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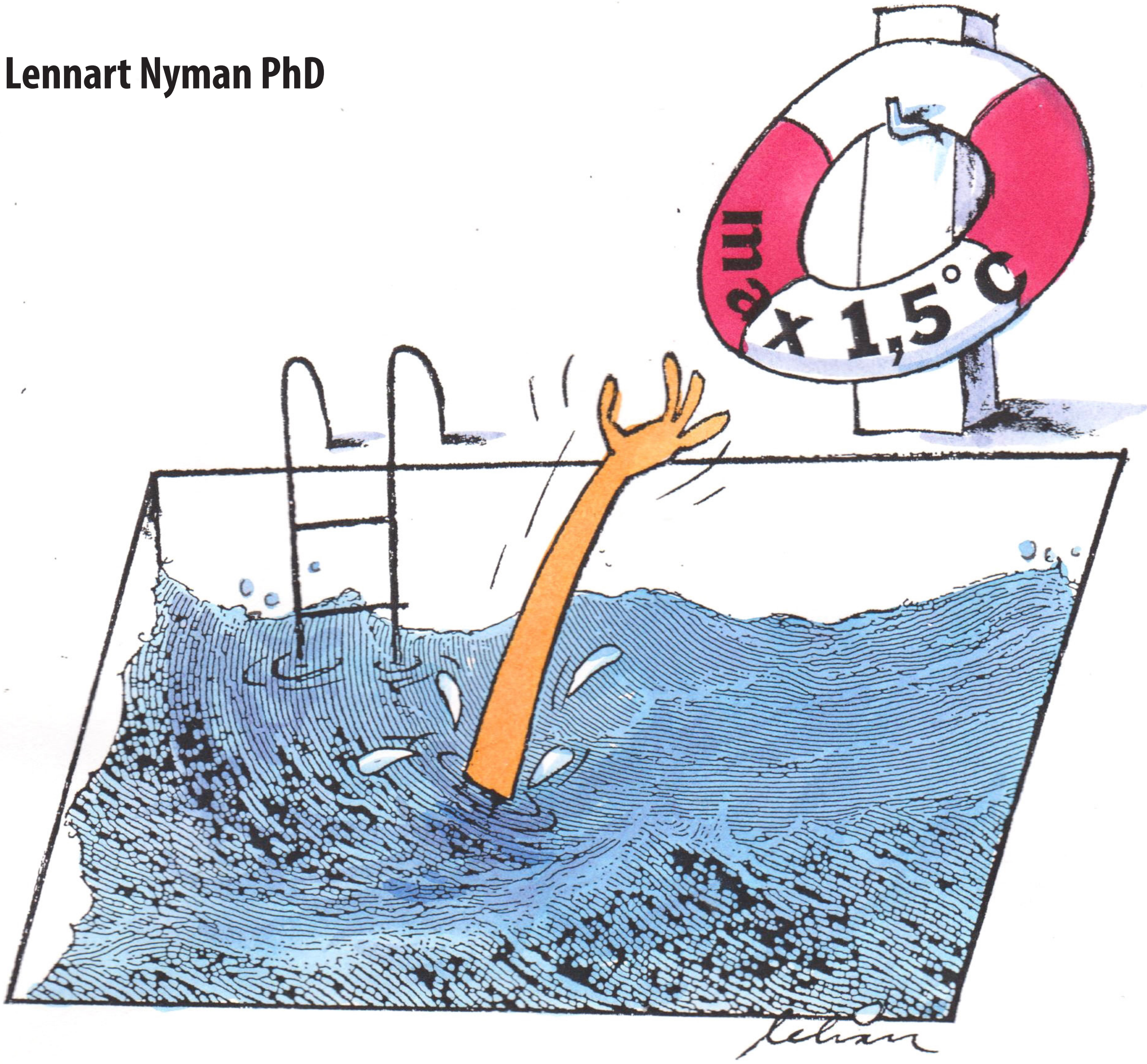
A 1.5 target is needed to save the Baltic Sea

Effects of global temperature increases on the biodiversity of the Baltic Sea.

by Lennart Nyman PhD



Air Pollution & Climate Secretariat

AirClim

AIR POLLUTION AND CLIMATE SERIES 35

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Effects of global temperature increases on the biodiversity of the Baltic Sea.

By Lennart Nyman PhD

Published in March 2016

Lennart Nyman is a scientist and environmentalist from Sweden who has worked for some 50 years studying various aspects of the Baltic ecosystem and other marine, freshwater and terrestrial ecosystems world wide. He has served for many years as Conservation Director with WWF-Sweden, and prior to that e g as Director of the Institute of Freshwater Research at Drottningholm, Sweden. He has been a member of numerous national and international boards, committees and societies on environmental issues.

Cover illustration: Lars-Erik Håkansson (Lehån).

Graphics and layout: Sven Ängermark/Monoclick

Language consultant: Malcolm Berry, Seven G Translations, UK

ISBN: 978-91-979623-7-7

Published in april 2016 by the Air Pollution & Climate Secretariat (AirClim) in corporation with Coalition Clean Baltic.

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The Secretariat is a joint project by Friends of the Earth Sweden, Nature and Youth Sweden, the Swedish Society for Nature Conservation and the World Wide Fund for Nature Sweden.
The report is also available in pdf format at www.airclim.org.

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Background

Few facts about the man-made effects of global climate change are as unchallenged and precise as the results of the so-called Keeling Curve (Figure 1).

This curve plots the increasing concentration of carbon dioxide in the Earth's atmosphere from 1958 until present time at an altitude of some 3,000 m in the clean air at the Mauna Loa Observatory in Hawaii. This is the longest continuous series of monitoring data for atmospheric carbon dioxide ever, and Charles David Keeling also perfected the measurement techniques. The concentration of carbon dioxide presently measured is probably higher than it has been in a million years and nowadays CO_2 levels are monitored at some 100 sites around the globe. As early as 1963 Keeling and his colleagues projected that carbon dioxide emissions at that time could raise the average surface temperature of the Earth by as much as 4 degrees C over the next century (1963–2063). Since 2005, Keeling's work has been continued by his son Ralph. In addition to finding a steady three per cent annual increase, Keeling also noted an annual maximum in May followed by a decreasing level during the northern spring and summer as new plant growth absorbs carbon dioxide from the atmosphere through photosynthesis. After reaching a minimum in October, the level again rises in northern fall and winter when plants die off and decay, releasing the gas back into the atmosphere. Carbon dioxide levels have risen from some 280 ppm in the 1800s to the present level of around 445 ppm (actually CO_2 equivalents). Currently the rate of CO_2 inputs exceeds 2.5 ppm annually, in comparison to annual inputs of 0.5 ppm in 1930–1950, 1 ppm in 1950–1970 and 2 ppm in 1970–1990.

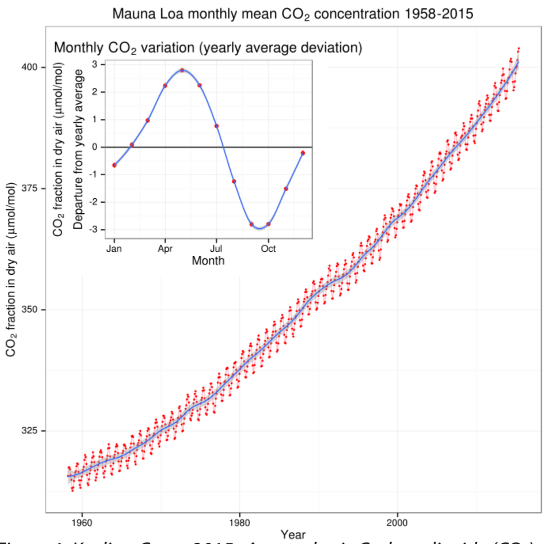

Figure 1. Keeling Curve 2015. Atmospheric Carbon dioxide (CO_2) concentrations from 1958–2015. https://en.wikipedia.org/wiki/Keeling_Curve.

