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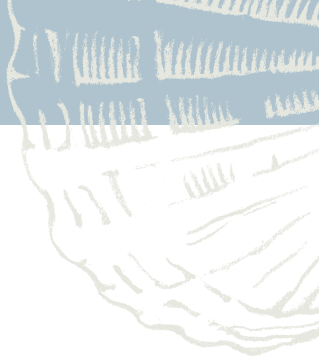

BarEcoRe: Barents Sea Ecosystem resilience under global environmental change

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BarEcoRe, *Barents Sea Ecosystem Resilience under global environmental change*, was conducted to investigate how the Barents Sea ecosystem can respond to anticipated changes in climate or human pressures. These investigations reveal how the Barents Sea ecosystem has responded to such perturbations in the past and what can make it more resilient to perturbations in the future. The project was funded by the Norklima program of the Norwegian Research Council, the Institute of Marine Research and the University of Tromsø, and involved scientists from these two institutions, as well as experts from a number of other national and international institutions (see complete list on page 19).

The scientific terms are explained in a glossary found on page 18.

Summary

BarEcoRe in a nutshell: Highlights from the project 2010–2013

The BarEcoRe project investigated how the Barents Sea ecosystem has responded to changes in ocean climate and human pressure in the past and what can make it more resilient to this kind of perturbations in the future. The strong data support for BarEcoRe was provided by the *Barents Sea Ecosystem Survey*.

In the central Barents Sea, fish and benthos communities have responded similarly to environmental gradients driven by the polar front, which separate Atlantic from Arctic waters. The north-eastward displacement of the polar front has led to concomitant shifts in the distributions of biological communities. These affect distribution of biological diversity of fish species with opposite effects on low fecundity and high fecundity communities.

Benthic species that are more sensitive to trawling disturbances are rare or absent in heavily trawled areas, which leads to benthic communities with reduced biodiversity.

Assessment of resilience based on structural properties of the Barents Sea ecosystem revealed a variety of complex geographical patterns. These suggest that resilience is achieved in different ways for different regions and biological communities in the Barents Sea.

Over the last decades, there have been large variations in abundance of plankton and individual species such as capelin and cod. In recent years, the biological productivity of plankton has remained stable and has supported large fish populations.

The past decadal variations in the state of the Barents Sea ecosystem could not be anticipated by early warning signals. There is also little empirical or theoretical support that early warning signals may be applicable for the Barents Sea ecosystem in the future.

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http://barecore.wikispaces.com/

Contents

0. The Barents Sea Ecosystem

The Barents Sea is a shelf sea situated north of Norway and Russia. The latitudes range from ca. 68 to 82°N, it covers an area of 1.6 million km^2, and the average depth is 230 meters. Atlantic warm water enters the Barents Sea predominantly from the southwest, while cold Arctic water dominates in the northeast. As a result, the ecosystem consists of a mixture of Arctic and Atlantic species. To date, more than 3000 benthos species and 200 fish species have been recorded. The Barents Sea is home for many commercial fish and shellfish species, including cod, haddock, capelin, herring and shrimps. It is a productive region with more than 10 tons of fish per km^2, on average.

Ocean circulation, changes in sea ice coverage and human exploitation affect the state of the Barents Sea ecosystem. Since the 1960s, temperature has increased by almost 1.5°C while ice cover has decreased by 10%. Climate models predict a further increase in ocean temperature of 1 to 3°C by 2060. Species abundances greatly varied in recent decades. For example, capelin biomass fluctuated between 0.1 and more than 7 million tonnes, and the geographical extent and abundance of king crab and snow crab have recently and rapidly increased.

