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A survey of some current trends, scientific standpoints and knowledge gaps in Baltic Sea science

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Rapporten ger exempel på framsteg eller förändringar gällande den naturvetenskapliga kunskapen om Östersjön under det senaste decenniet samt identifierar ett antal viktiga kunskapsluckor. Med Östersjön avses Östersjöområdet enligt Helsingforskommissionens (HELCOM) avgränsning innefattande Kattegatt. Rapporten omfattar endast rön inom naturvetenskaperna. Rapporten fokuserar på sex huvudområden: Övergödning, Miljögifter, Klimatförändringar och havsförsurning, Fisk och fiske, Biologisk mångfald, inklusive genetisk mångfald och främmande arter samt Födovävsinteraktioner.

Ett av det för närvarande mest omfattande problemen för Östersjön är den historiskt stora utbredningen av syrebrist som gäller stora delar av Egentliga Östersjöns bottnar samt konsekvenser av detta. De viktigaste bakomliggande faktorerna är: den nuvarande belastningen av näringsämnen, frekvensen och storleken på vattenutbytet med Nordsjön, mobiliteten hos de stora mängder näringsämnen som anlagrats i sedimenten under mer än 60 år av eutrofiering, blomningarna av kvävefixerande cyanobakterier, klimatförändringar samt potentiellt avsaknaden av stora rovfiskar.

Forskning om ***övergödning*** har under det senaste decenniet avsevärt förbättrat den kvantitativa förståelsen av näringsbelastning och interna processer. Modelleringsarbete och budgetberäkningar har visat att interna processer kan omsätta mycket stora mängder näringsämnen mellan olika förekomstformer på kort tid, vilket gör det svårt att särskilja sådana variationer från effekterna av belastningsminskning. Fosforläckage från sediment kan potentiellt göda kvävefixerande cyanobakterier, och s.k. top-down effekter som orsakas av den minskade torskpopulationen kan bidra till att Östersjön kan tänkas fastna i ett alternativt tillstånd med hög produktion. En alternativ eller kompletterande uppfattning är att tidsperspektivet helt enkelt är mycket långt i ett hav där vattenomsättningen tar mer än 30 år. Arbetet med miljökvalitetsnormer har givit en klarare bild av rimliga referensvärden och gränsvärden för tillståndsvariabler, men det har också framgått att det finns stora osäkerheter inom detta fält. Trots betydande långsiktiga förbättringar inom vissa kustområden, tack vare förbättrad avloppsrening, förekommer rapporter om ökande syrebrist i andra områden, eventuellt i samband med stigande vattentemperaturer. Under de senaste 25 åren har stora inflöden av kallt saltvatten från Nordsjön blivit betydligt ovanligare i jämförelse med de föregående 100 åren. Det finns en risk att de nuvarande lågfrekventa stora inflödena kommer att bli mindre effektiva i att återskapa förutsättningar för liv på djupt vatten, och eventuellt förvärra situationen genom att stärka haloklinen och minska syresättningen från ytvatten.

Ett antal viktiga *kunskapsluckor* kvarstår gällande vår kvantitativa förståelse av de generella biogeokemiska kretsloppen av kväve, fosfor och kol, exempelvis transport och sedimentbindning av fosfor, denitrifikation, kvävefixering och påverkan på kolcykeln av ökad belastning av organiskt material från vattendrag. Hur de organiskt bundna näringsämnena omsätts och hur stor andel som blir tillgänglig för produktion är en betydande osäkerhet i beräkningen av faktisk belastning. Den långsiktiga potentialen för sedimenten att frigöra näringsämnen från historiska avlagringar är viktig för att bedöma sannolika tidsperspektiv för avtagande näringsnivåer i vattnet. Orsakerna till förändringen av frekvensen för stora inflöden kan för närvarande inte förklaras. Etableringen av havsborstmasken *Marenzelleria,* en djupgrävande främmande art, har förändrat det bentiska samhället, och effekterna på sedimentens biogeokemi är ännu okända. Det finns fortfarande osäkerheter vad gäller det relativa bidraget till den totala belastningen från olika källor, samt förlusterna i färskvattensystem och kustzon (retention). Generellt behövs också ytterligare förståelse av kustzonens förmåga att fungera som ett ”filter” och kvarhålla näringsämnen genom sedimentering, men också att frisätta dem från sediment ovan haloklinen. Det finns betydande osäkerheter kring den långsiktiga effektiviteten av åtgärder inom jordbruket och andra former av markanvändning för att minska övergödning.

