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Climate Change Impacts on the Baltic Sea Fish Stocks and Fisheries - Review with a focus on Central Baltic herring, sprat and cod

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Abstract

Climate change is likely to induce substantial changes in the Baltic Sea, as it is a species-poor ecosystem where virtually all species live close to their environmental tolerance range. The vitality of the fish stocks and viability of fisheries should be supported by consideration of global change in the management of environment (protection, sustainable use and restoration) and of fisheries. A shift away from sector-by-sector management towards the integrated management of land, water and living resources may be necessary to sustain the productivity of fish stocks. The climate change and other concomitant human pressures induce substantial uncertainties for the future, especially as responses of marine ecosystems to changes in temperatures and in other forcing factors may not be linear, but abrupt changes may occur, which also need to be considered in exploitation of fish resources.

1 Introduction

1.1 Scope of the fish stocks and fisheries review

This review aims to highlight the expected effects of climatic change on fish resources in the Baltic Sea, especially on Baltic herring, sprat and cod in the Baltic Proper, because these species have the highest contribution to fisheries, to other fish stocks and to the ecosystem function. However, focusing on these stocks does not mean that the importance of other fish stocks and basins of the Baltic Sea could be ignored in the climate context. The review also addresses the fisheries sector as well as the fisheries and ecosystem management.

1.2 Fish biodiversity in the Baltic Sea

The diversity of the Baltic Sea fish community is linked in particular to the geological evolution of the basin after the last ice-age, to climatic and oceanographic evolution, and to biogeography i.e. distribution of species in space through geological time (e.g. Hiddink and Coleby 2011). The Baltic Sea fish stocks are from various origins: marine, freshwater and migratory species as well as glacial relicts. Besides, specimens from marine species which cannot establish themselves are irregularly found and an increasing numbers of invasive species occur. The number of species gets smaller with decreasing salinity and towards higher latitudes. In the Kattegat, 175 species of fish and lampreys have been found while in the Bornholm Basin 108, in the northern Baltic Proper 61 and in the Bothnian Bay 48 species have been observed (HELCOM 2012).

Marine fish species dominate especially in the open sea area but freshwater species are abundant in coastal and estuarine areas where salinity is low. The share of marine fishes decreases and freshwater fish increases towards the northern and eastern parts. River spawning migratory fish, such as Atlantic salmon, trout and whitefish support important commercial and especially recreational fisheries around the Baltic Sea. However, especially many migratory fish stocks have already collapsed or disappeared due to anthropogenic environmental changes (e.g. destruction of the reproduction areas of migratory species, eutrophication) and because of excessive exploitation.

Endemic fish species have not been reported to be found in the Baltic Sea (Ojaveer et al. 2010) but e.g. Ojaveer & Kaleis (2005) stated that the Baltic fish populations of marine origin have been adapted to the environmental conditions of the Baltic Sea so that they cannot be treated as having the same biological and life history parameters as their ancestors that live in comparatively constant oceanic conditions. A typical example is the Baltic herring, a subspecies of the Atlantic herring.

1.3 Characteristics of the marine fish populations of Baltic Sea

Herring

Herring has a wide distribution and high economic importance for fisheries in seas of the northern hemisphere. In the Baltic Sea, herring forms together with sprat and cod the bulk of the fish biomass and catches. The distribution of herring covers virtually the whole Baltic Sea as they can tolerate e.g. low salinity. However, studies about genetics of herring have found zones of decreased mixing of populations between the northern and southern populations in the Baltic Sea (Jørgensen et al. 2005a) although the genetic differences are small within the Baltic Sea and even between the Baltic herring and herring from the North Sea and the Atlantic Ocean (Ryman et al. 1984, André et al. 2011). Even herring which spawn on the same locations in discrete spawning waves may represent genetically distinct spawning populations (Jørgensen et al. 2005b).

Morphological variations among sub-populations of herring as well as variation in spawning times and migration patterns also support that locally adapted populations exist (e.g. Aro 1989; Parmanne et al. 1994). Moreover, the consistent area-specific patterns in weight-at-age (e.g. ICES 2012) and the spatial differences in the concentrations of persistent pollutants in the tissues of herring (Bignert et al. 2007, Karl & Ruoff 2007, Vuorinen et al. 2012) prove the existence of local relatively stable subpopulations. As suggested in the case of Atlantic herring (McQuinn 1997, McPherson et al. 2003, Mariani et al. 2005), the Baltic herring dynamics and population structure may well be described with the theory of metapopulations. Along these lines, there apparently exists a certain degree of isolation between Baltic Sea herring spawning populations but they mix during feeding. In fisheries management it is a challenging task to ensure that even weak subpopulations survive if the species is exploited in a mixed stock fishery and climate is changing at the same time.

The growth rate of herring is low in the Baltic Sea and they only grow to a fraction of the weight attained in more saline waters. The herring growth rates tend to decrease towards areas with lower salinity and salinity has been shown to be a factor to influence herring weight (e.g. Rönkkönen et al. 2004). Salinity may influence fish growth via direct impacts to physiology (see Boeuf & Payan 2001) or through influences in ecosystem function and in ecological interactions (Rönkkönen et al. 2004). As the weight-at-age does not exactly follow the salinity gradients, it is possible that the subpopulations of herring have differences in salinity tolerance or other environmental factors partly mask the impacts of salinity.

During the recent decades there have been remarkable variations in herring growth rates (Figure 1). The smaller fish are poor material for the processing industry (Stephenson et al. 2001) and slow growth rates also contribute to the high concentrations of persistent organic pollutants via bioaccumulation (Kiljunen et al. 2007, Peltonen et al. 2007). In the Gulf of Finland the weight-at-age peaked in 1975–1980 and thereafter decreased even to one third (J. Pönni, unpublished). Several reasons have been suggested to contribute to the decreased growth rate, linking the changes with impacts of fishing, fish species interactions (predation, competition), changes in migrations patterns, eutrophication, climate change, hydrography and alien species (Beyer & Lassen 1994, Raid 1998, Flinkman 1999, Cardinale & Arrhenius 2000, Rönkkönen et al. 2004, Casini et al. 2006, Peltonen et al. 2007, Casini et al. 2010). As the fluctuations in the herring growth rates during the recent decades have occurred relatively coherently but in somewhat different magnitude in different basins of the Baltic Sea, they are likely to at least partly arise from common, climate-induced processes.

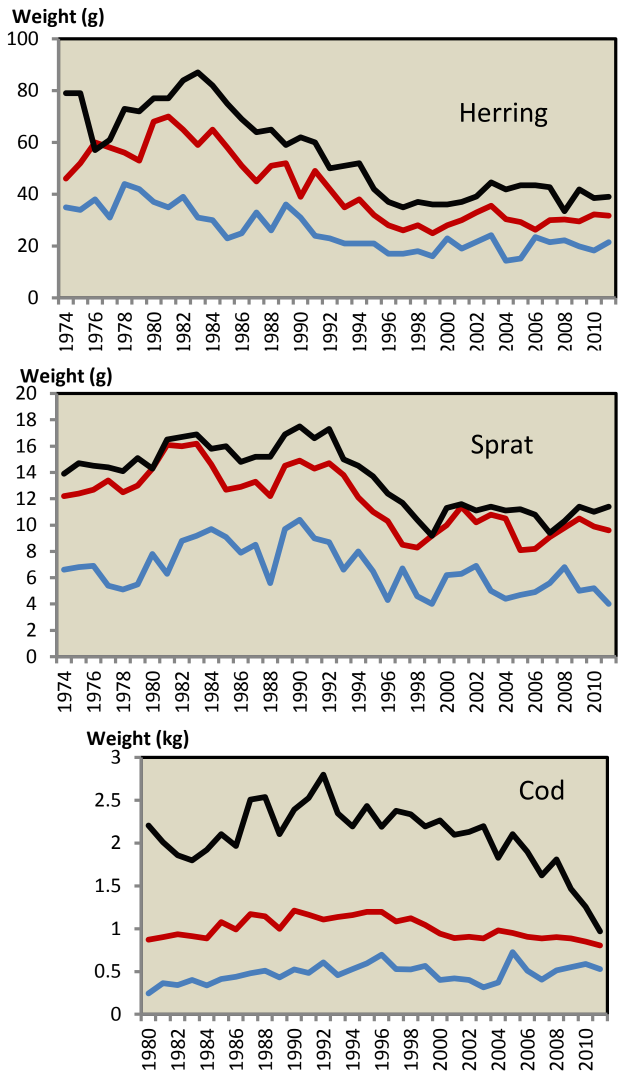

Figure 1: The average annual weight-at-age of the central Baltic herring, sprat and cod in ages 2 (blue), 4 (red) and 6 years (black) in the commercial catches (ICES 2012).

