Annex 4: Ecosystem Status Summary

This ecosystem status summary provides a short description of the current state and recent change of different components of the Norwegian Sea ecosystem while also briefly discussing possible causes of change. It was issued for the first time in 2021 (2020 meeting) and is updated annually. The ecosystem status summary is intended for a wide audience, including scientists, teachers, students, decision-makers, and the public interested in the Norwegian Sea ecosystem and marine environmental issues in general. It is prepared by the ICES working group on integrated ecosystem assessments for the Norwegian Sea (WGINOR) and is a summary of the scientific information prepared by the group. It does not constitute ICES advice.

Highlights

- In recent years the inflows of both Atlantic and Arctic water have been relatively fresh. At the same time the relative heat content has indicated a warm state, connected to reduced local ocean-to-air heat loss, and the increasing trend in relative freshwater content has stopped. The outlook for the coming years upstream, the Subpolar Gyre index is in a weak state indicating a change to warmer and more saline Atlantic inflow to the Norwegian Sea.
- During the period 2003 to 2023 primary production has varied slightly from year-to-year and without noticeable trend. The timing of the peak of production has gradually shifted to a later date by 10 days per decade.
- Zooplankton spring biomass, measured since 1995, declined in the mid-2000s. Since then, there has been no clear trend but variations between years. The biomass has been low in some subareas the last few years.
- A decline in spawning biomass started around 2009 for Norwegian spring-spawning herring and around 2015 for mackerel. These declines continued in 2023. Blue whiting biomass increased by more than a third in 2023, driven by historically high recruitment of two year classes.
- Long-term decrease in breeding numbers for Atlantic puffin and black-legged kittiwake continues at the Norwegian coast. Common guillemot numbers are still low but have increased markedly over the last decade.

Abundance indicators suggest declining population levels for hooded and grey seals, low levels for harbour seals, and highly uncertain for harp seals. Harbour porpoise bycatch levels estimated over the period 2006-2018 were unsustainable. The distribution of baleen whales has gradually shifted towards the Barents Sea and the North Sea. The abundance of minke whales in the region is estimated to have increased considerably in the last years.

Graphical summary

Topic	Overall trend	Situation in 2022/2023	Certainty	Possible implications
Ocean climate	Generally, warm and saline conditions prevailed from the early 2000s until 2016. Since 2012, temperature of the Atlantic inflow has been close to the long-term mean while salinity has been below the long-term mean since 2016. The extent of Arctic Water has increased from 2017.	The temperature of the Atlantic inflow is close to the long-term mean while salinity is below the long-term mean. The extent of Arctic Water continues to increase but the recent decline in relative heat content has ceased. A present relative weak North Atlantic Sub Polar Gyre (SPG) may lead to a warmer and more saline Atlantic Inflow in coming years.	Highly certain: dedicated monitoring with good spatial coverage exists.	The recent increase of Arctic Water may lead to increased new production due to relative high winter nutrient concentration and import of Arctic zooplankton.
Primary production	There is no trend in the level of spring and summer primary production in the Norwegian Sea deep basins since 2003. The timing of peak production has gradually shifted to a later date over the last two decades.	The primary production for 2022 is low (150g·C·m^{-2}) but within the range of previously observed values. The timing of the peak production in 2022 is average (day 160).	Certain: Phytoplankton estimates are based on satellite data covering the productive season with high geographic resolution. The production model is not calibrated for high latitudes and absolute estimates of primary production are uncertain.	Change in timing can lead to seasonal match/mismatch with reproduction and feeding of zoo and ichtyo-plankton.
Zooplankton biomass	Spring biomass of mesozooplankton was at a higher level from 1995 to mid-2000s and has been at a lower level in the following years. Summer biomass shows an increasing trend or no trend from 2010 until 2023	Biomass in 2023 was at similar level as the previous year for all subareas and both seasons but increased in the eastern Lofoten Basin in summer.	Moderately certain: plankton is patchily distributed, which leads to uncertain estimates. The timing of seasonal development relative to time of sampling can affect the level of biomass measured.	Reduced zooplankton biomass may have caused reduced food resources for planktivorous feeders, including pelagic fish. in the recent decade.
Zooplankton spatial distribution	Spring distribution of zooplankton has changed from higher biomasses in Arctic water in the west to become evenly distributed in the Norwegian Sea.	In 2023, the zooplankton was relatively evenly distributed in spring but with a confined high-concentration area in Arctic waters.	Moderately certain: The spatial distribution reflects and is affected by the timing of the survey and the timing of the zooplankton seasonal development.	Changes in the spatial distribution of plankton can affect the spatial distribution of planktivorous fish

