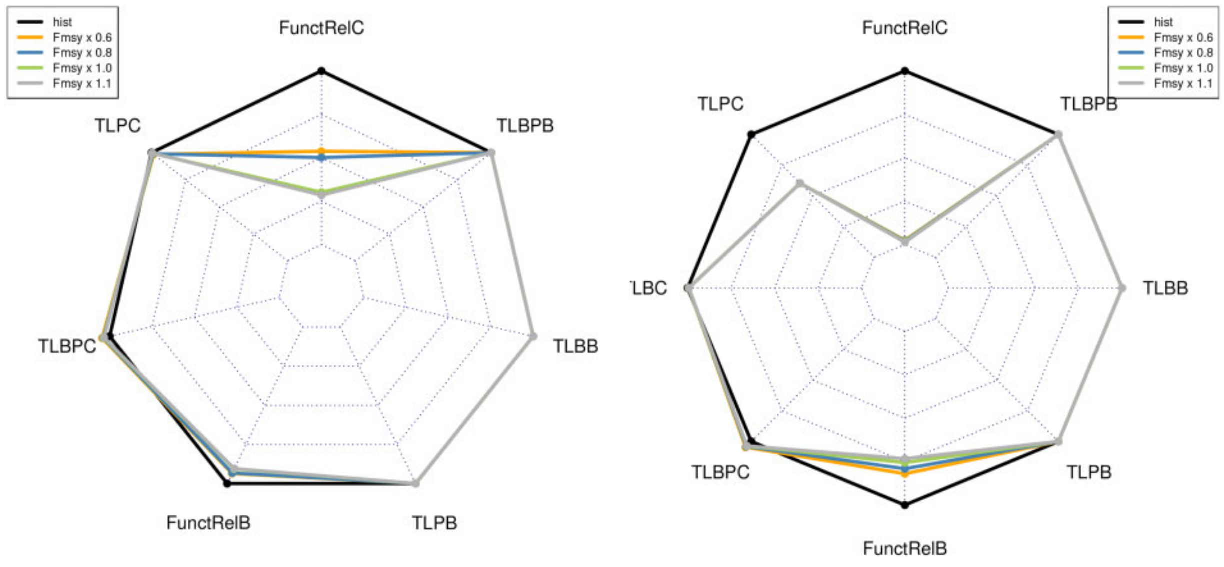

Figure 6. Model-derived indicators from the NoBa model calculated for the historical time slice (hist; 2006–2015, in black), and for the future time slice (2055–2065) for the four scenarios. Left panel shows the results from the scenarios only including the currently harvested species while right panel shows the results from the scenarios including harvest on e.g. mesozooplankton and mesopelagic fish. Historical time slice is equal across all simulations. Indicators are all shown with maximum (best) value at the outer edge of the spider plot. The indicators shown include trophic levels in catches for the pelagic and the benthic group (TLPC and TLBC, respectively), trophic levels in biomasses for the pelagic, benthic, and bentho-pelagic groups (TLPB, TLBB, and TLBPB, respectively). The relationship between the benthic and sum of the pelagic and bentho-pelagic biomass (FunctRelB) and catch (FunctRelC) are also displayed. For further information on the components included in each functional group and trophic level see Table 2. Notice that trophic level of the benthic catches only include haddock for the "commercial only" scenarios, and will not change. That indicator is therefore not included in (a).

Table 4. Best and less (not least) good results from a one polygon, 1 month, monitoring program for temperature (50–200 m) in the four Barents Sea regions from the NORWECOM.E2E model.

	Best results			**Less (not least) good results**		
	Polygon	**Month**	**Corr**	**Polygon**	**Month**	**Corr**
Atlantic	33	August	0.92	25	July	0.73
Arctic	43	June	0.90	49	June	0.30
Atlantic edge	19	April	0.94	19	January	0.81
Arctic edge	20	June	0.96	20	January	0.81

Table 5. Best and less (not least) good results for a one polygon, 1 month, monitoring program for NPP in the four Barents Sea regions from the NORWECOM.E2E model.

	Best results			**Less (not least) good results**		
	Polygon	**Month**	**Corr**	**Polygon**	**Month**	**Corr**
Atlantic	33	April	0.54	30	April	0.27
Arctic	47	July	0.69	47	May	0.01
Atlantic edge	19	July	0.56	12	May	0.02
Arctic edge	20	May	0.66	20	June	0.30

Table 6. Best results from two and three polygon monitoring programs for NPP in the Atlantic region of the Barents Sea from the NORWECOM.E2E model.

	Polygon1	**Polygon2**	**Polygon3**	**Month1**	**Month2**	**Month3**	**Corr**
Atlantic	33			April	August		0.55
	23	32		April			0.59
	5	33		July	April		0.65
	33			April	June	July	0.61
	23	32	33	April			0.61
	29	30	33	August	July	June	0.71

given in Tables 4 and 5. The results clearly show that it is possible (especially for temperature) to get a high correlation to the interannual variability using minimum effort but also how a poorly designed monitoring program with the same effort can give low or even no representation of the real variability. While temperature is well represented with only such a minimum observational network, this is not the case for NPP. This index is therefore further investigated by increasing the effort to monitor two and three polygons in the same or in different months. These results are shown for the Atlantic area in Table 6. There is an increase in performance from the one month, one polygon case (0.54 see Table 5) to 0.65 in the two polygon case (polygon 5 in July and 33 in April) and 0.71 in the three polygon case (polygon 29, 30, and 33 in months August, July, and June, respectively). The results also show that the performance increases when distributing the effort between polygons and months instead of using all resources in one polygon or 1 month.

Discussion

Indicators are a common part of management plans in many sectors (e.g. Borja *et al.*, 2010; Stupak *et al.*, 2007), but should be used with caution (Jennings, 2005). Key and flagship species can be important simple indicators if they represent a group of species or state of the ecosystem (Niemi and McDonald, 2004). For the indicators to work as intended, they depend on clearly defined thresholds and reference levels, which again should be connected to management targets and actions. The indicators included in the Barents Sea Management Plans are no exception to this.