Sprat

Sprat is a small, pelagic, schooling, zooplankton feeding fish species distributed over a broad geographical range. In Europe it occurs from the Black and Mediterranean Seas in the south to the European Atlantic shelf, including the North and Baltic Seas (Parmanne et al. 1994, Peck et al. 2012). It tolerates a wide range of salinities and is abundant also in estuarine habitats (Peck et al. 2012). Sprat makes seasonal migrations depending on the environmental conditions but there is no certainty if sprat in the Baltic Sea is a uniform population or not (Parmanne et al. 1994). The growth rate of sprat decreased during the 1990's (Figure 1).

Cod

Cod is a large predatory fish important for the ecosystem function and for fisheries. It is considered that there are two distinct cod populations in the Baltic Sea (excluding the Kattegat). The eastern stock is found east of Bornholm and up to the Gulf of Finland and Gulf of Bothnia and the western stock to the west of the Bornholm Island (Aro 2000 and references therein). However, the populations also mix and the distribution areas of each stock component tend to get wider when the abundance is increasing.

Nielsen et al. (2003) found that genetic differentiation increased gradually along a transect from the North Sea through the Danish straits to the Baltic Sea, while there were not significant differences between samples from Bornholm basin, Gdansk Basin and Gotland Basin. Genetic differences between populations can tell whether there is mixing between populations, but based on such information it is difficult to know if a collapsed fish population could be replaced with immigrants from adjacent areas, because even small genetic differences between populations can be constant and biologically meaningful in marine fish (Knutsen et al. 2011). In marine species even a minimal genetic difference inducing single amino acid replacement in a protein can be essential for adaptation to rising temperature, while adaptation is a challenge e.g. if a cold-water species has during evolution lost the genes needed for coping with rising temperature (Somero 2010).

As the cod spread out far away from the spawning grounds, a large cod stock can support substantial fisheries in the Bothnian Sea and Gulf of Finland while during times of low abundance cods are absent from these areas (e.g. Aro 2000). The cessation of reproduction in the northernmost reproduction areas due to unfavorable environmental conditions during the recent decades (Cardinale and Svedäng 2011) may influence the rate of dispersion of cod to the northern Baltic. Although the eastern Baltic cod stock has recently started to recover, after two decades of severe depletion, the stock has not re-occupied its former wide distribution range, but has so far mainly remained in a limited area in the southern Baltic Sea (Eero et al. 2012). The weight-at-age of cod has decreased dramatically during the last few years (Figure 1). It is remarkable that there have been changes in spatial distribution of key species as central Baltic herring and sprat abundance has gradually increased in the northern and decreased in the southern parts of the Main Basin (Eero et al. 2012). As fisheries compete with cod of the same prey stocks (herring and sprat), it is essential to consider the spatial overlap between species in developing ecosystem based fisheries management aiming at rebuilding predator stocks (Eero et al. 2012).

1.4 Fisheries and catches

The Baltic Sea has high fish production in respect to surface area and the fish stocks support substantial commercial and recreational fisheries (Figure 2). ICES (2012) has summarized the characteristics of the Baltic Sea fisheries:

"The main target species in commercial fishery are cod, herring and sprat. They constitute about 95% of the total catch. Other target fish species having either local economical importance or ecosystem importance are salmon, plaice, flounder, dab, brill, turbot, pike-perch, pike, perch, vendace, whitefish, burbot, eel and sea-trout.

The main fisheries for cod in the Baltic use demersal trawls, pelagic trawls and gillnets. The importance of longlines has increased in later years probably due to cheaper costs of vessels exploitation in that type of passive gear fishery and also due to maintained quality of the fish. In the cases where longlines are increasing it is in general at the expense of gillnet fishery. There was a substantial increase in gillnet fisheries in the 1990s and because of the change in stock age composition in late 1990's and early 2000. During 2005 the use of passive gears has increased in relation to trawls, which is probably a reflection of the rising fuel prices.

The catches of the pelagic species are used for human consumption, reduction to oil and meal and to animal fodder. The allocation of the catches into these categories differs not only by country, but also over time. The usage is to a large extent driven by the market conditions.

While feeding in the sea, salmon are caught by long lines (as drift nets have been banned in the Baltic) and during the spawning run they are caught along the coast, mainly in trap nets and fixed gillnets. Where fisheries are allowed in the rivermouths, set gill nets and traps nets are used.

The coastal fishery targets a variety of species with a mixture of gears including fixed gears (e.g. gill, pound and trap nets, and weirs) and Danish seines. The main species exploited are herring, salmon, sea trout, flounder, turbot, cod and freshwater and migratory species (e.g. whitefish, perch, pikeperch, pike, smelt, vendace, eel and burbot). In addition, there are demersal trawling activities for herring, cod and flatfishes in some parts of the Baltic, although the trawling is forbidden in the coastal zone in most of the countries. Coastal fisheries are conducted along the entire Baltic coastline."

During the 20th century the catches from the Baltic Sea increased ca. 10 fold when more fish was left for the fisheries after extermination of marine mammal populations, the sea became more eutrophied due to anthropogenic nutrient release and fishing became more efficient (Elmgren 1989, Thurow 1997). However, as the estimated total landings by the ICES (International Council for the Exploration of the Sea) may not include all unreported landings, discards and recreational removals, the true removals of fish from the populations may have been at least 35% higher during 2000-2007 (Zeller et al. 2011).

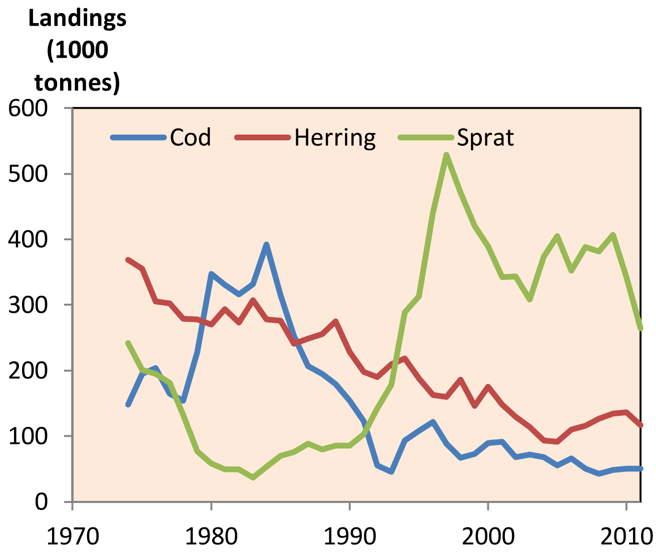

Figure 2: The landings of the central Baltic cod, herring and sprat during 1974–2011 (ICES 2012).

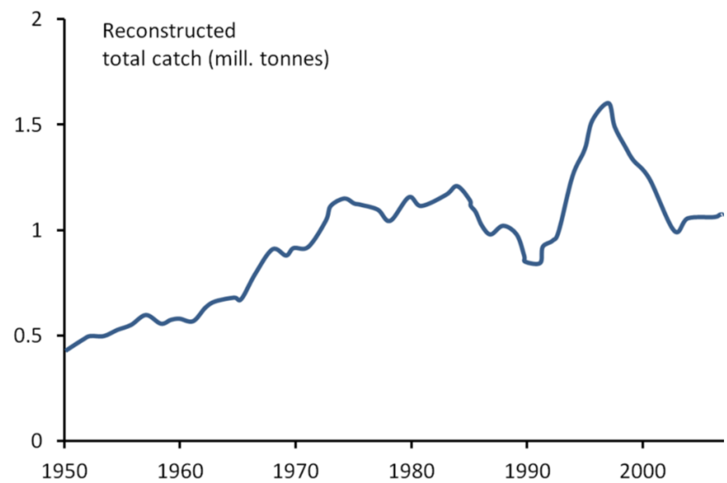

Figure 3: Reconstructed total catches (1950–2007) from the Baltic Sea in millions of tonnes (redrawn from Zeller et al. 2011).

Thus, the reconstructed removals increased from ca. 0.5 million tonnes in 1950's to ca. 1.6 million tonnes in 1997 in the Baltic Sea excluding Kattegat (Figure 3) but decreased to roughly 1.0 million tonnes in 2005–2007 as e.g. the abundance and catches of sprat decreased.

1.5 Fish stock assessment and advice to support management

Fish stock assessment is a fundamental element in fisheries management. Several monitoring programmes annually collect data on catches and fisheries in the Baltic Sea to be used in the assessment work, and also collect fishery-independent data on the stock dynamics of the most important marine fish stocks (e.g. ICES 2012). Such data sets have been collected during the past 2–4 decades, while more indirect calculation methods have been applied to derive fish biomass estimates in earlier decades (Elmgren 1989, Thurow 1997, Harvey et al. 2003, Alheit et al. 2005, Österblom et al. 2007). The assessments conducted and management advice considering the marine species can be found in ICES (2011, 2012). Salmon and trout are assessed in another expert group within the ICES.

