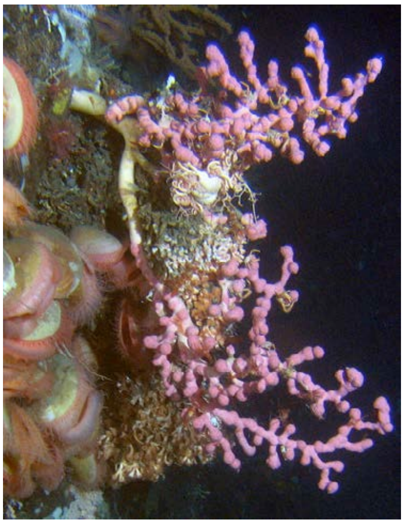
NINA Report 514

Norwegian marine ecosystems – are northern ones more vulnerable to pollution from oil than southern ones?

Elisabet Forsgren
Signe Christensen-Dalsgaard
Per Fauchald
Johanna Järnegren
Tor F. Næsje



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CONTACT DETAILS

NINA head office
NO-7485 Trondheim
Norway
Phone: +47 73 80 14 00
Fax: +47 73 80 14 01

NINA Oslo
Gaustadalléen 21
NO-0349 Oslo
Norway
Phone: +47 73 80 14 00
Fax: +47 22 60 04 24

NINA Tromsø
Polarmiljøsenteret
NO-9296 Tromsø
Norway
Phone: +47 77 75 04 00
Fax: +47 77 75 04 01

NINA Lillehammer
Fakkelgården
NO-2624 Lillehammer
Norway
Phone: +47 73 80 14 00
Fax: +47 61 22 22 15

www.nina.no

Abstract

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The prospect of petroleum industry activities in northern Norwegian marine areas, from Lofoten and northwards, including the Norwegian part of the Barents Sea, is much debated. This report addresses the question whether the Lofoten-Barents Sea ecosystems are different and more vulnerable to oil pollution as compared to more southern Norwegian marine ecosystems. We summarise a literature review looking for evidence in relation to this. We found that there are a number of aspects which differ between the two areas, in particular with respect to biodiversity (lower in the north), species distributions, and 'hot spot areas' with high productivity and animal aggregations (especially significant in the north). Based on this knowledge we focus on the vulnerability of these ecosystems to pollution from oil, and discuss likely general and species specific differences in vulnerability between northern and southern Norwegian marine ecosystems. Cleaning up marine oil spills in remote, icy areas like the Arctic is particularly difficult. Moreover, the Lofoten-Barents Sea ecosystem appears, in several ways, more vulnerable to pollution from oil. This is due to, for instance, lower biodiversity, which has been suggested to be associated with lower resilience. Also, this area is the home of many valuable and vulnerable organisms. For example, the Lofoten-Barents Sea hosts large seabird colonies and contains the nursery area of important fishes. In addition, there are significant conflicts of interest between petroleum activities and other activities in the area, for example, important fisheries and nature conservation.

Elisabet Forsgren (elisabet.forsgren@nina.no)
Signe Christensen-Dalsgaard (signe.dalsgaard@nina.no)
Johanna Järnegren (johanna.jarnegren@nina.no)
Tor F. Næsje (tor.naesje@nina.no)
Norsk institutt for naturforskning, 7485 Trondheim

Per Fauchald (per.fauchald@nina.no)
Norsk institutt for naturforskning, Polarmiljøsenteret, 9296 Tromsø

Sammendrag

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Oljeutvinning i nordlige norske havområder (fra Lofoten og nordover) har lenge vært omdiskutert. Denne rapporten tar for seg spørsmålet om de marine økosystemer i Lofoten-Barentshavet er forskjellige fra og mer sårbare for oljeforurensning enn områder lenger sør i Norge. I rapporten sammenfatter vi en litteraturgjennomgang av kunnskap relatert til dette. Vi fant flere aspekter som er forskjellige mellom disse økosystemene, for eksempel når det gjelder biodiversitet (lavere i nord), og forekomst av høyproduktive områder og ansamlinger av dyr (spesielt i nord). Basert på dette fokuserer vi på sårbarhet hos disse økosystemene med hensyn til oljeforurensing, og diskuterer sannsynlige generelle og artsspesifikke forskjeller i sårbarhet mellom de nordlige og sørlige norske områdene. Oppryddingsaksjoner i arktiske hav er meget vanskelige. Økosystemene i Lofoten-Barentshavet ser dessuten ut til å være mer sårbare for oljeforurensing av flere grunner. Dette skyldes blant annet at det trolig er mindre motstandskraft mot forstyrrelser i et artsfattigere system, og at dette området har mange spesielt verdifulle og sårbare arter. Lofoten-Barentshavet har mange store sjøfugl-kolonier, og er yngelområde for flere viktige fiskearter. I tillegg er det store interessekonflikter mellom oljeaktivitet og andre aktiviteter i området, som meget viktige fiskerier og naturvern.

Elisabet Forsgren (elisabet.forsgren@nina.no)
Signe Christensen-Dalsgaard (signe.dalsgaard@nina.no)
Johanna Järnegren (johanna.jarnegren@nina.no)
Tor F. Næsje (tor.naesje@nina.no)
Norsk institutt for naturforskning, 7485 Trondheim

Per Fauchald (per.fauchald@nina.no
Norsk institutt for naturforskning, Polarmiljøsenteret, 9296, Tromsø

Contents

Foreword

There is large pressure from the petroleum industry to extract oil and gas in northern Norway (Lofoten-Barents Sea area). At the same time this area has a valuable marine life of international importance. To deal with this is a challenge for many involved, including politicians and nature managers. An important question in this context is what the ecological consequences of an oil accident would be. There is no doubt that pollution from oil can have severe impact on the environment. But how severe the effect of an oil spill would be for different organisms, and whether the Lofoten-Barents Sea is especially vulnerable to pollution from oil is unclear. Based on a literature review, we address the question whether northern Norwegian marine ecosystems are any different from more southern ones, and whether they are likely to be more vulnerable to pollution from oil. This is a very complex and broad question, and there are large knowledge gaps. Nevertheless, we provide a brief summary of some characteristics of these ecosystems and discuss some aspects of their vulnerability. To predict ecological effects of oil accidents is very difficult, and we need more knowledge in order to approach more conclusive answers.

Trondheim, October 2009
Elisabet Forsgren

1 Introduction

1.1 Scope of the report

Petroleum industry activity (exploration, production, shipping) in northern Norwegian areas, from Lofoten and northwards, including the Norwegian part of the Barents Sea, is an area of much debate and conflicts of interest. This report addresses the question whether the Lofoten-Barents Sea marine ecosystems are significantly different from the more southern ones, i.e. Norwegian Sea and North Sea (**figure 1**), and whether they are likely to be more vulnerable to oil pollution. The report is based on a literature review and presents a brief overview of some aspects that should be central to answer this question. The report is not an exhaustive review of oceanography or ecosystem ecology of the areas, nor a review of eco-toxicological effects of oil on organisms. For more detailed information on different aspects, or comprehensive reviews of these marine ecosystems, we refer to already published articles (e.g. Loeng & Drinkwater 2007), books (e.g. Sakshaug et al. 1994, 2009) and reports (e.g. Dahle & Pedersen 2003, AMAP 2007, Gjøsæter et al. 2008).

Figure 1 *Map showing the Norwegian Sea and adjoining seas in the north eastern Atlantic (from Wikipedia commons).*

1.2 Management of the Lofoten-Barents Sea ecosystems

The Norwegian ecosystem-based management plan 2006-2010 for the Norwegian part of the Barents Sea and Lofoten area (**figure 2**) is an attempt to manage human activities (oil and gas industry, fishing, and shipping) in the area, to ensure a continued 'healthy' production and functioning of the ecosystem (Norwegian Ministry of the Environment 2006, Olsen et al. 2007).

There are also international efforts to achieve a holistic assessment of the environmental, social, economic, and human health impacts of current oil and gas activities in the Arctic (AMAP, Arctic Monitoring and Assessment Program, 2007). An important aim is to evaluate the potential impacts of development of Arctic oil and gas activities in the near future.

The Barents Sea is a relatively shallow (Arctic continental shelf) and highly productive sea (Sakshaug et al. 1994a, Loeng & Drinkwater 2007, Gjøsæter et al. 2008). It faces very large environmental variation in light and ice cover, temperature and water circulation patterns (Sakshaug et al. 1994a, Loeng & Drinkwater 2007). The area hosts marine life of significant international importance. These include some of the world's largest commercial fish stocks, large seabird colonies, marine mammals and deep cold water coral reefs (Gjøsæter et al. 2008).

