The effect of climate change on marine fish stocks:
prioritising the research agenda related to fisheries

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Contents

Summary

This report is commissioned by the Ministry of EL&I to provide input for the international process to determine the research priorities in the field of climate change impacts on fish stocks and fisheries. The report reviews the state of the art literature and identifies the following priority areas

- Improved knowledge on the eco-physiology of marine organisms, in particular how key abiotic factors interact (temperature x O2 x CO2 x pH), are required to improve the predictive capacity of models simulating climate impacts on marine species and ecosystems
- Development of full life cycle models that integrate the effect of CC on the different life stages and their connectivity (life cycle closure). Many marine organisms and fish are characterised by complex life cycles (eggs, larvae, juveniles and adults) which live in spatially distinct habitats and differ in their sensitivity for environmental factors
- Improving coupled biogeochemical and lower trophic level models to better capture climate-driven feedbacks and nutrient cycling
- Development of end-to-end ecosystem models such as Atlantis
- Study of the economic costs and trade-offs of changes in ecosystem goods and services resulting from various CC scenarios

In two additional chapters the report discusses the policy implications of climate change and shows how an Ecosystem Overview may be used as an integrated visualisation that enable a combined view of the main parts of the ecosystem, the temporal development of major organisms or groups of organisms and the temporal development of both natural and man-made drivers of change.

1. Preface

This report is compiled in response to a request of the ministry EL&I for advice on the research topics related to the impact of climate change on marine ecosystems and its implications for European policies. The report provides a brief summary of the state of the art scientific knowledge in this field and formulates a number of priority areas for future research. In addition, it provides two chapters on the Policy Implications of Climate Change Impact on Fish Stocks and on Ecosystem Overviews. The Policy Implication chapter is an update of a deliverable of a FP6-project RECLAIM that was produced in December 2009. The Ecosystem Overview chapter is an excerpt of paper of Lindeboom et al (in prep) on compiling time series of relevant data on Dutch marine ecosystems relevant for management.

Kennisvraag: Wat de belangrijke thema's voor toekomstig onderzoek moeten zijn, is nog onderwerp van discussie, maar het huidige en toekomstige GVB en het Green Paper van de EU Commissie bieden genoeg aanknopingspunten. Genoemd zijn o.a. een verdere uitwerking van de ecosysteembenadering, de toepassing van MSY, de advisering over TAC's en quota, slimme monitoring, dwz. ook ten dienste van de Kaderrichtlijn marien en N20000. Wat nog niet als thema is opgenomen is klimaatverandering: het effect ervan op mariene visbestanden en andere mariene soorten, het onderscheid tussen klimaateffecten en visserij-effecten, veranderingen in verspreiding en abundantie, mogelijke extinctie van soorten, verhoogde productiviteit van andere soorten, gevolgen voor de visserij en voor aquacultures, mogelijke consequenties voor het beheer. En dit dan zowel voor Noordelijke en Zuidelijke EU wateren, incl. het Arctisch gebied en de Middellandse zee. Gevraagd wordt inbreng in dit working paper: waar zal het onderzoek naar de effecten van klimaat zich op moeten richten?

2. Research priorities

Evidence is accumulating that the increase in CO_2 in the atmosphere as a result of burning fossil fuels is affecting the global climate, with far reaching implications for biological processes and ecosystem services (IPCC 2001). Governments are faced with the challenge to adjust their policies to cope with the potential impacts of climate change.

The pathways by which climate change (CC) affects marine populations and ecosystems are complex (Rijnsdorp et al. 2009). Firstly, it may affect the physiology of the individual, population dynamic processes and ecosystem processes (biogeochemical processes and food webs). Secondly, CC will not only influence temperature, but may also influence other environmental conditions such as wind, cloud cover, river run off, stratification, ocean circulation and acidification, hypoxia and sea level rise. Finally, fish populations and ecosystems are affected by other natural and anthropogenic activities, in particular fishing, that may increase the vulnerability for CC and makes it difficult to disentangle the climate change from other factors (Perry et al. 2010, Planque et al. 2010).