Performance and uncertainty in the Barents Sea management plan indicators

Among the abiotic indicators included in the BSMP, is temperature. Ecosystem changes are often linked to temperature (e.g. Eriksen *et al.*, 2015; Fossheim *et al.*, 2015), but the direct link between climate and ecosystem needs a better understanding (Hollowed and Sundby, 2014; Hollowed *et al.*, 2013b, 2018) even if climate change is believed to be the most important Barents Sea driver (Arneberg *et al.*, 2020). Reference levels can be established as *mean over a historical period* (Jepsen *et al.*, 2019), but as the direct link between ecosystem and climate often are poorly understood their value is limited as there is a lack of threshold levels before any kind of management actions are taken. The abiotic indicators therefore serves more as a tool to report on climate trends rather than ecosystem status, and models (possibly in combination with observations) are known to be an excellent tool for such assessment of the past, present, and future (Skogen *et al.*, 2021), when the model performance is known. In this study, the model temperature is initially too cold when comparing with data from WOA (2005–2012 values) and averaging over the Arctic and Atlantic part. However, the model adjusts to correct values for that period after about 5 years. The seasonal cycle (not shown) is in good correspondence with observations (Skogen *et al.*, 2018).

Studies of biological consequences of ocean acidification indicate that large groups of organisms will meet with stress or reduced success rate in seawater with reduced pH and carbonate concentration (Fabry *et al.*, 2008). Lauvset *et al.* (2016) mapped pH from the GLODAPv2 (Olsen *et al.*, 2016) data set, and report on an average upper 10 m pH in the Barents Sea of 8.11 which is in good agreement with the model after the initial adjustment. The declining trend in the simulation (-0.002 year^{-1}) is close to both observed and predicted changes in surface pH (IPCC, 2014; Lauvset *et al.*, 2015).

Based on satellite data, a strong increase in Barents Sea primary production has been reported (Dalpadado *et al.*, 2014), and a further increase is believed to have a negative impact on species that are adapted to regions of low productivity (Jepsen *et al.*, 2019). This increase is not supported by the present models. The study areas cover a large area on both sides of the Arctic Front and estimates of primary production varies a lot between the different water masses. Titov and Orlova (2011) give a mean value for GPP in the Barents Sea of 111 gCm^{-2}y^{-1}, while Slagstad *et al.* (2011) (using the SINMOD model) give a value of 53 gCm^{-2}y^{-1} for NPP. There is no general agreement on how NPP will be affected in the future Barents Sea (Steinacher *et al.*, 2010; Barange *et al.*, 2014; Skaret *et al.*, 2014; Slagstad *et al.*, 2015). However, based on a comparison between three different model studies, Mousing *et al.* (2020) conclude that the difference in model projections is due to differences in the projected physics.

The complexity of Atlantis makes it difficult to hit the exact levels of biomass and/or abundance of a specific species (Fulton *et al.*, 2011). However, the representation of the variability in larger functional groups was well represented in these simulations (Hansen *et al.*, 2019b).

Simple indicators, as shown here for e.g. temperature, NEA cod, herring, and Greenland halibut, are vulnerable to uncertainty in observations (Carstensen and Lindegarth, 2016). The biotic indicators are in particular vulnerable to uncertainty in parameter settings, trophic interactions, and forcing in complex ecosystem models (Lehuta *et al.*, 2016). Nevertheless, few studies have dealt with uncertainty in indicators (Carstensen and Lindegarth, 2016).

Observing system simulation experiments

The quality of observations is often uncertain and so is their representativeness (Fu *et al.*, 2011; Sandvik *et al.*, 2016). Observations are often pre-processed before use, and even interannual variability might not be preserved after interpolation (Rufino *et al.*, 2019). This will have a large impact of the precision for the indicators. The sampling strategy suggested through the OSSE analysis showed that it is possible to get a high degree of covariance between local monthly values and regional annual means of abiotic and lower trophic state variables with only a small, but well-funded, observational effort. However, the same analysis also shows that there are many pitfalls from using arbitrary observations to approximate the same without any further analysis. Except for a demonstration for the Arctic domain (Jepsen *et al.*, 2019), the splitting and reporting of the Barents Sea into four different areas has not been implemented yet. In the demonstration, temperature indicators are based on CTD profiles from the joint Norwegian–Russian ecosystem survey that offers a complete coverage of the Barents Sea in August/September every year, while estimates of net primary production were based on estimates downloaded from www.science.oregonstate.edu using the Vertically Generalized Production Model (VGPM, Behrenfeld and Falkowski, 1997). Some of the Barents Sea indicators are also made operational for the whole Barents Sea as part of Miljøstatus (https://miljostatus.miljodirektoratet.no/tema/hav-og kyst/havindikatorer/barentshavet/). In Miljøstatus, the temperature for the Barents Sea is reported as two different time series from observations along two transects: Fugløya-Bjørnøya at the Barents Sea entrance, and Vardø-N in the southeast 2–6 times every year. Both transects are strongly influenced by the inflowing Atlantic water and therefore show a strong covariance. As an approximation for the whole Barents Sea, the simulated temperature in the Atlantic part is strongly connected ($r = 0.97$) and also explains a large part of the variability in the Arctic part ($r = 0.75$). The Fugløya-Bjørnøya is inside area 25 (Figure 1), while Vardø-N goes through areas 30, 41, and 43 (in the Arctic area). A full annual mean of the temperature in area 25 is a good approximation to the temperature in the Atlantic area ($r = 0.79$), but not as good as the means of box 30 and 41 ($r = 0.87$ and $r = 0.89$, respectively). However, the best approximation is the August temperature from box 33 ($r = 0.92$, see Table 4) where the Kola section is found. As an approximation to the annual mean temperature in the Arctic area, the annual mean from box 43 is close to the June value (Table 4) from the same box ($r = 0.89$ and $r = 0.90$, respectively).