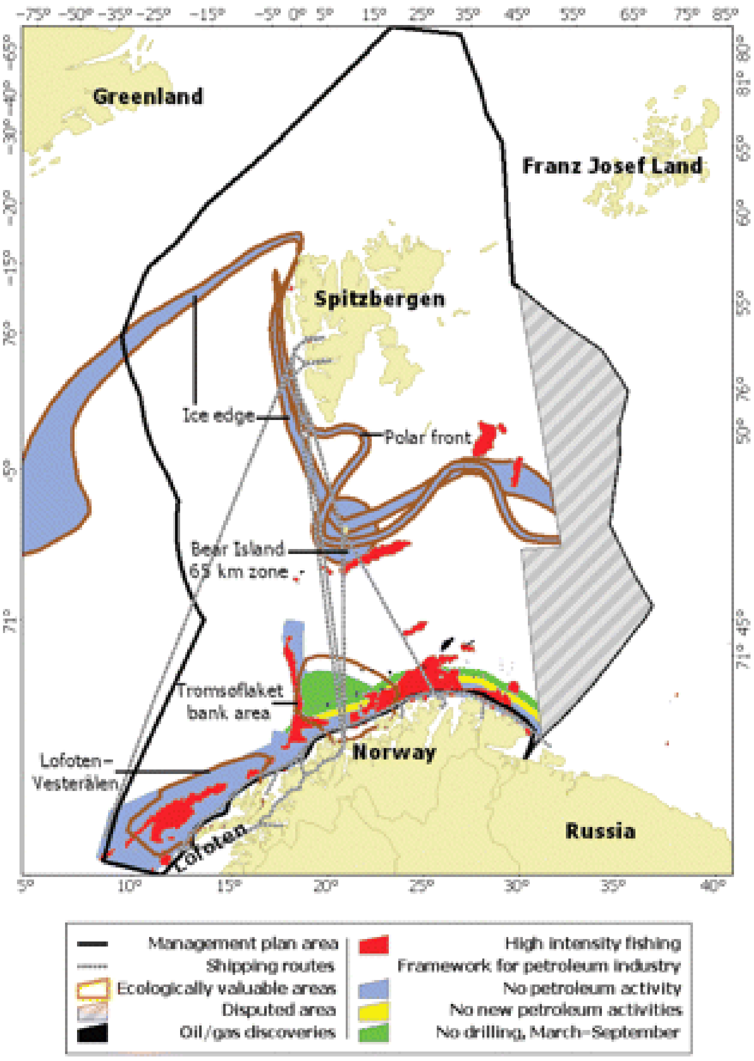


Figure 2 *Map showing the area covered by the Norwegian ecosystem-based management plan for the Barents Sea. It shows main fishing areas, shipping lanes and framework for hydrocarbon extraction (2006-2010), together with particular valuable and vulnerable areas (from Olsen et al. 2007, with permission from the author and Oxford Journals).*

2 Oil spill in the north

Several studies have documented effects of oil pollution on temperate marine ecosystems (e.g. Gomez & Dauvin 2005), and petroleum activities have also been monitored in these areas (Carroll 2000). However, our current knowledge of effects of oil spill and petroleum activities on marine ecosystems at high latitudes is much more scant. Most of what we know today comes from studies following the Exxon-Valdez oil spill in sub-Arctic Alaska (Peterson et al. 2003). The results point to many long term and unexpected negative effects of this accident on the Alaskan coastal ecosystem (Peterson et al. 2003). To date, no major oil spills have occurred in Arctic seas, and there is an urgent need for more studies to understand and predict risks and effects of pollution from oil in Arctic areas (Peterson et al. 2003). Whether organisms or communities in northern as opposed to more southern areas of the Norwegian continental shelf would respond differently to pollution from oil seems largely unknown.

There are several aspects of the environment which have important implications for the exploration, production and transport of petroleum in the Barents Sea and the associated potential for oil pollution in marine areas. There are a number of physical, chemical and biological processes that affect, change and degrade oil in cold waters, with (**figure 3**) or without ice cover (Sakshaug et al. 1994a, Gabrielsen & Sydnes 2009). For example, emulsions are formed due to wave action, while exposure to UV light and oxygen cause photo oxidation. In high latitude seas, oil degradation is likely to be slower than in temperate regions due to lower temperature, less light (in winter) and the presence of ice (Sakshaug et al. 1994a, AMAP 2007). Hence, there is an increased persistence of petroleum hydrocarbons in Arctic seas. Even the most volatile components will not escape from oil trapped under sea ice. Instead, many of them dissolve in sea water and become toxic for the marine flora and fauna (Sakshaug et al. 1994a, Gabrielsen & Sydnes 2009). Furthermore, extensive ice cover, low temperatures, darkness (in winter) and very limited infrastructure in this remote area make clean-up operations in case of an accident more difficult (Sakshaug et al. 1994a, AMAP 2007). However, burning of oil (i.e. one way to remove oil) in cold ice-free waters may not be more difficult because of slower evaporation of highly inflammable volatile components at low temperatures (Gabrielsen & Sydnes 2009). Oil-eating bacteria may also be of use in clean-up operations, provided there are enough nutrients in the water (Sakshaug et al. 1994a). Harsh weather conditions (strong wind and high waves) in the Barents Sea leads to high risks of oiling incidents and make oil removal difficult, though it should be remembered that the Norwegian Sea also experiences very harsh weather, and thus should face similar problems in this respect.

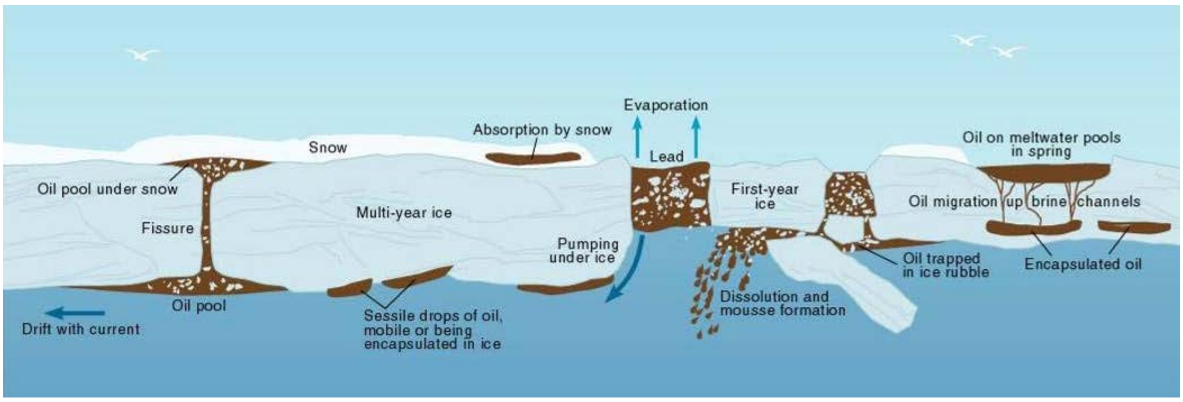


***Figure 3** Different behaviours of oil in ice-covered sea water (AMAP 2007, with permission).*

3 Are northern Norwegian marine ecosystems different from more southern ones?

An important question when assessing if northern Norwegian marine ecosystems (Lofoten-Barents Sea area) are more vulnerable to impact from oil activities than more southern ones (Norwegian Sea, North Sea) is whether the ecosystems of these areas are much different. This is certainly a very broad and complex question. We will briefly address some central aspects below, by reviewing suggested differences and similarities, as well as gaps of knowledge.

3.1 Oceanography

An overview of the physical oceanography of the Barents and Norwegian Seas is provided by Loeng and Drinkwater (2007). The Barents Sea has an average ice cover of ca 40%, though this varies extensively with season. It is lowest in August/September and highest in March/April. The southern part of the Barents Sea is characterised by warmer (3-6 ^{o}C) Atlantic surface water, which is more saline and nutrient rich than the northern cold (<0 ^{o}C) polar water from the Arctic. In summer, a layer of melt water overlays the polar water. Water of the mixing zone is called Arctic water and is delimited to the north-west by the polar front and to the south by the Arctic front. In the Norwegian Sea and the Barents Sea, Atlantic water is carried northwards with the Norwegian Atlantic Current. The upper layers of the Norwegian Sea is dominated by this Atlantic water, apart from on the Norwegian shelf where coastal water of lower salinity and seasonally varying temperature is transported by the Norwegian Coastal Current to the north.

The Barents Sea is a shelf ecosystem situated at the border between the Arctic and North Atlantic Oceans where water moves from the North Atlantic into the deep Arctic Ocean basin. From an Arctic Ocean perspective, the Barents Sea is a highly productive, deep, inflowing shelf sea (Carmack & Wassmann 2006). Compared to the other North Atlantic shelf ecosystems, however, the Barents Sea has relatively low productivity and low biodiversity (Frank et al. 2007). The major reason for the low average primary production is the vast areas north of the polar front which are covered by a seasonal and highly variable ice-cover. In these areas, primary production is generally low, but ice melting during summer stratifies the water masses and initiates a concentrated, short-lived phytoplankton bloom that supports high concentrations of zooplankton. These areas are targets for the northbound feeding migrations of capelin (*Mallotus villosus*), cod (*Gadus morhua)*, seabirds and marine mammals in late summer and early autumn. Thus, compared to the North Sea, the northern Barents Sea is characterized by a more short-lived, intense and spatially concentrated pulse of biological activity.

3.2 Productivity & food webs

Both the Barents Sea and the Norwegian Sea are highly productive areas. The most important group of phytoplankton in both the Norwegian and the Barents Sea is diatoms. The primary production varies considerably spatially and with season. In the Barents Sea the annual production varies between ca 20 and 200 g C m^{-2}, and is on average ca 60 g C m^{-2}, with the highest values in the Atlantic water (Sakshaug 1997, Loeng & Drinkwater 2007). The primary production of the Norwegian Sea is in general higher than in the Barents Sea (Sakshaug et al. 2009). However, the overall mean primary production of the Barents Sea has been suggested to be relatively similar to that of the Norwegian Sea (80-90 g C m^{-2}) (Loeng & Drinkwater 2007). In both the Barents Sea and the Norwegian Sea, zooplankton, especially *Calanus* spp. copepods, are numerous and act as an important link between phytoplankton and higher trophic levels. Hence, there does not seem to be very large differences in the base of the food web between the two seas.