1.6 Fisheries management

As the Baltic coastal states except Russia are members of the European Union, their fisheries are regulated by the EU which has a bilateral fisheries agreement with Russia. The EU member states have limited freedom to introduce national regulations except in inshore fisheries within the 12 nautical mile limit from the coastline.

The management of the Baltic Sea fisheries has been summarized as follows (Burns & Stöhr, 2011 and references therein).

"The EU countries agreed in 1983 on the Common Fisheries Policy (CFP). With about 2000 rules, it is one of the most comprehensive fisheries governance agreements world-wide regulating all aspects of fishing. In this governance system, the EU Council of Ministers is the highest decision-maker determining broad policy measures that are to be implemented by the member-state Fishing Ministries. The most important determination is the annual total allowable catches (TACs), which are distributed among the member states according to the "principle of relative stability". The European Commission (more precisely, DG Maritime Affairs and Fisheries, DG MARE) prepares and proposes the regulations for the Council. The Council together with the EU Parliament are the main co-deciders of legislation and policy.

Although the regulatory power is concentrated at the EU level, the decisions are informed by several knowledge sources. The most important knowledge source for EU fisheries policy is the International Council for the Exploration of the Sea (ICES), an umbrella organization for the national research institutes, where the data collected on status and prognosis of fish stocks are organized and interpreted. Based on the data obtained and the application of the precautionary principle, ICES provides recommendations for policy measures of which the annual Total Allowable Catch (TAC) is the most important. In addition, the Commission established the Scientific, Technical and Economic Committee for Fisheries (STECF) in 1993 and renewed it in 2005. The Committee consists of scientists that provide advice on the current status of fisheries resources, their development and any consequent economic implications. The second source of information comes from stakeholders that, especially in the recent years, have gained greater opportunities to provide advice to the European Commission."

In 2004 a new organization type, namely Regional Advisory Council (RAC), was established in EU fisheries management system by a Council Decision (2004/585/EC). The aim is to enhance to participation of fisheries and other sectors. RACs have a possibility to give recommendations and suggestions to the Commission. There are seven RACs. Five of them focus on specific geographical areas and two operate on highly mobile, long-distance fleets (EC 2012a).

Baltic Sea RAC was started in 2006. It has members from fishing sector ranging from fisheries organisations to processors and marketing. In addition, also environmental and consumer organizations have their representatives as well as recreational and sports fisheries. The Baltic Sea RAC has also a women's network. The RAC has three working groups: demersal fisheries, pelagic fisheries and a working group for salmon and trout fisheries (BSRAC 2012).

EU regulations comprise also technical regulatory measures, such as mesh sizes, minimum landing sizes, by-catch limitations and periods, and closed areas. In spite of some success, the CFP has not enabled optimal use of fish resources (http://ec.europa.eu/fisheries/reform/index_en.htm):

"Europe's fisheries policy is in urgent need of reform. Vessels are catching more fish than can be safely reproduced, thus exhausting individual fish stocks and threatening the marine ecosystem. Today, three out of four stocks are overfished: 82% of Mediterranean stocks and 63% of Atlantic stocks. The fishing industry is experiencing smaller catches and facing an uncertain future. It is time to make fishing environmentally, economically, and socially sustainable."

By bringing fish stocks back to sustainable levels, the new common fisheries policy (CFP) aims to provide EU citizens with a stable, secure and healthy food supply for the long term. It seeks to bring new prosperity to the fishing sector, end dependence on subsidies and create new opportunities for jobs and growth in coastal areas. At the same time, it fosters the industry's accountability for good stewardship of the seas.

The reformed CFP will enter into force in 2013. The overall objective of the proposal is to ensure fishing and aquaculture activities that provide long-term sustainable environmental conditions and contribute to the availability of food supplies. The policy shall be aimed at exploitation of living marine biological resources that restores and maintains fish resources at levels which can produce the maximum sustainable yield, not later than 2015. The CFP shall implement the precautionary and ecosystem approaches to fisheries management.

In addition to annually set TACs, the EU has adopted multiannual management plans for specific fisheries. Nine multiannual management and recovery plans have been established for nine different fisheries (EC 2012b):

"Each multiannual plan is based on a harvest control rule that is tailor-made for the fishery in question. This is a simple mathematical formula which converts quantifiable scientific data into proposed catch and effort limits for the coming year. As a general rule, annual changes in TAC and effort should not exceed a certain percentage, except where stocks are under the most pressure. In this way, the plans also provide greater stability for the fishing industry and enable operators to plan ahead."

In 2007 a multiannual plan for managing cod stock in the Baltic Sea was launched (Council Regulation (EC) No 1098/2007). Its aim is to reduce fishing mortality on a long period to set the set target. The multi-annual plan for cod is the only multi-annual plan in force in Baltic Sea so far, but a similar plan is being prepared for pelagic fisheries. The European Commission has also proposed a plan for the Baltic salmon.

2 Climate Pressure

Climatic variations induce changes in the environmental gradients across the Baltic Sea, e.g. in salinity, temperature, oxygen concentration and ocean acidification. Climate also influences the vertical stratification of the water column in respect to several environmental features. Due to climate change, the area covered with sea ice is expected to decrease which will influence the ecosystem in large areas (BACC 2008 and references therein). According to regional climate projections, air temperature over the Baltic Sea will increase by ca. 3°C during the 21st century, the largest changes predicted for the Gulf of Bothnia (Meier et al. 2012).

Climate is a driver inducing fluctuations in the salinity of the Baltic Sea. During the 20th century the mean salinity of the Baltic Sea was at its lowest, ca. 7.2, in 1930–1935, increased steadily from 1936 to 1954, remained at 7.9–8.2 during 1955–1979 and declined again to ca. 7.3 during 1980–1993

(Heino et al. 2008). Thus, the current low salinity period is not yet exceptional but the predicted changes for the next century are larger than any changes during the recent history of the Baltic Sea.

Both air temperature and sea surface temperature (SST) of the Baltic have already increased. Air temperatures increased by +0.08°C per decade during 1871–2004 (Heino et al. 2008). Sherman et al. (2009) found that SST had increased in 61 of the 63 Large Marine Ecosystems of the world during 1982–2006, and the most pronounced increase, 1.35°C, had occurred in the Baltic Sea. The exceptionally rapid warming of the Baltic Sea can apparently be explained by its northern location, strong influences from the surrounding continent, the small water volume and shallow mixed surface layer. Local long-term studies have confirmed that the summer SST has increased by at least 1°C during the past 50 to 60 years in the open sea of the northern (Rönkkönen et al. 2004) and southern Baltic (MacKenzie & Schiedek 2007). A more extensive review of expected climate driven changes in Baltic Sea hydrography is given in the Baltadapt Climate Info Bulletins (www.baltadapt.eu).

3 Environmental Consequences of Climate Change

3.1 Climate change is likely to influence the eutrophication

Eutrophication is apparently the foremost environmental problem in the Baltic Sea. To support the productivity of the key marine fish stocks, it is essential to improve the eutrophication status in the Baltic Sea by decreasing the anthropogenic nutrient release to the sea. The Baltic Sea Action Plan (BSAP) for ecosystem management and protection has defined management goals for the Baltic Sea (Helcom 2007).

Due to climate change, it will be necessary to increase the efforts to reduce nutrient loading even more than scheduled so far for example in the BSAP (Meier et al. 2012). Impacts of climate change on the eutrophication of the Baltic Sea have been highlighted in the Baltadapt Climate Info Bulletins (www.baltadapt.eu).

3.2 Climate change and biodiversity

As most species in the Baltic Sea live close to their tolerance limits in regard to one or more environmental factors, climate variations influence the distribution and productivity of species and the productivity of the fish stocks. During the ‘oceanization’ of the Baltic Sea in 1936–1954, various marine taxa such as certain copepods, jellyfish, barnacle, as well as cod, garfish and mackerel spread hundreds of kilometres northwards, whereas species preferring low saline waters retreated (Segerstråle 1969). During the recent desalination period (from 1980) a reverse process has taken place.

Climate change is likely to enable formerly subordinate species to increase and more alien species to become established. For example, both published and anecdotal information suggest that of the local fish species e.g. the three-spined stickleback may be increasing in the Baltic Sea as a consequence of intensive exploitation of predatory fish, eutrophication and climate change (Sieben et al. 2011, Candolin & Selin 2012). Increase of this species may induce chains of events inducing eutrophication in the coastal areas (Sieben et al. 2011) but as higher density in coastal areas promote invasion of stickleback to pelagic zone (Candolin & Selin 2012) they may increasingly compete for prey and feed on young herring, sprat and cod, and suppress production of these species.