The present analysis suggests the use of temperature from the ecosystem survey in August/September to be the best for producing an indicator in the Atlantic, Arctic edge, and Atlantic edge area, and slightly sub-optimal for the Arctic area where preferred period is May/June, thus the methods suggested in the demonstration report for the Arctic area, serves as a good candidate when used for a Barents Sea assessment. The use of satellite-based estimates for NPP offers a good coverage in both time and space but is limited by clouds and information on the sub-surface. The indicator is assessed with medium good validity, but a further calibration with *in situ* observations from the region is suggested (Jepsen *et al.*, 2019). If such a calibration is done, *in situ* measurements at times and in sub-areas as proposed in Tables 5 and 6 should be prioritized. For the composite indicators (Figure 6), the analysis shows that the Atlantic and Arctic shelf areas are good candidates for the trophic level, while the Atlantic shelf area is the best option for the functional relationship (Table 8).

Reference levels in simple indicators

The simple indicators for commercially important fish stocks in the BSMP use the same reference levels as in the fisheries, Blim and Bpa. In the new, updated version (Jepsen *et al.*, 2019), the reference levels have been defined as untouched nature. Untouched nature is defined as ecosystems not significantly impacted by any modern industrial activities (Nybø and Evju, 2020). This would be difficult to use in the Barents Sea, which has a history of fisheries for over a thousand years (Kurlansky, 1999; Starkey *et al.*, 2009). Therefore, directions and trends will be operative, not levels. It can, of course, be discussed if these reference levels can be calculated by the use of ecosystem models. Although this is possible (Blanchard *et al.*, 2014), it would be a reference level which should not be used in tactical management due to the level of uncertainty that emerges from assumptions and

Table 7. Correlation between simulated trophic levels in the different indicator areas from the Barents Sea management plans.

Area 1	Area 2	Pelagic	Benthic	Bentho-Pelagic
Atlantic s.	Arctic s.	−0.24	0.7	0.3
Atlantic s.	Atlantic se.	−0.25	−0.64	−0.17
Atlantic s.	Arctic se.	−0.18	−0.73	0.68
Arctic s.	Atlantic se.	0.2	−0.98	0.06*
Arctic s.	Arctic se.	−0.23	−0.96	0.66
Atlantic se.	Arctic se.	0.4	0.96	−0.45
Atlantic s.	Barents Sea	0.3	0.99	0.54
Arctic s.	Barents Sea	0.83	0.63	0.96
Atlantic se.	Barents Sea	0.19	−0.56	0.01*
Arctic se.	Barents Sea	−0.1*	0.65	0.78

* not significant ($p > 0.01$). *se.* is short for shelf edge, while *s.* is short for shelf. The areas correspond to those in 1.

Table 8. Correlation between simulated functional relationships in the different indicator areas from the Barents Sea management plans.

Area 1	Area 2	FunctRelB
Atlantic s.	Arctic s.	−0.21
Atlantic s.	Atlantic se.	0.06*
Atlantic s.	Arctic se.	−0.37
Arctic s.	Atlantic se.	−0.31
Arctic s.	Arctic se.	0,38
Atlantic se.	Arctic se.	1.0
Atlantic s.	Barents Sea	0.93
Arctic s.	Barents Sea	0.16
Atlantic se.	Barents Sea	−0.05*
Arctic se.	Barents Sea	−22

*not significant ($p > 0.01$). *se.* is short for shelf edge, while s. is short for shelf. The areas correspond to those in 1.

simplifications in complex ecosystem models (Fulton *et al.*, 2011). For planning and what-if scenarios, on the other hand, it is useful (Fulton *et al.*, 2005). In the BSMP, an open suggestion to take actions if the indicator falls below or increases above a certain threshold for the simple indicators, are in place. How any specific action would potentially impact both the system and the sectors are not discussed.

The fish stocks included as simple indicators, are already being managed separately, and are mostly in good shape (ICES, 2019, 2020a,b). Based on this, it is perhaps the lower trophic levels and abiotic indicators that are more important to include in the BSMP, as these are so far not included in the management of any of the sectors engaged in the Barents Sea. On the other hand, these components are impossible (or close to) to manage, hence even more challenging to couple to management actions.

The complex indicators included in the study represent the relationship between the total biomass in the benthic group divided by the total biomass of the pelagic and bentho-pelagic group, in addition to the trophic level within each of the three functional groups. Only the biomass was taken into account in the management plans, catches were not included for these indicators. As concluded in Jørgensen *et al.* (2013), composite indicators should be treated with care. Their complexity can easily conceal large individual changes at species or smaller group levels.

The functional relationship indicator (FunctRelB; Figure 6) was created to observe if the benthic group was decreasing with respect to the pelagic and bentho-pelagic group. There were no weighting among the species, or normalization of the individual species before being added to the composite indicator, hence the development of the indicator was to a large degree dependent on the dominant species or functional groups represented. This is rather unfortunate, particularly in the case of the pelagic biomass, where the zooplankton biomass dominated completely, causing large variations throughout the year. This is a model-specific challenge, as ecosystem models provide continuous time series of the different components, while observations are limited to a specific time window. As discussed previously, time and space matters for the simple indicators, hence it will also have an impact on the composite indicators. In particular, the inclusion of the highly variable zooplankton components in the pelagic functional group has previously been shown to be problematic (Moloney *et al.*, 2005). Also, a challenge with indicators that represent fractions, is that they do not provide any information about what is changing; the numerator or the denominator. However, they do inform us of a change in the balance of the trophic groups, and can be informative in that sense. Applying the period 2006–2015 as a reference period, lead to a decrease in FunctRelB for all the scenarios. Here, it was the benthic component that decreased, in combination with a slight increase in the pelagic and bentho-pelagic functional group. The same result would have been achieved with a stable benthic biomass over an increasing pelagic and bentho-pelagic biomass.

The trophic level within each functional group (TLPB, TLPBB, and TLBB; Figure 6) was supposed to catch differences in the Barents Sea ecosystem by the boreal species moving northwards, suppressing the arctic species in those areas. The boreal species has shorter feeding links, being less dependent on fatty species (Jepsen *et al.*, 2019). In the model results, the same challenges as above were seen. When the species were not weighted before being added to the composite indicator, the indicator became very dependent on the biomass dominant components, hence causing a (perhaps) false impression of a low change in the TL of the respective groups.