The Barents Sea is a relatively simple, low-diversity system compared with, for example, the North Sea (Frank et al. 2007). The food web is thus relatively simple in the Barents Sea (Sakshaug et al. 1994a). Nevertheless, the length of the food chain seems to be rather similar in the Barents, Norwegian and North Seas. In an attempt to compare the different trophic levels in the Norwegian and Barents Seas, Loeng and Drinkwater (2007) assessed the biomass, productivity and consumption at different trophic levels of these regions. They found, for example, that zooplankton, pelagic fish and squid had higher biomass in the Norwegian Sea than in the Barents Sea, while marine mammals and seabirds had higher biomass in the Barents Sea.

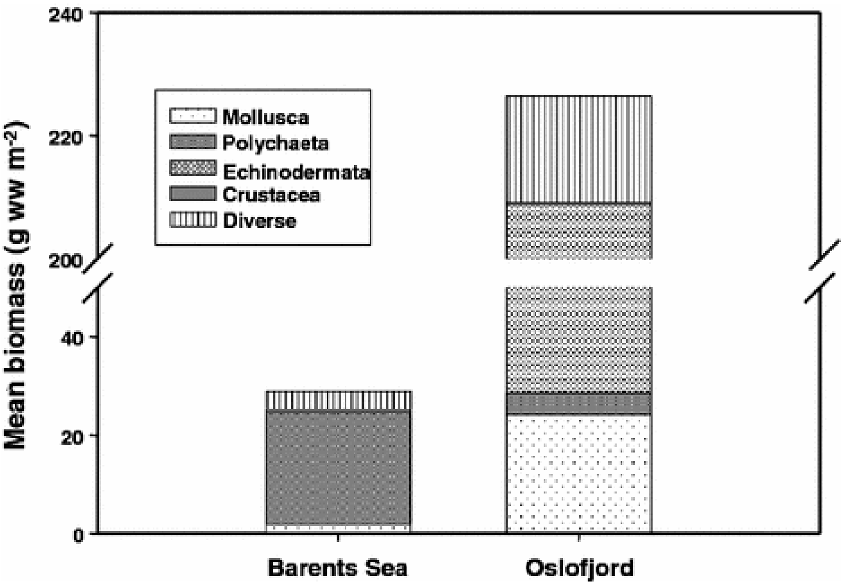
Studies of the Barents Sea ecosystem have provided clear examples of top-down control, with predators (fish) controlling lower trophic levels (zooplankton), while there are few convincing parallels from the well-studied North Sea (Reid et al. 2000). This is in line with studies suggesting that top-down control dominate in northern marine ecosystems while bottom-up control seems to govern predator-prey dynamics in southern areas (Frank et al. 2007). Trophic cascades are defined by top-down control and the propagation of indirect effects between nonadjacent trophic levels. Northern top-down control ecosystems seem particularly vulnerable to seemingly irreversible trophic cascades if top predators are removed, which can lead to complete restructuring of the food web (Frank et al. 2005). An example of this is the once cod-dominated northwest Atlantic ecosystem, where the collapse of the cod population have led to seemingly irreversible changes in the food web and the cod is now unable to recover, despite several management measures (Frank et al. 2005). Similarly, the collapse of the top predator cod in the Baltic Sea have led to trophic cascades and threshold-like shifts in this ecosystem, where an increased abundance of the cod’s prey, the planktivorous sprat (*Sprattus sprattus*) now hinders cod recruitment and recovery (Casini et al. 2009). Many marine ecosystems exhibit a ‘wasp-waist’ structure like this, where one or a few small planktivorous fish species (e.g. sprat) dominate their trophic level, and the radical variability of these fish populations propagate to both higher and lower trophic levels (Bakun 2006). All the Nordic seas exhibit features of this, with large stocks of a few pelagic planktivororus fish species.

There are also important examples of bottom-up effects in northern Norwegian areas, like diminishing fish populations leading to drastic declines in seabird populations (e.g. Anker-Nilssen et al. 1997, Barrett et al. 2006, Sandvik et al. 2005). This has clearest been demonstrated for the populations of Atlantic puffin (*Fratercula arctica*) at breeding in Røst, Lofoten Islands, northern Norway. Following the collapse of the Norwegian spring-spawning herring (*Clupea harengus*) stock in the late 1960s, the puffin population in Røst has declined from about 1.4 million pairs in 1979 to around 400,000 pairs (Anker-Nilssen 1992, Anker-Nilssen et al. 1997, Anker-Nilssen & Aarvak 2006). The survival rate of adult puffins in Røst does not differ from those in stable or increasing colonies (Harris et al. 2005), but their reproductive success is strongly linked to the availability and quality of first-year (0-group) herring in the colony area in summer (Durant et al. 2003). Recent studies of other seabirds have also documented complex food web interactions, for instance between black-legged kittiwakes (*Rissa tridactyla*) and their prey species in the Barents Sea (Anker-Nilssen et al. 1997, Barrett 2007, Sandvik et al. 2005).

3.3 Benthic communites

Spatial patterns of benthic diversity have been studied in areas along the Norwegian continental shelf (56-71 ^{o}N), from the North Sea in the south, through the Norwegian Sea, to the Barents Sea in the north (Ellingsen & Gray 2002). There was no latitudinal gradient in diversity of soft-sediment macrobenthos, but there was large variability between sites. In another study, where Arctic (Barents Sea) and temperate (Oslofjord) benthic communities were compared, several differences were found (Olsen et al. 2007). Both the infaunal abundance and biomass were considerably higher in Oslofjord compared to Barents Sea sediment cores (**figure 4**). The number of species was also higher in cores from the Oslofjord (101) as compared to those from the Barents Sea (65). Furthermore, looking at the five most abundant species, species composition differed between the areas, although deposit feeders dominated in both areas. In the Barents Sea, the benthic community was dominated by polychaetes, while it was dominated by large echinoderms in the Oslofjord (**figure 4**). Greater faunal activity in the surface layer of sediment from the Oslofjord, and a high abundance of large echinoderms, probably means that bioturbation (mixing of the sediment) is higher there than in the Barents Sea (Olsen et al. 2007).

Studies have found evidence of strong pelagic-benthic coupling of biological processes in ice free Arctic regions (Ambrose & Renaud 1995, Cochrane et al. 2009). This implies an efficient transfer of carbon from water column to benthos (Ambrose & Renaud 1995).



***Figur 4** Mean biomass of main faunal groups in sediment cores from the Barents Sea and the Oslofjord (from Olsen et al. 2007, with permission from Springer-Verlag).*

Whether benthic communities from Arctic and temperate regions of the Norwegian continental shelf respond differently to pollution from oil was addressed in an experiment by Olsen et al. (2007). They looked at the response of benthic communities (field-collected cores) from the Barents Sea and the Oslofjord to petroleum compounds, by assessing the effects of crude oil and drill cuttings on sediment oxygen demand (SOD). SOD rates have been widely used to assess benthic community processes, and respiration rates can indicate the physiological state of organisms and hence be used as a health index in toxicity studies.

Field cores of sediment from the benthic community of the Barents Sea responded to petroleum compounds by having higher SOD than cores in the control treatment, i.e. oil led to enhanced respiration rates. This was not the case in the temperate area, where SOD did not differ between treatments. Hence, the benthic community response to petroleum-related compounds clearly differ between sites in the Arctic and temperate regions, being strong only in the Arctic. The authors suggest that this difference in response could be explained by differences in community structure (see above) or sensitivity of individual taxa to petroleum-related compounds (Olsen et al. 2007). Polychaetes, the group with highest biomass in Barents Sea cores, are particularly sensitive to contaminants and accumulate petroleum compounds more than other groups (Nipper & Carr 2003, Ruus et al. 2005). In Oslofjord cores, echinoderms and molluscs (mainly bivalves) dominated the biomass. Bivalves seem less sensitive to petroleum compounds than other groups (Neff et al. 1976). Other explanations for the difference in response between Arctic and temperate areas could be differences in temperature, and different contamination history of the study areas, where the more contaminated Oslofjord area may have led to organisms being more tolerant than in the more pristine Barents Sea (Olsen et al. 2007).

3.3.1 Cold water corals

In recent years it has been acknowledged that Norway harbour some of the world's largest aggregations of cold water corals (CWC) (**figure 5, figure 6**). As late as in 2003 the (so far) largest reef in the world was discovered just south of Lofoten, the Røst reef, covering ca 100 km^2. These large reef complexes are mainly built up by the scleractinian coral *Lophelia pertusa*, creating three-dimensional structures that function as habitat and refuge for a large number of species. Over 1300 species has been identified in association with CWC reefs in the northeast Atlantic, a number that is similar to the biodiversity of tropical coral reefs (Roberts et al. 2006). Despite the large size these structures can attain, the reef grows very slowly, increasing in size only approximately 1-2 mm/year (Mortensen 2000). However, they become very old. The Sula reef located in central Norway has been dated to approximately 8600 years old (Hovland et al. 1998).