Pelagic fish biomass	Spawning-stock biomass of Norwegian spring-spawning herring and mackerel continued to decline while blue whiting increased sharply to a record high value.	Herring spawning-stock biomass decreased by 10% and mackerel by 7% whereas blue whiting increased by 36% compared to previous year. Estimated recruitment of blue whiting is at a historical high for two year-classes. Fishing remains above scientific advice for all stocks.	Highly certain for herring and blue whiting, moderately certain for mackerel due to repeated revisions of stock perception from assessment: estimates are based on quantitative stock assessments.	Changes in pelagic fish biomass have direct implications for fisheries opportunities.
Pelagic fish spatial distribution	Since the mid-2000´s, mackerel distribution expanded westward into Icelandic and Greenlandic waters, then retracted eastward from 2015. By 2020, most of the mackerel stock was feeding in the Norwegian Sea. In 2022, mackerel expanded westward again to west coast of Iceland but density was low.	No mackerel in Greenlandic waters. Similar presence and density in Icelandic Waters in 2023 as measured in 2022.	Highly certain: based on ecosystem surveys in the Nordic Seas in spring (May) and summer (July)	Changes in pelagic fish spatial distribution have direct implications for fisheries opportunities.
Seabirds	Substantial long-term declines for most species, including common guillemot, Atlantic puffin, and black-legged kittiwake.	No clear signs of improvements, except common guillemot abundance appears stable in colonies which provide shelter from eagle predation.	Highly certain: Trends are derived from dedicated monitoring.	Many bird colonies are at risk of extinction, and some have already disappeared.
Marine mammals	Decline or sustained low levels of pup production in several seal species. Long-term shift in summer distribution of baleen whales from the Norwegian Sea to the Barents Sea. Unsustainable levels of harbour porpoise bycatch.	No new data on abundance and distribution.	Highly certain: Trends in pup production are based on dedicated surveys. Moderately certain: Data are scarce on bycatch and productivity-connectivity for harbour porpoises	Changes in marine mammals affect foodweb structure and long-term viability of marine mammal populations

Climate

Current status and recent changes

The Norwegian Sea ocean climate and its interannual variability is determined by the amount of Atlantic water flowing into the area (warmer and more saline), the amount of Arctic water flowing in (colder and fresher), the properties of these water masses (e.g. how warm and saline the Atlantic water is) [1], and heat loss from the sea to the air [2].

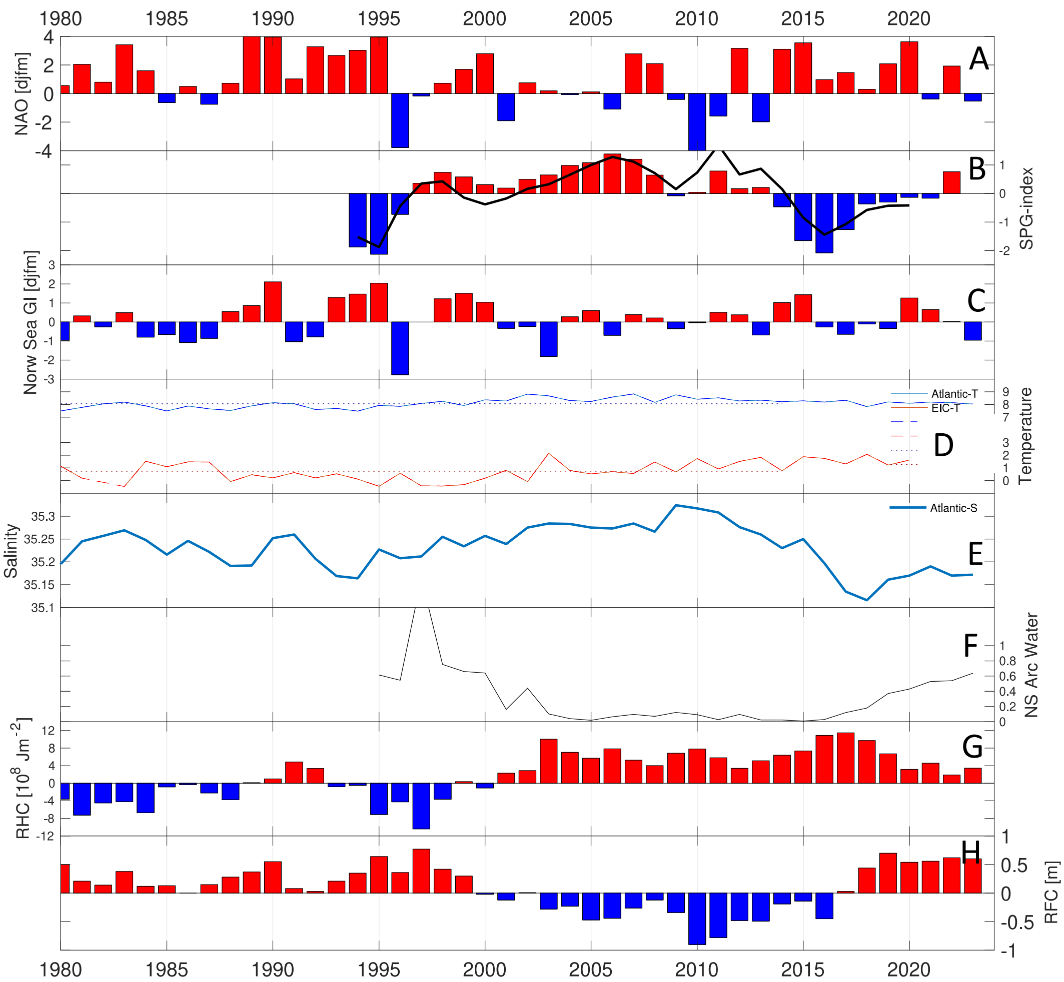


Figure A4.1 A subset of climate indicators for the Norwegian Sea: a) North Atlantic Oscillation Index (NAO), b) Subpolar Gyre index (SPG, note that strong gyre is represented by negative values and weak gyre by positive values), c) Norwegian Sea Gyre index, d) Atlantic Water Temperature at Svinøy section and East Icelandic Current Temperature, e) Atlantic Water Salinity at Svinøy section, f) Arctic Water amount in the Norwegian Sea, g) relative heat content (RHC) and h) Relative Freshwater Content (RFC).