This carbon dioxide is the single most important greenhouse gas emitted by human activities and, as one of its many effects, it leads to an increase in temperature of the global climate. It is predicted (Collins et al. 2013) that even if the greenhouse gases emitted remain constant at the present level there will be a continued global temperature increase of about 0.6 degrees C during the course of the 21st century relative to the year 2000, due to accumulation of already emitted CO_2. This warming will occur in addition to the 0.85 degree C global mean temperature increase experienced since the 1880s (Stocker et al. 2013).

Another effect of increasing carbon dioxide in the atmosphere is that it acts as the primary source of ocean acidification. One-third of the carbon dioxide emitted is absorbed by the world's oceans. In the sea it reacts with calcium and water to produce carbonic acid, which leads to a lowering of the pH. The current rate of ocean acidification is probably unprecedented in the past 300 million years (Pörtner et al. 2014). Based on current data it has been estimated that the pH will drop from the present level of 8.1 by another 0.5 units, which means that acidification will more than double in the 21st century in the Baltic Sea (Thor et al. 2014). This phenomenon has already caused severe implications for the global distribution of commercially important fish species and other sources of seafood. Global seafood security is at risk, and at lower trophic levels there will be a decrease in availability of carbonate ions, which are important building blocks required by marine organisms to build their skeletons, shells and other calcareous structures. One of the most species-rich marine ecosystems – the coral reef – is also projected to experience long-term degradation (primarily by coral bleaching) (Frieler et al. 2013). Climate change will also impact other drivers of biodiversity loss e.g. habitat modification, pollution, invasive species and extinction of species and unique local populations (Wennerström et al. 2013) with limited capacity for ecological adaptation to a warmer climate (Field et al. 2014). On a global time scale, species extinctions are already above the highest rates found in the fossil record, and past climate changes were considerably slower than those anticipated for the 21st century. Even slow rates of change in the past, however, drove significant ecosystem shifts and mass extinction of species.

Obviously, human activities triggered by the temperature increase will cause profound environmental impact and affect many of the world's species and ecosystems (Williams et al. 2011). In fact, every part of the world and its interdependent social, economic, political and biological systems will be affected by climate change and related factors. Simply keeping global temperature rises below 2 degrees C requires urgent and sustained global efforts from the world community. Clearly, management actions and decisions that are taken now must not narrow options for adapting to future conditions. Immediate action must also be taken to increase resilience to improve livelihoods and environmental wellbeing in the face of a changing climate, and to cut greenhouse gas emissions on a global scale.

The effects of global temperature increases of 2 and 4 degrees C, respectively, on the biodiversity of the Baltic Sea region are dealt with in some detail below. These levels are chosen because simulations (IPCC emission scenarios A1B and A2) indicate a warming range of 2 to 4 degrees C within the Baltic Sea region by the year 2100 (HELCOM 2013).

Impacts of climate change on ecosystems of the Baltic Sea: An introduction

The Baltic Sea covers an area of some 377,000 km^2, slightly larger than Finland, but its drainage area is more than four times as large, at 1,700,000 km^2 (Figure 2). After the Black Sea it is the second largest brackish-water body in the world.

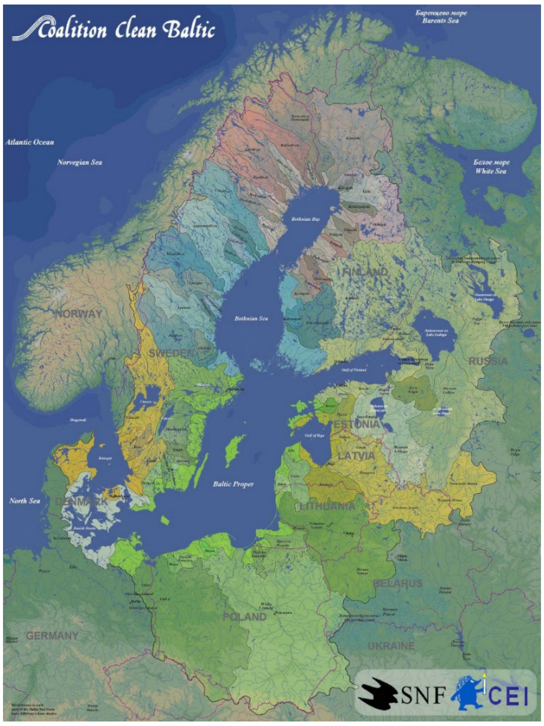

Figure 2. The Baltic Sea and its drainage area

Temperature is the fundamental climate-driven factor that directly affects all aspects of living organisms. Increasing temperature will thus favour warm-water species and be harmful to cold-water species. A decrease in salinity will induce further stress in marine species and favour freshwater species, while an increase in salinity will give the opposite result. Changes in the oxygen concentration and pH of seawater are also climate-driven factors that have profound effects on biological systems. Changes in temperature, salinity, pH and oxygen concentration are the most important factors that will shape future biological communities in the Baltic Sea, because most species here are of either freshwater or marine origin. Another driver in changing the aquatic environment is the projected sea-level rise, the extent of which is still debated.

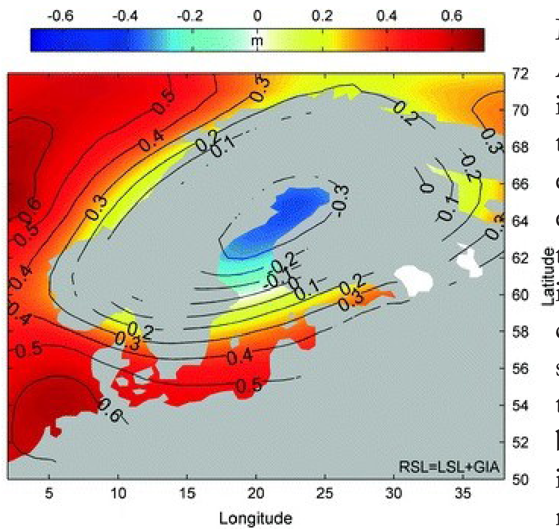

Figure 3. A high-end estimate of projected regional sea-level rise in the Baltic Sea for 2090–2099 relative to the 1990–1999 baseline (from: Grinsted 2015)

Melting of the Arctic and Antarctic ice masses, and indeed all glaciated areas of the world, is a factor of such enormous magnitude, as are environmental interactions, that they elude our possibilities to assess them with any certainty. However, having said that, it is probably safe to assume that the Baltic Sea basin will face a net sea-level increase of around 0.6 to 1.1 m during the 21st century, according to a compilation of mid-range and high-range sea-level rise scenarios (HELCOM 2013) and Figure 3.

Another way of displaying the projected change in relative sea level is given in Figure 4, which shows implications of 1 m sea level rise for scenarios of CO_2 emissions continued at current level based on an ensemble of climate models from Climate Central. Most prominent impacts can be seen in the coastal areas of Kaliningrad (Russia), Poland, Germany and Denmark in the south and the Åland islands (Finland) in the north of the Baltic Sea (as presented below and shaded lighter blue).