Med några få undantag har de flesta klassiska ***miljögifterna*** visat fortsatt minskande halter i organismer, och många befinner sig under vad som för närvarande anses vara säkra nivåer och föreslagna gränsvärden. Våra uppskattningar av tidsperspektiven för haltminskningar har, liksom den allmänna kunskapen om ekologiska effekter av dessa föroreningar, förbättrats. Det har skett framsteg inom metoder för att beräkna ekologiskt säkra nivåer där också födovävs-effekter bedöms. Populationer av känsliga toppredatorer som sälar och havsörnar har återhämtat sig kraftigt, men det finns några oroande tecken på misslyckad reproduktion i delar av Bottenhavet och miljöövervakningsdata antyder att hälsan för kustnära fisk kan ha försämrats. Tillgången på korrekt bevarade organismprov möjliggör idag återskapande av långa tidsserier för potentiellt nya och gamla miljöföroreningar.

För majoriteten av använda substanser finns det omfattande *kunskapsluckor* gällande transport i den marina födoväven och påverkan på biota. Den stora ökningen av substanser använda inom industrin kräver metoder där potentiellt miljöförorenande ämnen kan upptäckas tidigt. Forskning om allmänna miljöegenskaper för nya substanser, biomarkör-metoder och modeller som kvantifierar flöden av kemikalier i samhället och naturen är viktiga komponenter. Klimatförändringar kommer sannolikt att påverka artsammansättning och näringsvävens struktur, vilket också påverkar transporten av miljögifter. Förändringar i hur miljögifter transporteras i näringsväven kan också orsakas av nytillkomna arter (t.ex. förekomsten av *Marenzelleria* som potentiellt kan remobilisera föroreningar ur historiska depåer). Effekter och metabolism av miljöfarliga ämnen i det mikrobiologiska samhället är till stor del okänd och många av arterna har inte identifierats. Även förekomst och effekter i naturen av nanopartiklar, mikroskopiska plastpartiklar och av komplexa blandningar i låga koncentrationer men med additiva effekter är till stor del okänd.

Framsteg inom forskningen om ***klimatförändringar*** inkluderar utvecklingen av regionala klimatmodeller (RCM) och regionala bedömningar och scenarier för befintliga och framtida effekter av klimatförändringarna, inte minst genom arbetet inom IPCC och BACC-projektet. Det är tydligt att klimatförändringar kan ha betydande påverkan på den marina miljön genom förändringar i det hydrologiska och biogeokemiska kretsloppet, temperatur och salthalts regimer, havsnivå, pH m.m. Sådana förändringar kan direkt och indirekt påverka arters utbredning, sammansättning av organismssamhällen och biologisk mångfald samt därmed ekosystemens funktion. Vissa observerade förändringar i dominansen av exempelvis biomassa och distribution av fisk, zoo- och växtplankton under de senaste decennierna har visat sig ha direkta och/eller indirekta kopplingar till klimatförändringar.

Det finns dock fortfarande stora *kunskapsluckor* kring vad de övergripande effekterna av klimatförändring kommer att vara för hela Östersjön eftersom det är svårt att kvantifiera de potentiella effekterna. Det finns också bristande kunskaper om de fysiologiska toleransintervallen för olika arter samt deras intra- och interspecifika kopplingar för att kunna uppskatta hur artspecifika effekter kommer påverka artsamhällenas, och slutligen ekosystemets, respons på klimatförändringar. Det finns behov av förbättrade RCM:er, med bättre data och klimatstatistik för att förstå biogeokemiska återkopplingar och cirkulationsmönster, inklusive kvantifiering av den hydrologiska cykeln och värmebalansen, gasutbytet mellan mark och atmosfär, effekter av aerosoler och förändringar i markanvändning, förståelsen av kolcykeln och systemets buffrande kapacitet mot försurning. Det finns fortfarande stora kunskapsluckor gällande samspelet och återkopplingarna mellan miljöproblem såsom klimatförändringar, övergödning och överfiske, samt hur dessa komplexa interaktioner kan påverka artutbredning, biologisk mångfald, näringsväven, ekosystemfunktioner och tillhandahållandet av ekosystemtjänster.