Total heat content and freshwater content in the Norwegian Sea is estimated from *in situ* measurements of temperature and salinity. These data indicate a trend from cold and freshwaters in the mid-1990s until about 2003 when the state changed to warm and saline, which prevailed until about 2016 (Figure A4.1G, H). Since 2016, the freshwater content has increased considerably. This has been associated with a gradual decrease in heat content, although this decrease is less than expected. The inflowing Atlantic water, which is monitored in the Svinøy section (at about 63°N) largely follows these changes (Figure A4.1D, E), but since 2012, the temperature has been close to the long-term mean. The amount of Arctic Water in the Norwegian Sea has increased since 2016 after being low for more than a decade (Figure A.1F). In summary, the temperature of Atlantic inflowing water has been close to the long-term mean while the amount of Arctic Water in the Norwegian Sea has increased.

Possible reasons for recent changes

The strength of the Subpolar Gyre in the Labrador and Irminger Sea influences the properties of the Atlantic water flowing into the Norwegian Sea, e.g. temperature, salinity, and nutrients. When the gyre is strong, it brings increased amounts of cold and freshwater from the western part of the North Atlantic eastward into the Iceland Basin and the Rockall plateau, diluting the warm and saline water of the North Atlantic Current south of the Greenland-Scotland ridge. This causes the Atlantic water flowing into the Norwegian Sea to become colder and fresher. When the gyre is weak (positive SPG index), the inflowing Atlantic water becomes more influenced by the warmer and relatively saline water from the Gulf Stream.

In addition, atmospheric conditions influence the ocean climate in the Norwegian Sea. Important variability in atmospheric conditions can be measured through the North Atlantic Oscillation (NAO) index. When the NAO-index is in a positive phase, the Subpolar Gyre tends to be strengthened, and inflowing Atlantic water thus becomes colder and fresher. At the same time, ocean to air heat loss in the Norwegian Sea also tends to decrease with a positive NAO-index.

The change from fresh and cold conditions in the 1990s to warm/saline conditions after 2003 can thus be attributed to a switch from a relatively strong to a weak Subpolar Gyre from 1995 to 1996, and hence warmer and more saline Atlantic source water flowing into the Norwegian Sea (Figure A4.1B, D, E). During the 2010 the NAO-index was mainly in a positive phase that coincide with a relative strong SPG especially from 2015–2017 – that likely is connected to the fresher Atlantic Inflow during some years after. However, the in the 2020s the NAO has been in a more negative state, and with an accompanying weakening SPG. The overall freshening is also influenced by eastward expansion of Arctic Water into the Norwegian Sea (Figure A4.1F). There are indications that the influence of the East Icelandic Current, that brings Arctic Water from the Iceland Sea to the southern Norwegian Basin, has increased in recent years.

Phytoplankton

Current status and recent changes

Net primary production (NPP) is calculated based on optical signals (e.g. ocean color and infrared radiation) measured by the MODIS satellite and represent the production of biomass available to other organisms in the ecosystem. The Vertically Generalised Production Model (VGPM [3]) is used to derive NPP from satellite observations.

Annual estimates of NPP integrated for spring and summer have remained stable over the observation period (2003–2023) around 170 grammes carbon per square meter per year ($gC \cdot m^{-2} \cdot y^{-1}$) ± 15% (Figure A4.2). Years 2006 and 2007 had the lowest reported primary production while 2019 was the year with highest reported primary production. The apparent increasing trend observed in 2010-2020 has halted and recent observations have returned to average-low values. Absolute estimates of NPP may be biased, as satellite measurements are restricted to the upper water column, and NPP estimates rely on parameterization originally developed for lower latitudes. However, relative changes in NPP between years are considered robust.

Behind the interannual variations in the seasonal timing of the peak of production there is a general trend of peak production occurring at later dates. This has gradually shifted from day 150 to 170, i.e. 10 days per decade.

Possible reasons for recent changes

There is no clear reason for the change in seasonal timing of the peak in primary production. Increased flow of fresh Arctic water into Nordic Seas has increased stability of surface layer stratification [4] and this could be involved in delaying NPP.