As opposed to their shallow water relatives, CWC do not host any symbiotic algae but gather their food as predators or suspension feeders. The corals can be found in a wide depth range (ca 40-3600 m) but are in Norwegian waters mainly found between 200-600 m. At these depths the temperature and salinity are usually stable throughout the year, although temperature declines slightly northwards.

The existence of CWC in the northern Norwegian areas has been known for centuries and large occurrences are documented up to Finnmark (71 °N). Much of the mapping has taken place in recent years through MAREANO (www.mareano.no) (**figure 5**), and new occurrences are continuously being discovered.

The physical habitat for CWC is much the same in the north as in the south, although slightly colder, but the temperature difference is within the tolerance range for the species. It is unknown whether CWC are more sensitive to human activity in the northern areas than the southern, but the slow growth of the reefs means that any damage done to them will take a very long time to repair and repeated disturbance might lead to permanent destruction. Also the fact that the largest CWC reefs exist in the Lofoten area is important to take into consideration.

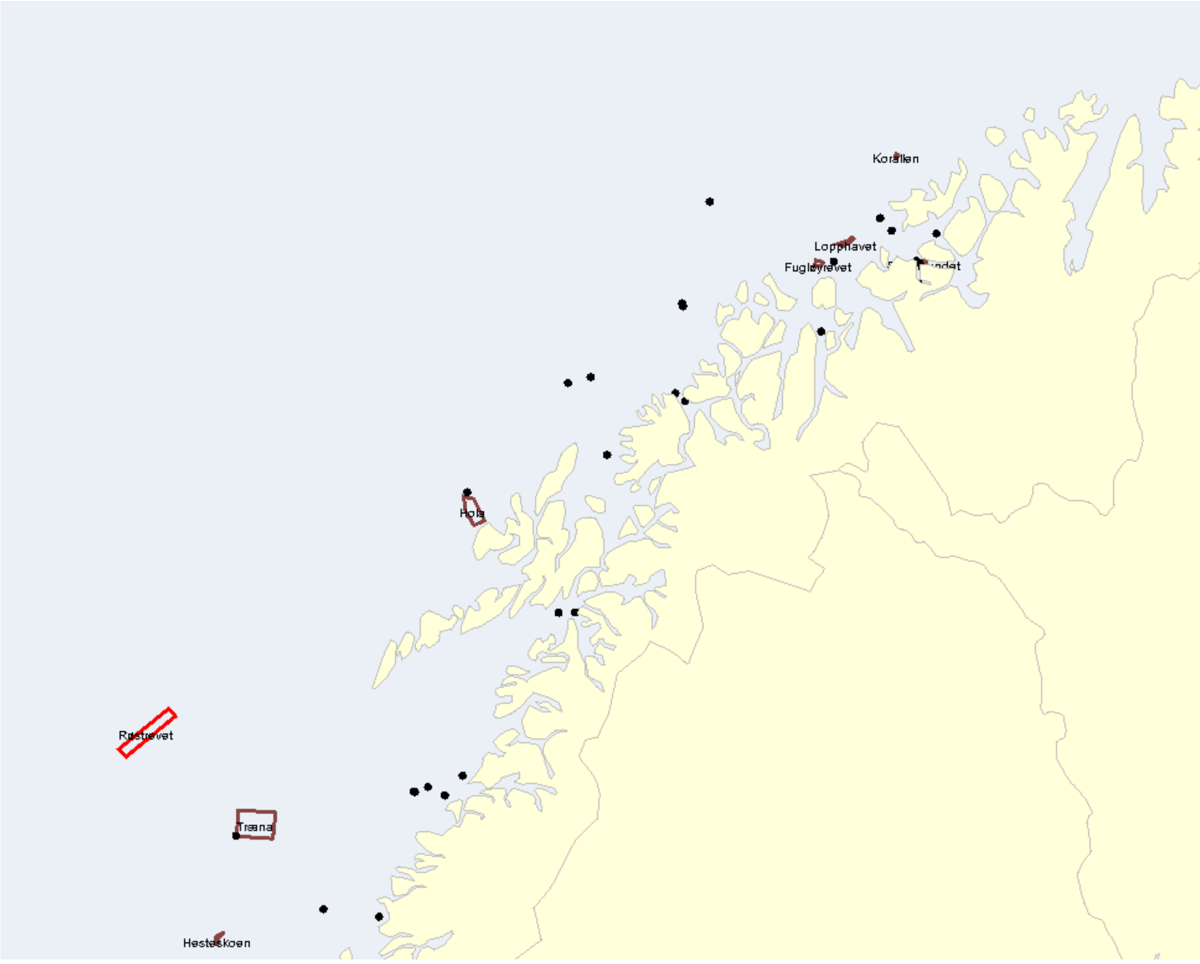


Figure 5 *Documented localities of cold water corals in northern Norway mapped by MAREANO (from the MAREANO website (www.mareano.no), with permission from the Norwegian Institute of Marine Research).*

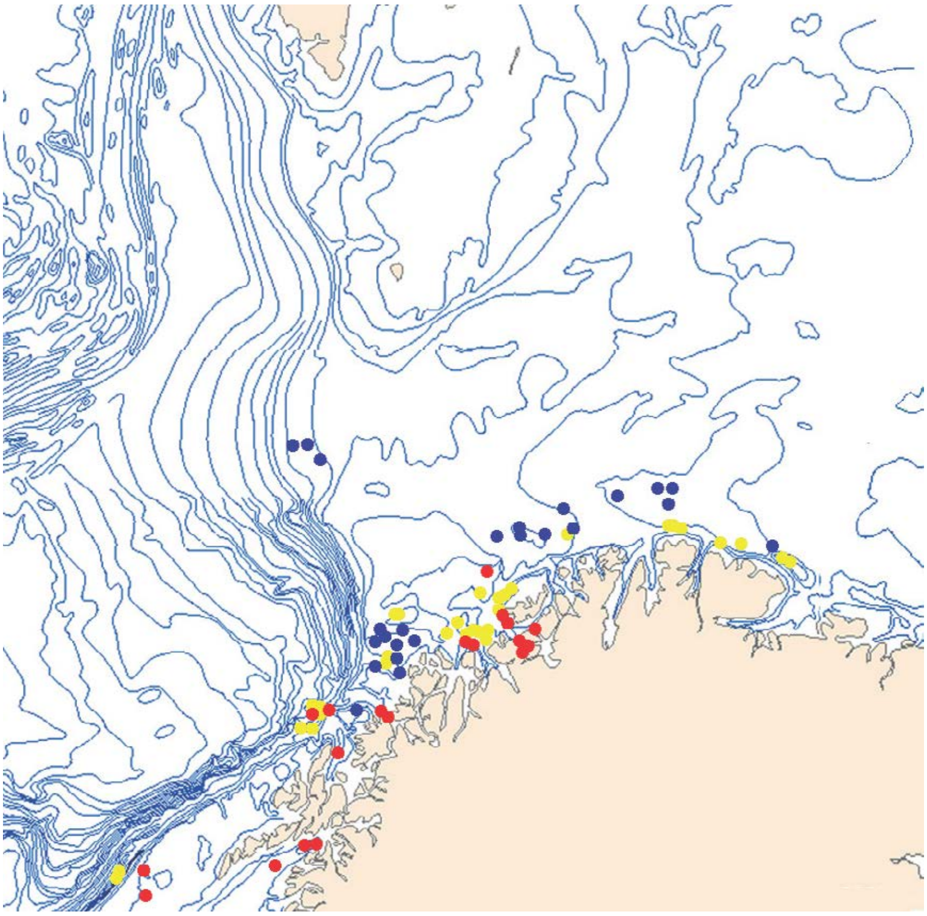


***Figure 6** Distribution of coral in the Barents Sea. Red symbols: Verified occurrences of* Lophelia pertusa*. Yellow: Occurrences of* L. pertusa *indicated by Norwegian fisheries. Blue: Occurrences of corals indicated on Russian fishery maps. (from Mortensen 2005, with permission from the Norwegian Institute of Marine Research)*

3.3.2 Sponge communities

Although even less studied than the coral reefs, both regarding biology and distribution, deep-living sponges dominate the biomass in parts of the Barents Sea (Ereskovsky 1995). This primitive group of organisms can be found on all types of sea bottom and in all geographic and bathymetric regions. They can attain sizes from a few millimetres up to meters in diameter, and create three-dimensional structures on the bottom that attracts other fauna by supplying hard substrate, refuge or enhanced food supply. Sponge communities, much like the coral reefs, create habitats for other species and thereby contribute to increase local biodiversity (Bett & Rice 1992). About 250 invertebrate species have been found in association with sponge communities in the Faroes (Klitgaard 1995).

As with the CWC, sponges are slow-growing organisms. No exact ageing has been done so far, but investigations suggest that they can live for over decades or centuries (Dayton 1979; Gatti 2003).

Tromsøflaket in particular has large occurrences of sponges, registered through trawl-surveys by the Norwegian Institute of Marine Research (IMR) (**figure 7**) and MAREANO mapping. Like CWC, the sponges live at depths where the physical environment is stable through the year but with a slight decrease in temperature with latitude. As for CWC, the slow growth of the sponges mean that any damage done to them will take a very long time to repair and repeated disturbance might lead to permanent destruction. The fact that large sponge communities are unique to this area is important to take into consideration.