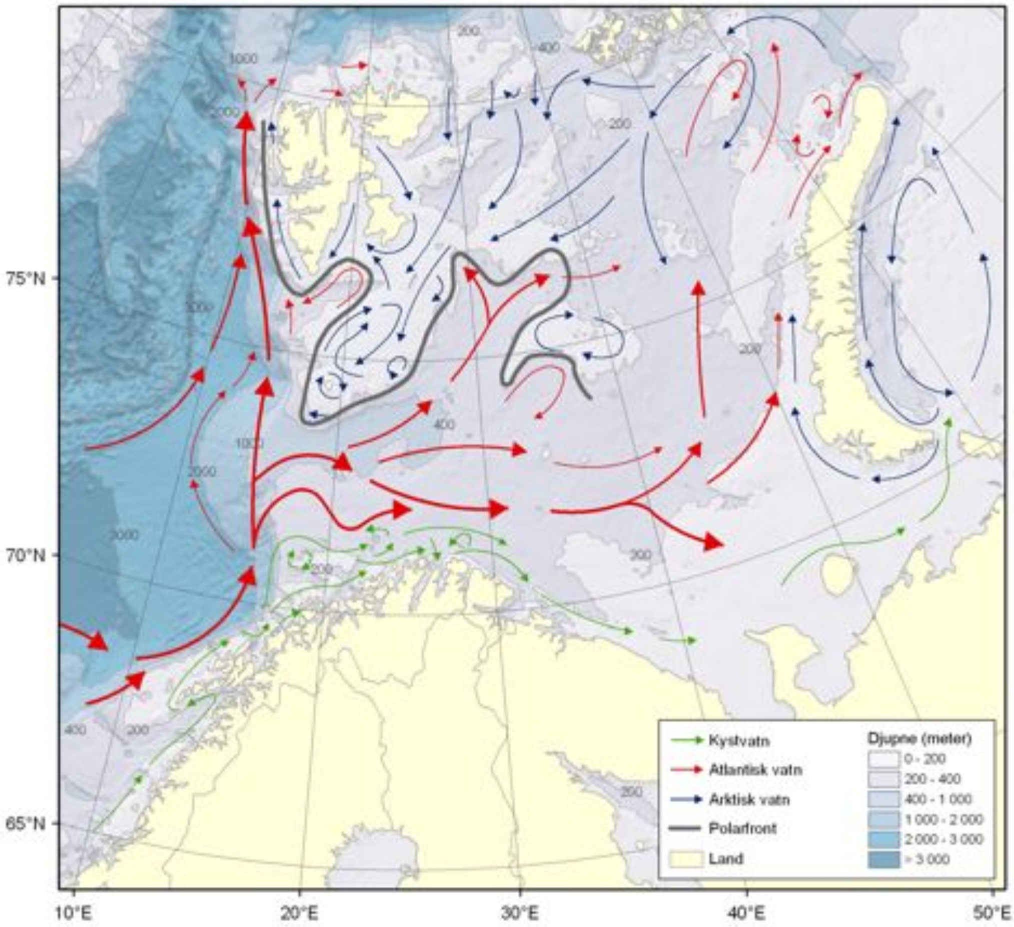

Figure 1: The Barents Sea. Main ocean currents are indicated for the Atlantic waters (red), Arctic waters (blue) and the coastal current (green).

1. Past changes in ecosystem structure, climate and fishing

To describe the structure of the Barents Sea ecosystem and understand how it can respond to climate change or fishing pressure, it is essential to conduct repeated observations of the ecosystem. BarEcoRe has developed from the unique series of scientific data known as the *Barents Sea Ecosystem Survey*, a joint effort between IMR[1] and PINRO[2] to collect synoptic information about the physical and biological components of the Barents Sea ecosystem [1, 2]. This allows for an integrated understanding of ecosystem processes, in comparison to previous practice when different parts of the ecosystem were sampled in separate cruises, time periods and depths. The survey covers the whole Barents Sea shelf from August to early October, the months with the least sea ice cover. Since the start in 2003, temperatures in the Barents Sea have been the highest on record [1, 3]. This has been accompanied by important changes in the geographical distribution and abundance of several species. These changes highlight the need for continuous large-scale comprehensive monitoring to reveal how changes in ocean climate or human pressures can affect the dynamics of the ecosystem.

Atlas for Barents Sea species

New data on fish and benthos from the whole Barents Sea shelf have been used to construct an atlas of the geographical distribution of 100 species of fish [4] and to map the large scale distribution of macro-benthos species. The data are further used to relate distributions and species composition to environmental factors.

Fish and benthic communities respond to the environment

Areas with similar environment conditions often have similar species composition. Such areas are observed north of the polar front with large areas covered with same type of fish and benthos species [5, 6]. Geographical areas with relatively similar environment and consequently species composition are called ecological communities. When moving into other types of environment (e.g. cold/deep to warm/shallow) the species composition changes. Abrupt changes in species composition across areas, coinciding with changes in the environment, are observed across and south of the Barents Sea polar front, which appear to affect fish and benthic communities in a similar way (Figure 2).

Trawling makes benthic communities more robust to … trawling

Benthic communities differ between areas exposed to bottom trawling and not exposed. In trawled areas vulnerable non-moving, large-bodied, stiff, fragile species living on the sediment surface were rare or absent, whereas more robust, mobile, burrowing, small-bodied species with a retractable and flexible body were present. The effect of trawling on benthic community structure was found to vary regionally: it was weak in the Norwegian coast and Bear-Island area, strong in the Hopen Deep area, non observable in the frontal area and around Svalbard [7].

Changes in ocean climate affect fish communities distribution

Observations from the last decade reveal a systematic spatial expansion of the fish community along the Polar Front in recent years (2006–2009). In this period the volume of Arctic water decreased and the volume of water with intermediate temperatures increased. Simultaneously, the abundance of cod and a few other species increased, and the species composition of several fish communities adjacent to the Polar Front changed. In addition, the southern boundary of the fish community

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[1] Institute of Marine Research, Norway

[2] Knipovich Polar Research Institute of Marine Fisheries and Oceanography, Russia

dominated by Arctic species gradually moved north [8]. These community changes are consistent with the hypothesis that ocean climate drives changes in the geographical distribution of fish communities in the Barents Sea.

Figure 2: Fish and benthic communities in the Barents Sea.

2. Feeding interactions

Stable plankton production

Zooplankton species play a key role in the Barents Sea by channelling food from primary producers (phytoplankton) to animals higher up in the food web (fish, sea birds, mammals, etc.). Zooplankton biomass can vary greatly between years, but in recent years, the meso-zooplankton biomass has remained relatively stable (5–7 $g.m^{-2}$ dry weight). This happened even when the stock size of capelin, a dominant planktivorous fish species in the Barents Sea, reached high levels. This indicates favourable conditions for meso-zooplankton production in recent years.

Abundant jellyfish

The current ocean warming is also favourable to the jellyfish medusae *Cyanea capillata* [9]. Abundant jellyfish can significantly impact the pelagic community through direct predation, competition for food, or indirect trophic cascades. The majority of jellyfish occupies the central parts of the Barents Sea, which is a core area for many 0-group fishes, although no negative relationship between jellyfish and 0-group fishes has been observed. In recent years, the geographical distribution of jellyfish medusae has progressed northward.