Oceanographic variations influence the physiology of fish as well as the ecological fitness of fish via changing the ecosystem structure and function. Johannesson et al. have summarized the impacts of environmental changes on the Baltic Sea biota as follows:

“Environmental change challenges local and global survival of populations and species. In a species poor environment like the Baltic Sea this is particularly critical as major ecosystem functions may be upheld by single species. A complex interplay between demographic and genetic characteristics of species and populations determines risks of local extinction, chances of re-establishment of lost populations, and tolerance to environmental changes by evolution of new adaptations. Recent studies show that Baltic populations of dominant marine species are locally adapted, have lost genetic variation and are relatively isolated. In addition, some have evolved unusually high degrees of clonality and others are representatives of endemic (unique) evolutionary lineages. We suggest that a consequence of local adaptation, isolation and genetic endemism is an increased risk of failure in restoring extinct Baltic populations. Additionally, restricted availability of genetic variation owing to lost variation and isolation may negatively impact the potential for evolutionary rescue following environmental change."

3.3 Climate change and ecosystem regime shifts

Ecosystems are at constant change. The changes can be gradual, but numerous studies have found and discussed step-like shifts in aquatic ecosystems. Regimes are considered as relatively stable states, during which e.g. gradual increase in temperature or nutrient loading has little effect but as a threshold is reached a large shift occurs that might be difficult to reverse (Scheffer & Carpenter 2003). It has been stated that the anthropogenic effects (nutrient and pollutant release, hunting of marine mammals, depletion of predatory fish) together with climate change have pushed the Baltic Sea ecosystem through a series of regime shifts during the 20th century (Österblom 2007, Möllmann et al. 2009). Alheit et al. (2005) emphasized that climatic forcing induced the remarkable shift in the ecosystem in late 1980's, which occurred simultaneously with a corresponding shift in the North Sea. As a consequence, phytoplankton biomass increased, growing season extended, abundance of copepods (that are essential food for key fish species) exhibited coherent changes in abundance with NAO (North Atlantic Oscillation) and increased the productivity of the sprat population (Alheit et al. 2005).

3.4 Climate changes and zooplankton production

Zooplankton is an essential link in the food chain between lower trophic levels and the fish populations in the open sea. Virtually all young fish feed on zooplankton and thus, variations in zooplankton community influence the nourishment of larval and young fish, and contribute to the year-class strength and to the productivity of the fish stocks. The pelagic food chain (in which zooplankton plays an essential role) has become more important for fish production in the open sea during the recent decades because hypoxia has e.g. decimated the energy pathways from the benthic fauna to cod in large deep water areas (Elmgren 1989, Tomczak et al. 2012).

Several studies have pointed out that climatic variations in the Baltic Sea and northern Atlantic area propagate through hydrography to productivity of zooplankton suitable for larval and older herring, sprat and cod. In particular, the decrease of the large copepod *Pseudocalanus* which live in the Baltic proper on the margin of distribution with respect to salinity is considered as a key factor controlling herring and cod stock dynamics (Hinrichsen et al. 2002, Möllmann et al. 2003, Rönkkönen et al. 2004). However, also abundant stocks of planktivorous fish can contribute to shifts in zooplankton community, which can lead to retarded growth and poor condition in planktivorous fish (Dippner et al. 2001, Möllmann et al. 2005, Casini et al. 2006, Casini et al. 2010). Another contemporary change in zooplankton has taken place as eutrophication and climate warming have contributed to the blooms of cyanobacteria which have diverted the energy pathways in the ecosystem in a way which does not support fish production (Karjalainen et al. 2007). Furthermore, climate warming may support invasion of alien species, such as the predatory warm-water-preferring *Cercopagis pengoi* waterflea which may add another level to the food chain especially in areas with low salinity, and thereby decrease fish production (Gorokhova et al. 2000, 2005).

4 Consequences of Climate Change on Fish Stocks

Climate change challenges local and global survival and productivity of marine populations and species, and endangers fisheries. In particular, multiple stresses on fish stocks e.g. climate change together with excessive exploitation can endanger survival of the unique fish populations adapted to the Baltic Sea. In the Baltic Sea, climate change is likely to have drastic consequences to the fish stocks and fisheries as changes will take place e.g. in salinity, temperature, oxygen content, acidification as well as in ecosystem function. Decreased salinity is likely to decrease marine fish reproduction, which is the most sensitive life cycle stage, while large fish can survive in lower salinities.

4.1 Climatic impacts on reproduction of fish

Cod

The climatic effects contributing to the reproduction of cod have been emphasized in several studies (Köster et al. 2005 and the references therein, McKenzie et al. 2005, 2007, Heikinheimo 2008, Eero et al. 2011). Cod is a marine species, but the eastern Baltic Sea cod in particular, is adapted to low salinity. The eggs are buoyant and can survive if the salinity is above 11 and oxygen concentration is above 2 ml/l (Wieland et al. 1994). These thresholds delimit the pelagic habitat suitable for cod reproduction which is also known as the reproductive volume (Wieland et al. 1994).

The conditions for cod reproduction depend on the frequency and magnitude of inflows of saline oxygen-rich North Sea water and precipitation and freshwater run-off from the drainage basin. The reproduction of cod is poor during periods without major inflows of saline oxygen-rich water (Nissling 2004). During these stagnant periods the decomposing sinking organic material depletes oxygen reserves in deep water. While the eastern Baltic cod historically spawned at three known locations: the Bornholm Deep, the Gdansk Deep and the Gotland Deep (Aro 1989), due to unfavourable environmental regime only the Bornholm Basin is known to serve as a spawning site in recent years (Cardinale and Svedäng 2011). Anyhow, so far cod reproduction has succeeded each year to some extent in spite of low abundance of spawning fish, unfavourable oceanographic conditions and high abundance of clupeid fish, sprat in particular which feed on the eggs and larvae of cod (e.g. Cardinale & Svedäng 2011, ICES 2012). Indeed, Heikinheimo (2008) has questioned the utility of the reproductive volume concept, because she found that variations in salinity together with the spawning stock abundance better explained the eastern Baltic cod year-class strength.

The long term projections for the salinity, temperature and oxygen concentration (Meier et al. 2012) suggest that the cod reproduction area may slightly decrease towards the 22nd century even if nutrient loading would decrease. However, there was relatively large variation among models, and e.g. the expected increase in agricultural nutrient load may increase nutrient loads to the sea and bring about unwanted changes in water quality (Meier et al. 2012).

So far excessive fishing has been a major force to delimit cod production in the Baltic Sea. In spite of the relatively poor conditions for the reproduction during the last two decades of the 20th century, lower fishing pressure on cod would have enabled a rapid increase in cod biomass (e.g. Heikinheimo 2008). However, inefficiency in fisheries management and illegal fishing enabled too large catches in respect to the productivity of the cod stock, whereby the spawning stock was on a low level during two decades since the late 1980's (Cardinale & Svedäng 2011, ICES 2012). Ultimately, in 2005–2010 the fishing mortality in the Eastern Baltic cod (dwelling in the areas to the east of Bornholm Island) decreased drastically as a consequence of new fisheries management methods, and a rapid increase in the cod spawning stock biomass is taking place even in the current 'cod hostile' environment which indicates the fundamental impact of fishing on the Baltic Sea fish stocks (Cardinale & Svedäng 2011, Eero et al. 2012) and highlights the need for adaptive fisheries management in the case of multiple stressors affecting the fish stocks.

Sprat

Sprat eggs are buoyant in salinities above 6 (Parmanne et al. 1994). Thus, they float higher than cod eggs and are not as much exposed to hypoxia. Although the spawning areas of sprat and cod overlap, sprat is able to utilize larger areas for spawning (Köster et al. 2003). From these areas sprat spread to large areas up to the Bothnian Sea and Gulf of Finland where they substantially contribute to the catches (e.g. ICES 2012). However, the sprat larvae are often exposed to temperatures below 5°C which is a temperature below which the mortality of larvae increases (Nissling 2004). The variations in reproduction success have induced large fluctuations in sprat stock density and in catches (Köster et al. 2003, Nissling 2004) although predation mortality by cod and fishing pressure also influence the spawning stock biomass (ICES 2012).

While the rising trend in water temperatures due to climate change apparently favors high sprat abundance (MacKenzie & Köster 2004, MacKenzie et al. 2007), lower salinity causes an adverse impact. Anyhow, for example the projected salinities during 2070–2100 (Graham et al. 2008, Meier et al. 2012) would imply that salinity is likely to be high enough e.g. in the Gotland deep area to enable sprat reproduction. However, it is likely that the area suitable for the reproduction of sprat will diminish from its eastern and northern parts (MacKenzie et al. 2007).

Herring

The distribution of herring encompasses virtually the whole Baltic Sea and the spawning of herring takes place in coastal areas of all major basins (Parmanne et al. 1994). Although high temperatures have been considered to support herring recruitment (MacKenzie et al. 2007 and references therein), coastal eutrophication due to excessive anthropogenic nutrient loads and increasing temperatures is likely to decrease the areas suitable for reproduction of spring spawning herring. The autumn spawning herring – which in the past was important but had greatly decreased already by early 1970's – spawns in deeper water (Parmanne et al. 1994), but also in these areas increasing eutrophication and coastal hypoxia may have decreased reproductive success.