There is a growing body of literature that studied the effects of CC and climate variability (mainly temperature). These studies have provided compelling evidence that recent warming coincided with shifts in latitudinal and bathymetric distribution (Perry et al. 2005, Dulvy et al. 2008, Sunday et al. 2012) and shifts in phenology ((Edwards & Richardson 2004); (Fincham et al. 2012)). It may also lead to changes in fish productivity (Cheung et al. 2010); (Brown et al. 2010). Recent studies further indicated that the maximum body size of fish are decreasing (Baudron et al. 2011), which could be due to the effect of increased temperatures and decreased oxygen levels (Cheung et al. 2012b).

To predict potential effects of acidification requires ecological and physiological knowledge. It seems plausible that some commercially targeted species, especially shellfish, could suffer direct negative consequences of acidification whilst other species will be robust to direct effects. The critical question of whether acidification will affect overall system productivity remains open (Le Quesne & Pinnegar 2012).

The complexity of pathways by which climate change (CC) affects marine populations and ecosystems makes any interpretation of observed changes uncertain and highlights the need for models to explore the different hypothesis. Hence, models are an indispensable tool to (i) study how climate change may impact marine populations and ecosystems; (ii) disentangle the role of CC and exploitation; (iii) forecasts the potential implications of future climate change. A broad range of mechanistic models have been developed that describe relevant processes and reflect the different levels of organisation affected by CC: ecophysiological models of a species or a specific life stage; population dynamic models; life-cycle closure models; foodweb models and global ecosystem models. These models are in an early stage of development and have not been properly validated.

Recent work has emphasized the following research priorities

- Improved knowledge on the eco-physiology of marine organisms, in particular how key abiotic factors interact (temperature x O_2 x CO_2 x pH), is required to improve the predictive capacity of models simulating climate impacts on marine species and ecosystems (Jørgensen et al. 2012)
- Development of full life cycle models that integrate the effect of CC on the different life stages and their connectivity (life cycle closure). Many marine organisms and fish are characterised by complex life cycles (eggs, larvae, juveniles and adults) which live in spatially distinct habitats and differ in their sensitivity for environmental factors (Rijnsdorp et al. 2009).

- Improving coupled biogeochemical and lower trophic level models to better capture climate-driven feedbacks and nutrient cycling and ocean productivity
- Development of end-to-end ecosystem models such as Atlantis (Fulton 2010).
- Study of the economic costs and trade-offs of changes in ecosystem goods and services resulting from various CC scenarios

3. Policy Implications of Climate Change Impacts on Fish Stocks[1]

3.1 Discrimination between changes due to climate change and fisheries

Climate change will lead to an increase in the uncertainty about the state of fish stocks and ecosystems, underlining the importance of the precautionary approach to fisheries management. Although science is able to provide broad-brush forecasts about change in distribution of fish resources (e.g. Cheng et al., 2009), fisheries management operates on a regional scale for which the effects of climate change are still uncertain due to the lack of regional down-scaled climate models. Also, analysis of the historic changes in relation to climate variability has shown that the observed response is not easily understood at the single species level, and that ecosystem interactions play a role as well. Moreover, because the response may be non-linear, without knowledge on the mechanism, any prediction for climates which have not yet been observed may be uncertain.

3.2. Changes in abundance and distribution

Changes in distribution may result in biological stocks moving from one management area to other management area(s) which may lead to a greater (mis)match between the biological stock structure and the management areas. This will be particularly relevant if a stock or species becomes available in another management area for only part of the year, leading to an allocation problem of the TAC among countries (relative stability). One example of this is mackerel in the North Sea.

The establishment of populations of new species in a management area, may attract fisheries to start exploiting the new resource for which no management regulations are yet in place. For example, red mullet, seabass and squid are expanding northward and significant new fisheries are developing. Similarly, anchovy are spreading into the Channel and southern North Sea, where they are now subject to new and expanding fisheries, whereas numbers of anchovy further south in the Bay of Biscay have declined in recent years (ICES, 2009). The response time of the management system to changes in the resource base and fisheries developments is generally low in comparison with the rate of change in the ecosystem or in the fisheries, which may aggravate management problems (Berkes et al. 2006).