Fluctuating capelin

Capelin is the major grazer of zooplankton and is the major prey fish for several fish-eating fish, sea birds and sea mammals in the Barents Sea. Its role is further magnified by its instability. The biomass of the capelin stock can fluctuate between 0,1 and 7 million tonnes with rapid declines and recovery in the course of 2–3 years [10]. Three collapses of the stock have happened in the last 30 years with profound effects on the ecosystem. Capelin is capable of rapid rebuilding because of its immense recruitment capacity combined with rapid individual growth when food is abundant. During stock rebuilding phases, capelin can satisfy its high food requirements by expanding its feeding area (Figure 3). In recent years, temperatures in the northern and north-eastern parts of the Barents Sea have become suitable for capelin and other pelagic fish to feed on a high plankton production [11, 12]. Year-to-year changes in zooplankton biomass appear to be strongly controlled by capelin [13]. Periods of warm water expansion appear to favour large stock of capelin with a wide geographical distribution.

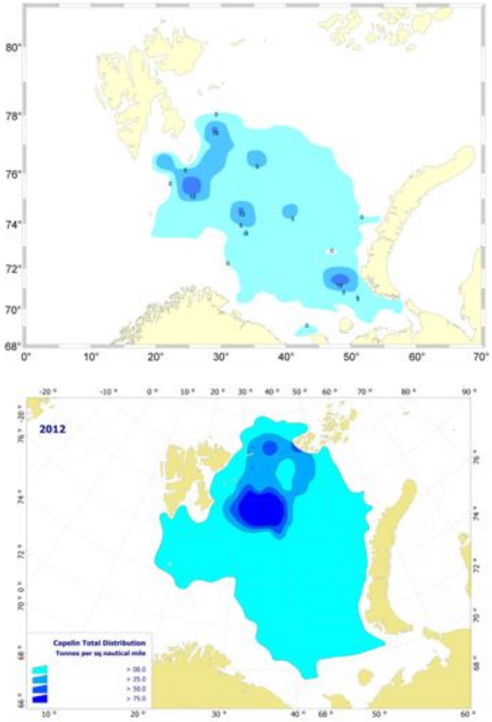


Figure 3: Geographical distribution of capelin in 2003 (top) and 2012 (bottom) during time of respective low and high abundance.

Cod stock at record high level

When the northern areas of the Barents Sea become available for capelin, they also allow for its main predator, cod, to expand northwards and feed on the abundant capelin stock year-round. Consequently, it is likely that warming will also boost the production and the spatial extension of the Barents Sea cod stock.

Cod is a predatory species present in many ecosystems of the North Atlantic shelves. In contrast to most regions where cod stocks have drastically declined, the Barents Sea cod stock is currently at a record high level. While most prey species are found in spatially segregated habitats, cod is widely distributed, except in the deepest parts of the Barents Sea, where shrimps prevail [10]. Cod abundance is generally higher in areas occupied by capelin and herring and lower in the north-eastern areas occupied by polar cod [14]. Feeding success increases with the local abundance of capelin and polar cod but not with herring abundance, suggesting that herring might escape predation [15].

Birds and mammals tracking their preys

During winter, the geographical distributions of top predators are often overlapping with those of single prey species. In contrast, during summer, top predator distributions are loosely coupled to the distribution of their preys, suggesting that they rely more on persistent habitat features than on specific prey species distributions [16]. Predator abundance in summer is high relative to winter, but the more rigid spatial organization and the diversity of available preys may reduce the impact of predation on single prey species.

Food web of the Barents Sea

The detailed feeding links are well understood for few species, as described above for cod and capelin. But there are many more species in the Barents Sea, which together constitute a complex food web. The analysis of the food web topology by means of appropriate quantitative tools can provide insights into the vulnerability of food webs. BarEcoRe conducted an extensive compilation of species and feeding links to construct the most comprehensive Barents Sea food web topology to date (Figure 4). This includes 250 animal groups, from zooplankton to whales and over 1500 feeding links [17]. This is the data support for future analysis of how the entire Barents Sea food web may respond to climate and fishing pressure.

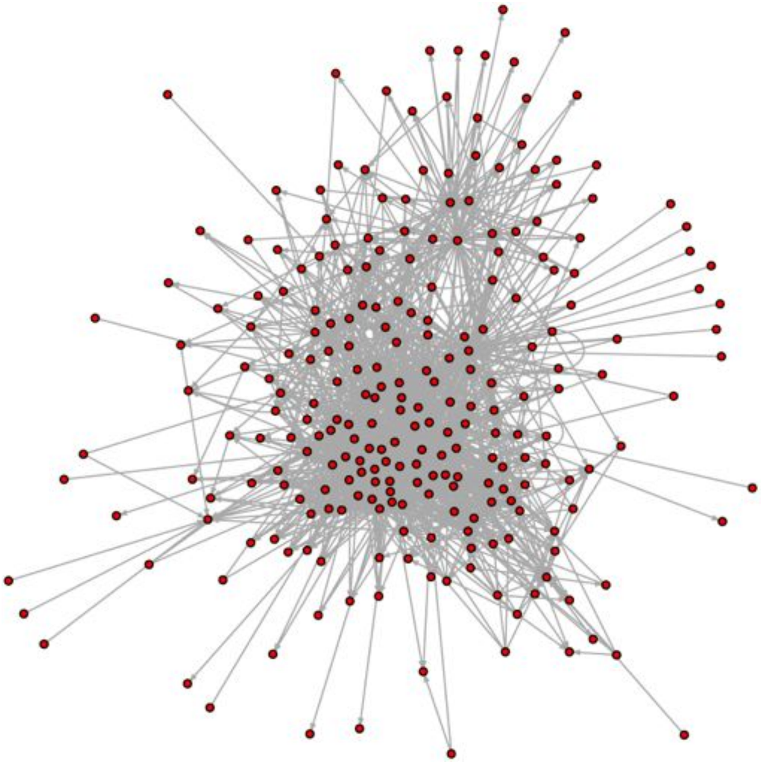


Figure 4: Network representation of the BarEcoRe Barents Sea food web, from plankton to whales. Circles symbolise individual species and arrows indicate feeding links.