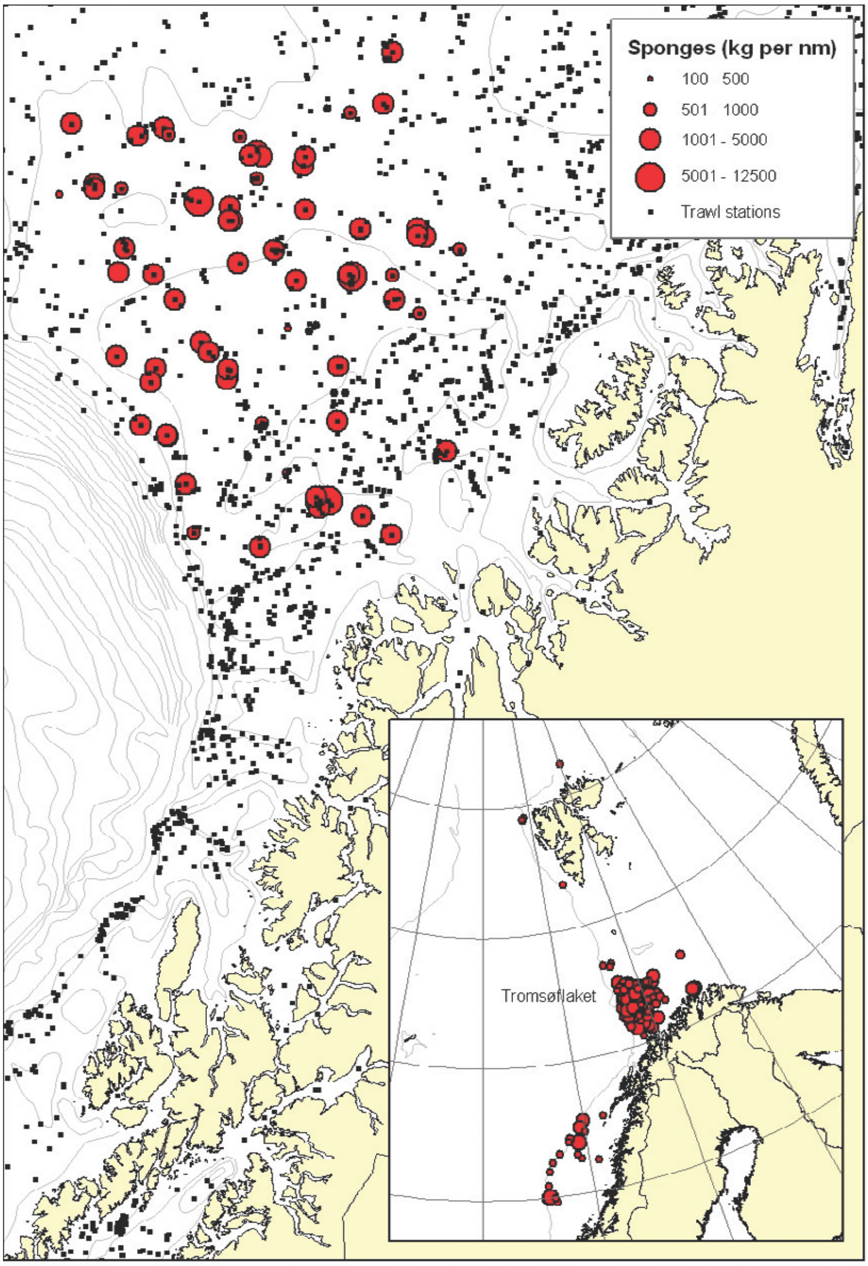


Figure 7 *Sponge by-catch by demersal trawl in survey by Institute of Marine Research (from Mortensen 2005, with permission from the Norwegian Institute of Marine Research).*

3.4 Important fish stocks

There are commercial fish stocks of major importance in both the Norwegian Sea and in the Barents Sea. The Norwegian Sea is characterised by migratory pelagic species, Norwegian spring-spawning (NSS) herring, and blue whiting (*Micromesistius poutassou)*. The Barents Sea has both important pelagic species (e.g. capelin, immature NSS herring and polar cod, *Bore-*

ogadus saida) and demersal species (e.g. North-East Arctic (NEA) cod, and haddock, *Melanogrammus aeglefinus*). Both cod and herring have important spawning areas in the Lofoten and Vesterålen area (**figure 8**). The fish larvae drift northwards with the Norwegian Coastal Current out of the Norwegian Sea and into the Barents Sea where they stay until they have become larger (herring, ca 3 yrs) or sexually mature (cod, ca 6-8 yrs). Capelin has a more northern distribution and mainly stays within the Barents Sea for its whole life (from Vesterålen and northwards) (**figure 8**).

The Lofoten-Barents Sea area has some of the most valuable fish stocks of the Atlantic Ocean, and is one of the world's most important fishing areas. Economically, the NEA cod is the most important (Hjermann et al. 2007b). The Lofoten-Barents Sea area holds the largest remaining stock of Atlantic cod and likely also the world's largest capelin stock (Gjøsæter 2009). The large commercial fish stocks in the Barents Sea occur mainly in water masses of Atlantic origin, though capelin feed near the ice edge in summer. Capelin plays a major role in the Barents Sea ecosystem as food for cod, seabirds and marine mammals. Cod is an important predator in both the Norwegian and the Barents Sea, while NSS herring is a key species in the Norwegian Sea. These three species (capelin, cod, herring) are strongly interlinked through processes of predation, competition, and cannibalism (Hjermann et al. 2007a,b).

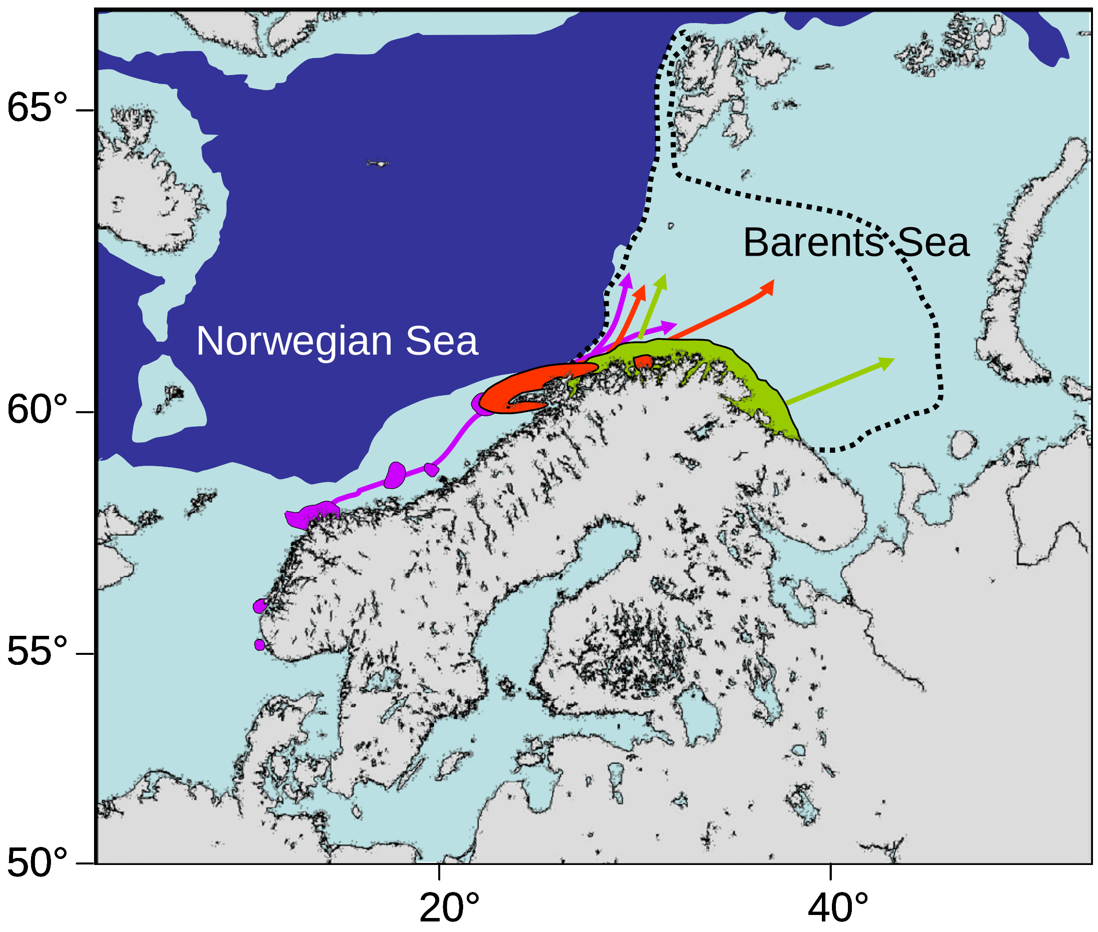


***Figure 8** Map showing spawning locations and advection routes of eggs and larvae of three fish stocks: North-East Arctic cod (red), Norwegian spring-spawning herring (purple), and Barents Sea capelin (green). The dotted line indicates maximum extension of these species in the Barents Sea in the first summer after spawning. Light blue: continental shelf (<250 m), dark blue: deep sea. (after Hjermann et al. 2007b, with permission from the author and Inter-Research)*

3.5 Seabirds

The high productivity of Norwegian waters supports large numbers of seabirds, both during the breeding season and throughout the rest of the year. Approximately six million pairs of sea-birds breed along the coastal mainland of Norway and on Svalbard (Bakken et al. 2006, Barrett et al. 2006). The distribution of breeding sites along the Norwegian coast is, however, very un-even (**figure 9**). Approximately 75% of all Norwegian seabirds are breeding on Svalbard and the mainland coast of the Barents Sea, while another 20% breed along the Norwegian Sea (Bakken et al. 2006, Barrett et al. 2006), whereas less than 5% breed in the North Sea area (south of 62° N).