4.2 Climate change and other key processes influencing the fish stocks in the central Baltic Sea

Both anthropogenic impacts and interactions between species are of prime importance for the Baltic Sea fish stocks. In fisheries management it is essential to understand the tight interaction between cod, herring and sprat and how these interactions are modified by climate change (Figure 4).

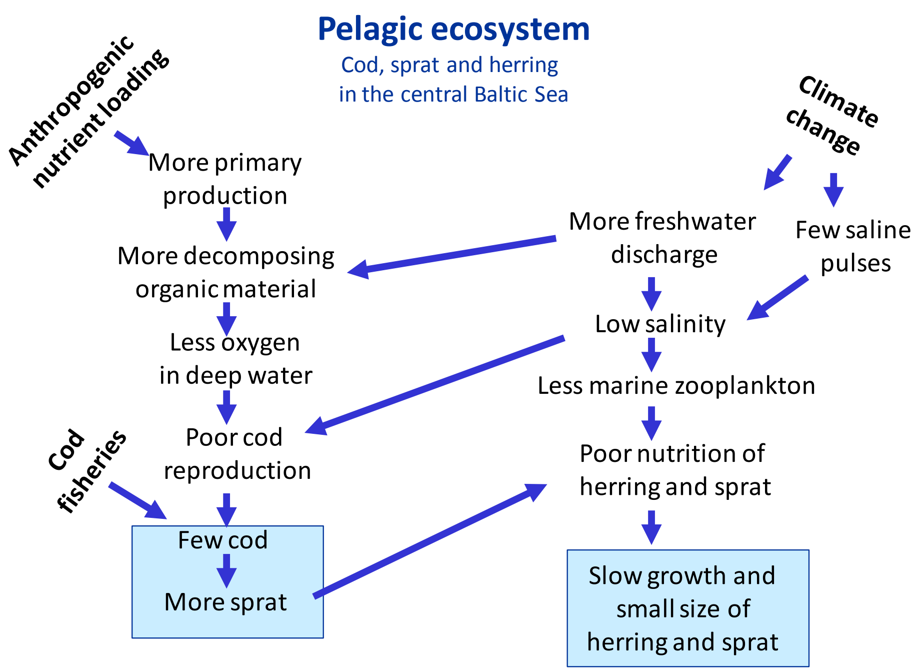

Figure 4: Key processes to influence the fish stocks in the central Baltic Sea.

Herring and sprat constitute a major part of the diet of large cod and e.g. in the early 1980's the predation by cod strongly contributed to the dynamics of sprat especially because cod was abundant and sprat stock on a low level (e.g. ICES 2012). Also the predation on young herring peaked in the early 1980's when cod abundance was on the highest level (ICES 2012). Herring and sprat are the major constituents of the diet of large cod, but sprat and herring feed on the pelagic eggs of cod and thereby delimit the stock size of cod (Köster and Schnack 1994, Köster and Möllmann 2000). Because of such interactions among species, the Baltic open sea fish community has a tendency to shift between cod-dominated and clupeid (sprat and herring)-dominated states, though fishing and climate-driven oceanographic variations can contribute to the shifts between cod-dominated and clupeid-dominated states (Rudstam et al. 1994, Nissling 2004, Österblom et al. 2007, Heikinheimo 2011).

4.3 Dynamics, management and ecosystem services of cod in a changing climate

During ca. 20 years from the late 1980's until early 21st century, fishing on cod in the Baltic Sea was excessive considering the relatively unfavourable climatic and oceanographic regimes in cod reproduction (e.g. Cardinale & Svedäng 2011, ICES 2012). Larger catches of cod would have been taken with lower fishing intensity or by catching older specimens, and the recruitment would have been higher if the spawning stock would have been larger. However, a larger cod stock would suppress the abundance of herring and sprat. Total catches of sprat, herring and cod could decrease if cod would recover. However, the predators such as cod also feed on prey species which are not utilized by fisheries (Pauly et al. 1998, 2002) and some predation mortality can even be considered beneficial for the prey species, for ecosystem function and even for the fishing industries. In the Baltic Sea more predation on herring could increase herring weight-at-age as cod selectively feed on smaller individuals from each age-groups (e.g. Beyer & Lassen 1994). Additionally, higher mortality on herring and sprat would also alleviate the competition for food and thus increase the growth rate of herring (Peltonen et al. 2007). Larger herring would e.g. support fishing industries by providing larger fish for processing (Stephenson et al. 2001).

The risks associated with excessive fishing mortality also include unwanted genetic changes in harvested populations (e.g. Kuparinen & Merilä 2008). Another disadvantage of removing the top-predators such as cod from a food web is the increased likelihood of outbursts of unwanted species (Pauly et al. 2002) whereas an abundant cod stock might control the increase of alien species and the production from such species would add to the nourishment of the cod stock.

Above all, a low exploitation rate serves as quarantine against the risk of collapse or even extinction of a heavily exploited species or population (Roberts & Hawkins 1999, Musick et al. 2000). A population which is heavily exploited already when the specimens are young consists of only few age-groups. Poor recruitment due to unfavourable environmental conditions during several successive years can decimate such populations. Decreasing the exploitation rates can be considered as a sound strategy to follow when seeking to build capacity against the adverse effects of climatic variations and climate change. In the Baltic Sea there is not any other fish species capable to fill in the ecological niche presently occupied by cod and to support equally valuable catches.

Optimization of cod fisheries would not just ensure maintaining steady biomass and high level in annual cod catches even if environmental variations occur but also help to resolve the problems arising from the high concentrations of persistent pollutants such as dioxins and PCBs in the Baltic Sea fish (Kiljunen et al. 2007, Peltonen et al. 2007). Currently, the Baltic Sea ecosystem is severely contaminated by organic toxic substances such as PCBs and dioxins. In fatty fish such as salmon and herring the concentrations especially in the central and northern Baltic often exceed the limits set by EU for foodstuffs (Bignert et al. 2007, Karl and Ruoff 2007, Vuorinen et al. 2012). Higher predation mortality in herring and sprat would decrease the fraction of very old individuals having the highest concentrations of toxic substances. Besides, some predation on these fish stocks could also decrease their completion of food resources (e.g. zooplankton), increase growth rate, induce higher rate of growth dilution of persistent pollutants (as fish eat less per unit of weight increase and that way acquire less such substances) and decrease concentrations of these contaminants in fish (Kiljunen et al. 2007, Peltonen et al. 2007). Apparently, predation by cod would be more efficient than fishing to enhance the growth rates of herring and sprat and to decrease the concentrations of persistent pollutants in fish (Peltonen et al. 2007).

Cod supports the most valuable fisheries in the Baltic Sea, it is a key species in the ecosystem, and it supports numerous ecosystem services. But it is also the most susceptible of the key species to the effects of climate change. As the shifts in the vital environmental constraints have not yet prevented reproduction of cod, we do not yet know how close the total failure of reproduction has been. The cod stock must not be exploited efficiently especially during the periods of poor recruitment and the management model parameters derived in good environment cannot be applied in altered environment (Köster et al. 2009, Lindegren et al. 2010, Eero et al. 2011). The management must ensure that a wide age and size spectrum in the population will enable survival of the cod stocks even though climate change together with other environmental stressors would cause exceptionally poor reproduction in one year or even in several successive years. Exceptionally small year classes of cod are more likely to occur in future, because in addition to the impacts of climate change, other anthropogenic pressures on marine life are also continuously increasing.

While cod may control the abundance of prey fish, the cod stock on the other hand supports nutrition for the increasing number of seals. Anyhow, MacKenzie et al. (2011) consider that dual management objectives (recovery of both seal and cod populations) are realistic but success in achieving these goals will also depend on how climate change affects cod recruitment.

5 Adaptation Measures

The fishing in the Baltic Sea is a diverse trade, the operational environment of which is constantly changing. Fisheries have always needed to adapt as changes have taken place in fish resources, technologies, regulation of fishing, demand of fish, costs of fishing etc. These factors together with the pace and magnitude of the climate-induced changes determine if and how well the fish stocks and fisheries will be able to adapt.

There are few major fish stocks in the Baltic Sea, but they constitute renewable natural resources which have enabled maintaining major fisheries for hundreds of years. Although, the current share of fishing is relatively small in the economies in any of the riparian countries around the Baltic Sea, it is likely that also in future there will be demand of fish, especially as the worldwide demand of food and raw material is rapidly increasing.

It is inevitable that fishing can only continue if there is a sound resource base i.e. productive fish stocks available. During the recent decades the exploitation of the Baltic Sea fish resources has been excessive leading to loss of profit and to damage to the fish stocks and to the marine environment. An improved status of fish stocks can be achieved through environmental management (protection, sustainable use and restoration) and through fisheries management.