3. Geographical species distribution under climate change

The Barents Sea is home for more than 100 fish species, many of which are commercially exploited. The geographical distribution of many of these species is expected to change as a result of future modification of temperature, salinity and other environmental conditions. Such changes in the geographical distribution of species may directly affect the fishing industry and indirectly modify the dynamic of the Barents Sea ecosystem through regional modification of species assemblages.

During BarEcoRe, we developed Species Distribution Models (SDMs) for 51 species to investigate the relationship between their past geographical distributions and environmental conditions. We use these sets of SDMs outputs to answer two main questions:

1. Is the distribution of the species strongly related to the environment, and more specifically to temperature and salinity?
2. What type of modification in species distribution could be expected if sea temperature increases and surface salinity decreases?

Five of the species studied (amongst which, Greenland halibut and haddock) present a spatial distribution strongly correlated to environmental variables, with a fairly large potential for change under climate scenario. Most of these changes take the form of northward and eastward migration as temperature increases. About 2/3rd of the species spatial distributions are weakly associated with environmental conditions and the remaining twelve species are moderately linked to temperature and salinity conditions.

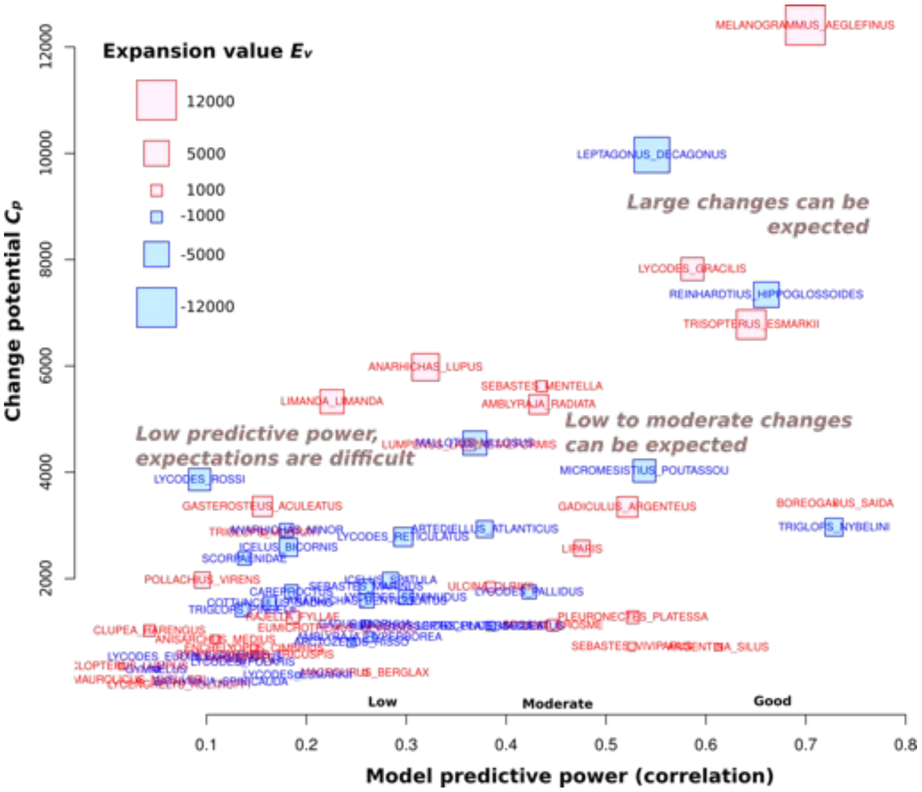


Figure 5. Expected potential changes in geographical distribution (y-axis) and spatial extent (square/colour symbols) against the predictive power of the SDMs (x-axis). Species represented in upper-right areas are those for which distribution is expected to change most and with greatest certainty. Species located in the lower left region are those for which environmental models perform poorly and expected changes in distribution are moderate and highly uncertain.

4. Biological diversity

Biological diversity and fisheries management

Biological diversity, in its broadest sense, refers to the diversity of organisms living in a particular area. However, the concept of biological diversity is plagued by vagueness: it can be interpreted in many ways and measured with different tools. This has restricted its application within fisheries management that requires clear-cut objectives, targets and thresholds. Recent studies [18, 19] have successfully unified the scientific framework for measuring diversity unambiguously, opening the way for incorporating biological diversity explicitly and efficiently into marine management frameworks.

A biological diversity baseline for the Barents Sea

Biological diversity is an integrated function of the state of an ecosystem. It summarizes the abundances of all species belonging to a given system at a given time, which is the result of all interactions occurring among the species and between the species and their environment. Measures of diversity are for the ecosystem approach to management, what species-specific indices are for single species management.

The data collected during the *Barents Sea Ecosystem Survey* (section 1) was analysed to provide the first reference baseline for biological diversity of fish and invertebrate species in the Barents Sea (Figure 5). This baseline can be used to evaluate future changes in diversity and offers an integrated diagnostic tool for the management of the Barents Sea ecosystem.