Distributional shifts of fishable resources may result in changes in the distribution of the fishery which will lead to a change in the ecosystem effects of fishing such as the occurrence of unintended by-catch. Alternatively, the change in distribution of harbour porpoises in the southern North Sea has led to an increase in the bycatch in the coastal fisheries. Climate induced changes in the distribution or abundance of fisheries resources may also give rise to changes in the competition among fisheries, such as between mobile and static gear.

Distributional shifts may affect the effectiveness of technical measures (e.g. closed areas). A clear example is the Plaice Box which was established in 1989 to reduce the fishing effort in the coastal nursery grounds of North Sea plaice and improve both the sustainable landings and spawning stock biomass. In contrast to these expectations, the landings and the spawning stock biomass have decreased mainly due to a change in the distribution of the undersized plaice. In the mid-1990s, part of undersized plaice left the Plaice Box by moving to deeper waters outside the Plaice Box. Although the distributional change may be (partly) due to an increase in temperature (Teal et al. 2012), it cannot be ruled out that the change is also related to the decrease in trawling impact affecting the food availability in the Plaice

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[1] This chapter is an update of Rijnsdorp, Deerenberg, Engelhard, Pinnegar (2009) Policy Implementation Deliverable 5.5. of RECLAIM.

Box (van Keeken et al. 2007, Hiddink et al. 2008). Since the management implications are quite different, scientific insight on the role of climate and fishing is of paramount importance to develop a sound and credible scientific basis for fisheries management.

Distributional shifts may affect the effectiveness of technical measures (e.g. closed areas) for conservation of biodiversity (Natura 2000). If species-specific objectives are formulated, a climate induced change in the ecological condition, may render the objective untenable. For instance, setting an objective to maintain a certain density of animals in a Natura 2000 site that is at the southern limit of the distribution of the species, will inevitably fail to achieve species protection if climate change results in the temperature rising above the maximum tolerance limit of the species (Portner and Peck, 2010). Therefore it is necessary to (re-) formulate the biodiversity objectives in such a way that they will be robust to climate change (for example, see the section on the EU MSFD above), by putting less emphasis on individual species and more on habitats. Designing networks of protected areas that offer appropriate habitats to species assemblages under different climate regimes may be a more fruitful approach.

Finally, distributional shifts will have economic and management consequences when fishers aiming to exploit the same stock will have to move to a different location, which could result in a change in the number of days at sea, an increase in fuel costs or in the distance to be covered between the fishing port and fishing grounds. Changes in the frequency of storms predicted by some models, may also impact upon the ability of fishers to access fish resources, particularly if a 'days at sea' based management system is in place.

3.3. Possibilities of species extinctions

Species extinctions may occur when species are no longer able to adapt to the climate induced changes in their environment. This may for instance occur in ocean basis such as the Mediterranean Sea where the species are unable to shift their range to the north (Ben Rais Lasram et al. 2010).

3.4. Climate change effects on the productivity of other species

Productivity changes will make the current management regulations inappropriate. For example, when productivity increases, current reference points would unnecessarily restrict the fisheries, whereas a decrease in productivity will jeopardize sustainable management as reference points are over-estimated. In both situations management reference points will need to be evaluated against and readjusted to the climate-induced change in productivity.

Climate change will also affect the resilience of exploited stocks to climate change, and increase the uncertainty in estimated reference points and hence make the science base for fisheries management more uncertain. Signatories of the WSSD declaration in 2002, subscribed to an international political commitment to maintain or restore stocks to levels that can produce the maximum sustainable yield (MSY), with the aim of achieving these goals for depleted stocks on an urgent basis, and where possible not later than 2015. MSY is a 'moving target' that will be greatly influenced by the prevailing climatic conditions, as well as the abundance of other species that are prey, predators or competitors of the species of concern.