Forskning under det senaste decenniet har lett till framsteg i vår förståelse av ***fisk och fiske***, inte minst när det gäller orsakerna till några av de storskaliga förändringar som upptäcks i fiskpopulationer. Samarbetet mellan olika forskningsområden har ökat och kombinationen av exempelvis klimatförändringar, övergödning och överfiske har visat sig kunna leda till förändringar i artsammansättning, biomassa och artfördelning. Flera av de viktigaste fiskarterna har visat sig ha genetiskt distinkta populationer, med lokala anpassningar av t.ex. äggens flytkraft och återvändande till reproduktionsområden. Det är också klarlagt att ett hållbart fiske kan leda till att bestånden återhämtar sig och att den ekonomiska avkastningen ökar.

Viktiga *kunskapsluckor* inkluderar förståelsen av trofiska interaktioner, födosammansättning och den bentisk-pelagiska kopplingen. Det är fortfarande oklart om det finns ett direkt samband mellan primärproduktion och fiskbiomassa, och hur fiskpopulationer är strukturerade och påverkas av migrationsmönster och rekrytering. Dessutom finns det stora osäkerheter kring effekterna av flera och samverkande miljöproblem, och hur t.ex. förändringar i hydrologi och klimat kommer att påverka populationer och näringsvävar. För dessa och andra kunskapsluckor finns det behov av mer och bättre data, inklusive fältdata på fiskpopulationernas storlek och åldersstruktur, samt en fortsatt och ökad integrering av ekosystemmodellering med forskning baserad både på experiment och observationsstudier.

Framsteg inom forskning om ***biologisk mångfald*** inkluderar upptäckten att artrikedomen i Östersjön är mycket större än vad som tidigare var känt. Flera arter har genomgått särskilda anpassningar till det bräckta vattnet och hyser unika genetiska variationer. Exempel på sådana arter är torsk, sill och blåmusslor, liksom den nyupptäckta endemiska smaltången (*Fucus radicans*), som har genomgått en snabb artbildning under de senaste 400-1000 åren. Det har visat sig att fler än 120 främmande arter har etablerat sig i Östersjön sedan

1800-talet, främst till följd av mänskliga aktiviteter. Etableringen av främmande arter är, till en viss del, en följd av den naturligt pågående artsuccessionen och hittills har det inte rapporterats att främmande arter medfört att naturligt förekommande arter utrotats. Det är till och med möjligt att främmande arter kan öka den funktionella mångfalden. Under det senaste decenniet har kunskapen om vikten av funktionell mångfald och biologiska egenskaper kopplade till ekosystemens funktion ökat.