Response of fish diversity to climate

"Macro-Ecological Models" are a class of statistical models that can be used to describe how diversity is related to environment conditions. These models revealed major differences between two groups of fish species in the Barents Sea: low-fecundity species, *i.e.* species producing a low number of eggs each year (e.g. thorny skate, liparid fish and twohorn sculpin) and high fecundity species (e.g. ling, anglerfish and polar cod). There is a greater diversity of low fecundity species in Arctic waters, whereas higher diversity is found in Atlantic waters for species with high fecundity (Figure 6). It is therefore anticipated that any changes in the balance between Arctic and Atlantic waters in the Barents Sea will result in a reorganization of these two communities, with most of the low-fecundity species retracting further north and most of the high fecundity species expanding further into the Barents Sea [20].

BarEcoRe has now established the foundations for a biological diversity baseline for the Barents Sea. As long as the *Barents Sea Ecosystem Survey* is maintained and the appropriate data is collected and provided in a consistent manner, significant changes in the ecosystem affecting diversity can be detected. Although we are still far from a global understanding of the relationships between all the species and their environment, the clear link, identified during BarEcoRe, between water masses and low and high fecundity species offers a way to anticipate the effect of any changes in these water masses.

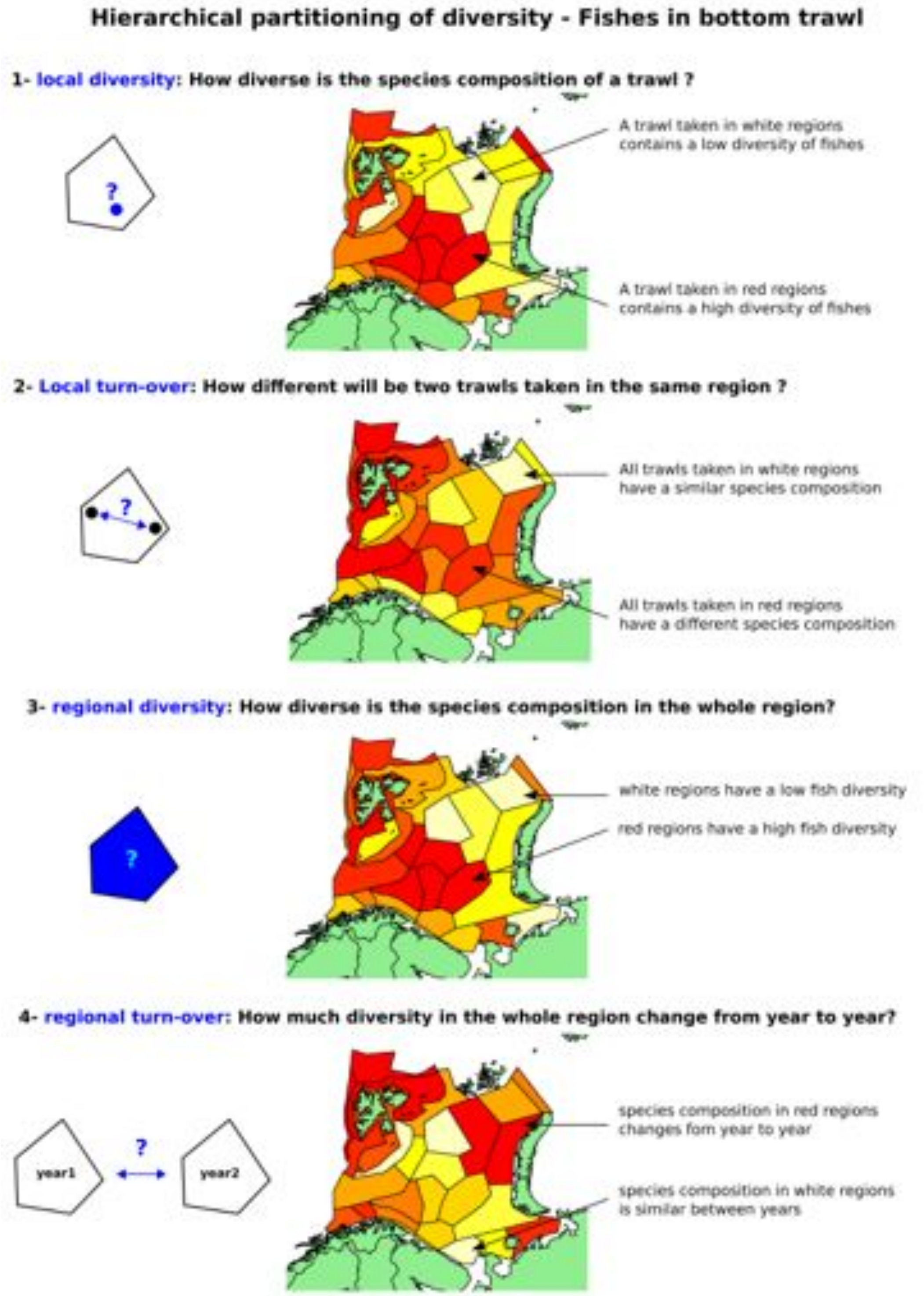
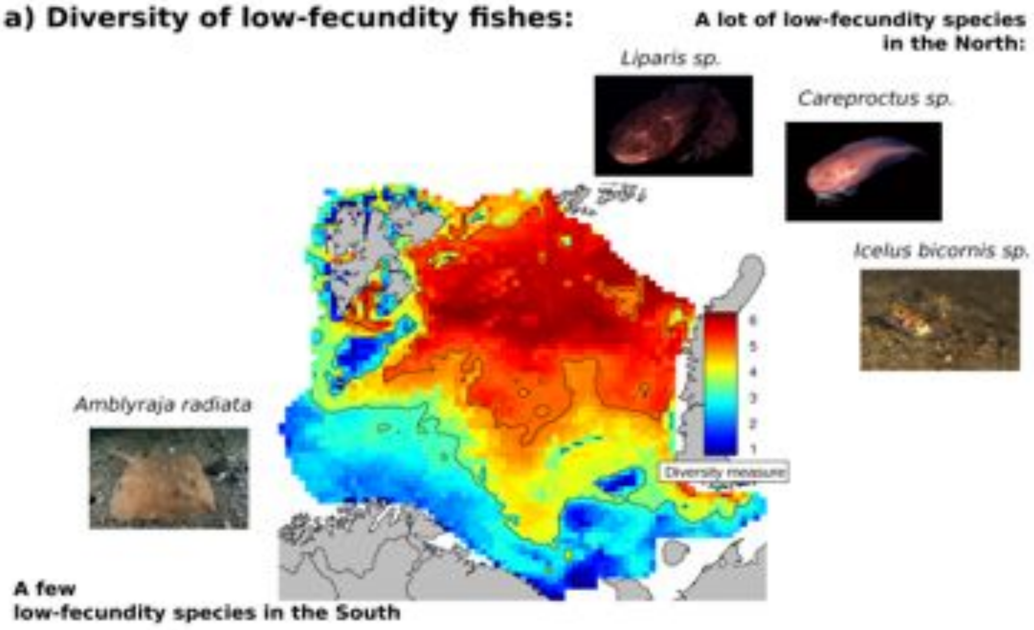