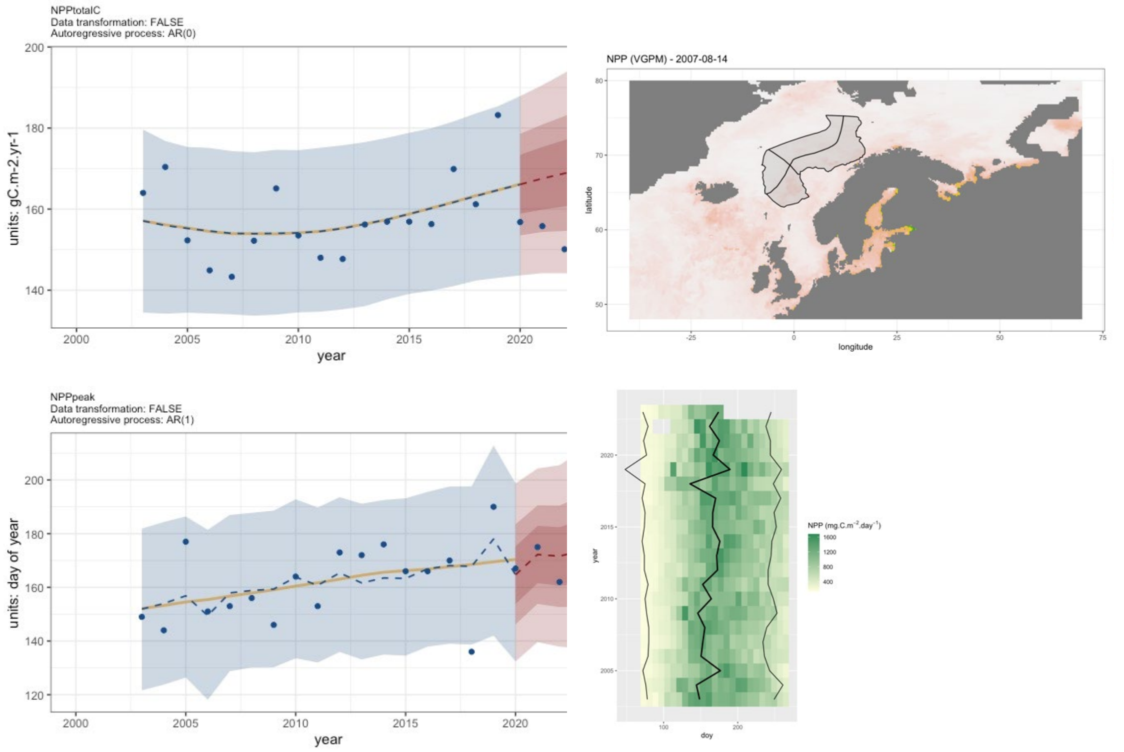


Figure A4.2 Net primary production. Upper-left panel: annual estimates of spring-summer NPP (observations shown as blue dots). Lower-left panel: annual estimates of the timing of peak production. Upper-right panel: estimated NPP (mg·C·m-2·day-1) over the Northeast Atlantic (snapshot on the 14 August 2007). The Norwegian Sea polygon used for annual estimates is highlighted. Lower-right panel: seasonal and interannual variations in NPP. The left, central and right lines show respectively the timing of start, peak and end of the production season.

Zooplankton

Current status

The zooplankton biomass indices, for all four subareas of the Norwegian Sea in spring, May (28 years) and summer, July and August (14 years) were either at similar levels, slightly lower or slightly higher in 2023 compared to 2022 (Figure A4.3). An exception was summer biomass in the eastern Lofoten Basin which increased significantly in 2023. In 2021, a decrease in spring zooplankton biomass was observed at the western Norwegian Sea Basin, and the biomass has been at a low level since then. In 2023 the biomasses were generally at similar levels in all subareas and seasons, but with somewhat lower values in the western Lofoten Basin.

Recent changes

There have been two main changes in spring zooplankton biomass during the last three decades: 1) There has been a long-term decline in all subareas, and 2) the previously higher zooplankton level in Arctic water north and east of Iceland, and in the frontal region between Atlantic and Arctic waters in the western Norwegian Sea Basin, has been reduced to a lower level than the Atlantic water in the central Norwegian Sea. For the period 1995 to mid-2000s the plankton indices in spring were relatively high, with fluctuations between years. In the mid-2000, the indices decreased and remain at a lower level. The largest decline was in Arctic water east and north of Iceland, with approximately 60 % reduction from the "high-biomass" period to the "low-biomass" period. During the last decade, zooplankton biomass in the eastern areas has shown an increasing tendency.

Possible reasons for recent changes

The reasons for the changes in zooplankton biomass are not obvious. The period with lower zooplankton biomass coincides with higher-than-average heat content in the Norwegian Sea (see the climate section of this annex (Annex 4) and reduced inflow of Arctic water into the southwestern Norwegian Sea [5]. The higher spring biomass in the years 1995–2005 is concurrent with higher Arctic inflow in the Norwegian Basin [5]. Phenological drivers, such as match/mismatch with the phytoplankton bloom, may also have affected zooplankton abundance. The high biomass of pelagic fish (see the pelagic fish section of this annex (Annex 4) feeding on zooplankton has been suggested to be one of the main causes for the reduction in zooplankton biomass. However, carnivorous zooplankton and not pelagic fish may be the main predators of zooplankton in the Norwegian Sea [6], and there is no time-series on the biomass of carnivorous zooplankton stocks or consumption. Zooplankton biomass estimates are uncertain because of the naturally high spatial patchiness of zooplankton and these uncertainties are accounted for in the reported series (Figure A.43a,b). Additional uncertainties in the year-to-year changes in biomass may arise from the rapid seasonal changes in biomass relative to the duration of the survey and different timing of the zooplankton seasonal development between years.