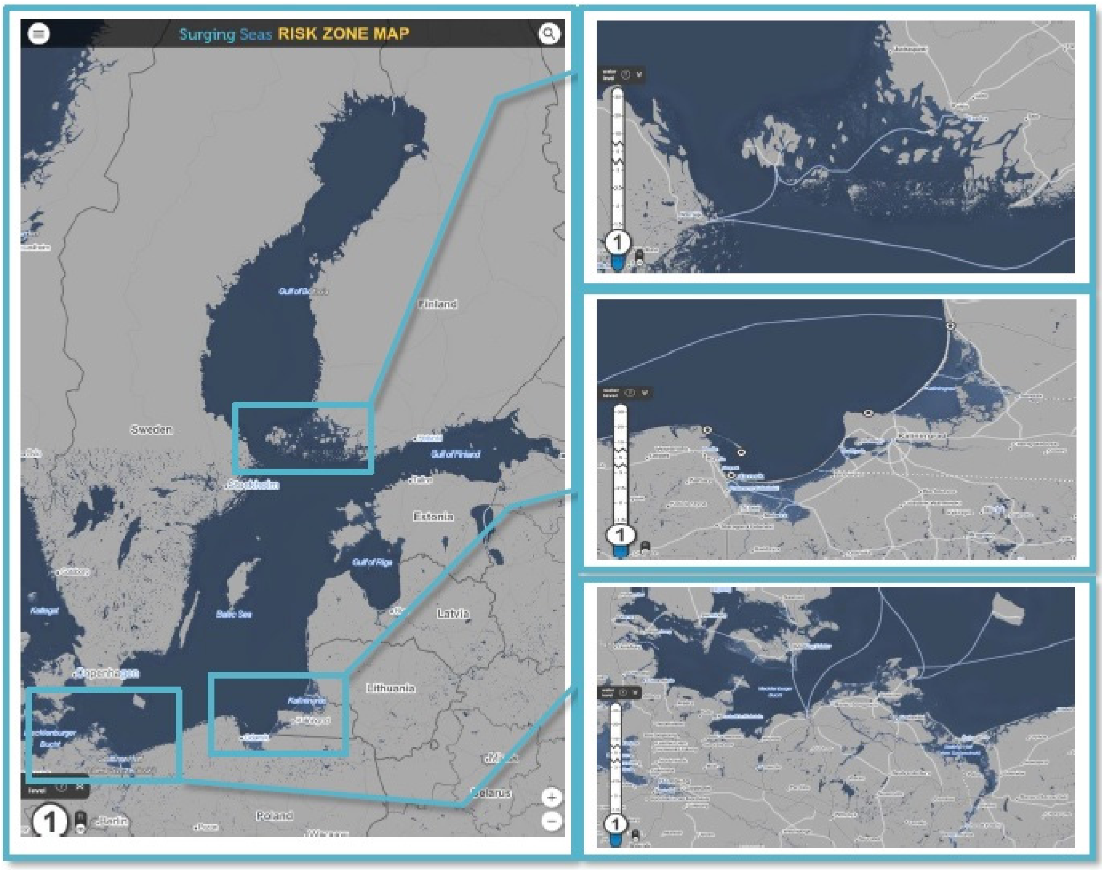

Figure 4. Simulation of a potential one metre sea-level rise based on a scenario of CO_2 emissions continued at the current level for the whole Baltic and its potentially most affected parts: the Åland archipelago, South-East and South-Western Baltic (from Climate Central's Surging Seas Risk Zone Map). The maps show areas vulnerable to near-term flooding from different combinations of sea level rise, storm surge and tides or to permanent submersion by long-term sea level rise, based on satellite-based elevation data from NASA.

More pessimistic authors have predicted that each degree of global warming might ultimately raise global sea levels by more than two metres (Levermann et al. 2013). In the Baltic Sea area this rise is partly compensated for by the vertical land movement following the last glacial period in northern Europe, which ranges from zero in the southern parts of the Baltic to more than 0.8 m/century in the north-western part of the Gulf of Bothnia. The increased sea-surface temperature will also lead to a decreased extent of ice in winter, probably by some 50–80 per cent by the year 2100 with a 2 to 4 degree scenario (Andersson et al. 2014). As emphasized in the Background section of this report, climate change at any level at or above the present temperature level will affect biodiversity at large, including species ranges and ecosystem functioning.

In more detail, this will include changes within species, such as their physiological response, climate niche requirements, their interaction with other species, and indeed evolutionary aspects at the micro and macro level, and in fact genetic biodiversity at the population level (Wennerström et al. 2013). The risk levels are directly associated with the projected increase in global mean temperature, and even temperature increases below today's threshold level of 2 degrees C may represent significant risks to unique human and natural systems (Oppenheimer et al. 2014) (Figure 5). Changes and depletion in biodiversity in the Baltic Sea will make it less able to adapt to climate change.

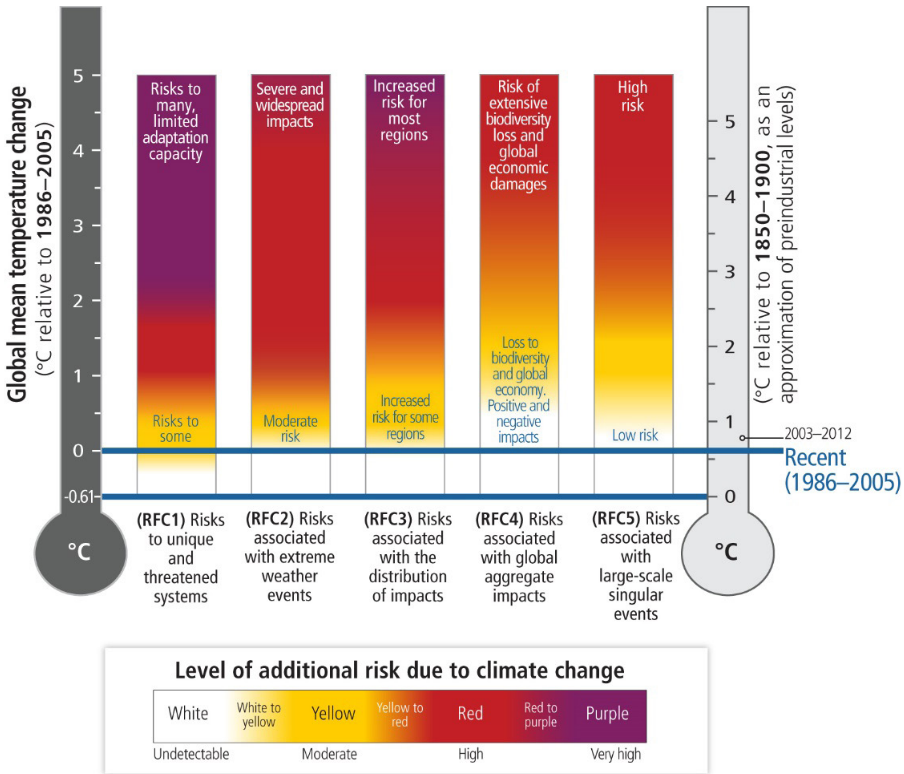

Figure 5. Risk levels associated with climate change (from: Oppenheimer et al. 2014)

Rising temperature will directly affect the productivity and distribution of individual organisms through changes in the properties of water chemistry and may cause indirect effects by changing species interactions and thus ecosystem stability. Such interactions will change predation pressure, structure and diversity of local ecosystems at all trophic levels for benthos, phytoplankton, zooplankton, fish and marine mammals. The geographic distribution of fish and other components of the Baltic Sea ecosystems could indeed undergo such profound changes in the 21st century that maintenance of healthy and productive ecosystems becomes a critical issue for mitigation at the international level.