Figure 5: Partitioning of fish diversity in the Barents Sea between different spatial and temporal scales.


a) Diversity of low-fecundity fishes:

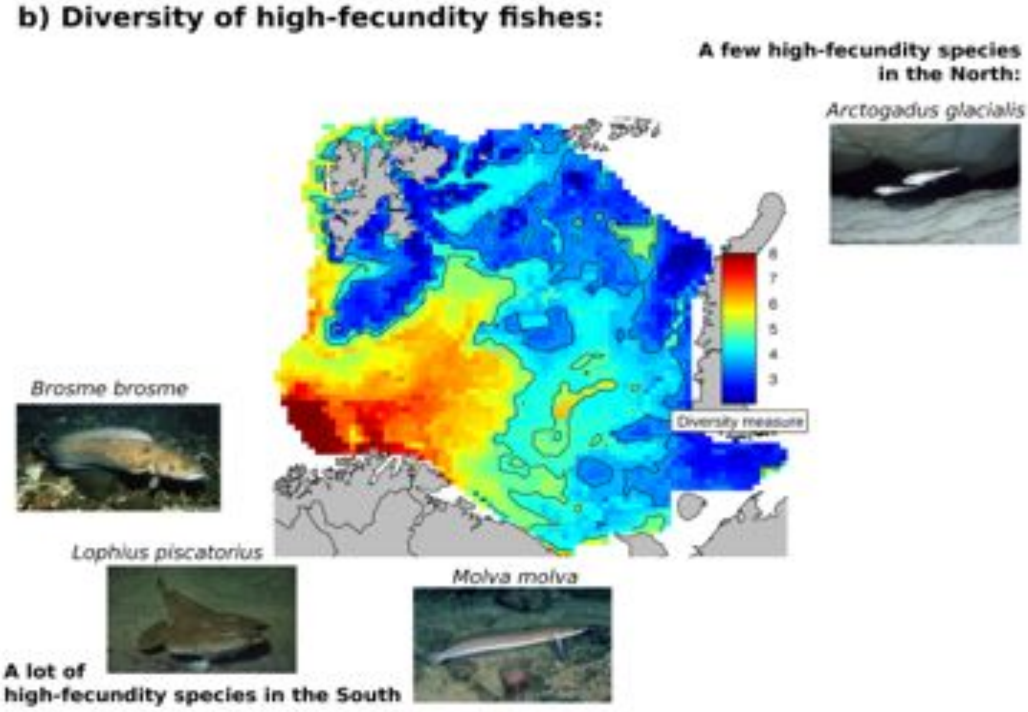

b) Diversity of high-fecundity fishes:

Figure 6: Geographical distribution of fish diversity for two separates guilds: low fecundity (top) and high fecundity (bottom) fishes.

5. Resilience

Defining resilience

Resilience can be broadly defined as *'the ability to absorb disturbance and still maintain structure and function'*. However, the term *'resilience'* has been associated with a multitude of meanings ranging from clearly defined descriptive ecological concepts to vaguely specified or normative management objectives [21]. The BarEcoRe project focused on ecological aspects of resilience that can be quantified and are related to the structure and temporal dynamics of the Barents Sea ecosystem.

Resilience and the structure of ecosystems

There is no direct and unique measure of ecosystem resilience, but various properties that characterize the structure of an ecosystem can be related to its resilience to environmental perturbations. These include measures of diversity, redundancy and modularity [22]. Diversity can promote the adaptive capacity of an ecosystem, by providing a high degree of flexibility in the face of novel situations. Redundancy, the fact that several species can perform similar functions, allows an ecosystem to retain its main functionalities in spite of species loss or substitution. Modularity, which implies that species interact within separate compartments, can restrict the impact of a perturbation to few species by blocking its propagation to the entire ecological network.