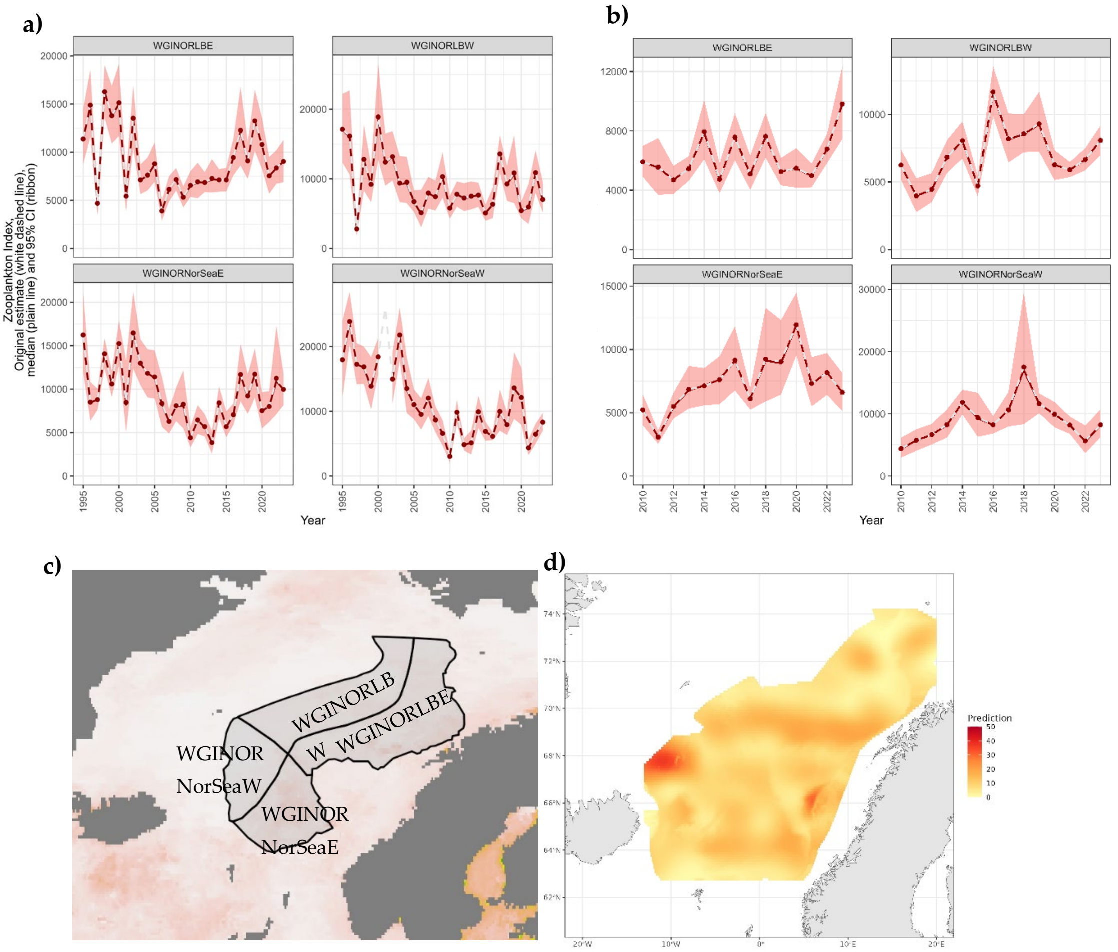


Figure A4.3 Indices of zooplankton biomasses (mg dry weight m-2) in the upper 200 m of the water column in the Norwegian Sea and adjacent waters, a) in May during the period 1995–2023, b) in July/August during the period 2010–2023. Also displayed c) the four subareas used for analysis along with d) zooplankton biomass distribution in May 2023.

Pelagic Fish

Current status

Three fish stocks dominate the pelagic ecosystem of the Norwegian Sea: Norwegian spring-spawning herring (NSSH, *Clupea harengus*), Northeast Atlantic mackerel (*Scomber scombrus*), and blue whiting (*Micromesistius poutassou*). In 2023, estimated spawning-stock biomass (SSB) for all three stocks ranged from 3.7 to 6.2 million tonnes [7–9]. Combined SSB for all three stocks was 13.6 million tonnes (Figure A4.4a).

Combined catch of the three stocks was 2.9 million tonnes in 2022, of which approximately 1.0 million tonnes was blue whiting, 1.0 million tonnes was mackerel, and 0.8 million tonnes was herring [7–9]. Current exploitation levels, relative to biological reference points, show that fishing pressure on all three stocks is above that which leads to maximum sustainable yield (F_{MSY} [7–9]). Furthermore, herring exploitation is above management plan fishing targets (F_{mgt}). Stock status, for all three stocks is above all biological reference points related to the risk of impaired reproductive capacity. However, herring SSB is very close to biological reference limits (MSY $B_{trigger}$), as the 95 % SSB confidence limits include the reference limits and is predicted to decline below MSY $B_{trigger}$ in year 2024.

Recent changes

The 2023 stock assessment results show that herring Spawning-stock biomass (SSB) is in decline again, 10% from 2022 to 2023, after a slight increase in 2021. The cumulative biomass decline from last biomass peak, in 2008, to 2023 is 48% [8]. Mackerel SSB also began declining again in 2023, by 7% compared to previous year, after several years of similar biomass values. Biomass peak was in 2015 and the cumulative decline is 43% in 2023 [7]. Blue whiting SSB continued increasing and was estimated 36% higher in 2023 compared to 2022 and in projected to increase another 9% in 2024 [9].

The distribution area of herring in May changed as limited herring was present in the southeast and northeast parts of the Norwegian Sea in 2023 compared to 2022 [10,11]. By July 2023, the herring had shifted westward and northward compared to May [11,12]. The mackerel distribution in the Nordic Seas in summer 2023 was similar to the observed distribution in summer 2022 with the western boundary of mackerel presence located west of Iceland (longitude 27 °W) [12,13]. The distribution of blue whiting in the spawning area expanded in 2023 compared to 2022 with blue whiting also present in the northern part of spawning grounds which was not recorded in 2022 [14,15].