The severe and increasing anthropogenic environmental stress on the Baltic Sea calls for a holistic view so that the impacts of an individual sector of human activity (such as marine transport, construction, excavation, release of substances, fishing etc.) are not evaluated in isolation from the other activities. Thus, the management of the living resources of the Baltic Sea should rely on the principles of the ecosystem approach i.e. of the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. It remains to be seen if the reform of the common fisheries policy or the management of marine environment relying largely on EU regulation will be influential. Österblom et al. (2010) discuss how the ecosystem approach could be made operational in the Baltic Sea concluding that emphasis on multilevel governance structures that provide space for experimenting and spread of social innovations at local and regional scales can provide key elements for stimulating an adaptive capacity for dealing with this dynamic ecosystem and the services generated.

Reliable data is needed to support assessment and management of the marine ecosystem and the fisheries. For example, as there may be substantial biases in the catch statistics, the total catch estimates should also include unreported landings, discards and recreational catches (e.g. Zeller et al. 2011) as well as unobserved fishing mortality (mortality of fish due to encounter with fishing gear, e.g. Rahikainen et al. (2004)). However, the needs for the quality of the monitoring and the modeling of the marine environment and the fish stocks depend on the level of exploitation. If fish stocks are intensively exploited, intensive monitoring and reliable modeling are needed to support management that will avoid excessive exploitation and collapses of populations. If the marine environment will be more variable due to climate change, more monitoring efforts would be needed in future. However, the costs of observing fisheries are large as there are many small fleets. The resources that will be allocated on monitoring also depend e.g. on the valuation – i.e. are other ecosystem services relying on the fish stocks and on a healthy ecosystem considered or just the commercial value of the catches?

According to the Commission proposal for a new CFP regulation, multiannual approach in management of all stocks will become a rule, not an exception. In comparison to time scales relevant in climate change dynamics the multiannual plans still have a short-term perspective and thus are not a tool for adaptation as such. The CFP regulations are usually set for 10 year periods, which is also a rather short time in comparison to climate change dynamics. However, the idea of long-term thinking could be incorporated into EU fisheries policy development. A possible method is so called 'adaptation tipping points' approach. A tipping point is a situation when changes caused by climate change reach a magnitude when the existing management strategy will not anymore meet the agreed objectives. In such a situation a policy may fail and new one is needed (Kwadijk et al. 2010). Identification and characterization of such tipping points or triggers as "warning signs" could help fisheries management to take into account possible climate change impacts.

6 Knowledge Gaps

Although much is known about the dynamics of the principal marine fish species and about the processes that have shaped the fish stocks, uncertainties are substantial in forecasting the dynamics of the ecosystem and the fish species. In particular, it is challenging to forecast the influences of simultaneous changes in several forcing factors. It is evident that each species should not anymore be examined in isolation from other species and from the environment, especially as a fish population collapse can release unforeseen ecological processes on other ecosystem levels. So far few efforts have been made to include the impacts of fish and fisheries in models on ecosystem dynamics. Anyhow, ecosystem modeling is needed to assess the human impacts on fish populations and to assess the potential value arising from a healthier ecosystem and from productive fish populations. Ecosystem services and non-monetary values which fish stocks support are poorly known although they may be much more important than the economic value of commercial catches.

There are uncertainties as regards population structures of many Baltic Sea fish stocks as they may consist of sub-populations which mix on the feeding grounds. It is unlikely that immigrants from other populations (e.g. from the North Sea) would be able to substitute the original ones and moreover, collapses of original populations and species may facilitate immigration of unwanted alien species.

It is a challenge to forecast the marine ecosystem dynamics though high quality work is being conducted around the Baltic Sea. Fish stocks are dependent on the production on lower trophic levels. But will the food webs in the Baltic Sea support energy to higher trophic levels or will the function of the food webs change so that pathways of energy will be diverged away from fish production? Will there be more harmful algal blooms, diseases and species competing about the same resources with fish?

It is widely agreed that fishing should not cause damage to fish stocks, to non-target species or to marine environment. But the adaptation of fisheries depends on many other aspects than fish resources including e.g. socio-economic issues. These may be even more challenging to predict than dynamics of fish stocks. Management has to find out how much fish could be caught and how much to leave in the sea so as not to endanger future catches and to ensure ecosystem function. And how to manage in a socially and economically reasonable way – e.g. how to find a balance between nations or fleets and between commercial, recreational and artisanal fishing? And how much to weight the expected long term productivity compared to the short term gains?

7 Summary and Conclusions

The Baltic Sea is a productive ecosystem but several aspects make the ecosystem and the species of the Baltic Sea and the fisheries particularly vulnerable for climate change. Fish stocks are impacted as the Baltic Sea is experiencing a larger rate of temperature elevation than any other large marine ecosystem. Changes are occurring in hydrography, in saline water pulses from the North Sea to the Baltic Sea, in freshwater run-off, in loads of substances to the sea and in the biogeochemical processes and pathways of substances in the sea. Concomitantly with the climate change, the Baltic Sea is facing increasing anthropogenic stress due to a multitude of other human activities (even if some positive changes have taken place, especially recovery of some species once heavily reduced due to chemical pollution).

A cornerstone for the management of renewable natural resources is that the exploitation must not deplete the resource beyond recovery. In the Baltic Sea fisheries this is a very relevant aspect considering that re-colonization from adjacent areas is unlikely if current populations from the Baltic Sea disappear. Species adapted for the local environment are unlikely to be re-established if once lost from the Baltic Sea. The Baltic Sea has restricted connections with possible donor areas of marine species which may hinder re-colonization if local populations became extinct, while established populations are not able to "escape" climate change by shifting their distribution ranges northwards. Due to isolation from other populations, the species have lost genetic variation, which may prevent their evolutionary rescue from climate change. The steep vertical and horizontal environmental gradients and seasonal variations challenge survival of species and delimit re-colonization as virtually all species live close to their environmental tolerance range in respect to one or more environmental factors. As the Baltic Sea is a species-poor ecosystem where major ecosystem functions are upheld by single or a few species, disappearance of such a species could lead to a major reorganization of the ecosystem with unforeseen and very likely unwanted consequences.

While many local populations suffer from climate change, invasions of alien species may increase, but the impacts of such species for ecosystem function and for fisheries are very difficult to forecast.

Climate change is inducing a multitude of shifts in the Baltic Sea which influence the fish stocks and fisheries. Fisheries management should promote sustainability in fisheries better than in the past, i.e. manage the fisheries considering the impacts of climate change and concomitant increasing exploitation of the Baltic Sea for various purposes. Ecosystem approach should cover human actions so that the resilience of the Baltic ecosystem towards unwanted shifts could be rebuilt. The roles of fish in the ecosystems should be better understood to e.g. find out how fisheries influence the whole ecosystem and if fisheries management could support mitigation of the anthropogenic effects on the sea, including the effects of climate change.

References

Alheit, J., Möllmann, C., Dutz, J., Kornilovs, G., Loewe, P., Mohrholz, V. and Wasmund, N. (2005): Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. ICES J. Mar. Sci. (62):1205–1215.

Andre, C., Larsson, L.C., Laikre, L., Bekkevold, D., Brigham, J., Carvalho, G.R., Dahlgren, T.G., Hutchinson, W.F., Mariani, S., Mudde, K., Ruzzante, D.E., and Ryman, N. (2011): Detecting population structure in a high gene-flow species, Atlantic herring (Clupea harengus): direct, simultaneous evaluation of neutral vs putatively selected loci. Heredity 106: 270–280.

Aro, E., (1989): A review of fish migration patterns in the Baltic. — Rapp.P.-v. Réun. Cons. int. Explor. Mer. 190: 72-96.

Aro, E. (2000): The spatial and temporal distribution patterns of cod (Gadus morhua callarias L.) in the Baltic Sea and their dependency on environmental variability – implications for fishery management. Ph.D. thesis. Department of Ecology and Systematics. University of Helsinki.

Beyer, J.E. and Lassen, H. (1994): The effects of size-selective mortality on the size-at-age of Baltic herring. Dana 10: 203-234.

Bignert A, Nyberg E, Sundqvist KL, Wiberg K. (2007): Spatial variation in concentrations and patterns of the PCDD/F and dioxin-like-PCB content in herring from the northern Baltic Sea. Journal of Environmental Monitoring 9:550-556.

Boeuf, G. and Payan, P. (2001): How should salinity influence fish growth? Comparative Biochemistry and Physiology Part C 130: 411-423.

BSRAC 2012. Baltic Sea Regional Advisory Council. (website accessed September 21, 2012, URL: http://www.bsrac.org/ooizzCMS/DA/home)

Burns, T.R. and Stöhr, C. (2011): Power, knowledge, and conflict in the shaping of commons governance. The case of EU Baltic fisheries. International Journal of the Commons 5, No 2 (2011). 13 pp.