Optimal set of indicators

As complex or composite indicators can hide large individual changes at species or smaller group levels, a complete view on the system depends on a combination of simple and complex indicators. This is only valid if the complex indicators can add to the knowledge gained by the simple ones combined. The advantage of the composite indicators is that they provide a simplified measurement of a complex system. This can make it easier for the public, for managers or politicians to understand the direction the ecosystem is moving towards. However, their simplicity is a challenge as it does not provide the complex information needed to have an overview of the whole system.

The suggested list of biological, both simple and composite, indicators made in Jepsen *et al.* (2019) provides a reasonable and well thought-through set. However, the important word here is *biological.* Socio-economic and economic indicators are completely lacking from the plans, and we recommend that these should be included to give a proper overview of the whole system. As pointed out in Hornborg *et al.* (2019), economic, social–cultural, and institutional indicators are necessary and important also for managers and politicians to make decisions based on ecological and socio-economic trade-offs emerging from changes in management strategies.

By adding these, the view of the different species would not only be on their biological properties, but also on their importance as resources in the system. Some stocks in the Barents Sea have a larger impact on the communities along the coast, due to their commercial value. It is an extremely difficult discussion to enter, but trade-offs between sectors are differently handled due to the "value" of the resource in question, whether it is a species on the redlist, an invasive species, or a commercially valuable species. These discussions and decisions are for managers and politicians, but without the proper set of tools, it is difficult to highlight the importance of the different components in the system.

The low response to different harvest strategies found in the complex biomass-dependent indicators shows the importance of a suite of indicators, as suggested in the management plans. The commercial species are represented by abundance or biomass indices, which easily pick up the differences in the harvest levels. However, the increased ecosystem vulnerability found in Hansen *et al.* (2019b) was not evident in the suggested indicators. It should be discussed and evaluated how this could be made clearer by refining, changing, or adding indicators. The BSMP does not include any information on how to handle drivers and effects (e.g. Lockerbie *et al.*, 2020), another point which potentially should be made more clear in the next revision of the indicators.

Management actions, thresholds, and reference levels in a changing future

For indicators to be useful for management, the management targets have to be clear (e.g. Tam *et al.*, 2017). Without clear management targets, it's difficult to define thresholds and reference values. The targets that are listed in the management plans (miljostatus.miljodirektoratet.no) are overarching rather than specific. For the marine areas, the most relevant would be "The ecosystem should be in a good condition and deliver ecosystem services"; "No species or types should go extinct, and the development of threatened and near-threatened species and types are to be improved" and finally "A representative selection of Norwegian nature are to be kept for coming generations. " We would argue that these specific targets are difficult to link to useful indicators for management strategies. This also makes it increasingly difficult for the available ecosystem models to test how the indicators are performing (e.g. Burgass *et al.*, 2017).

In the Norwegian management plan, no thresholds or reference points are defined for abiotic and lower trophic levels indicators, only aims to have such values for a period of the same climate. However, aims, thresholds, and reference points are defined for most other indicators, based on international levels for sea bird breeding success (OSPAR, 2016), breeding stock precautionary size (e.g. ICES, 2020a), red-listing (Norwegian red list) and pollution in biota, water, and sediments (OSPAR and more). So far, although the Norwegian government has embraced the ecosystem-based management (Anon., 2011), management of the different sectors has mostly been done separately. This was also reflected here, in the lack of social-economic indicators. With the prospects of increasing human activities in the Barents Seas, from multiple sectors and on several levels of the ecosystem, in combination with climate change, we should move towards a joint ecosystem-based management of cumulative effects (Skern-Mauritzen *et al.*, 2018).

Decision trees or evaluation frameworks can be used to help guide an ecosystem-based management. Within the management plans, an evaluation framework guided by a traffic-light system is included (Jepsen *et al.*, 2019). This considers the degree of evidence that a change in the indicator has occurred, and how certain the expert panel is of a given connection between the indicator and a driver, and the indicators role in the ecosystem. If there is high certainty on the occurrence and on its role in the ecosystem, this will be flagged as red, whereas low uncertainty and low impact on the ecosystem will be flagged as green. Only trends in phenomena are discussed, among others due to the uncertainty in links and how well the different indicators are sampled. Another example is presented in Lockerbie *et al.* (2020), where the different indicators are weighted according to the certainty on the links between the occurred change in an indicator and its driver. These frameworks and decision trees are very important, as they guide managers and politicians in their decisions on actions resulting from a change. However, the lack of rules/thresholds and actions connected to the colour in the framework leads us to question if this process will have to start from scratch if (when) an indicator moves into the red area.

We found the indicators included in the management plans, to be vulnerable to area and season (as exemplified via the OSSE experiment), and potentially also to how they are incorporated in the composite indicators. With low level of defined management targets, and no links to management actions (at least these are not included in the available online reports), we question the validity and usefulness of the indicator system. Although it does provide an informative overview of a selection of key species, the lower trophic levels, and the physics in the Barents Sea, we have yet to see how this information will be used in a management setting if one of the indicators should cross a threshold.

Concluding remarks

A number of indicators have been suggested as part of the Barents Sea management plans (BSMP). The indicators cover a large part of the ecosystem from ocean physics to marine mammals. Due to the large area and the fact that some species and processes only occur in parts of the Barents Sea, it is suggested to divide the area into sub-areas and report the indicators in each of them (Jepsen *et al.*, 2019). However, as many of the indicators lack reference and thresholds levels, clear management targets, and a corresponding management action, they represent a good overview of the system rather than a useful management tool.

The use of composite indicators is an attempt to add knowledge through simplified measurements of a complex system. However, their simplicity is a challenge as they represent the most biomass-heavy species and not the overall changes. Also the lack of cross-sectorial indicators represents a potential problem for the understanding of the full system in relation to the BSMP.

Downscaling physics from a climate model, model-based projections of the simple indicators are given. However, it should be noted that the present study is only using one future scenario (RCP4.5) and one realization of it through the NorESM1-ME climate model. This is a clear limitation and has to be taken into consideration when interpreting the results. Through the ENSEMBLES project (http://ensembles-eu.metoffice.com), it was recommended to use results based on two or more Regional Climate Models that again are forced by at least two Global Climate Models for climate impact studies (ENSEMBLES, 2009). The present projections should therefore only be considered as one member of a future ensemble of studies on the consequences of climate change.