Possible reasons for recent changes

Herring SSB is dominated by recruitment of large year-classes at irregular intervals with many years of small year-classes in between [8] (Figure A4.4b). There is no indication that another large year-class will enter the spawning stock in the coming years. Fishing above the advised level has accelerated the stock decline during a period of low recruitment. Since 2013, unilaterally determined quotas have led to annual commercial catch being 31% higher than the advised total allowable catch (TAC) on average [8].

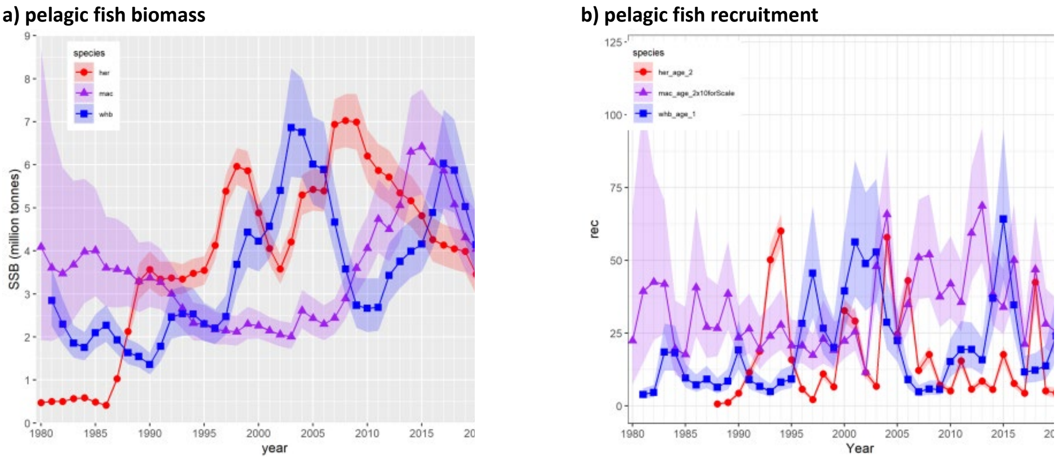


Figure A4.4. a) estimated spawning-stock biomass (lines) including 95% confidence intervals (shaded areas) for Norwegian spring-spawning herring (red filled circles), mackerel (purple filled triangles) and blue whiting (blue filled rectangles) from first stock assessment year, ranges from 1980 or 1988, to 2023 [7–9]. B) estimated year-class size at recruitment for Norwegian spring-spawning herring (age 2; red filled circle), mackerel (age 2; purple filled triangles) and blue whiting (age 1; blue filled triangle) from first year of assessment, ranges from 1980 to 1988, to 2023 [7–9]. Note mackerel recruitment is multiplied by 10 to be on the same magnitude as values for herring and blue whiting.

The 2023 assessment changed the perception of the mackerel stock, SSB revised upward and fishing mortality downward, and the revision is greater in the years prior to 2018 compared to years 2019 to 2022 [7]. It is not properly understood why the perception changed in the 2023 assessment. Systematic revisions in perception of the stock have occurred repeatedly in last several assessments and suggest lack of robustness in the assessment which could be due to model misspecifications or conflicting trends in the five input time-series. Since 2010, unilaterally determined quotas have led to annual commercial catch being 40% higher than the advised TAC on average. Fishing above advised TAC is believed to have contributed to the observed decline in spawning stock size.

Sharp increase in blue whiting SSB is driven by recruitment of two record large year classes, 2020 and 2021, to the spawning stock [9]. Biomass is estimated to be record high for the assessment period. The 2020 year-class is considered fully recruited to the spawning stock and is the biggest year-class in the stock. Since 2015, unilaterally determined quotas have led to annual commercial catch being on average 35% higher than the advised TAC [9]. The blue whiting fishery targets few age classes, mostly 3–5 year-olds, hence the stock declines quickly when poor recruitment coincides with excessive fishing as seen after the last SSB peak in 2017.

Seabird

Current status

Five species of seabirds feeding in the pelagic (3) and coastal (2) parts of the ecosystem, are selected as indicator species for the eastern part of the Norwegian Sea, i.e. along the central part of the Norwegian coast (hereafter eastern Norwegian Sea).

The three pelagic species are the black-legged kittiwake (*Rissa tridactyla*, hereafter kittiwake), the Atlantic puffin (*Fratercula arctica*, hereafter puffin) and the common guillemot (*Uria aalge*). The main reason for selecting these species is that they feed in different parts of the pelagic ecosystem. The kittiwake obtains its food (first-year herring, sandeels, gadoids, lanternfish, crustaceans, and pteropods) within the upper half meter of the sea surface. The common guillemot typically feeds at depths down to 80 m and may eat very small fish such as 0-group cod but feed its chick mainly 10–20 cm long saithe, haddock, sandeel and herring that are brought one by one to the colony. The puffin usually brings loads of smaller fish to its chick and typically feeds at depths down to 30 m, relying in this part of the Norwegian Sea mainly on first-year herring, sandeel, and gadoids.