In the case of North Sea cod, Cook & Heath (2005) estimated that climate change has been eroding the maximum sustainable yield at a rate of 32,000 t per decade since 1980. Calculations show that the North Sea cod stock, could still support a sustainable fishery under a warmer climate but only at very much lower levels of fishing mortality, and that current 'precautionary reference' limits or targets (e.g. FMSY), calculated by ICES on the basis of historic time-series, may be unrealistically optimistic in the future. Climate change may lead to a collapse of fisheries resources in certain management areas. Drinkwater et al. (2005) showed that cod stocks at the southern end of their geographical range may decrease or even collapse if temperature increases by 1-4 oC. In the Baltic, climate change is expected to increase the hypoxia events which may inhibit cod spawning, ultimately leading to a collapse of the stock (ref). Stakeholders may argue that there is no need to protect the resource as it will collapse anyway. Also it may jeopardise the stability of the fisheries agreements among the different resource users (Brandt and Kronbak, 2009).

3.5. Implications for fisheries and aquaculture

The study of how climate change may impact the distribution and productivity of commercially exploited fish stocks is still in its infancy. Nevertheless, (Cheung et al. 2010) explored the potential impact of climate change scenario's on the global catch potential for a number of exploited marine fish and invertebrates using a bio-climate envelope approach. They showed that climate change may lead to large-scale redistribution of global catch potential, with an average of 30–70% increase in high-latitude regions and a drop of up to 40% in the tropics. Moreover, maximum catch potential declines considerably in the southward margins of semi-enclosed seas while it increases in poleward tips of continental shelf margins. From the same research team, a recent publication suggested that the maximum body size of fish species could decrease as a result of the higher temperatures and reduced level of oxygen (Cheung et al., 2012).

Climate change may increase the cost of fishing if the distance to the fishing grounds increases when species shift their distribution. It is likely that the catch efficiency of fishing gears will be affected by changes in temperature and oxygen levels as fish physiology and behaviour adapt, but the direction and strength of the effect is uncertain.

Impact of climate change on aquaculture was reviewed by (Callaway et al. 2012). Marine aquaculture mainly occurs in coastal habitats. Sea-level rise will shift shoreline morphology and may reduce the habitats suitable for aquaculture. Increased frequency of storm surges may pose a risk for aquaculture infrastructure such as seed collectors, fish cages, etc. Climate change may increase the risk of harmful algal blooms that will have an adverse effect on the farming of molluscs. Ocean acidification may negatively impact the early developmental stages of shellfish. Some of the most damaging but least predictable effects of climate change relate to the emergence, translocation and virulence of diseases, parasites and pathogens.

On the positive side, global warming may allow the farming of warm water species. Fish-farming is dependent on fishmeal and fish-oil produced by the global market of reduction fisheries, to a large extend dependent on the productivity of upwelling regions such as off the coast of Peru and Namibia. Hence, fish farming potential is impacted by the effects of climate change on the production of small pelagics (Merino et al. 2010).

3.6. Implications for management

Fisheries management

Fisheries resources will not only be impacted by climate-change, but also by fisheries. The contribution of climate change and fisheries to changes in the ecosystem are not always easy to disentangle, as they will interact and affect resources in a non-linear manner. The uncertainty about the multiple effects of climate change give rise to a situation where different stakeholders disagree about the relative effect of climate change and fisheries, and differ in their view on the management measures required. See for instance the debate about the Plaice Box (Verweij et al. 2010).

The changes in distributions of commercially exploited fish stocks (see 2.2) may raise international disputes, when major fish concentrations leave their traditional management area and enter a new management area. The current debates between the EU and Norway and Iceland about the mackerel is an example.

The scientific prognosis that Baltic cod may collapse under the climate change scenario's of the IPCC, may be taken to mean that there is no need to protect the cod and that the fisheries can therefore be allowed to take the remaining fish. The question is how certain the prognosis of the stock collapse is.