Benthos

Benthic communities in the Baltic Sea are distributed according to the decreasing salinity towards the north. This distribution reduces the diversity and structure of benthic communities, which are also influenced by strong vertical gradients, with larger diversity in shallow-water communities than in communities below the halocline (salinity gradient). Climate variability obviously affects salinity, stratification and the distribution of hypoxic water (HELCOM 2013). Saltwater inflows thus regulate the composition of benthic marine species at all taxonomic levels. A decrease in salinity will cause a retreat of marine species to the south, but bottom-water conditions will have a greater influence on benthic species distribution in the deeper open-sea areas. The area of hypoxia in the Baltic Sea has already increased and is now the most widespread on record; a bottom-area the size of Denmark is presently lifeless. This has caused a drastic decrease and even disappearance of benthic macro-fauna from much of the open sea. Ecological responses will differ in the various sub-basins of the Baltic Sea depending on the degree to which HELCOM countries implement reductions of phosphorus and nitrogen according to the Baltic Sea Action Plan. This uncertainty makes it difficult to estimate the future impact of the predicted climate change on deep-water benthos. Benthic communities in shallow-water with hard and soft bottoms differ markedly from those in deep-water areas, because light conditions allow the growth of algae and vascular plants. The impact of eutrophication will also increase with higher temperatures, and more filamentous algae will thrive and reduce biodiversity. However, the composition and distribution of this species richness changes and declines gradually from the Kattegat and its marine environment to the northernmost part of the Gulf of Bothnia and the innermost part of the Gulf of Finland, where there is almost pure fresh water. In the northern region, two glacial relict species of crustaceans account for more than 80 per cent of the benthic biomass – Saduria entomon and Monoporeia affinis (Kjeldberg 2015). This sensitivity to low salinity and other environmental parameters (e.g. temperature and low oxygen levels) makes shallow-water communities vulnerable to climate change, particularly during their reproductive phase. In the littoral zone, decreasing salinity will affect seaweeds of the genus Fucus (mainly bladder-wrack – Fucus vesiculosus), eelgrasses (Zostera marina), and to a lesser degree the red alga Furcellaria lumbricalis (known as Baltic agar), mussel beds and other habitat-forming species and their associated fauna and flora. The disappearance of mussel beds will also affect eider ducks, which feed on mussels. Acidification as a by-product of higher levels of carbon dioxide will strongly affect calcifying organisms such as zooplankton and bivalves. Acidification will thus affect all physiological processes and potentially influence both the diversity and function of benthic communities. Changes in wind speed and climate, may, although statistically uncertain, increase erosion of shore ecosystems, and this erosion is already changing shorelines, particularly in the southern and south-eastern parts of the Baltic. These areas are also most likely to experience increased erosion, because the sea-level increase will be the highest in the Baltic Sea region. The combination of high water levels and strong winds may also result in severe damage to present sand spits in Poland and Lithuania, and to soft coastal cliffs in Denmark, Germany, Poland and Lithuania. These changes to the coastline will, however, be rather slow and gradual, but will in the course of the century have considerable effects on shore and near-shore environments. Such changes will of course cause problems for people living close to the Baltic shoreline, especially in low-lying areas of the southern and eastern parts of the Baltic, which will be flooded and also subjected to increasing coastal erosion. This, in turn, will also impact the extension of present natural reserves along the coasts (Figure 6), which will require changed boundaries by the end of this century. The natural ecosystems will have time to adapt, though, and our own species (Homo sapiens) will, no doubt, be able to do the same.

Not all ecosystems will be negatively affected by climate change, however. Littoral vegetation will flourish, because of milder winters and less risk of the scraping of ice. This positive effect will also influence many Fucus communities in shallow water where mild winters cause denser growth of Fucus belts, which contributes to higher production of the associated invertebrate fauna provided that increased production of filamentous algae does not decrease water transparency too much (HELCOM 2013).

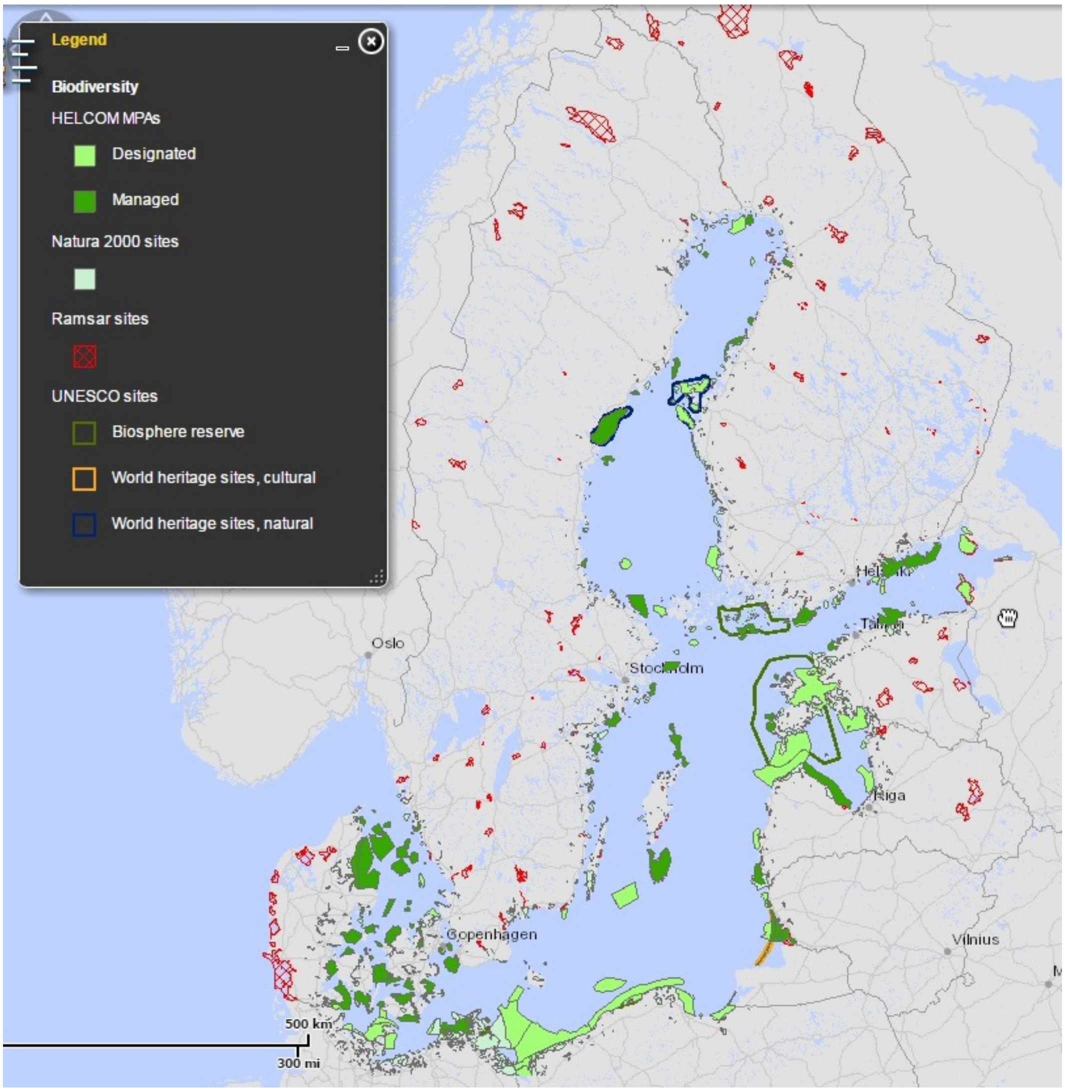

Figure 6. Extension of Baltic Sea Protected Areas: MPAs, Natura 2000, Ramsar Convention and UNESCO sites (HELCOM Data and Map Service, 2015)

Both 2 degree and 4 degree increases in temperature will, in combination with increased precipitation decrease salinity, cause lower oxygen levels and continued runoff from terrestrial sources, factors that in concert will lead to increased production of bacteria in competition with phytoplankton. This will add two additional levels in the food web, which will decrease production of fish at the highest trophic level, since 70–90 per cent of the energy is lost at each level (Andersson 2014).

This is explained further in Figure 7 (from Andersson 2014). Higher temperatures and lower oxygen levels will negatively affect the benthic fauna, such as Saduria entomon and Monoporeia affinis. Warmer and longer summers will also increase the frequency and distribution of algal blooms (blue-green algae). Increasing nutrient discharges and higher inflow of freshwater will cause increased depletion of oxygen, resulting in large-scale habitat loss and greatly reduced biodiversity.

Microscopic algae (cyanobacteria) will provide additional input of nitrogen to the biological system, but do not offer significant nutritional value to other levels of the food web.