Structural assessment of Barents Sea ecosystem resilience

Diversity, redundancy and modularity can be measured and compared across space and time. In BarEcoRe, taxonomic diversity was studied for fish and invertebrates [20]. Functional diversity and redundancy were analysed specifically for the fish communities, by combining data on geographical distribution and information on species-specific ecological traits [23]. Modularity was assessed using regional food web topologies, based on data of feeding relationships among prominent species [24].

Fish functional diversity varied substantially in both space and time [23]. The highest functional diversity was registered in the central-west Barents Sea, an area influenced by the polar front and inhabited by many fish species that are similar with regard to functional traits (Figure 7). In the north, functional diversity was low in the first sampling years but later increased, possibly due to the warmer temperatures and reduced ice coverage that made this area more favourable for fish. In the east, coexisting species were more functionally distinct than in the west, implying higher adaptability. The observed high functional heterogeneity also implies that species loss in the west may lead to substantial loss in ecosystem function. Functional redundancy was consistently high in the deep slope of the central-west Barents Sea, an area characterized by several migrating species that live in the pelagic, feeding on plankton.

The Atlantic and Arctic regions of the Barents Sea had distinct food web topologies [24]. In the Arctic region there were fewer species that were more connected via feeding relationships than in the Atlantic (Figure 8). Five distinct compartments were detected in the Atlantic but only four in the Arctic. In both regions, modularity was partly associated with habitat, with species living and feeding near the bottom being uncoupled from those living in the open waters.

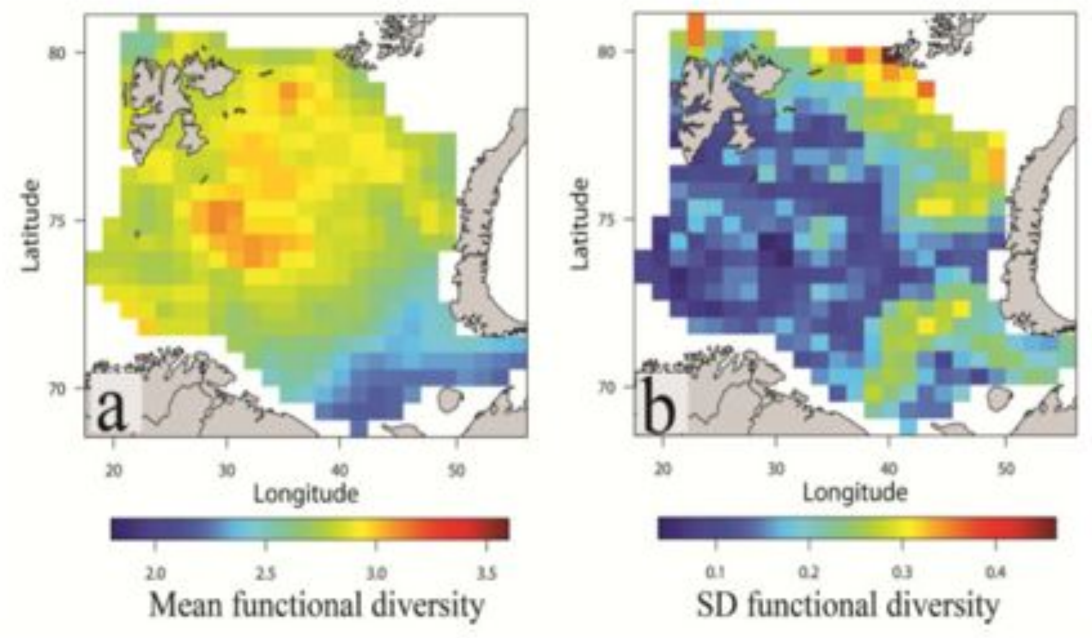


Figure 7: Spatial and temporal (2004-2009) in Barents Sea fish functional diversity (FD). a) FD means across year show a consistently high diversity in central Barents Sea, but low diversity in South-East. b) FD standard deviations across years show greatest change taking place in South-East and North-East

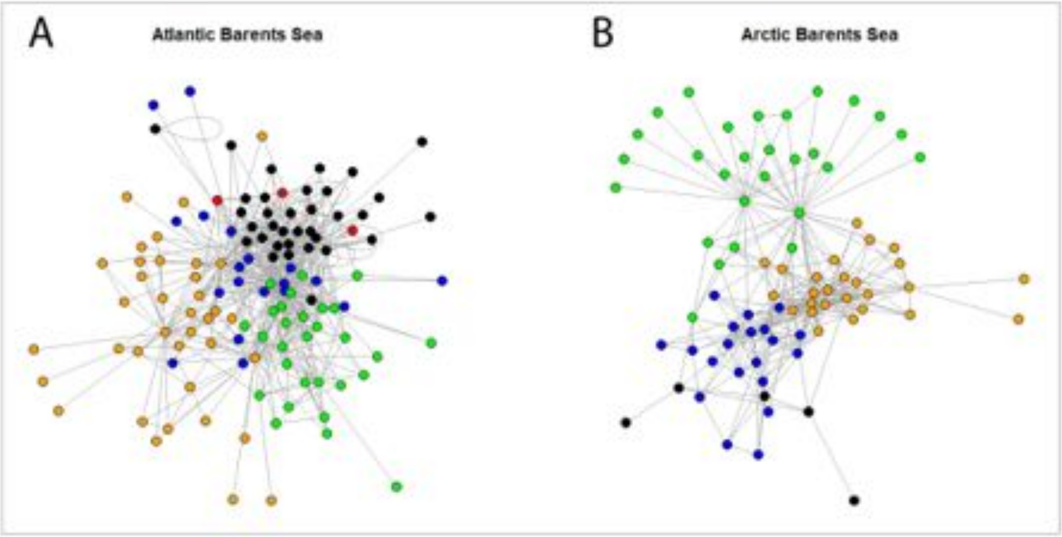


Figure 8: Food web topology of the Barents Sea for the A) Atlantic and B) Arctic region. The dots indicate species and their colour shows the compartment to which a species is affiliated.