The effects of climate change on fish species low in the food chain (eg. Norway pout, capelin, sandeel) may indirectly affect the exploitable resources and the conservation objectives of species higher up in the food chain such as mammals, birds, tuna, sharks, and may spark a conflict between different stakeholders. In the debate on marine management, it is important to clearly specify the management objectives. Is the management focused on the conservation of biodiversity or on the sustainable use of a fisheries resource.

Climate change will challenge the current way in which the scientific basis of fisheries management is organised. Climate change will increase the uncertainty about the dynamics of the resources and makes the future less predictable; the implications will be particularly relevant for the medium and long term management considerations: (i) implications for the biological reference points for fisheries management; (ii) effectiveness of the MSY approach; (iii) design of multi-annual management plans; (iv) design of the network of MPA's; (v) formulation of biodiversity conservation objectives. For short term management climate change will be largely irrelevant.

The emergence of new fisheries on species which have not been exploited before, will require additional data collection to allow science based advice. On the other hand, sampling level requirements for traditional species may not be feasible anymore if these species are declining due to climate change. In order to improve our understanding on the impacts of climate change on marine ecosystems in general, and on exploited fisheries resources in particular, long term data collection programs need to be maintained and even expanded to include other trophic levels and ecosystem components. Because ecosystem models play an important role in studying the impact of climate change on fisheries resources, dedicated research programs are needed to collect information on vital rates (growth, survival, physiology) to validate and improve predictability / reduce uncertainty in these models.

Climate change may require a reform of the current marine resource management plans to make them robust to the impact of climate change. As climate change is expected to be too slow with regard to the time steps in the current management policies (annual TACs in the CFP), it does not provide an impetus for implementing an adaptive management although there may be other reasons in support for this.

Nature management

Species or ecosystems with a special conservation status will be affected by climate change and may shift their distribution patterns. Because the response to a change in for instance temperature will differ between species, climate change is expected to influence the species composition and ecosystem functioning. This may imply that management measures imposed to conservation of biodiversity may need to be reconsidered. Along the same line, the ecosystem effects of fisheries may change when fisheries follow the change in distribution of their target species and may move into more or less vulnerable ecosystems.

Similar to fisheries management, the uncertainty about how climate change will impact the marine populations and ecosystems, make it problematic to reach consensus about the management measures required for biodiversity conservation if there is scientific uncertainty about the cause of changes in the status of threatened species. For example, the long lived bivalve *Arctica islandica* lives at the southern edge of its range in the southern North Sea, and an increase in temperature may push the southern limit to the north. At the same time, the species is vulnerable for bottom trawling. This raises the question whether specific conservation measures are required to conserve this species on the Dutch continental shelf.

4. Ecosystem overviews[2]

After the development of EMIGMA, which enables the handling of large amounts of long-term data series, it was realized that for integrated data use and analyses a further overall visualisation of data and cause-effect relationships is a prerequisite. The newly developed Ecosystem Overviews (EO) are an integrated visualisation that enable a combined view of the main parts of the ecosystem, the temporal development of major organisms or groups of organisms and the temporal development of both natural and man-made drivers of change.

Figure 9 is an example of an integrated ecosystem overview that we developed for the Dutch coastal marine ecosystem.