Det finns betydande *kunskapsluckor* när det gäller den biologiska mångfalden, inklusive funktionell mångfald och främmande arter. Det är fortfarande oklart hur de kumulativa och synergistiska effekterna, orsakade av antropogena miljöförändringar och belastningar (t.ex. belastning av miljögifter och näringsämnen, intensivt fiske, klimatförändringar, förlust av livsmiljöer och potentiellt främmande och invasiva arter) kommer att påverka Östersjön biologiska mångfald. Idag är fler än 60 arter och 16 naturtyper klassade som hotade och/eller minskande. Dessa förluster av biologisk mångfald hotar funktion och resiliens, samt tillhandahållandet av ekosystemtjänster. Den relativt enkla födoväven och relativt låga biologiska mångfalden anses göra Östersjön sårbar, då nyckelfunktioner upprätthålls av enskilda arter. Bevarandet av den biologiska mångfalden på alla nivåer; gener, arter, funktionella grupper och livsmiljöer, genom god förvaltning är därför avgörande för Östersjöns framtid, inte minst under föränderliga miljöförhållanden. Det finns ett behov av att kartlägga genetiskt anpassade lokala populationer och förstå centrala ekologiska funktioner för att bevara samhällen som har hög funktionell mångfald och fyller kvantitativt betydelsefulla funktioner. Studier bör omfatta sambanden mellan funktionella egenskaper över hela bredden av organismer i Östersjön ända till näringsvävs-konceptet. Det är fortfarande oklart hur arter och funktionella grupper kommer att reagera på enskilda och samverkande störningar, inklusive hur antropogen påverkan inverkar på arters genetiska mångfald.

En ofta förekommande fråga inom forskning om Östersjöns ***näringsvävar*** har varit om regimskiften har skett vilka förändrat näringsväven och stabiliserat den i ett alternativt stabilt tillstånd. Detta har diskuterats för interaktionen mellan frisättning av fosfor från sedimenten och kvävefixering hos cyanobakterier, samt för förändrad s.k. top-down kontroll av torsk, vilket lett till ökade skarpsills-populationer. Det finns inga entydiga svar och det finns både information som stödjer och motsäger att det existerar regimskiften till alternativa stabila tillstånd. Inga dramatiska långsiktiga förändringar i växt- eller djurplankton har rapporterats under det senaste årtiondet, men informationen om djurplankton är mycket knapphändig och retrospektiva studier av bevarat material görs för närvarande. Bortsett från situationen i Finska viken visar miljöövervakningen ingen tydlig långsiktig ökning av cyanobakterieblomningar i öppna Egentliga Östersjön. I det bentiska organismsamhället har syrebristen kraftigt minskat förekomsten av potentiella livsmiljöer och diversiteten, med en ökning av arter som kan tolerera syrebrist, mest anmärkningsvärd är den dramatiska ökningen av *Marenzelleria*. Ett starkt fokus inom forskningen rörande bentiska samhällen har varit de ekologiska funktioner som utförs av olika organismer, där vikten av funktionell mångfald framhävts. Blåstångens djuputbredning vid Askö har ökat från cirka 6 meter under 70-talet till 9.5 meter, vilket motsvarar det djup den nådde på 40-talet, vilket har ökat förekomsten av denna viktiga livsmiljö.

Våra *kunskapsluckor* när det gäller näringsväven är många och omfattande. Några viktiga luckor avser samspelet mellan samhällen i sediment och i det fria vattnet (bentisk-pelagisk koppling), hur viktiga bentiska arter är i fiskars diet, kustområdenas roll för reproduktion hos pelagiska arter, orsakerna till nedgången i *Monoporeia*, brist på djurplanktondata, orsaker till att torsk koncentreras i södra Egentliga Östersjön samt skarpsill i nordöstra Egentliga Östersjön, samt och konsekvenserna av detta.

Vår förståelse av Östersjön har ökat kraftigt under det senaste decenniet. Många processer är kvantitativt mer kända och modeller har utvecklats för att beskriva dem. Våra största och viktigaste kunskapsluckor finns inom förståelsen av näringskedjan och de allmänna biogeokemiska kretsloppen av näringsämnen och kol. Det finns fortfarande ett stort behov av grundläggande tvärvetenskapligt arbete, både i fält, laboratorium och teoretiskt. Eftersom de flesta av de storskaliga processerna i Östersjön endast kan studeras på den rumsliga och tidsmässiga skala de inträffar, kan värdet av kvalitetssäkrad, högfrekvent och långsiktig miljöövervakning inte överskattas. Att i större utsträckning sammankoppla långtidsövervakning och långsiktig ekologisk forskning, inklusive experimentellt arbete och modellering, är en kraftfull mekanism för att åstadkomma effektivt dataflöde, kvalitetssäkring, bevarandet av metodologisk och taxonomisk kompetens och att förse modellering med nya idéer för konceptuell förståelse.