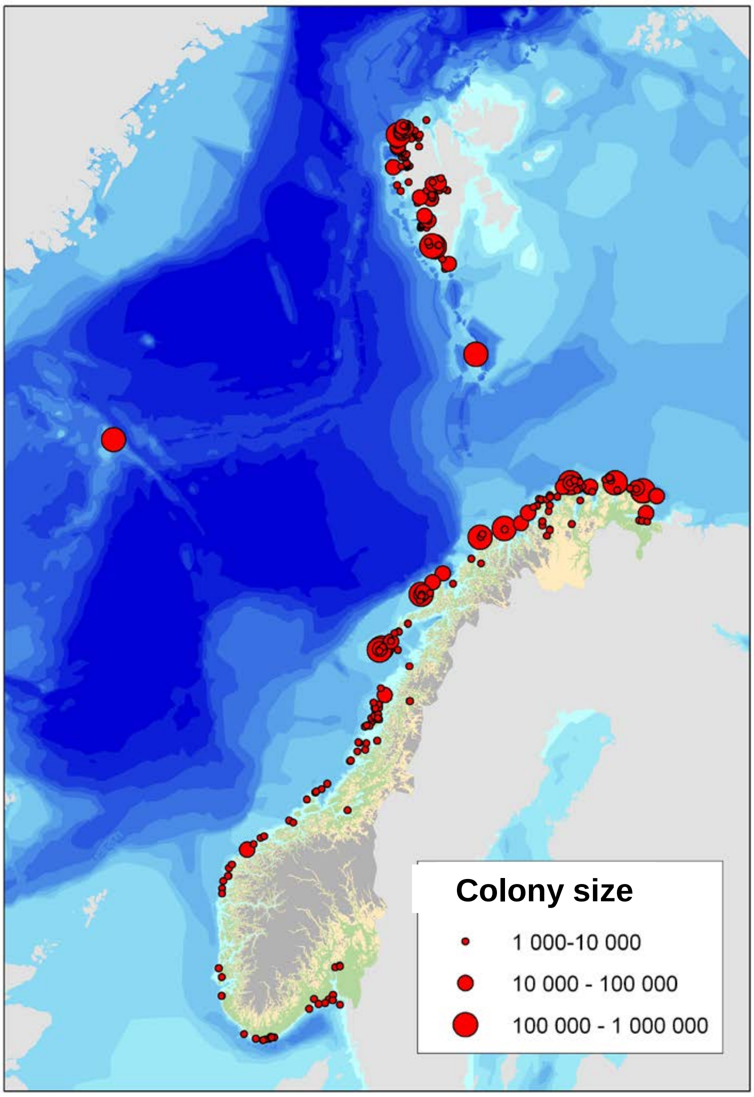


Figure 9 *The distribution of seabird colonies along the Norwegian coast and Svalbard. The size of circles reflects colony size. (from Norwegian Polar Institute / NINA)*

Breeding behaviour and feeding characteristics of seabirds in Norwegian waters change over a north-south gradient. With some exceptions, all the large colonies of cliff-nesting species are situated north of the Arctic Circle. The seabird communities of the Barents and Norwegian Seas are dominated by pelagic-feeding species comprised mainly of diving (mostly auks) and surface-feeding birds (mostly black-legged kittiwakes and fulmars) breeding in large colonies (Bakken et al. 2006, Barrett et al. 2006), whereas coastal species dominate the smaller communities in the south (**table 1**) (Barrett et al. 2006).

Table 1 *The proportion (%) of seabirds in different ecological groups according to their feeding characteristics (area and behaviour) shown for each of the four marine eco-regions of the Norwegian coast (Barrett et al. 2006) and Svalbard (% calculated from estimates in Bakken et al. (2006)).*

Feeding characteristic	Svalbard	Barents Sea	Norwegian Sea	North Sea	Skagerrak
Pelagic surface-feeding	33	18	7	6	<1
Pelagic diving	65	67	64	11	0
Coastal surface-feeding	<1	10	18	50	84
Coastal diving	<1	3	4	4	<1
Coastal benthic-feeding	<1	2	8	30	15
Total	100	100	100	100	100

Seabird life histories are characterised by high annual survival and low fecundity (Weimerskirch 2002), but the pelagic species generally have smaller clutches and higher survival than those feeding in coastal areas (Schreiber & Burger 2002). Coastal species therefore most often have a higher reproductive potential, one component explaining the generally lower vulnerability of populations in southern areas compared to those further north.

3.6 Distribution & variability of populations

It is clear that the Barents Sea is subjected to dramatic variability in a number of environmental factors over different time scales, which strongly affect the conditions for marine life. Light conditions change seasonally from a long period of darkness in winter to continuous light in the summer months. Likewise, there is large seasonal variation in ice cover. The circulation patterns change between years, partly following the oscillations of the NAO (North Atlantic Oscillation) and AO (Arctic Oscillation) (e.g. Stenseth et al. 2004). In some years the inflow of nutrient-rich, warm, saline Atlantic water is much larger than in other years. Such events highly influence the productivity in the area.

An important question is whether there is larger variation in population size of organisms in the Barents Sea, than in temperate areas. It has been suggested that fish stocks do not reach a ‘steady state’ but fluctuate considerably, with best growth in years with a high influx of Atlantic water and high zooplankton productivity, followed by stock reductions or collapses in ‘cold’ years (Sakshaug et al. 1994b, Sakshaug 1997). Capelin, for example, shows extreme fluctuations in abundance between years (Sakshaug et al. 1994b, Loeng & Drinkwater 2007, Hjermann et al. 2004a). Recent work also point to the importance of other factors than Atlantic water influencing these complex dynamics, as in the case of the capelin, where overexploitation and predation by other fish is important (Hjermann et al. 2004a,b). Whether Arctic populations actually vary *more* than temperate ones, seems less well documented, and the Norwegian Sea ecosystem is certainly also highly variable. For example, the recruitment of herring, a key species of the system, shows large fluctuations between years, partly due to climatic conditions (Toresen & Østvedt 2000, Fiksen & Slotte 2002). The North Sea ecosystem is also characterized by large variation. Recent changes in the plankton community has largely been related to climate forcing, particularly changes in the strength of westerly winds that affect local climate as well as the inflow of oceanic water into this semi-closed ocean basin (Edwards et al. 2002, Reid et al. 2003, Beaugrand & Ibanez 2004, Alheit et al. 2005). An abrupt change in climate in the 1980's has been found to be associated with a shift in the recruitment of a number of fish species and changes in the plankton community, suggesting that a climate driven regime shift took place in this period (Beaugrand & Ibanez 2004, Alheit et al. 2005, deYoung et al. 2008). Thus, although some top-down forced changes have been suggested (Reid et al. 2000; Maes et al. 2005), most studies suggest that the North Sea system is mainly driven by bottom up forces through climate (Aebisher et al. 1990, Frederiksen et al. 2006).

Climate variability and the seasonality of the Barents Sea lead to very large differences in distribution of many species. Seasonal migrations and aggregations of many animals occur. These include marine mammals gathering in open water areas in the ice, sea birds at breeding or feeding sites, and fish spawning migrations (e.g. Loeng & Drinkwater 2007). Additionally, advection, currents and retention lead to large concentrations of fish eggs and larvae in certain areas of the Barents Sea (e.g. Hjermann et al. 2007).

3.7 Species diversity

In the North Atlantic, northern areas have lower species richness than more southern ones, and species diversity decreases with both decreasing ocean temperature and higher latitude (Frank et al. 2006, 2007). This fits with the general pattern of declining biodiversity with latitude across different environments (Hillebrand 2004). Marine biodiversity seems to be related to whether the ecosystem becomes relatively more dominated by top-down or bottom-up processes and, as mentioned above, top-down control is more common in northern marine ecosystems (Frank et al. 2007). Ecosystems dominated by top-down control have been suggested to represent a form of biological instability, where regime shifts, or 'quasi-permanent' ecosystem changes, can be induced by depleting large predators (e.g. by overfishing) (Strong 1992, Frank et al. 2007). Hence, southern areas are likely more resilient to effects of overfishing than northern areas.

3.8 Other stressors

If organisms already are stressed from various natural or human-induced perturbations in the environment, it is likely that any additional stressor could be especially difficult to handle. The final descent to extinction is often driven by synergistic processes (amplifying feedbacks) that can be disconnected from the original cause of decline (Brook et al. 2008). Examples of such synergistic effects can be those caused by climate change, eutrophication and overexploitation. Here we briefly mention some examples of such stressors that may influence how marine ecosystems are able to cope with increased pollution from oil.