Indicators are often based on existing observations and time series, and these are not necessarily the best representation for the variable in mind. In science, we observe on the premise that natural truth is observable and understandable, but this is not necessarily the case (Lynch *et al.*, 2009). The establishment of a management system based on indicators should therefore be accompanied by an OSSE exercise to ensure the best sampling strategy, and models and observations should thereafter be used operationally together to generate synergies and increase our knowledge on marine ecosystems to support management (Skogen *et al.*, 2021).

Data Availability

The data underlying this article will be shared on a reasonable request to the corresponding author.

Funding

This study was supported by the European Union's Horizon 2020 Research and Innovation programme under grant agreements no. 727890 (INTAROS) and no. 678193 (CERES). C.H. acknowledge support from the REDUS project funded by the Norwegian Ministry of Trade, Industry and Fisheries (project number 3680-14809).

References

Aksnes, D., Ulvestad, K., Baliño, B., Berntsen, J., Egge, J., and Svendsen, E. 1995. Ecological modelling in coastal waters: towards predictive physical-chemical-biological simulation models. Ophelia, 41: 5–36.

Anon. 2006. The integrated management plan for the marine environment of the barents sea–lofoten area. St.meld.nr.8 2006 (2005-2006). Norwegian Ministry of Climate and Environment.

Anon. 2011. Update of the integrated management plan for the marine environment of the barents sea–lofoten area. St.meld.nr.10 2011 (2010-2011). Norwegian Ministry of Climate and Environment.

Anon. 2015. Update of the integrated management plan for the barents sea – lofoten area including an update of the delimitation of the marginal ice zone. Stortingsmelding no.20, 2014-2015. Norwegian Ministry of Climate and Environment.

Anon. 2020. Status for miljøet i barentshavet (in norwegian). Tech. Rep. 2020-13. Institute of Marine Research.

Arneberg, P., Vee, I., Franzen, S., and van der Meeren, G. 2020. Status for miljøet i Barentshavet og havområdene utenfor Lofoten og vesterålen – rapport fra overvåkingsgruppen 2020. Tech. Rep. Fisken og Havet, særnr. X2020, Institute of Marine research, 126 pp.

Arnold, C. P., and Dey, C. 1986. Observing-systems simulation experiments: past, present, and future. Bulletin of the American Meteorological Society, 67: 687–695.

Audzijonyte, A., Gorton, R., Kaplan, I., and Fulton, E. 2017. Atlantis User's Guide, Part I: General Overview, Physics & Ecology. Tech. Rep. CSIRO Living Document, CSIRO.

Barange, M., Merino, G., Blanchard, J. L., Scholtens, J., Harle, J., Allison, E. H., Allen, J. I., *et al.* 2014. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change, 4: 211–216.

Behrenfeld, M. J., and Falkowski, P. G. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography, 42: 1–20.

Blackford, J., and Gilbert, F. 2007. pH variability and CO2 induced acidification in the North Sea. Journal of Marine Systems, 64: 229–241.

Blanchard, J., Andersen, K., Scott, F., Hintzen, N., Piet, G., and Jennings, S. 2014. Evaluating targest and trade-offs among fisheries and conservation objectives using a multispecies size spectrum model. Journal of Applied Ecology, 51: 612–622.

Bode, A., Barquero, S., Gonzales, N., Alvarez-Ossorio, M., and Varela, M. 2004. Contribution of heterotrophic plankton to nitrogen regeneration in the upwelling ecosystem of La Coruna (NW Spain). Journal of Plankton Research, 26: 11–28.

Borja, A., Elliott, M., Carstensen, J., Heiskanen, A.-S., and van de Bund, W. 2010. Marine management - towards an integrated implementation of the European marine strategy framework and the water framework directives. Marine Pollution Bulletin, 60: 2175–2186.

Broms, C., Strand, E., Utne, K., Hjø llo, S., Sundby, S., and Melle, W. 2016. Vitenskapelig bakgrunnsmateriale for forvaltningsplan for raudåte. Tech. Rep. Fisken og havet 8-2016. Institute of Marine Research.

Burgass, M., Halpern, B., Nicholson, E., and Milner-Gulland, E. 2017. Navigating uncertainty in environmental composite indicators. Ecological Indicators, 75: 268–278.

Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., *et al.* 2010. Global biodiversity: indicators of recent declines. Science, 328: 1164–1168.

Carstensen, J., and Lindegarth, M. 2016. Confidence in ecological indicators: a framework for quantifying uncertainty components from monitoring data. Ecological Indicators, 67: 306–317..

Coll, M., Shannon, L., Kleisner, K., Juan-Jordá, M., Bundy, A., Akoglu, A., Banaru, D., *et al.* 2016. Ecological indicators to capture the effects of fishing on biodiversity and conservation. Ecological Indicators, 60: 947–962. doi: 10.1016/j.ecolind.2015.08.048.

Dalpadado, P., Arrigo, A., Hjøllo, S., Rey, F., Ingvaldsen, R., Sperfeld, E., Dijken, G., *et al.* 2014. Productivity in the Barents Sea - response to recent climate variability. PLoS One, 9: e95273.

Eriksen, E., Ingvaldsen, R., Nedreaas, K., and Prozorkevich, D. 2015. The effect of recent warming on polar cod and beaked redfish juveniles in the Barents Sea. Regional Studies in Marine Science, 2: 105–112.

Fabry, V., Seibel, B., Feely, R., and Orr, J. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science, 65: 414–432.

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R., Aschan, M., and Dolgov, A. 2015. Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5: 673–678.

Frank, K. T., Petrie, B., Choi, J. S., and Leggett, W. C. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science, 308: 1621–1623.

Fu, C., Xu, Y., Bundy, A., Gruss, A., Coll, M., Heymans, J., Fulton, E., *et al.* 2019. Making ecological indicators management ready:

assessing the specificity, sensitivity, and threshold response of ecological indicators. Ecological Indicators, 105: 16–28.

Fu, W., Høyer, J., and She, J. 2011. Assessment of the three dimensional temperature and salinity observational networks in the Baltic Sea and North Sea. Ocean Science, 7: 75–90.