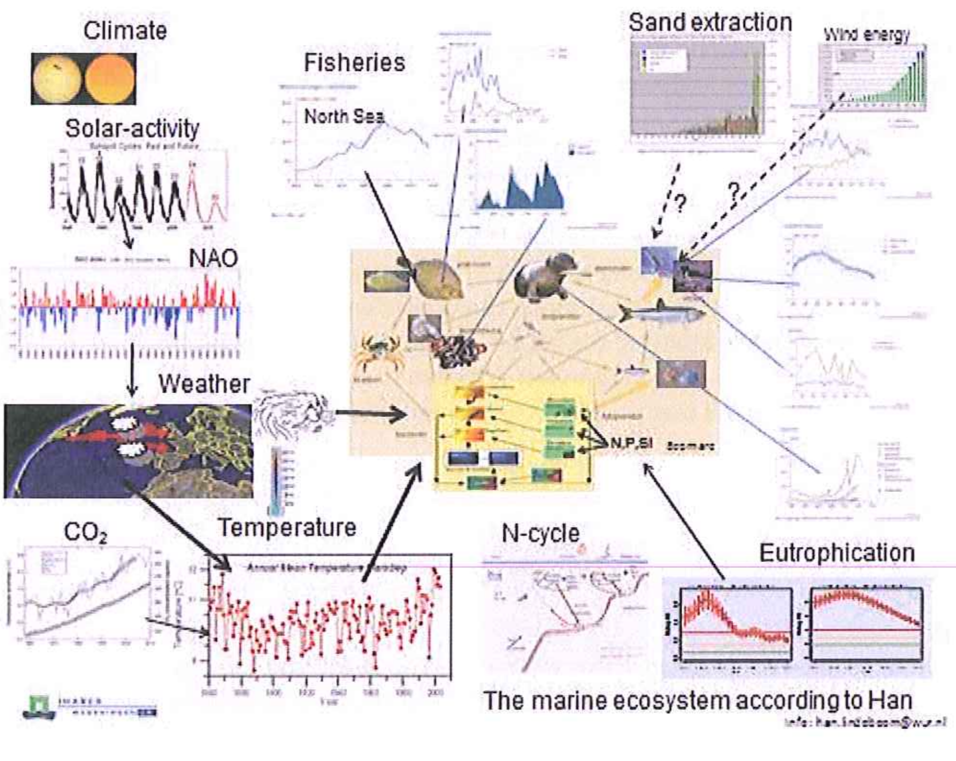

***Fig 9**: Example of an Ecosystem Overview of the Dutch Coastal Zone (mainly Wadden Sea). See text for further explanation.*

This Figure depicts a conceptual model (or picture) of the ecosystem, drivers of change and trends in important species. Central is a simplified diagram of the mean features of the ecosystem and food web. Major features like small food web (plankton), benthos, fish, birds and sea mammals are depicted

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2 From: Lindeboom H.J., J. van der Meer, R. Witbaard, J. Kok, E.H. Meesters, S. Alvarez-Fernandez, P. Ruardij. (Submitted). North Sea management tools: Modelling, EMIGMA and Ecosystem Overviews. In: Regional Environmental Change

(source Ecomare). This central picture is surrounded by the temporal development of drivers of change like climate, fisheries, eutrophication, sand extraction and wind energy (sources: van Aken 2008; Brinkman 2008; www.zeeinzicht.nl). Also temporal trends in important species like fish, birds and mammals (sources CBS 2011; Wortelboer 2010) have been added to this picture. Since we hypothesize that the nitrogen cycle, with or without a major denitrification step, may play an important role in the changes we also added a picture of the major features of this cycle. The arrows indicate the hypothesized or conceptual influence of the different drivers upon the different features of the ecosystem.

In the picture several striking phenomena can be observed, giving food for thought. The annual mean temperature of the Marsdiep (van Aken 2008) has been high in the last two decades but was also almost as high between 1860 and 1870. Marine regime shifts have been detected in 1977/78, 1988/89 and 2000/01 (Weijerman et al. 2005; Alvarez et al. in press), indicating that these might be approximately eleven years events, suggesting that there might be a link with solar activity. The 1988/89 regime shift with i.e. a sharp decrease in Plaice abundance seems to be related to a shift in temperature (Weijerman et al. 2005; Alvarez et al. in press). When comparing the temperature increase of 1.5° C in the last decades (van Aken 2008) with the modelled temperature increase due to CO_2 increase of 0.5°C, we could hypothesize that about one-third of the increase has an anthropogenic cause, while two-thirds could be more related to natural variability. We realize that this is a very far-fetched hypothesis, but in this way the tool is used to trigger out of the box thinking. Another driver of change in the last decades is the decrease in eutrophication, whereby a shift from a nitrogen limited system to a phosphate limited system around 1990 lead to a shift in algal composition and dominance (Philippart et al. 2000). Fisheries, through (over)harvesting of living resources or damaging of benthic ecosystems is another major driver of change (Lindeboom 2005). While sand extraction and beach nourishment could influence turbidity and sedimentation and wind farms create new hard substrates for specific benthos or have an influence on birds. The effect of these drivers is largely unknown but seems relatively small. Climate change is seen as a major cause of change, whereby changes in wind (see also the model results) might be as important or even more important than changes in temperature.