Other pollutants
The Barents Sea is by no means heavily polluted, and concentrations of heavy metals and Persistent Organic Pollutants (POPs, which include PCB, DDT and brominated flame retardants) are generally lower in the Arctic than in temperate regions (Gabrielsen & Sydnes 2009). The concentration of POPs in low-level trophic animals are lower here than in the Norwegian

Sea (Gabrielsen & Sydnes 2009). Despite this, some animals living here show surprisingly high levels of some contaminants, as a result of pollutants being transported over long distances. POPs are relatively resistant to biodegradation and are bioaccumulated and biomagnified in the lipid-rich Arctic food web (Gabrielsen & Sydnes 2009). They pose a risk to marine organisms, especially to top-trophic marine mammals. These contaminants can be particularly problematic in Arctic marine mammals because of these animals' seasonal accumulation/cycling of lipid stores (Gabrielsen & Sydnes 2009). Marine mammals in the area have been found to have levels of contaminants that are over the threshold of what is thought as being safe with respect to the animal's health, like in polar bears. Especially cubs show high levels, presumably due to lactation (Gabrielsen & Sydnes 2009). Also seabirds that feed at the top of the food chain have shown to be adversely affected by accumulating high levels of such contaminants (Bustnes et al. 2003, Sakshaug et al. 2009).

Climate change

Future climate change (global warming) is expected to be amplified in northern high latitudes, with warming most pronounced over the Arctic Ocean (Graversen et al. 2008, Serreze et al. 2006, Moritz et al. 2002). Climate change can impact the pattern of biodiversity through species' distributions. Species invasions are projected to be most intense in the Arctic and the Southern Ocean, implying future ecological disturbances (Cheung et al. 2009). In addition, associated with increasing atmospheric CO_2, significant ocean acidification (i.e. decreasing pH) occurs and is likely to have detrimental effects on marine organisms (Dupont et al. 2008, Vézina & Hoegh-Guldberg 2008). Ocean acidification is predicted to be more rapid and affect cold seas (Arctic, Antarctic) to a greater extent due to higher dissolvability of CO_2 in cold water and lower buffering capacity. The largest changes in pH worldwide are predicted to occur in Arctic surface waters, with potentially large implications for marine ecosystems (Steinacher et al. 2009).

Fishing

Currently, the major commercial fish stocks in the Barents Sea are harvested sustainably. According to the ICES criteria (ICES 2008a) the stocks of NEA cod, NEA haddock, northern shrimp (*Pandalus borealis*) and capelin have full reproductive capacity and are harvested within sustainable limits. However, the stocks of NEA Greenland halibut (*Reinhardtius hippoglossoides*), golden redfish (*Sebastes marinus*) and deep-sea redfish (*S. mentella*) have as a consequence of high historic fishing pressure been fished down to very low levels. These threatened species are long-lived and have low potential growth rates. Although the fisheries at present are strongly regulated, the rebuilding of these stocks will take many years. Norwegian coastal cod is of special concern. The spawning stock biomass and recruitment are at historically low levels, and according to the ICES advice, no catch should be taken from this stock in 2009, and a recovery plan should be developed and implemented. In contrast to the Barents Sea, the North Sea is one of the most heavily fished marine ecosystems in the world, with a fishing mortality that is currently above what is considered to be optimal for many of the exploited stocks (ICES 2008b). The spawning stock biomass (SSB) of Atlantic cod has for example declined from a maximum of 253,000 metric tons in 1971 to 50,000 tons in 2008 (ICES 2008b). Fishing mortality has frequently been well above what is considered to be sustainable, and the spawning stock has been reduced to a level that most likely impairs its productivity (Horwood et al. 2006).

4 Vulnerability of northern Norwegian marine ecosystems to pollution from oil

4.1 Oil pollution and vulnerability of organisms

Discharges of oil to the sea from normal petroleum activities in the Lofoten-Barents Sea area have been suggested not to have any significant impact on the environment (Sakshaug et al. 1994a, von Quillfeldt et al. 2009). On the other hand, larger accidental oil spills could cause severe harm to the ecosystem (Sakshaug et al. 1994a, von Quillfeldt et al. 2009). Shipping is likely to involve a much higher risk for oiling incidents than exploration and production of oil in the Lofoten-Barents Sea (von Quillfeldt et al. 2009), but offshore blow-outs have the potential to cause immense damage in a single event. Possible consequences of year-round petroleum activities in the Lofoten-Barents Sea area have been addressed many places, for example, by the Norwegian Ministry of Petroleum and Energy (2002).

Compared to POPs, most oil compounds are so easily oxidized that they do not accumulate in Arctic food webs (Gabrielsen & Sydnes 2009). Nevertheless, oil pollution can significantly affect the environment, both through direct lethal effects and through long-term effects. Long term effects can result from chronic persistence of oil, delayed sub-lethal effects on populations (via changes in behaviour, decreased health, growth, viability and reproduction) as well as indirect effects through trophic interactions and cascades in the ecosystem (Peterson et al. 2003). After the Exxon-Valdez incident in 1989, there was high direct mortality of wildlife. For example, hundreds of thousands of animals, including sea birds and otters, and billions of salmonid and herring eggs died as a direct effect (Gabrielsen & Sydnes 2009, Peterson et al. 2003). In addition, many cases of unforeseen long term negative effects have been documented, and several of the affected populations have not yet recovered (Peterson et al. 2003). The finding that chronic, delayed and indirect long-term risks are profound needs to be taken into account when assessing ecological risks of oil in the marine environment.

The vulnerability of a species depends on a number of factors (e.g. von Quillfeldt et al. 2009). Species that show the following attributes are usually more vulnerable to perturbations in the environment than other species:

- highly specialised species (habitat, diet, nursery areas, etc)
- slow life history
- younger stages of an organism (eggs and larvae of marine animals)
- species unable to escape unfavourable conditions
- species living near the limit of its distribution
- species that are low in abundance, declining or limited to a small geographic area
- key stone species may not be more vulnerable, but deserve special attention due to their role in the ecosystem
- animals with hair or feathers are especially vulnerable to oil spill (loss of insulating capacity)

There are several characteristics of the Lofoten-Barents Sea region that should be kept in mind when assessing the vulnerability of this ecosystem to pollution from oil. An important aspect is that there is substantial geographic variation - certain areas in the Lofoten-Barents Sea region are much more productive than others, for example, the polar front, the ice edge, and polynyas. An oil spill at such localities could have very severe effects. Another aspect is that Arctic habitats are characterised by extreme seasonal change, driving extensive animal migrations at sea and on land. To a large extent, the seasonal patterns/aggregations of animals determine the vulnerability of the Lofoten-Barents Sea ecosystem (AMAP 2007). Hence, many species in the area are sometimes very concentrated, and therefore an oil spill at the wrong place at the wrong time could affect a substantial part of a population.

4.2 Vulnerability of certain animal groups

In the Lofoten-Barents Sea management plan, particularly valuable and vulnerable areas are identified (largely coinciding with the blue, yellow, and green areas in **figure 2**). The Norwegian Government has established objectives for species management in this area, which fit obligations in various international agreements (Stortingsmelding (Parliament's Report) no. 8, 2005-2006). It is beyond the scope of our report to provide a detailed vulnerability analysis of a range of marine species in the Lofoten-Barents Sea area. Nevertheless, below we review some aspects of vulnerability for some of the most of important groups of organisms living in the area (but note that we do not cover marine mammals), and lastly discuss some attributes of this ecosystem which may render them more vulnerable to pollution from oil. These suggestions are based on the north-south differences in marine ecosystems as outlined above (section 3), as well as on information regarding the distribution of species. Through searches on the ISI Web of Science we found only one study (Olsen et al. 2007) that directly assess whether northern Norwegian ecosystems respond differently to oil pollution than more southern ones. Hence, there is an urgent need for more studies testing whether these ecosystems function in different ways that make them more (or less) susceptible to oil pollution.

4.2.1 Benthic organisms

Sites of high benthic biomass in the Barents Sea seem to coincide with areas of high primary production, such as the marginal ice zone and the polar front (Gulliksen et al. 2009). The highest biomass is found around Bjørnøya (Bear Island) and on the banks, for example, Spitsbergenbanken (Gulliksen et al. 2009). In line with the general decline in biodiversity with latitude, benthic infauna biomass and biodiversity were found to be lower in the the Barents Sea as compared with in the Oslofjord (Olsen et al. 2007). However, another study did not find any latitudinal gradient in diversity of soft-sediment macrobenthos (Ellingsen & Gray 2002).

The significantly stronger response of soft bottom benthic communities from the Barents Sea to oil pollution, compared to communities in the Oslofjord (see section 3), may suggest that benthic communities in the Arctic are more vulnerable to this type of pollution.

Valuable species groups in the north include sponges and reef-building deep sea corals. These systems contain high biodiversity, primarily through providing habitat to a large number of other species. They are slow-growing organisms that become very old, making them particularly sensitive to disturbances. Damage to such systems will take a long time to repair, and continued disturbances can lead to permanent extinction. Sponges have their largest occurrences in the northern areas. Cold water corals do not seem more abundant in these northern areas, but the world's largest cold water coral reef has been found outside Lofoten.

4.2.2 Fish

Fish stocks such as cod and herring are close to their climatic limits in the Lofoten-Barents Sea, and have short, intensive spawning seasons and localised spawning areas. This should make them more vulnerable to perturbations, for example, from oil spills. On the other hand, commercial fish stocks in the Barents Sea seem to be relatively well managed and not overfished to the same extent as in the North Sea (ICES 2008 a,b), which should make them less susceptible to other stressors.