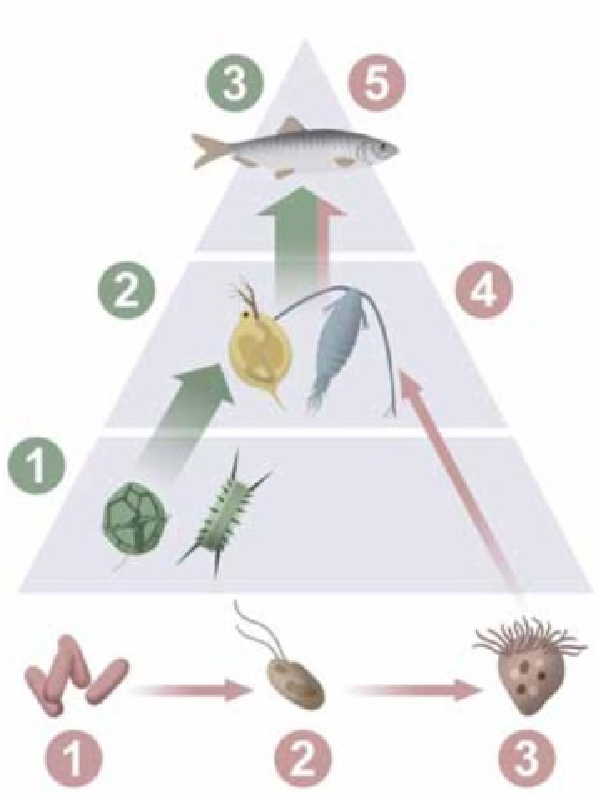

Figure 7. Two different food webs in the Baltic (from: Andersson, 2014). Green numbers and arrows show the classical food web, where phytoplankton (1) are eaten by zooplankton (2) which are food for fish (3).Brown numbers and arrows show the bacterial food web,

Phytoplankton

An increase in temperature and a decrease in salinity will result in a change in the species composition and length of the phytoplankton bloom season (HELCOM 2013). These changes will, in turn, influence both the benthos and the zooplankton community composition, and increase the mismatch between the different communities. In addition, increased freshwater discharge and nutrient loads may affect both the biomass and composition of the phytoplankton community. The spring bloom will be dominated primarily by dinoflagellates, because warm winters appear to favour dinoflagellates rather than diatoms. This large-scale change appears basin-specific and may only be found in the central and northern Baltic Proper. These changes – mainly in the spring bloom – will affect both the food web and the functioning of the entire pelagic ecosystem. So far, the changes found in the phytoplankton communities in the northern Baltic Proper and Gulf of Finland have caused a decline in the spring bloom but an increase in phytoplankton biomass later in summer. These changes are mainly the result of the eutrophication process, and the most important factors controlling these developments appear to be summer temperatures and winter nitrate concentrations, at least in the Gulf of Finland (HELCOM 2013). On a short-term basis at least, a higher freshwater discharge will obviously reduce primary production, although this may differ from basin to basin. This effect is particularly true in the Gulf of Bothnia, where river runoff carries a large load of brown-coloured dissolved organic carbon (DOC) in addition to increased nutrient availability (HELCOM 2013). DOC reduces the amount of light available for phytoplankton growth, but enhances bacterial growth. Ultimately this process may lead to a decrease in phytoplankton production and a corresponding increase in bacterial production. It has been suggested that warmer water will increase thermal stratification (forming water strata with different temperatures), which would favour cyanobacterial bloom species in summer and also prolong the main productive period. These ecosystem changes will influence both the quantity and quality of organic matter and ultimately affect benthic dynamics. The most important loading of organic matter available to benthic communities below the halocline is the result of the spring bloom of both dinoflagellates and diatoms, while cyanobacteria (blue-green algae) provide poor nutrition for pelagic and benthic consumers (HELCOM 2013). Finally, the effect of higher water temperature on the phytoplankton food web is still unclear and will probably also depend on basin-specific characteristics.

The 2-degree and 4-degree scenarios will both lead to ecosystem changes, but it is still unclear what the end result will be, other than basin-specific differences in response to climate change. There is however reason to believe that enhanced thermal stratification will favour production of cyanobacterial communities (blue-green algae), which, as mentioned, provide poor nutrition for both pelagic and benthic communities.

Zooplankton

As in all trophic levels of the Baltic Sea, the zooplankton community will also react strongly to changes in temperature, salinity and acidification. Pseudocalanus acuspes is an important zooplankton species, which is fed on by cod larvae and clupeid fish. This marine species declined in the 1980s when salinity also declined (HELCOM 2013). A related species (Pseudocalanus elongatus), which is another important food item for clupeid fish, has also declined as a result of environmental change (Thor et al. 2014). However other zooplankton species, such as the copepods Acartia spp and Temora longicornis, increased their biomass as a result of warmer spring temperatures, so some species are primarily restricted by salinity and acidification whereas others react positively to warmer water. In fact, a number of zooplankton species have been found to react positively to mild winters (HELCOM 2013). The end effect of a warmer and less saline Baltic Sea on its zooplankton community is, however, very hard to predict because zooplankton abundance is controlled by both climate change and predation by herring and sprat, and indeed by young fish of most species.

Both the 2-degree and 4-degree scenarios will result in ecosystem changes (like those described above for benthos and phytoplankton), and the composition and abundance of the trophic level of zooplankton depends not only on environmental variables but also on predation and fisheries.

Diadromous and freshwater fish

During the 21st century there will be at least three major drivers of ecosystem change in the Baltic Sea. The first driver, climate change, will be responsible for higher water temperature and increased precipitation. Other drivers are directly linked to human intervention, such as our 1) influence on fishing mortality, which will lead to changes in the fish community, e.g. species interaction, food web changes and population structure, 2) future levels of nutrient loading and 3) possible introductions of alien species and their functional consequences for the Baltic ecosystem (MacKenzie et al. 2007). This section of the report will deal with possible effects of the first driver. The Baltic Sea behaves as a gigantic estuary, with a salinity cline of almost pure fresh water in the northernmost part of the Gulf of Bothnia, changing gradually to almost marine conditions in the Sound area in the south-west. Such conditions impose a physiological stress on freshwater and marine species, including the diadromous species that utilize both environments during their lives.

Of all the fish species found in the Baltic, roughly two-thirds are of freshwater origin or are anadromous (spawn in fresh water and grow mainly in a marine environment) or catadromous (spawn in the sea and mainly migrate to fresh water to grow). The entire lifecycle of the single most important diadromous/anadromous species – the Atlantic/Baltic salmon (Salmo salar) – depends on and is triggered by temperature conditions. When entering the Baltic from rivers it is triggered by temperatures in excess of 10 degrees C. Survival of smolts is highest at intermediate temperature (9–11C), and when in the open sea growing salmon avoid warm water (above 11C) and move to deeper, colder layers (Alm 1958, Jutila et al. 2005). There is also evidence to show that modestly higher temperatures may increase parr growth and survival and also shorten smolt age and cause changes in the timing and size of smolt runs (Jensen 1992). Spawning migration back to the rivers is also temperature dependent, with salmon arriving earlier when temperatures are higher than normal (Dahl et al. 2004). Sea trout (Salmo trutta), although in most respects similar to salmon, can tolerate rather high salinity, even as parr (not smoltified), but are less tolerant of high salinity as adults than salmon. Their temperature preference, however, appears close to that of salmon. In short, both species will move to deeper layers in the Baltic during their fattening phase, where the availability of suitable prey may be less abundant. When talking about the major effects of climate change on salmon and sea trout, the most severe threat to their long-term survival is rising summer temperatures during their young freshwater phases. When temperatures can exceed 20–25 degrees for weeks this can be fatal to their survival.