Representatives of the coastal species are the common eider (*Somateria mollissima*, hereafter eider) and the European shag (*Phalacrocorax aristotelis,* hereafter shag). The eider mainly feeds on benthic prey like crustaceans, molluscs, and echinoderms. The shag is a fish specialist which typically dive in shallow waters and feeds on gadoids and/or sandeels.

Recent changes

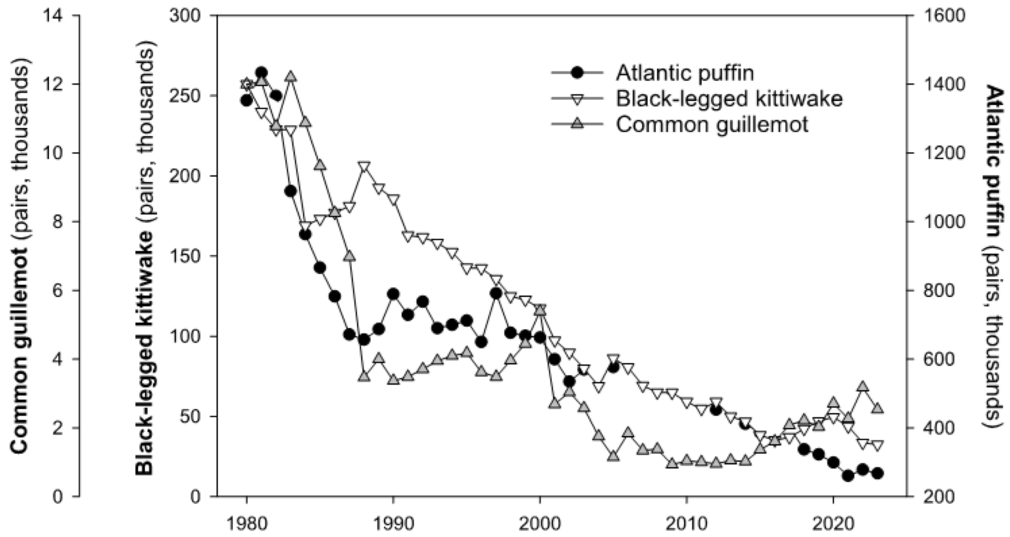
For the three pelagic species, time-series of their population development in the eastern Norwegian Sea (Figure A4.5a) were derived from their estimated breeding numbers in 2013 [16] and annual monitoring of trends in selected breeding colonies (Runde (62.4°N), Sklinna (65.2°N), Røst (67.5°N) and Anda (69.1°N, only kittiwake and puffin)). The remote island of Jan Mayen (71.1°N) in the northwestern Norwegian Sea holds only < 10,000 pairs of kittiwakes, < 5000 pairs of puffins and < 1000 pairs of common guillemots. Monitoring there started in 2011, and has been done for common guillemot only, showing a declining trend.

The breeding population of kittiwakes in the eastern Norwegian Sea has declined by 87% since monitoring started in 1980. Its outlook is grim, with several large colonies already gone extinct and many more risking extinctions within few decades. In the same area and period, the breeding population of puffins has declined by 80% and that of common guillemots by 79%. The small remaining population of common guillemot breeds under boulders and in crevices where the birds are less exposed to predation by white-tailed eagles and has shown clear signs of increase over the last decade. The species is still considered to be at high risk of extinction as a breeding species along a large part of the Norwegian mainland coast.

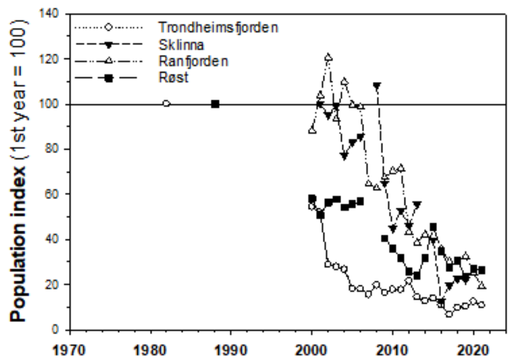
For the two coastal species, trends in breeding populations in the eastern Norwegian Sea (Figure A4.5 b,c) are monitored in selected areas along the mainland coast (Trondheimsfjorden (63.4°N, only eider), Sklinna (65.2°N), Ranfjorden (66.2°N, only eider), and Røst (67.5°N). Data from 2022-2023 have not been added yet but these are not expected to change the overall trends.

The breeding population of eiders in the eastern Norwegian Sea has declined by about 81% since the first counts in the mid-1980s. In contrast, shag populations in both colonies monitored increased from the mid-1980s to around 2005 but have decreased markedly thereafter.

a) population trends for black-legged kittiwake, common guillemot and Atlantic puffin



b) population trends for common eider



c) population trends for European shag

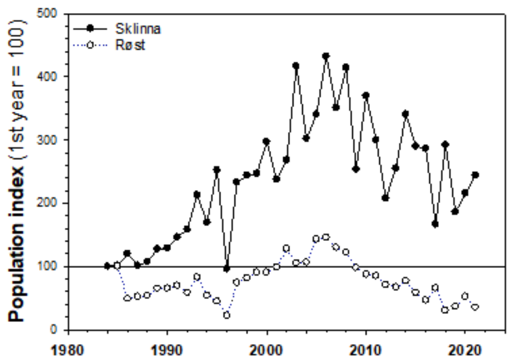


Figure A4.5 Population trends for seabirds breeding in the Norwegian part of the eastern Norwegian Sea since 1980, divided by (a) pelagic feeding species black-legged kittiwake, common guillemot and Atlantic puffin, (b) coastal benthic feeding common eider and (c) coastal fish-feeding European shag.