Fulton, E., Link, J., Kaplan, I., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., *et al.* 2011. Lessons in modelling and management of marine ecosystems: the Atlantis experience. Fish and Fisheries, 12: 171–188.

Fulton, E., Smith, A., and Punt, A. 2005. Which ecological indicators can robustly detect effects of fishing? ICES Journal of Marine Science, 62: 540–551.

Fulton, E., Smith, A., Smith, D., and Johnson, P. 2014. An integrated approach is needed for ecosystem based fisheries management: insights from ecosystem-level management strategy evaluation. PLoS One, 9: e84242.

Garber, J. 1984. Laboratory study of nitrogen and phosphorous remineralization during decomposition of coastal plankton and seston. Estuarine, Coastal and Shelf Science, 18: 685–702.

Garcia, S., Zerbi, A., Aliaume, C., Do Chi, T., and Lasserre, G. 2003. The ecosystem approach to fisheries. Tech. Rep. Fisheries Technical Paper. No443, FAO.

Gehlen, M., Malschaert, H., and Raaphorst, W. 1995. Spatial and temporal variability of benthic silica fluxes in the southeastern North Sea. Continental Shelf Research, 15: 1675–1696.

Hansen, C., Drinkwater, K., Jähkel, A., Fulton, E., Gorton, R., and Skern-Mauritzen, M. 2019a. Sensitivity of the norwegian and barents sea atlantis end-to-end ecosystem model to parameter perturbations of key species. PLoS One, 14: e0210419.

Hansen, C., Nash, R. D. M., Drinkwater, K. F., and Hjøllo, S. S. 2019b. Management scenarios under climate change – a study of the Nordic and Barents seas. Frontiers in Marine Science, 6: 668. doi:10.3389/fmars.2019.00668

Hansen, C., Skern-Mauritzen, M., van der Meeren, G., Jähkel, A., and Drinkwater, K. 2016. Set-up of the nordic and barents seas (noba) atlantis model. Tech. Rep. Fisken og havet 2-2016. Institute of Marine Research.

Hjøllo, S., Huse, G., Skogen, M. D., and Melle, W. 2012. Modelling secondary production in the Norwegian Sea with a fully coupled physical/primary production/individual-based *Calanus finmarchicus* model system. Marine Biology Research, 8: 508–526.

Hollowed, A., Barange, M., Beamish, R., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M., *et al.* 2013a. Projected impacts of climate change on marine fish and fisheries. ICES Journal of Marine Science, 70: 1023–1037.

Hollowed, A., Planque, B., and Loeng, H. 2013b. Potential movement of fish and shellfish stocks from the sub-arctic to the arctic ocean. Fisheries Oceanography, 22: 355–370.

Hollowed, A. B., Cheng, W., Loeng, H., Logerwell, E., and Reist, J. 2018. Regional assessment of climate change impacts on Arctic marine ecosystems. *In* Climate Change Impacts on Fisheries and Aquaculture, pp. 703–728. Ed. by Phillips. B. F and M. Perez-Ramirez,. Wiley Blackwell, Hoboken,New Jersey, United States.

Hollowed, A. B., and Sundby, S. 2014. Change is coming to the northern oceans. Science, 344: 1084–1166.

Hornborg, S., van Putten, I., Novaglio, C., Fulton, E., Blanchard, J., Plagányi, E., Bulman, C., *et al.* 2019. Ecosystem-based fisheries management requires broader performance indicators for the human dimension. Marine Policy, 108: 103639.

ICES. 2019. Working Group on Widely Distributed stocks. Tech. Rep. 1:36, ICES Scientific Reports. doi:10.17895/ices.pub.5574.

ICES. 2020a. Arctic Fisheries Working Group. Tech. Rep. 2:52, ICES Scientific Reports. doi:10.17895/ices.pub.6050.

ICES. 2020b. Working Group on the integrated Assessments of the Barents Sea (wgibar). Tech. Rep. 2:30, ICES Scientific Reports. doi:10.17895/ices.pub.5998.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the 5th Assessment Report of the Intergovernmental Panel on Climate Change. 151 pp.

Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. Fish and Fisheries, 6: 212–232.

Jepsen, J., Arneberg, P., Ims, R., Siwertsson, A., and Yoccoz, N. 2019. Test av fagsystemet for økologisk tilstand. erfaringer fra pilotprosjekter for arktisk tundra og arktisk del av barentshavet. Tech. Rep. NINA Rapport 1674, Norsk institutt for naturforskning.

Jørgensen, S. E., Burkhard, B., and Müller, F. 2013. Twenty volumes of ecological indicators - an accounting short review. Ecological Indicators, 28: 4–9.

Kjesbu, O., Bogstad, B., Devine, J., Gjøsæter, H., Howell, D., Ingvaldsen, R., Nash, R., and Skjæråsen, J. 2014. Synergies between climate and management for atlantic cod fisheries at high latitudes. Proceedings of the National Academy of Sciences United States of America. 111(9): 3478–3483 doi: 10.1073/pnas.131634211.

Kurlansky, M. 1999. A Biography of the Fish That Changed the World. Random House. London WC2R 0RL, England

Lauvset, S., Gruber, N., Landschutzer, P., Olsen, A., and Tjiputra, J. 2015. Trends and drivers in global surface ocean pH over the past 3 decades. Biogeosciences, 12: 1285–1298.

Lauvset, S., Key, R. M., Olsen, A., van Heuven, S., Velo, A., Lin, X., Schirnick, C., *et al.* 2016. A new global interior ocean mapped climatology: the 1x1 glodap version 2. Earth System Science Data Discussion, 8: 325–340.

Lehuta, S., Girardin, R., Mahévas, S., Travers-Trolet, M., and Vermard, Y. 2016. Reconciling complex system models and fisheries advice: practical examples and leads. Aquatic Living Resources, 29: 208.

Levin, P., Fogarty, M., Murawski, S., and D, F. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem--based management of the ocean. PLoS Biol, 7: e1000014.

Lind, S., Ingvaldsen, R. B., and Furevik, T. 2018. Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. Nature Climate Change, 8: 634–639..