This new way of visualisation was presented in the Advisory Committee of the International Council for Exploration of the Sea (ICES) and in the Biodiversity Commission of the Oslo-Paris Commission (OSPAR). Both encouraged further development in close cooperation with these commissions. To create a useful tool for marine management it was decided to focus on pressures and descriptors and to separate the drivers in manageable and non-manageable drivers. Figure 10 gives an example for North Sea Biodiversity. Again, central is a simplified picture of the local ecosystem. Now we distinguish between non-manageable pressures (like climate and ocean inflow) and manageable pressures (like fisheries, artificial hard substrates and Marine Protected Areas (MPAs)). As indicators different faunal groups, like zooplankton, fish and birds are depicted, while the occurrence of different habitats is also seen as an important indicator for this descriptor (ICES 2008[a]). Once accepted as visualisation tool, the big challenge now is to include all available and useful data series and to further analyse the relationships.

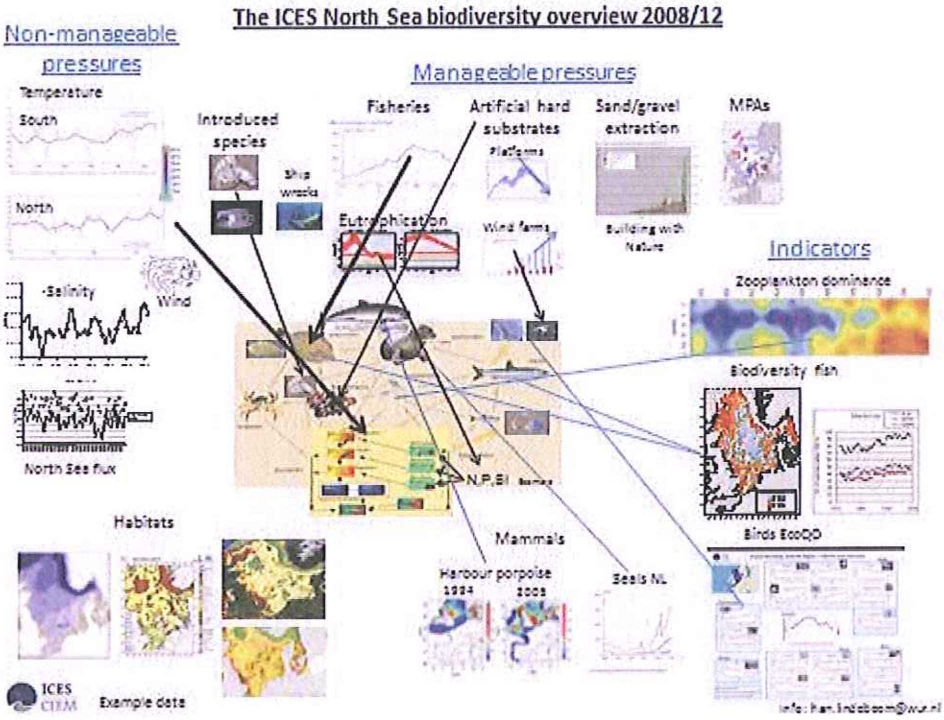

Fig 10: Example of an Ecosystem Overview focussing on North Sea Biodiversity with indicators, non-manageable and manageable pressures (source of pictures: ICES 2008[3]).

ICES has many data series and it will be possible to make these overviews for the eight major ICES sea areas. Then these can easily be used for more detailed analyses. As an example we will analyse the trends in certain fish stocks in the North Sea and six other European seas in relation to changes in temperature in these seas.

5. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

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The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Dr. Lorna Teal
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Date: 6th of November 2012