Some populations of other fish species are also anadromous, such as certain whitefish species (Coregonus sp), grayling (Thymallus vulgaris), perch (Perca fluviatilis) and ide (Leuciscus idus), all of which are basically freshwater species that can tolerate a rather low salinity. Grayling and vendace/cisco (Coregonus albula) can also spawn successfully in brackish water along some coastal areas of the Gulf of Bothnia. This group of species, along with numerous other freshwater species such as pike (Esox lucius), perch (Perca fluviatilis), pike-perch/sander (Stizostedion lucioperca), ruffe (Gymnocephalus cernuus), burbot (Lota lota) and a score of cyprinid species, sticklebacks (Gasterosteus aculeatus and Pungitius pungitius) and the Eurasian minnow (Phoxinus phoxinus) can spawn and occupy marginal coastal areas and archipelagos along the shores of the Baltic States, Russia and Finland, and along almost the entire Swedish east coast. All of these basically freshwater species will expand their territories when salinity drops. With the exception of burbot and ruffe this group of fishes will also be favoured by rising water temperature. Finally, the diadromous European eel (Anguilla anguilla) will be favoured by increasing water temperatures during its freshwater phase and is perfectly adapted to an oceanic marine environment on its spawning migration to the Sargasso Sea, when it does not feed.

A 2-degree scenario will benefit almost all freshwater fish species because warmer and less saline water will reduce their physiological stress and increase their growth, provided that lower trophic levels will be populated by equally tolerant species that can be preyed upon by plankton-eating fish and those feeding on benthic invertebrates. The habitats of freshwater species will also increase, particularly those whose survival and growth are enhanced by warmer water. However, species shifts are already occurring, and may increase in a warmer Baltic Sea. Local declines in predators such as perch appear to coincide with increased densities of sticklebacks, which prey on perch larvae (Byström et al. 2015). Even at today's level of temperature increase there will be a significant increase in temperature in the northernmost parts of the Gulf of Bothnia, where the increase per decade will be roughly double that of the southern parts of the Baltic. The northernmost areas will have an increase of 0.5 to 0.6 degrees C/decade in autumn and winter, whereas the southern and central parts of the Baltic will only have a significant increase in spring and summer of some 0.2 to 0.3 degrees C/decade. Even with this rather modest increase it is possible that the vendace populations of the northernmost parts of the Gulf of Bothnia may decline during the 21st century. More low-temperature dependent species such as salmon, burbot and ruffe will have reduced areas and depth layers where oxygen concentration, salinity and temperature will suit their life cycles. In addition, anadromous fish, like salmon and sea trout, may suffer great losses when short-term heat waves occur during summer in their freshwater habitats around the Baltic region. This threat is most pronounced in small rivers in the Baltic region, in Poland and in southern Sweden. A study of Pacific salmon (Oncorhyncus) off the Pacific coast of Canada (Sumaila 2015) has predicted a decline in salmon stocks (sockeye and chum) by 2050 as a result of climate change impacting key marine and coastal organisms, ecosystems and services that they provide.

These authors call for rapid reductions in CO_2 emissions and eventually atmospheric drawdown and other measures to protect ocean health.

It should also be noted that a sea-surface temperature increase in summer of around 2 degrees C in the southern Baltic Sea will rise to some 4 degrees above the present level in the northernmost parts of the Gulf of Bothnia during the 21st century (according to the A1B and A2 scenarios – HELCOM 2013).

The results of a 4-degree scenario depend to a great degree on the discharge of nutrients into the Baltic Sea (i.e. the level of future eutrophication). Increasing nutrient discharges will cause depletion of oxygen, and anoxic bottoms will cause large-scale habitat loss and greatly reduce the biodiversity of benthic communities. Strong westerly winds and currents will occasionally provide an inflow of salt water from the North Sea, which will again improve the environmental requirements of most marine fish, cod in particular (see below). This temperature rise, which will vary considerably from north to south in the Baltic, is likely to reduce the entire biomass of fish, because hardly any species that is normally found in this area will have the potential to live there in future, and all fish species that depend on relatively low water temperatures during part of their life cycle are likely to become less abundant in the Baltic ecosystem. These losses of fish stocks will of course cause great depletion of genetic variation within all species present, most of which are genetically distinct from other stocks of the same species outside the Baltic Sea basin.

The only fish that will be favoured by the much warmer water is the European eel (Anguilla anguilla), because it is basically a warm-water fish that does not feed at all during its spawning migration when leaving the freshwater habitats where it reaches sexual maturity. The river lamprey (Lampetra fluviatilis) is an anadromous species that inhabits the entire Baltic basin. It feeds on benthic invertebrates, fish eggs and even dead or living fish and is likely to survive as long as there is benthic fauna available and summer temperatures do not exceed its tolerance levels.

Marine fish

As pointed out above the reduced salinity and increased water temperature will favour freshwater fish species, and, consequently, disfavour marine fish that require oxygen-rich water. Around one-third of all fish species occurring in the Baltic are of marine origin. Because three species of marine fish account for some 80 per cent of the fish biomass in the Baltic, this development will greatly impact and change the entire ecosystem of the Baltic Sea. These three species are also the best documented regarding the effects of climate variability (MacKenzie et al. 2007) – viz. cod (Gadus morhua), herring (Clupea harengus) and sprat (Sprattus sprattus). As with most fish species, conditions for successful egg development and early life stages determine the size of strong or weak year classes in cod. Egg development is determined by minimum oxygen and salinity, and these thresholds are the basis for the so-called reproductive volume (RV). Sprat eggs float shallower than cod eggs and their survival is mainly affected by winter cooling. Herring recruitment appears positively correlated with temperature. Cod eggs are preyed upon by both herring and sprat, and the effect on future cod spawning biomass depends on the size of predatory fish populations and the timing and distribution of cod spawning. An important indirect effect of the outcome of this interaction is the abundance of zooplankton, which influences larval survival in all three species, and indeed survival and growth even among adults in both herring and sprat. On leaving the larval stage and throughout their lives, cod prey on various size groups of herring and sprat, so there is a delicate balance between the three species.

Flatfishes such as plaice, dab, flounder, sole and turbot are or have been of commercial importance in parts of the Baltic Sea. Plaice (Pleuronectes platessa) is mainly dependent on an inflow of salt- and oxygen-rich water, and its decline in the Baltic Sea is also caused by overfishing and recruitment failure (e.g. Temming 1989). Dab (Limanda limanda) nowadays inhabits only part of the south-western Baltic Sea. Compared with plaice and cod, dab eggs require higher salinities for fertilization and to remain buoyant in water layers where oxygen concentrations allow egg development (Nissling et al. 2002). Flounder (Platichthys flesus) is able to reproduce at much lower salinities than other flatfishes and both biomass and spatial distribution are much larger than in the other two species (mentioned above). Even so, inflows of water with high salinity, although infrequent, will also increase catch rates and landings, and have beneficial effects on reproduction (Nissling et al. 2002). Sole (Solea solea) is limited in distribution by low salinities but are probably favoured by warmer water. Sole are rarely seen in the Baltic and even further west, in the Kattegat-Belt Sea, it is close to its northerly limit of distribution. Turbot (Scophthalmus maximus) is found in the entire Baltic Sea, which is unexpected as it primarily is a marine fish. There are also three species of sand lance/sand-eel (Ammodytes sp and Hyperoplus) that inhabit most of the Baltic Sea. They are preyed upon by the Baltic salmon, which may lose this food source when salinity drops.

A 2-degree increase temperature scenario will negatively affect all essentially marine fish species and will change predation patterns (and food web structure) at all levels of biodiversity, because salinity and oxygen levels will also drop and the frequency of inflows of more saline and oxygen-rich water from the North Sea will occur rather infrequently. Populations of marine fish will decline first of all in the Bothnian Bay, in the Gulf of Finland and in shallow coastal areas of Estonia and Latvia.