Link, J. S., Brodziak, J. K. T., Edwards, S. F., Overholtz, W. J., Mountain, D., Jossi, J. W., Smith, T. D., *et al.* 2002. Marine ecosystem assessment in a fisheries management context. Canadian Journal of Fisheries and Aquatic Sciences, 59: 1429–1440.

Lockerbie, E., Shannon, L., Lynam, C., Coll, M., and Jarre, A. 2020. A comparative framework to support an ecosystem approach to fisheries in a global context. Ecology and Society, 25(2): 16: doi: 10.5751/ES-11508-250216.

Lohse, L., Kloosterhuis, H. T., van Raaphorst, W., and Helder, W. 1996. Denitrification rates as measured by the isotope pairing method and by the acetylene inhiluition technique in continental shelf sediments of the North Sea. Marine Ecology Progress Series, 132: 169–179.

Lohse, L., Malschaert, F., Slomp, C., Helder, W., and Raaphorst, W. 1995. Sediment-water fluxes of inorganic nitrogen compounds along the transport route of organic matter in the North Sea. Ophelia, 41: 173–197.

Lynch, D. R., McGillicuddy, D. J., and Werner, F. E. 2009. Skill assessment for coupled biological/physical models of marine systems. Journal of Marine Systems, 76: 1–3.

MacKenzie, K., Tillman, A.M, Assman, K.M, Menze, S, , and Renaud, P. and Jørgensen, L.L.In prep. Global Ecology and Biogeography. . Structure, function and pelagic-benthic coupling along a latitudinal gradient in the Barents Sea, a rapidly changing ecosystem.

Maier-Reimer, E., Kriest, I., Segschneider, J., and Wetzel, P. 2005. The Hamburg Oceanic Carbon Cycle Circulation model hamocc5.1 – technical description release 1.1. Tech. Rep. Reports on Earth System Science 14, Max Planck Institute for Meteorology, Hamburg, Germany.

Marshall, A., Biggs, G., van Leeuwen, S., Pinnegar, J., Wei, H.-L., Webb, T., and Blanchard, J. 2016. Quantifying heterogeneous responses of fish community size structure using novel combined techniques. Global Change Biology, 22: 1755–1768.

Martinsen, E., and Engedahl, H. 1987. Implementation and testing of a lateral boundary scheme as an open boundary condition in a barotropic ocean model. Coastal Engineering, 11: 603–627.

Mayer, B. 1995. Ein dreidimensionales, numerisches schwebstoff-transportmodell mit anwendung auf die Deutsche Bucht. Tech. Rep. GKSS 95/E/59, GKSS-Forschungszentrum Geesthacht GmbH, iSSN 0344-9629, 104 pp.

McBride, M., Hansen, J., Korneev, O., Titov, O., Stiansen, J., Tchernova, J., Filin, A, et al. 2016. Joint Norwegian - Russian Environmental Status 2013. Report on the Barents Sea Ecosystem. Part II - Complete Report. Tech. Rep. 2, IMR/PINRO Joint Report Series, ISSN 1502-8828, 359 pp.

Melsom, A., Lien, V., and Budgell, W. 2009. Using the regional ocean modeling system (ROMS) to improve the ocean circulation from a GCM 20th century simulation. Ocean Dynamics, 59: 969–981.

Moll, A., and Stegert, C. 2007. Modeling pseudocalanus elongatus population dynamics embedded in a water column ecosystem model for the northern North Sea. Journal of Marine Systems, 64: 35–46.

Moloney, C., Jarre, A., Arancibia, H., Bozec, Y.-M., Neira, S., Roux, J.-P., and Shannon, L. 2005. Comparing the benguela and humboldt marine upwelling ecosystems with indicators derived from inter-calibrated models. ICES Journal of Marine Science, 62: 493–502.

Mousing, E., Utne, K., Olafsdottir, A., Hjøllo, S., and Skogen, M. 2020. Mackerel migration in the Norwegian Sea – importance of temperature, prey availability and population size.

Niemi, G., and McDonald, M. 2004. Application of ecological indicators. Annual Review of Ecological Systems, 35: doi: 10.1146/annurev.ecolsys.35.112202.130132.

Nybø, S., and Evju, M. 2020. Fagsystem for fastsetting av god økologisk tilstand. forslag fra et ekspertråd. Tech. Rep. 2:52, ICES Scientific Reports. doi: 10.17895/ices.pub.6050.

Olsen, A., Key, R., van Heuven, S., Lauvset, S., Velo, A., Lin, X., Schirnick, C., *et al.* 2016. The global ocean data analysis project version 2 (GLODAPv2) – an internally consistent data product for the world ocean. Earth Systems Science Data, 8: 297–323.

Olsen, E., Kleiven, A., Skjoldal, H., and Quillfeldt, C. 2011. Place-based management at different spatial scales. Journal of Coastal Conservation, 15: 257–269.

Oreskes, N., Shrader-Frechette, K., and Belitz, K. 1994. Verification, validation and confirmation of numerical models in the earth sciences. Science, 263: 641–646.

OSPAR. 2016. Common indicator: Marine bird breeding success/failure. OSPAR Agreement 2016–10.

Ottersen, G., Kim, S., Huse, G., Polovina, J., and Stenseth, N. 2010. Major pathways by which climate may force marine fish populations. Journal of Marine Systems, 79: 343–360.

Pätsch, J., Kühn, W., Moll, A., and H, L. 2009. ECOHAM4 user guide - ECOsystem model, HAMburg, version 4. Tech. Rep. 01-2009, Institut für Meereskunde, Hamburg, Germany.

Pohlmann, T., and Puls, W. 1994. Currents and transport in water. *In* Circulation and Contaminant Fluxes in the North Sea, pp. 345–402. Ed. by J. Sündermann. Springer, Berlin.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., and Fujimori, S. 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42: 153–168. doi: 10.1016/j.gloenvcha.2016.05.009.

Rufino, M. M., Bez, N., and Brind'Amour, A. 2019. Influence of data pre-processing on the behavior of spatial indicators. Ecological Indicators, 99: 108–117..

Sandø, A., Melsom, A., and Budgell, P. 2014. Downscaling IPCC control run and future scenario with focus on the Barents Sea. Ocean Dynamics, 64: 927–949.