6. Early warning signals

Critical transitions and early warning signals

Early warning signals generally refer to the temporal evolution of a system and consist of simple properties that change in distinctive ways prior to a *critical transition*. This can be illustrated by the increasing stretching of a rubber band, which is reversible up to the point when the rubber band breaks. An early warning signal provides advance indication that the rubber band is approaching critical rupture. Mathematically, critical transitions correspond to so-called catastrophic bifurcations, and they arise in dynamic systems with alternative stable states. For example, it was shown experimentally that the imminent extinction of a population of *Daphnia*[3] could be announced by an early warning signal known as *critical slowing down* [25].

Regime shifts in marine ecosystems

Regime shifts refer to rapid changes in ecosystem structure between periods of relative stability, as for example, the large amplitude concomitant changes in the climate and biology of the North Pacific ocean which occurred in 1977 and 1989 [26]. Regime shift have been reported in several studies on large marine ecosystems [27], but there is no evidence that these correspond to critical transitions in a mathematical sense. In BarEcoRe, using a simple food web simulation model, we investigated whether observed regime shifts in marine ecosystems could result from simple random variations rather than critical transitions. Model simulations showed that regime shifts could occur every 18 years on average in the absence of critical transitions or exceptional climatic or fishing events [28].

Early warning signal for the Barents Sea

Early warning signals can be applied to ecosystems that shift between alternative stable states through catastrophic critical transitions. Abrupt transitions that are catastrophic bifurcations, in a mathematical sense, have been described in many numerical models and have been reported in experimental studies or field observations. To date, ecological studies that have successfully demonstrated the applicability of early warning signals were conducted on simple systems (1–3 species and 1 environmental perturbation) that could be described by a non-linear model with bistability. In addition, early warning signals require long time series (1,000 to 100,000 observations) and interpretation is greatly facilitated when controls (i.e. similar but unperturbed systems) are available. The Barents Sea is a large marine ecosystem. It is constituted of thousands of interacting species. Despite great efforts deployed in numerous research cruises, the series of observations are short: with one data point per year, the longest available time series is only 50 points. Furthermore, neither a dynamic model nor experimental controls are available. It is therefore highly unlikely that early warning signals can be successfully applied for the Barents Sea ecosystem. In BarEcoRe we tested several early warning signals tools on capelin time series, which displays the strongest and most rapid variations, from high stock levels to near total collapses in 1–2 years. These tools failed to provide an early warning signal the stock collapses.

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[3] *Daphnia* is a cladoceran freshwater flea widely used in experiments.

7. Glossary:

0-group fishes: fish observed in their year of birth.

Benthos/benthic: animals living on the sea bed (by opposition to pelagos).

Community (ecological): ensemble of species occupying the same geographical area.

Critical transition: Abrupt shift in the behavior of a system when certain parameters reach a threshold.

Demersal: animals (fish), which partially depend on the sea bed for food or habitat.

Diversity (biological): variety of organisms living in a particular area.

Early warning signals: simple properties that change in distinctive ways prior to a *critical transition.*

Feeding success: amount of food consumed per unit time (typically measured in energy: Joules).

Mesozooplankton: planktonic animals in the size range 0.2-20 mm, for example: the copepod *Calanus finmarchicus.*

Modularity: the degree to which a system's components may be separated and recombined. In ecology, modularity refers to the concept that ecological networks (e.g. food webs) are composed of modules.

Pelagos/pelagic: refers to animals living in the water column (by opposition to benthos).

Planktivorous: who eats plankton.

Redundancy: the notion that multiple distinct elements perform the same function.

Resilience: the ability to absorb disturbance and still maintain structure and function.

Taxon/taxa: a taxonomic entity, typically a species. It can also be a sub-species, a genus, a family or any other taxonomic level.

Topology (food web): An ensemble of species and of the trophic links between them. A food web topology describes 'who eats whom' in a biological community.

Trophic cascade: changes in abundance in a trophic level (e.g. removal of large predatory fish by fishing) causing changes in all lower trophic levels.

Recruitment (fish): the number of individual fish of the same cohort reaching a specific age or stage in a population. For example, recruitment at age 2 is the number of fish reaching age 2 in a given year.

8. People who made BarEcoRe

BarEcoRe, *Barents Sea Ecosystem Resilience under global environmental change*, is a project funded by the Norklima program of the Norwegian Research Council (project 200796/41), the Institute of Marine Research and the University of Tromsø. BarEcoRe ran during the period June 2010 to May 2013. The project involved scientists from the Institute of Marine Research and the University of Tromsø, as well as experts from a number of national and international institutions.

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More documentation, reports, presentations and videos can be found at: ***http://barecore.wikispaces.com/***

The BarEcoRe project team en route for a memorable fishing trip around Herdla at the annual meeting in 2011

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