Candolin, U. and Selin, M. (2012): Density-dependent habitat selection in a growing threespine stickleback population. International Journal of Zoology, Volume 2012, Article ID 378913, 6 pp. doi:10.1155/2012/378913

Cardinale, M., and Arrhenius, F. (2000): Decreasing weight-at-age of Atlantic herring (Clupea harengus) from the Baltic Sea between 1986 and 1996: a statistical analysis. – ICES Journal of Marine Science, 57: 882–893.

Cardinale, M. and Svedäng, H. (2011): The beauty of simplicity in science: Baltic cod stock improves rapidly in a ‘cod hostile’ ecosystem state. Marine Ecology Progress Series 425: 297–301.

Casini, M., Cardinale, M. and Hjelm, J. (2006): Inter-annual variation in herring, Clupea harengus, and sprat, Sprattus sprattus, condition in the central Baltic Sea: what gives the tune? Oikos 112: 638-650.

Casini, M., Bartolino, V., Molinero, J.C. and Kornilovs, G. (2010): Linking fisheries, trophic interactions and climate: threshold dynamics drive herring Clupea harengus growth in the central Baltic Sea. Marine Ecology Progress Series 413: 241–252.

Dippner, J. W., Hänninen, J., Kuosa, H., and Vuorinen, I. (2001): The influence of climate variability on zooplankton abundance in the Northern Baltic Archipelago Sea (SW Finland). – ICES Journal of Marine Science, 58: 569–578.

EC 2012a. Regional Advisory Councils. European Commission. (web site accessed September 21, 2012, URL: http://ec.europa.eu/fisheries/partners/regional_advisory_councils/index_en.htm)

EC 2012b. Multi-annual plans. European Commission. (website accessed September 21, 2012, URL:http://ec.europa.eu/fisheries/cfp/fishing_rules/multi_annual_plans/index_en.htm)

Eero, M., MacKenzie, B.R., Köster, F.W., and Gislason, H. (2011): Multi-decadal responses of a cod (Gadus morhua) population to human-induced trophic changes, fishing, and climate. Ecological Applications, 21: 214–226.

Eero, M., Vinther, M, Haslob, H., Huwer, B., Casini, M., Storr-Paulsen, M., Koster, F.W. (2012): Spatial management of marine resources can enhance the recovery of predators and avoid local depletion of forage fish. Conservation Letters 0: 1–7.

Elmgren, R. (1989): Man's impact on the ecosystem of the Baltic Sea: Energy flows today and at the turn of the century. Ambio 18: 326-332.

Flinkman, J., Aro, E., Vuorinen, I., and Viitasalo, M. (1998): Changes in northern Baltic zooplankton and herring nutrition from 1980s to 1990s: top-down and bottom-up processes at work. Mar. Ecol. Prog. Ser. 165: 127–136.

Gorokhova, E., Aladin, N. and Dumont, H.J. (2000): Further expansion of the genus Cercopagis (Crustacea, Branchiopoda, Onychopoda) in the Baltic Sea, with notes on the taxa present and their ecology. Hydrobiologia 429: 207–218, 2000.

Gorokhova, E., Hansson, S., Höglander, H., Andersen, C.M. (2005): Stable isotopes show food web changes after invasion by the predatory cladoceran Cercopagis pengoi in a Baltic Sea bay. Oecologia 143: 251–259.

Graham et al. (2008): Projections of future anthropogenic climate change. In.: BACC Author Team: Assessment of climate change for the Baltic Sea Basin. Springer Verlag Berlin Heidelberg. P. 133-219

Harvey, C. J., Cox, S. P., Essington, T. E., Hansson, S., and Kitchell, J. F. (2003): An ecosystem model of food web and fisheries interactions in the Baltic Sea. – ICES Journal of Marine Science, 60: 939–950.

Heikinheimo, O. (2008): Average salinity as an index of environmental forcing on cod recruitment in the Baltic Sea. Boreal Environment Research 13: 457-464.

Heikinheimo, O. (2011): Interactions between cod, herring and sprat in the changing environment of the Baltic Sea: A dynamic model analysis. Ecological Modelling 222: 1731–1742.

Heino, R., Tuomenvirta, H., Vuglinsky, V.S. et al. (2008): Past and Current climate change. In.: BACC Author Team (2008) Assessment of Climate Change for the Baltic Sea Basin. Springer-Verlag, Berlin and Heidelberg, pp. 35-131.

HELCOM (2012): Checklist for Baltic Sea Fish and Lamprey Species. In: Checklist of Baltic Sea Macro-species. Baltic Sea Environment Proceedings No. 130. pp. 196-199.

HELCOM, (2007): HELCOM Baltic Sea Action Plan. HELCOM Ministerial meeting, Krakow, Poland 15th November 2007. 102 p.

Hiddink, J.G. and Coleby, C. (2011): What is the effect of climate change on marine fish biodiversity in an area of low connectivity, the Baltic Sea? Global Ecology and Biogeography, 21: 637–646.

Hinrichsen, H-H., Möllmann, C., Voss, R., Köster, F.W., Kornilovs, G. (2002): Biophysical modeling of larval Baltic cod (Gadus morhua) growth and survival. Canadian Journal of Fisheries and Aquatic Sciences, 59, 1858–1873.

ICES (2011): Report of the ICES Advisory Committee, 2011: Book8, Baltic Sea. 134 p.

ICES (2012): Report of the Baltic Fisheries Assessment Working Group (WGBFAS). ICES Advisory Committee ICES CM 2012/ACOM: 10. 853 p.

Johannesson, K., Smolarz, K., Grahn, M., and Andre, C. (2011): The Future of Baltic Sea Populations: Local Extinction or Evolutionary Rescue? AMBIO (2011) 40:179–190. DOI 10.1007/s13280-010-0129-x

Jørgensen, H.B. Hansen, M.M., Bekkevold, D., Ruzzante, D.E. and Loeschcke, V. (2005a): Marine landscapes and population genetic structure of herring (Clupea harengus L.) in the Baltic Sea. Molecular Ecology 14: 3219–3234.

Jørgensen, H. B. H., Hansen, M. M., and Loeschcke, V. (2005b): Spring-spawning herring (Clupea harengus L.) in the southwestern Baltic Sea: do they form genetically distinct spawning waves? ICES Journal of Marine Science, 62: 1065-1075.

Karjalainen, M., Engström-Öst, J., Korpinen, S., Peltonen, H., Pääkkönen, J.-P., Rönkkönen, S., Suikkanen, and Viitasalo, M. (2007): Ecosystem consequences of cyanobacteria in the northern Baltic Sea. Ambio 36(2-3): 195-202.

Karl, H. and Ruoff, U. (2007): Dioxins, dioxin-like PCBs and chloroorganic contaminants in herring, Clupea harengus, from different fishing grounds of the Baltic Sea. Chemosphere 67: 90–95

Kiljunen, M., Vanhatalo, M., Mäntyniemi, S., Peltonen, H., Kuikka, S., Kiviranta, H., Parmanne, R., Tuomisto, J.T., Vuorinen, P.J., Hallikainen, A., Verta, M., Pönni, J., Jones R.I. and Karjalainen, J. (2007): Human dietary intake of organochlorines from Baltic herring: Implications of individual fish variability and fisheries management. Ambio 36(2-3): 257–264.

Knutsen, H., Olsen, E.M., Jorde, P.E., Espeland, S. H., André, C. and Stenseth, N. C. (2011): Are low but statistically significant levels of genetic differentiation in marine fishes 'biologically meaningful'? A case study of coastal Atlantic cod. Molecular Ecology 20, 768–783.

Kuparinen, A. and Merilä, J. (2008): Detecting and managing fisheries induced evolution. TRENDS in Ecology and Evolution 22: 652-659.

Kwadijk, J.C.J., M. Haasnoot, J.P. M. Mulder, M.M.C. Hoogvliet, A.B.M. Jeuken, R.A.A. van der Krogt, N.G.C. van Oostrom, H. A. Schelfhout, E. H. van Velzen, H. van Waveren and M. J. M. de Wit (2010): Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. Wiley Interdisciplinary Reviews: Climate Change 1(5): 729-740.

Köster, F.W., and Möllmann, C. (2000): Trophodynamic control by clupeid predators on recruitment success in Baltic cod? ICES Journal of Marine Science, 57: 310–323.

Köster, F.W. and Schnack, D. (1994): The role of predation on early life stages of cod in the Baltic. Dana, 10: 179-201.

Köster, F.W., Hinrichsen, H-H., Schnack, D. et al. (2003): Recruitment of Baltic cod and sprat stocks: identification of critical life stages and incorporation of environmental variability into stock-recruitment relationships. Scientia Marina, 67 (Suppl. 1), 129–154.

Köster, F.W., Vinther, M., MacKenzie, B.R., Eero, M., and Pliksh, M. (2009): Environmental effects on recruitment and implications for biological reference points of Eastern Baltic Cod (Gadus morhua). J. Northw. Atl. Fish. Sci., 41: 205–220. doi:10.2960/J.v41.m636

Lindegren, M., Möllmann, C., Nielsen, A., Brander, K., MacKenzie, B.R., and Stenseth, N.C. (2010): Ecological forecasting under climate change: the case of Baltic cod. Proc. R. Soc. B, 277: 2121–213.