Possible reasons for recent changes

The largest changes in seabird numbers in the eastern Norwegian Sea are linked to ocean climate variability [17,18] and most likely mediated through substantial changes in prey abundance and availability with dire consequences for reproductive success and recruitment [19–24]. To some degree, this has also affected survival rates [25–27], which in addition can occasionally be severely hit by extreme weather events [28–31]. Still, an increasing number of studies document effects of other natural and man-induced changes that may also contribute to the variation in seabird breeding performance. This includes factors such as competition with fisheries [23,32,33] and increased predation from white-tailed eagles [34,35], as well as contaminants [36] and human disturbance [37]. The magnitude of seabird bycatch in some of Norway's most important fisheries has also been quantified in a series of recent studies [38–40]. Outbreaks of highly pathogenic avian influenza (HPAI) hit many colonies of seabirds along the Norwegian coast in 2022 and 2023. Apparently, black-legged kittiwakes were among the species most affected, together with great skuas and northern gannets. Studies have been initiated to quantify the population level impacts.

Marine mammals

Current status

Nine marine mammal species are closely associated with core ecological processes and human activities in the Norwegian Sea area. Minke (*Balaenoptera acutorostrata*), fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*) and sperm whales (*Physeter macrocephalus)* dominate in biomass but are mainly present in summer and autumn; hooded seals (*Cystophora cristata*) and northern bottlenose whales (*Hyperoodon ampullatus*) have a partially arctic distribution; while harbour porpoises (*Phocoena phocoena*), grey seals (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*) are resident on the continental shelf of Norway. All nine marine mammal species have been significantly affected by historic harvesting levels, but only minke whales, grey and harbour seals are currently hunted in the area. Killer whales (*Orcinus orca*) may occur across the Norwegian Sea and year-round but are mainly associated with the herring and mackerel migrations. Marine mammals are significant determinants of energy flow through foodwebs. Skern-Mauritzen *et al*. [41] recently estimated the total annual biomass consumption by marine mammals in the Norwegian and Greenland Seas at 4.6 (CI: 1.9–8.6) million tonnes. This exceeds the estimated 1.45 million tonnes removed by fisheries. More than 60% of the marine mammal consumption is comprised by euphausiids and other non-commercial crustaceans [41]. While there is a potential for direct competition with fisheries for capelin, herring and gadoids, marine mammals may also promote ecosystem productivity through enhancing nutrient recycling [42].

Recent changes

Commercial sealing is believed to have reduced the abundance of the Northeast Atlantic hooded seal population by more than 80% from the mid-1940s to 1980. After that, abundance models have shown a continued slow decline, despite full protection since 2007 [43]. It should, however, be noted that the uncertainty around the postwar population size is considerable and that the modelling framework for this species is going through a revision. Harbour and grey seals are subject to a quota regulated hunt and some incidental bycatch along the Norwegian coast [44,45]. Over the past decade, declines observed in central Norway have led to full protection in some areas [44,45]. New surveys have shown continued low levels of pup production in both grey seals and hooded seals [45].

Fin and humpback whales have shown strong recoveries in the Northeast Atlantic over the past decades [46–48] and there is evidence of a recent long-term shift in distribution from the Norwegian Sea to the Barents Sea ecoregion, particularly for humpback whales [47]. The abundance estimate of Northeast Atlantic minke whales has increased considerably. These three baleen whale species are pelagic feeders with variable preferences for crustaceans and small fish.

Relative abundance indicators suggest stable occurrence of the deep-diving sperm whale in the Norwegian Sea area over the period 2002-2018 [46,47]. During the same period, abundance estimates for harbour porpoises and killer whales have been highly variable and do not show a clear trend. Abundance trends are not available for northern bottlenose whales, but sightings of this deep-diving species doubled during the last whale survey cycle (2014-2018) compared to previous cycles [46,47].

Moan *et al*. (2020) [49] reported that the annual bycatches of harbour porpoises in Norwegian waters ranged from 1151 to 6144 for the period 2006 to 2018, with an average of about 2900. While this was considered unsustainable, there was an overall reduction to a sustainable annual average of about 1600 porpoises during the last five years of the study. However, more recent estimates that corrected for 'drop-out rates' of animals from the nets during hauling suggested that porpoise bycatch rates for the same area are still not sustainable [50].

Possible reasons for recent changes

Bycatches in bottom-set gillnets are the suspected culprit for the reductions in grey seal pup production along the Norwegian coast [45,51], but seal predation by killer whales could also play a role [52]. The overall reduction in harbour porpoise bycatches over the last 10 years are possibly due to reduced effort in the monkfish fishery.

The lack of recovery in the Northeast Atlantic hooded seal population is not well understood. Maximum abundance of this population was recorded prior to the development of modern offshore fisheries in the 1950s and 60s, which could have changed the carrying capacity for hooded seals. Information on hooded seal diet is scarce but several commercial prey species have been identified from analyses of stomach content and fatty acids [53–55]. Changes in the availability and condition of sea ice used for haul-out off east Greenland may also have affected the energy balance of hooded seals and are likely linked to increased predation rates by polar bears [56,57].

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