The fish life stages seemingly most sensitive to oil pollution are egg and larvae, and these become relatively concentrated along narrow advection routes in the Lofoten-Barents Sea area (Hjermann et al. 2007b). Some northern fish species (e.g. polar cod) spawn under the ice in winter and their eggs develop there. They hatch when the ice starts melting in the spring, a time when plankton blooms occur. In case of an oil spill where oil gets trapped under the sea ice, the eggs and larvae of these fish species might suffer substantially. Fish whose eggs are benthic and laid in relatively shallow waters (e.g. sandy/gravel bottom), which, for example, is the case for capelin and herring, should also be especially at risk (Hjermann et al. 2007b).

The consequences of an oil spill on fish populations in the Lofoten-Barents Sea depend on a large number of oceanographic (e.g. currents, wind) and ecological (e.g. spawning sites, natural mortality) factors (Hjermann et al. 2007b). We currently have limited knowledge of these factors, and in addition, they show a large degree of uncertainty and stochasticity. Hence, predicting the impact of an oil spill on fish populations is extremely hard (Hjermann et al. 2007b).

4.2.3 Seabirds

Seabirds are among the marine organisms that are most highly vulnerable to oil spills. This is mainly because they spend most of the time at the sea and are largely dependent on the marine environment for foraging. Furthermore, all age classes are at high risk, and only a few seconds of contact with heavier petroleum products or crude oil are likely to be fatal for an individual. The impact of oil on seabirds occur both through short-term acute exposure, toxic exposure through ingestion and long-term interactions with prey species affected by the oil spill (Peterson et al. 2003). Differences in individual vulnerability among seabirds reflect difference in factors such as area utilisation, breeding behaviour, foraging methods, and distribution at sea. Species that swim on the surface and dive for food (i.e. auks, marine ducks, loons and cormorants) will in general have the greatest potential for direct exposure to oil spills, whereas more mobile surface-feeding seabirds (i.e. gulls, gannets and petrels), which plunge from the air or feed from the surface while in flight, are less exposed (Anker-Nilssen 1987, Burger & Gochfeld 2002, Piatt et al. 1990). During the breeding season, seabirds that nest in large colonies of hundreds of thousands of individuals are particularly vulnerable to oil spills (Burger & Gochfeld 2002). On a longer timescale, the recovery from an oil spill will depend on the long-term interactions of prey species, and will therefore depend on feeding characteristics (Irons et al. 2000, Lance et al. 2001, Peterson 2001, Peterson et al. 2003). The overall vulnerability of the populations will be a function of their size and population trend, potential rate of recovery, proportion of population at risk and potential for immigration from other populations (Anker-Nilssen 1987, Williams et al. 1995).

When comparing the overall vulnerability of seabirds in northern Norwegian ecosystems to those in more southern ones, there are some apparent differences. First of all, the distribution of seabirds in Norway makes the Lofoten-Barents Sea area stand out as the most vulnerable in relation to oil spills. Considering that 75% of all Norwegian seabirds breed in the Lofoten-Barents Sea area (comprising the Norwegian mainland and Svalbard), and most seabirds here usually occur in high density aggregations, this area will be very vulnerable to an oil spill, particularly in the vicinity of the breeding colonies in summer or in important feeding, moulting or roosting areas. Diving species are generally more vulnerable to oil spills than the surface-feeding species. Moreover, pelagic species tend to have longer foraging ranges and utilise larger sea areas than coastal species. The feeding characteristics of the seabirds in the Lofoten-Barents Sea area, where about two thirds of all seabirds belong to pelagic diving species, therefore strongly contribute to make the area more vulnerable to oil spills.

Seabirds are in general adapted to life in a highly variable environment, and most species therefore have high adult survival and low fecundity. There are, however, differences in the potential for restitution between species. Pelagic seabirds, which are the most abundant of those breeding in the Lofoten-Barents Sea, typically have the highest survival and lowest fecundity rates and therefore the lowest potential for recovery. In general, the recovery of a population after an incident of high adult mortality will therefore be slower in the north compared to the south.

A further aspect of vulnerability is the distribution of species presently entered on the Norwegian Red List (Kålås et al. 2006). The largest colonies of the critically endangered common guillemot (*Uria aalge*) are found in the Lofoten-Barents Sea region. This is a species that is both highly vulnerable to oil spills and, probably from a combination of different causes, in risk of local extinction at the Norwegian mainland. An oil spill close to one of the colonies during the breeding season may have very large consequences. There is now increasing evidence that the birds stay within the region throughout most of the year. Furthermore, a large part of the European wintering population of Steller’s eider (*Polysticta stelleri*), which is red-listed as vulnerable (Kålås et al. 2006), spend the winter in the fiords of eastern Finnmark (Øien & Aarvak 2007). Likewise a large fraction of Europe’s winter population of king eider (*Somateria spectabilis*) is found in the Barents Sea (Svorkmo-Lundberg et al. 2006).

4.2.4 Food web / ecosystem aspects

High latitude areas, like the Lofoten-Barents Sea region, have lower biodiversity than regions further south, and top-down control seem more common in such northern marine ecosystems (see section 3). Ecosystems dominated by top-down control have been suggested to represent a form of biological instability, where regime shifts, or ‘quasi-permanent’ ecosystem changes, can be induced by depleting large predators (e.g. by overfishing) (Strong 1992, Frank et al. 2007). Hence, southern areas are more resilient to, for example, effects of overfishing than northern areas. Interestingly, and related to this, experiments manipulating marine species diversity found that increased diversity enhanced ecosystem stability, defined as the ability to withstand recurrent perturbations (Worm et al. 2006). This was linked to increased resistance to disturbance or to enhanced recovery afterwards. A large scale comparison of long-term trends in regional biodiversity in marine systems confirmed this. Systems with higher species richness appeared more stable, showing lower rates of collapse and extinction of commercially important fish and invertebrate taxa over time (Worm et al. 2006). Increased stability and productivity are likely explained by a more diverse array of species providing a larger number of ecological functions. Thus, this may suggest that northern marine ecosystems are particularly vulnerable to human impact and disturbances because of lower species richness.

5 Conclusions

The impact of oil spill on the ecosystem is extremely hard to predict (Hjermann et al. 2007b). It depends on a large number of factors, including for example, weather, light and ice conditions, currents, timing and locality, as well as a variety of ecological factors. Moreover, we need more knowledge on both the direct and long-term toxicological effects of oil-related compounds on organisms. Also, some organisms are already under pressure from other stressors. Another problem making it hard to foresee effects on the ecosystem level is that not only direct effects are expected but also many indirect effects, some of which might cause trophic cascades. High latitude ecosystems have a lower biodiversity than lower latitude ones, i.e. they are less complex. Biodiversity has been suggested to affect how well ecosystems can resist and recover from perturbations, where species rich areas are more resilient and better able to withstand perturbations (Worm et al. 2006). So far, no major oil spill incidents have occurred in high Arctic seas, and hence we have little knowledge of the ecological effects of such incidents. Nor do we have any experience of cleaning-up operations in these regions, which are likely to be more difficult due to cold temperature, darkness (winter) and ice.

The Lofoten-Barents Sea area has marine life of significant international importance. It is home to a wide range of valuable marine species, some of which are unique to this region. The variety of organisms spans from large cold water coral reefs, to seabird colonies and polar bears. It also holds some of the world‘s most commercially important fish stocks. The ecosystem faces extreme variation in light over the year, which highly affects the production. There is also large variation in production between areas within the region. There can also be large concentrations of fish larvae in certain areas due to advection. Some species living here, for example capelin, show extreme fluctuations in population size between years. Some species are probably not so vulnerable to pollution from oil while others are very vulnerable, like most sea birds. Moreover, different life stages of the same species may show different vulnerability. For example, fish eggs and larvae seem much more sensitive than adult fish. The consequences of an oil spill in this region very much depend on when and where it happens. If an oil spill occurs at the ‘worst’ place (e.g. ice edge) at the ‘worst’ time (e.g. during spring bloom) the impacts could be very severe.

Taken together, there are several aspects of the Lofoten-Barents Sea region suggesting that oil spills in this region are likely to make more damage to the environment than further south in the Norwegian Sea and in the North Sea (**table 2**). However, there are large knowledge gaps and we are far from any conclusive understanding of this complex question.

***Table 2** Some aspects of the Lofoten-Barents Sea area, based on the report, that could affect whether this marine ecosystem is more vulnerable to oil pollution than the ecosystems further south in the Norwegian Sea and in the North Sea.*

	Lofoten-Barents Sea	Comments
Oil activities:		
Oil degradation	slower	low temperature, darkness, ice
Cleaning up	more difficult	infrastructure, darkness, temperature, ice
Vulnerability:		
Benthic organisms		
-Soft bottom benthos	more vulnerable	stronger response to oil (experiment)
-Sponges and corals	more vulnerable	more sponges, world's largest CWC reef
Fish	more vulnerable	important keystone species important nursery areas largest remaining stock of Atlantic cod
Seabirds	more vulnerable	larger and more aggregated populations pelagic, diving, low fecundity species
'Whole ecosystem'	more vulnerable	fewer species (less resilience) 'hot spot' areas and animal aggregations
Conflicts of interest:	higher	important fisheries tourism (e.g. Lofoten, Svalbard) nature conservation

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Norwegian Institute for Nature Research
NINA head office
Postal address: NO-7485 Trondheim, NORWAY
Visiting address: Tungasletta 2, NO-7047 Trondheim, NORWAY
Phone: + 47 73 80 14 00
Fax: + 47 73 80 14 01
Organisation number: NO 950 037 687 MVA

www.nina.no

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