MacKenzie, B., Eero, M. and Ojaveer, H. (2011): Could seals prevent cod recovery in the Baltic Sea? PLoS ONE 6 (5) e18998. www.plosone.org

MacKenzie, B.R., Gislason, H., Möllmann, C. and Köster, F.W. (2007): Impact of 21st century climate change on the Baltic Sea fish community and fisheries. Global Change Biology 13: 1348–1367.

MacKenzie, B. and Köster, F. (2004): Fish production and climate: sprat in the Baltic Sea. Ecology, 85: 784–794.

MacKenzie, B.R. and Schiedek, D. (2007): Daily ocean monitoring since the 1860s shows record warming of northern European seas. Global Change Biology (2007) 13, 1335–1347, doi: 10.1111/j.1365-2486.2007.01360.x

MacKenzie, B.R., St.John, M.A, Schnack, D., Rohlf, N., Linkowski, T., Beyer, J.E. (2005): Baltic cod recruitment – the impact of climate variability on key processes. ICES Journal of Marine Science 62: 1408–1425.

Mariani, S., Hutchinson, W.F., Hatfield, E.M.C., Ruzzante, D. E., Simmonds, E.J., Dahlgren, T.G., Andre, C., Brigham, J., Torstensen, Else, Carvalho, G.R. (2005): North Sea herring population structure revealed by microsatellite analysis. Marine Ecology Progress Series. 303: 245–257.

McPherson, A.A. Stephenson, R.L., Taggart, C.T. (2003): Genetically different Atlantic herring Clupea harengus spawning waves. Marine Ecology Progress Series. 247: 303–309.

McQuinn, I.H. (1997): Metapopulations and the Atlantic herring. Reviews in Fish Biology and Fisheries 7: 297-329.

Meier, H. E. M., Hordoir, R., Andersson, H.C., Dieterich, C., Eilola, K., Gustafsson, B.G., Höglund, A., and Schimanke, S. (2012): Modeling the combined impact of changing climate and changing nutrient loads on the Baltic Sea environment in an ensemble of transient simulations for 1961–2099. Clim Dyn DOI 10.1007/s00382-012-1339-7

Musick, J.A, Harbin, M.M., et al. (2000): Marine, Estuarine, and Diadromous Fish Stocks at Risk of Extinction in North America (Exclusive of Pacific Salmonids). Fisheries 25(11): 6-30

Möllmann, C., Kornilovs, G., Fetter, M., and Köster, F. W. (2005): Climate, zooplankton, and pelagic fish growth in the central Baltic Sea. ICES Journal of Marine Science, 62: 1270-1280.

Möllmann, C. et al. (2009): Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime shift in the Central Baltic Sea. Global Change Biology 15: 1377–1393.

Möllmann et al. (2003): The marine copepod, Pseudocalanus elongatus, as a mediator between climate variability and fisheries in the Central Baltic Sea. Fish. Oceanogr. 12:4, 1–9.

Nielsen, E.E., Hansen, M.M., Ruzzante, D.E., Meldrup, D., and Grønkjær, P. (2003): Evidence of a hybrid-zone in Atlantic cod (Gadus morhua) in the Baltic and the Danish Belt Sea revealed by individual admixture analysis. Molecular Ecology 12: 1497–1508.

Nissling, A. (2004): Effects of temperature on egg and larval survival of cod (Gadus morhua) and sprat (Sprattus sprattus) in the Baltic Sea – implications for stock development. Hydrobiologia 514: 115–123.

Ojaveer, E., and Kalejs, M. (2005): The impact of climate change on the adaptation of marine fish in the Baltic Sea. ICES Journal of Marine Science, 62: 1492-1500.

Ojaveer, H., Jaanus, A., MacKenzie, B.R., Martin, G., Olenin, S., et al. (2010): Status of biodiversity in the Baltic Sea. PLoS ONE 5(9): e12467. doi:10.1371/journal.pone.0012467

Parmanne, R., Rechlin, O. and Sjöstrand, B (1994): Status and future of herring and sprat stocks in the Baltic Sea. Dana 10: 29–59.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. and Torres, F. (1998): Fishing down marine food webs. Science 279: 860-863.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J., Watson, R. and Zeller, D. (2002): Towards sustainability in world fisheries. Nature 418: 689-695.

Peck, M.A. et al. (2012): The ecophysiology of Sprattus sprattus in the Baltic and North Seas. Progress in Oceanography 103: 42–57.

Peltonen, H., Kiljunen, M., Kiviranta, H, Vuorinen, P.J., Verta, M. and Karjalainen, J. (2007): Predicting effects of exploitation rate on weight-at-age, population dynamics and bioaccumulation of PCDD/Fs and PCBs in herring (Clupea harengus L.) in the northern Baltic Sea. Environmental Science and Technology, 41: 1849-1855.

Rahikainen, M., Peltonen, H. and Pönni, J. (2004): Unaccounted mortality in northern Baltic Sea herring fishery – magnitude and effects on estimates of stock dynamics. Fisheries Research. 67: 111-127.

Raid, T. (1998): Herring in the North-Eastern Baltic Sea in the 1970-1990s: ecology stock structure and fishery. PhD Thesis. University of Helsinki and Estonian Marine Reseach Institute. 56 p.

Roberts, C.M. and Hawkins, J.P. (1999): Extinction risk in the sea. TREE 14: 241-246.

Rudstam, L.G., Aneer, G., and Hilden, M. (1994): Top-down control in the pelagic Baltic ecosystem. DANA 10: 105-130.

Ryman, .N, Lagercrantz, U., Andersson, L., Chakraborty, R. and Rosenberg, R. (1984): Lack of correspondence between genetic and morphologic variability patterns in Atlantic herring. Heredity 53: 687–704.

Rönkkönen, S., Ojaveer, E., Raid, T. and Viitasalo, M. (2003): Long-term changes in Baltic herring (Clupea harengus membras) growth in the Gulf of Finland. Canadian Journal of Fisheries and Aquatic Sciences, 61: 219–229.

Scheffer, M. and Carpenter, S.R. (2003): Catastrophic regime shifts in ecosystems: linking theory to observation. TRENDS in Ecology and Evolution 18 (1): 648-656.

Segerstråle, S.G. (1969): Biological fluctuations in the Baltic Sea. Prog Oceanogr 5:169-184.

Sherman, K., Belkin, I.M., Friedland, K.D., O´Reilly, J., Hyde, K. (2009): Accelerated warming and emergent trends in fisheries biomass yields of the World's large Marine Ecosystems. Ambio 38:215-224.

Sieben, K., Ljunggren, L., Bergström, U. and Eriksson, B.K. (2011): A meso-predator release of stickleback promotes recruitment of macroalgae in the Baltic Sea. Journal of Experimental Marine Biology and Ecology 397:79–84.

Somero, G.N. (2010): The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine ‘winners’ and ‘losers’. The Journal of Experimental Biology 213: 912-920.

Stephenson, R., Peltonen, H., Kuikka, S., Pönni, J., Rahikainen, M., Aro, E. and Setälä, J. (2001): Linking biological and industrial aspects of the Finnish commercial herring fishery in the northern Baltic Sea. In: F. Funk, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherell (eds.). Herring: Expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks, pp. 741-760.

Thurow, F. (1997): Estimation of the total fish biomass in the Baltic Sea during the 20th century. – ICES Journal of Marine Science, 54: 444–461.

Tomczak, M.A., Niiranen, S., Hjerne, O. and Blenckner, T. (2012): Ecosystem flow dynamics in the Baltic Proper — using a multi-trophic dataset as a basis for food–web modeling. Ecological Modelling 230: 123–147.

Vuorinen, P.J, Keinänen, M., Kiviranta, H., Koistinen, J., Kiljunen, M., Myllylä, T., Pönni, J., Peltonen, H., Verta, M., and Karjalainen, J. (2012): Biomagnification of organohalogens in Atlantic salmon (Salmo salar) from its main prey species in three areas of the Baltic Sea. Science of the Total Environment 421-422: 129–143.

Wieland, K., Waller, U. and Schnack, D. (1994): Development of Baltic cod eggs at different levels of temperature and oxygen content. Dana 10: 163-177.

Zeller, D., Rossing, P., Harper, S., Persson, L., Booth, S., Pauly, D. (2011): The Baltic Sea: Estimates of total fisheries removals 1950–2007. Fisheries Research 108: 356–363.

Österblom, H. et al. (2007): Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. Ecosystems (2007) DOI: 10.1007/s10021-007-9069-0

Österblom et al. (2010): Making the ecosystem approach operational — Can regime shifts in ecological-and governance systems facilitate the transition? Marine Policy34: 1290–1299.

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