A 4-degree scenario will be even more detrimental to all fish of marine origin. In addition to the changes in salinity and temperature, the predicted reduction in ice cover will lead to increased stratification which, in turn, may lead to reduced primary production (Behrenfeld et al. 2006). Primary production is generally positively related to fish production, so overall fish production is likely to decrease even more, particularly in the southern part of the Baltic Sea, which is rarely covered by ice even now. Increased annual and winter precipitation will lead to increased runoff of nutrients. The combined effects of climate change, including a lowering of pH and eutrophication, will affect all trophic levels of the marine ecosystem, but it is difficult to predict the outcome. The most economically important fish at present – the Baltic cod – will be drastically hit by the environmental changes. Reproduction will be impaired and fewer food choices will be available when the benthic fauna is reduced. In the southern Baltic bottom-water anoxia may spread, reducing cod recruitment. However, the creation of new food webs for larval fish may decouple the match between them and preferred zooplankton species. Few fish species will be able to adapt to such warm, freshwater, low-oxygen, turbid and more acidic waters, neither native nor alien.

Glacial relict species

At least two species of fish survived in the Baltic during and after the last glaciation in northern Europe – more than 10,000 years ago. They are the four-horn sculpin (Triglopsis quadricornis) and the sea snail (Liparis liparis). Both species require cold, well-oxygenated water and are tolerant of low salinities (Ojaveer et al. 1999). The sculpin also lives in a number of deep oligotrophic lakes, but the sea snail is found only in marine habitats. These species are mainly found in northern coastal areas of the Baltic Sea, where the sculpin in particular can be found in rather high abundances. Both species are likely to perish when their habitat requirements vanish with higher temperatures and lower oxygen levels. It is likely that extinction will occur in the 4-degree scenario.

Invasive/exotic species

This expression refers to any plant or animal species that, through deliberate or unintentional human assistance has become established outside its normal range. In aquatic species, shipping is by far the most common vector, and the Baltic Sea has a score of species at all taxonomic levels, and their origin can be from any ocean on the planet. These exotic species can be found in phytoplankton (e.g. Alexandrium minutum of unknown origin); Bonnemaisonia hamifera, a macrophyte from the China Sea; zooplankton (Acartia tonsa, a crustacean species of Indo-Pacific origin); Mnemiopsis leidyi, a West Atlantic comb jelly, which feeds on other zooplankton species and fish eggs and fish larvae; Anguillicola crassus, an invertebrate nematode parasite of Indo-Pacific origin; Marenzelleria sp., three polychaete tube worms from North America; Cordylophora caspia, a benthic suspension feeder, a hydroid of Ponto-Caspian origin; Crassostrea gigas, another benthic feeder and a mollusc from the Japan Sea; and, finally, another mollusc of Ponto-Caspian origin, the zebra mussel (Dreissena polymorpha).

Among fish, at least three salmonids from western North America, Oncorhynchus gorbusha, O. kisutch and O. mykiss (pink and coho salmon and rainbow trout) have been found, but none of these species has established self-sustaining populations, nor has so far any of the sturgeon species (Acipenser sp). However, sturgeon have now been re-introduced in the southern Baltic through a German/Polish Sturgeon Rehabilitation project, which will rear and stock sturgeon in rivers.

On the other hand, a round goby of Ponto-Caspian origin, Neogobius melanostomus, became established in the early 1990s, and is now found in the entire coastal area of the Baltic Proper.

A 2-degree scenario will rarely provide any survival advantage to any of these exotic species over the native flora and fauna, possibly with the exception of the round goby, which is a predator on young specimens of native benthic fish. On the other hand, during growth, the round goby is preyed upon by perch, pike, pikeperch, cod and turbot. Another potential winner is the zebra mussel which, like the round goby, may extend its distribution substantially. The greatest threat in competition with the native fauna probably comes from the comb jelly, which can tolerate a wide range of temperatures and salinities. Its effective predation may lead to a greatly increased abundance of the phytoplankton community, which it does not feed on.

In a 4-degree scenario it is likely that the round goby will extend its range even further and take over habitat from native benthic fish. There is also reason to believe that some exotic invertebrates may outclass some of its native competitors. The zebra mussel may also extend its range in the Baltic Sea when the water becomes both warmer and less saline (see above). The same advantage at almost any temperature and salinity level will benefit the comb jelly, the most effective zooplankton feeder in the Baltic (present in the Baltic Sea since 2007). After having been introduced in the Black Sea in the 1980s it now dominates the pelagic ecosystem.

Fish- and mussel-eating birds

The reduction and eradication of mussel beds and many shallow-water species of fish will directly impact bird species that depend on these species for food. It is not likely, though, that waders feeding on invertebrates along shores and shallow coastal wetlands will be significantly impacted, because these bird species depend on prey that is not directly influenced by the physiological changes in the Baltic Sea arising from climate change. Examples of birds belonging to the threatened group are cormorants (Phalacrocorax carbo), long-tailed ducks (Clangula hyemalis), guillemots (Uria aalge), eider-ducks (Somateria mollissima), terns (e.g. Sterna hirundo and Hyrdoprogne caspia), gulls (e.g. Larus canus, Larus fuscus and Larus argentatus), mergansers (Mergus merganser and Mergus serrator), and common goldeneye (Bucephala clangula). Birds that are less likely to be affected include numerous species of waders that feed on invertebrates in very shallow water.

Marine mammals

There are four species of marine mammals in the Baltic Sea. One of them is a small whale – the harbour porpoise (Phocoena phocoena). Its abundance has rapidly declined over the past 100 years because of bycatches in bottom-set gillnets, environmental toxins such as persistent organic pollutants, and intense offshore activities such as shipping, wind farm construction and oil and gas pipelines. The Baltic population of the harbour porpoise is estimated to be around 450 individuals and is distributed mainly in coastal areas of

Denmark and Germany and in decreasing numbers along the eastern coasts and in the Gulf of Finland. It does not seem to exist anymore north of the Åland Archipelago. The harbour porpoise feeds mainly on herring and sprat, which contributes to its tissue load of PCB and other toxic substances. The three other species of Baltic marine mammals are seals. The grey seal (Halichoerus grypus) has a northerly distribution from the southern Baltic Proper, increasing in abundance north of Gotland and in the Bay of Riga up to the Åland Archipelago, and then gradually decreasing again in the Gulf of Bothnia. The ringed seal (Pusa hispida botnica) is an Arctic species trapped in the Baltic Sea after the last ice age. The largest part of the population is found in the Gulf of Bothnia, but it is also distributed through the Gulf of Finland, the Bay of Riga and in low numbers in the Archipelago Sea in south-western Finland. The third seal species is the harbour seal (Phoca vitulina). In the Baltic Sea this species has a very limited distribution – west of the island of Öland in Swedish waters. The total number of seals in the Baltic Sea is estimated at some 35,000, and the number is presently increasing, the grey seal in particular.

With declining bycatches by fisheries and decreasing toxins in their food intake, these warm-blooded, air-breathing mammals will not be directly affected by a temperature or salinity change, with the exception of the ringed seal, which needs substantial sea ice during its breeding season. The other two seals may breed on land, mainly uninhabited islands or skerries. The harbour porpoise will also be endangered because the threat to this group of animals will be indirect, since their food is almost exclusively dominated by fish, and both a 2- and 4-degree temperature increase scenario will negatively affect Baltic fish populations. The ringed seal also feeds on Saduria entomon (see above – Benthos) which will also be disadvantaged by rising temperature and declining oxygen levels.