Sandø, A., Mousing, E., Budgell, W., Hjøllo, S., Skogen, M., and Ådlandsvik, B. 2021. Barents Sea plankton production and controlling factors in a fluctuating climateAccepted, ICES Journal of Marine Science..

Sandvik, A., Skagseth, Ø., and Skogen, M. 2016. Model validation: issues regarding comparison of point measurments and high-resolution modeling results. Ocean Modelling, 106: 68–73.

Shchepetkin, A. F., and McWilliams, J. C. 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Modeling, 9: 347–404. doi:10.1016/j.ocemod.2004.08.002.

Shin, Y.-J., and Shannon, L. J., 2010. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 1. The indiseas project. ICES Journal of Marine Science, 67: 686–691.

Shin, Y.-J., Shannon, L. J., Bundy, A., Coll, M., Aydin, K., Bez, N., Blanchard, J. L., *et al.* 2010. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2.setting the scene. ICES Journal of Marine Science, 67: 692–716.

Siwertson, A., and Arneberg, P. 2019. Pilottest av fagpanelprotokollen for vurdering av god økologisk tilstand – arktisk del av Barentshavet (pilottest of the expert panel protocol for assessing good ecosystem state – arctic region of the Barents sea).

Skaret, G., Dalpadado, P., Hjøllo, S., Skogen, M., and Strand, E. 2014. *Calanus finmarchicus* abundance, production and population dynamics in the Barents Sea in a future climate. Progress in Oceanography, 125: 26–39.

Skartveit, A., and Olseth, J. A. 1986. Modelling slope irradiance at high lattitudes. Solar Energy, 36: 333–344.

Skartveit, A., and Olseth, J. A. 1987. A model for the diffuse fraction of hourly global radiation. Solar Energy, 38: 271–274.

Skern-Mauritzen, M., Olsen, E., and Huse, G. 2018. Opportunities for advancing ecosystem-based management in a rapidly changing high latitude ecosystem. ICES Journal of Marine Science, 75: 2425–2433.

Skogen, M., Budgell, W., and Rey, F. 2007. Interannual variability in Nordic Seas primary production. ICES Journal of Marine Science, 64: 889–898.

Skogen, M., Hjøllo, S., Sandø, A., and Tjiputra, J. 2018. Future ecosystem changes in the north east atlantic: a comparison between a global and a regional model system. ICES Journal of Marine Science, 75: 2355–2369.

Skogen, M., Ji, R., Akimova, A., Daewel, U., Hansen, C., Hjøllo, S., van Leeuwen, S., *et al.* 2021. Disclosing the truth: are models better than observations? Marine Ecology Progress Series.

Skogen, M., Olsen, A., Børsheim, K., Sandø, A., and Skjelvan, I. 2014. Modelling ocean acidification in the Nordic and Barents seas in present and future climate. Journal of Marine Systems, 131: 10–20.

Skogen, M., and Søiland, H. 1998. A user's guide to NORWECOM v2.0. The NORWegian ECOlogical Model system. Tech. Rep. Fisken og Havet 18/98, Institute of Marine Research, Pb.1870, NO-5024 Bergen, 42 pp.

Skogen, M., Svendsen, E., Berntsen, J., Aksnes, D., and Ulvestad, K. 1995. Modelling the primary production in the North Sea using a coupled 3 dimensional Physical Chemical Biological Ocean model. Estuarine, Coastal and Shelf Science, 41: 545–565.

Slagstad, D., Ellingsen, I., and Wassmann, P. 2011. Evaluating primary and secondary production in an Arctic Ocean void of summer sea ice: an experimental simulation approach. Progress in Oceanography, 90: 117–131.

Slagstad, D., Wassmann, P., and Ellingsen, I. 2015. Physical constrains and productivity in the future Arctic Ocean. Frontiers in Marine Science, 2: 85. doi:10.3389/fmars.2015.00085.

Starkey, D., Thor, J., and Heidbrink, I. 2009. A History of the North Atlantic Fisheries: Vol. 1, from Early Times to the Mid-Nineteenth Century. Bremen: Hauschild Verlag.

Stegert, C., Moll, A., and Kreus, M. 2009. Validation of the three-dimensional ECOHAM model in the German Bight for 2004 including population dynamics of *Pseudocalnus elongatus*. Journal of Sea Research, 62: 1–15.

Steinacher, M., Joos, F., Frölicher, T., Bopp, L., Cadule, P., Cocco, V., Doney, S., *et al.* 2010. Projected 21st century decrease in marine productivity: a multi-model analysis. Biogeosciences, 7: 979–1005.

Stupak, I., and Asikainen, A., Jonsell, M., E., Lunnan, K., Mizaraite, A., Pasanen, D., Parn, K.., *et al.* 2007. Sustainable utilisation of forest biomass for energy-possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. Biomass and Bioenergy, 31: 666–684.

Tam, J., Link, J., Rossberg, A., Rogers, S., Levin, P., Rochet, M.-J., Bundy, A., *et al.* 2017. Towards ecosystem-based management: identifying operational food-web indicators for marine ecosystems. ICES Journal of Marine Science, 74: 2040–2052.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A. 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93: 485–498.

Tett, P., Gowen, R., Painting, S., Elliott, M., Forster, R., Mills, D., Bresnan, E., *et al.* 2013. Framework for understanding marine ecosystem health. Marine Ecology Progress Series, 494: 1–27.

Titov, O., and Orlova, E. 2011. Lower trophic levels. *In* The Barents Sea. Ecosystem, Resources and Management. Half a Century of Russian-Norwegian Cooperation, pp. 77–119. Ed. by T. Jakobsen and V. Ozhigin. Tapir Academic Press, Trondheim, Norway, 825 pp.

Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, Ø., *et al.* 2013. Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM). Geoscientific Model Development, 6: 301–325.

Weijerman, M., Link, J. S., Fulton, E. A., Olsen, E., Townsend, H., Gaichas, S., Hansen, C., et al. 2016. Atlantis ecosystem model summit: report from a workshop. Ecological Modelling, 335: 35–38, doi:10.1016/j.ecolmodel.2016.05.007.

Handling editor:: Marta Coll