Fisheries

Since 2006, Baltic fisheries have mostly been managed under the EU Common Fisheries Policy (CFP) and negotiations are mainly based on advice from the International Council for the Exploration of the Sea (ICES) and the Scientific, Technical and Economic Committee for Fisheries (STECF). However, fishing closures and quota decisions will not work if environmental factors change drastically. Driving forces such as climate change, fishing, eutrophication and invasive species will interact with each other and have major and complex impact on the Baltic ecosystem (MacKenzie et al. 2007), and predictions of how fish populations will respond to a combination of all these drivers are very difficult to assess. It is likely that future marine fish stocks will depend much more on frequent inflows of salt water than today, however, an increase in precipitation and runoff and a change in the seasonality of runoff may reduce the frequency of inflows into the Baltic Sea. There is no consensus regarding future wind conditions in the Baltic Basin. Cod, being the major fish predator in the Baltic Sea, will be negatively affected by the drop in salinity and oxygen concentration, and the warmer water will increase oxygen consumption rates in the deep parts of the Baltic where cod eggs develop. Even though nutrient loading may decrease, large reserves of organic matter nutrients will remain in the deep-water sediments, so oxygen conditions will improve only slowly (MacKenzie et al. 2007). Also, if fish species that feed on cod eggs (sprat and herring) benefit more from the warmer water than do cod, the present dominance of those two species could become stabilized. The only way to improve survival rates for cod in the Baltic Sea is a reduction in fishing mortality and an increased intensity and frequency of salt-water inflows. The interaction between increased temperature and eutrophication will also affect benthic fish (both freshwater and marine species) by intensifying anoxic events in shallow coastal waters. Such events will negatively affect the presence of benthic fish species, and their prey, but may not cause any decline in pelagic species like herring and sprat. As indicated above, the ranges of marine species will decrease and this will also affect cold-adapted species such as salmon and sea trout.

Fisheries management during the 21st century will have to adapt to new environmental conditions, the range and scope of which are still little known. Fish populations with decreasing biomasses, due to the effects of climate change, should be exposed to a much lower fishing mortality than today, including zero fishing for certain species, such as cod and salmon. Such actions should be components of management strategies, which must adapt to future climate change. These management strategies will also affect intra-specific genetic variability. Continued high fishing mortality in combination with detrimental environmental conditions for eggs, larval survival and timing of zooplankton availability may lead to reductions or extinctions of local and/or regional fish stocks. Genetic adaptation of fish genotypes to local environmental conditions is also slower than the projected change in the environment, and other fish of the same species that migrate to the area may not be adapted to those conditions, and may, therefore, be unable to reproduce.

A 2-degree scenario will require stronger quota restrictions to lower the fishing mortality of cod, sprat and herring, but fisheries may continue targeting the same species. Local cold-water adapted species, like vendace, salmon and cod (and flatfish species) may also experience shrinking ranges, hence lower fishing intensity. It is likely that there will be a ban on fishing for salmon and sea trout. Some cyprinid species and pike-perch may extend their ranges, and the latter may benefit local small-scale fisheries.

A 4-degree scenario may result in a collapse of commercial fisheries in the Baltic Sea. If environmental conditions change so drastically that locally adapted marine fish are unable to reproduce successfully, there will hardly be any invasive/exotic species that can replace them, and the freshwater fish fauna that may survive and be able to adapt to new conditions will not have enough biomass to make up for the losses of marine species. Increasing westerly wind patterns and more frequent inflows of salt water will help maintain a certain low level of fish production, provided that runoff also carries less nutrients from agricultural sources. New knowledge is required, e.g. on how fish production (yield) and food webs are related to various environmental conditions, past and present. Genetic population data is also vital to understanding consequences of local fish extinction, caused by overfishing or environmental conditions. A first, and important step, is to establish a Baltic Multiannual Plan within the CFP. The most important recommendation (by the Fisheries Secretariat and the Seas at Risk, 1 April 2015) is that the "Fish Stock Agreement should include pre-agreed conservation measures that are triggered as soon as stock levels fall below biomass levels capable of producing maximum sustainable yield (BMSY)".

Capacity of the Baltic Sea ecosystems to adapt to possible environmental changes and mitigation measures

I have tried to show above that the human-induced warming of the Baltic Sea will cause large changes at all trophic levels of this brackish-water bay of the North Sea. In addition to increased temperature and sea level, salinity will drop and so will the oxygen levels of deep-water areas. Thus, the biodiversity of the Baltic Sea will change and gradually diminish, and fish production will decrease. These changes will happen even during a status quo situation, and it is very unlikely that future ecosystems will be able to adapt unaided by human activities. On the other hand there are many mitigation measures that will reduce the speed of change even though our knowledge of the full role of the ocean in climate is lacking.

During the 21st century there is reason to believe that global surface seawater temperature may rise some 4 degrees above present. This level may be even higher in the northern areas of the Gulf of Bothnia. Salinity may also drop as a consequence of higher water temperature and increased precipitation, a fact that will favour all freshwater species at all trophic levels and simultaneously disfavour all species of marine origin. Because of the thermal horizontal stratification of water with different salinity and oxygen concentrations the remaining freshwater fauna will, however, also be negatively affected. Rising sea levels and increased incidence of storms will cause flooding and coastal erosion of coastal areas, in particular along the coasts of the southern Baltic Sea, and inevitably lead to environmental, economic and social disparities. Our knowledge of the geo-physical parameters mentioned above, although still rather scanty, provides tools for mitigation measures that will at least slow down the speed at which changes are happening.

All is not gloomy, though. Since signing the Helsinki Convention some 40 years ago, the total loading of toxic pollutants has been greatly reduced, as have nutrient emissions, while the abundance of the cod stock has increased, but as stated above, numerous serious problems remain. However, climate change proceeds, and continues to endanger the positive environmental gains that have been achieved.

A summary of possible changes of biodiversity in the Baltic Sea:

2-degree scenario

- Increased erosion of shore ecosystems, mainly in the south and southeast.
- Increased production of cyanobacteria (blue-green algae) will influence both biomass and composition of benthos, phytoplankton, zooplankton and fish communities negatively.
- Warmer and less saline water will benefit almost all freshwater species of fish, but species that are low-temperature dependent will become less abundant.
- Basically marine species at all trophic levels, including fish, will be negatively affected, first and foremost affecting the northernmost parts of the Bothnian Bay, in the Gulf of Finland and in shallow coastal areas of Estonia and Latvia.
- Few exotic species will benefit from this moderate temperature increase, with the exception of the comb jelly which is capable of changing the entire ecosystem.
- Stronger fishing quota restrictions must be applied, e.g. to cod, herring and sprat, and possibly include a ban on salmon and sea-trout caught off shore.
- Freshwater fish such as pike, pike-perch and perch may extend their ranges and increasingly support local coastal fisheries.
- Reduced availability of mussels and other benthic macro-invertebrates may limit access to food for birds relying on these resources.
- Wild salmon river populations in the Baltic Proper will face severe survival problems.
- Decreased winter ice cover in the Baltic Sea will disfavour the reproduction of ringed seals.

4-degree scenario

- Coastal erosion and flooding of low-lying shore areas will impact human settlements (especially in the southern and south-western parts of the Baltic Proper), and coastal nature reserves will have to be extended further inland from the present shoreline.
- Cyanobacteria (blue-green algae) will out-compete phytoplankton, leading to ecosystem changes at all trophic levels, in addition to a reduction in total fish production.
- The effects of this level of temperature increase depend on e.g. future discharge of nutrients, salinity and oxygen conditions, but it is likely that the entire biomass of fish will diminish so much that open-sea fisheries will come to an end. Local coastal fisheries may still operate though.
- It is vital that ecosystem-based fisheries measures are based on conservation measures that are triggered as soon as stock levels fall below biomass levels capable of producing maximum sustainable yield.
- Most glacial relict species, especially the four-horn sculpin and the sea snail, are likely to become extinct, in addition to some exotic species, probably with the exception of e.g. the round goby, the zebra mussel and, above all, the comb jelly.
- Fish- and mussel-eating birds will diminish in abundance, and the much lower level of fish production will also affect seals and the harbour porpoise.

Acknowledgments

I gratefully acknowledge all comments and suggestions provided by Gunnar Norén, Reinhold Pape and Mikhail Durkin during the course of this evaluation.

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