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2 English summary

This report gives examples of progress or changes in scientific knowledge of the Baltic Sea during the last decade and identifies some important knowledge gaps. The area considered are the waters defined as the Baltic Sea Area by the Helsinki Commission (HELCOM) including the Kattegat. The report covers only findings in the natural sciences. The report focuses on six main fields: Eutrophication; Environmental contaminants; Climate change and ocean acidification; Fish and fisheries; Baltic Sea biodiversity, including genetic diversity and non-indigenous species; as well as Food web interactions.

One of the currently most fundamental problems in the Baltic Sea is the record extent of oxygen-depleted bottoms covering large parts of the Baltic Proper and the consequences of this. The main underlying factors are: the current load of nutrients, the frequency and magnitude of water exchange with the North Sea, the mobility of the large amounts of nutrients sequestered in the sediment during more than 60 years of extensive nutrient load, the blooms of nitrogen-fixing cyanobacteria, climate change and potentially the absence of big predatory fish.

Eutrophication research has in the last decade greatly increased the quantitative understanding of loads and internal processes. Modeling work and budget calculations have revealed that internal processes can shift very large amounts of nutrients between different pools in short time spans, making it difficult to separate such variations from effects of load reductions. Potentially phosphorus release from sediments can fuel nitrogen fixing cyanobacterial blooms and top-down effects caused by the decreased cod population can contribute to maintaining the Baltic in an alternative, high production, state. An alternative or complementing view is simply that the time perspectives are very long in a sea where the turnover time for water is more than 30 years. The development of environmental quality standards has advanced research to identify reference values for state variables, but it has also become clear that there are large uncertainties in this field. In spite of considerable long-term improvements in some coastal areas, following improved sewage treatment, there are also reports of increasing anoxia in other areas, potentially related to increasing water temperatures. In the last 25 years major inflows of cold saltwater from the North Sea have become considerably less frequent than in the preceding 100 years. There is a risk that major inflows with the current low frequency regime will become less efficient in restoring life in the deep waters of the Baltic Proper and potentially aggravate the situation by strengthening the halocline and decreasing oxygenation from surface waters.

A number of major *knowledge gaps* remain regarding our quantitative understanding of the general biogeochemical cycles of nitrogen, phosphorus and carbon such as transport and sediment binding of phosphorus, denitrification, nitrogen fixation and effects on the carbon cycle due to increased load of riverine organic matter. The availability for production and fate of organically bound nutrients in riverine load is a substantial uncertainty in calculating actual loads. The long-term potential of the sediments to deliver nutrients from historic deposits is an important component for estimating time for recovery. The causes of change in the regime of major inflows can presently not be explained. The arrival of the deep-burrowing non-indigenous polychaete worm *Marenzelleria* has changed the benthic community, with yet unclear effects on sediment biogeochemistry. There are also uncertainties in the relative contribution to total load from different sources on land, as well as the losses in fresh water systems and the coastal zone (retention). In general the importance of the coastal zone as a “filter” in retaining nutrients by sedimentation, but also releasing them from sediments in water above the halocline, need further investigation. The long-term effectiveness of potential mitigation options for eutrophication in agriculture and other forms of land use have substantial uncertainties.

Most classic environmental ***contaminants*** have, with a few exceptions, shown continued decreasing concentrations in organisms and many are below what is currently considered safe levels. Estimates of time perspectives for recovery have become clearer, as has the general knowledge of the ecological behavior of these contaminants. Progress has been made in estimating ecologically safe organism concentrations also considering food web transport. Sensitive top predators like seals and eagles have made strong recoveries, but there are signs of unsuccessful reproduction in eagles in parts of the Bothnian Sea and monitoring indications of potentially decreased health in coastal fish. Suitably preserved organism samples now enables us to rapidly reconstruct long-term time series for new and old potential environmental contaminants.

For the vast majority of substances in use there are considerable *knowledge gaps* in marine food web transport and environmental fate as well as effects in biota. The large increase in industrially used substances calls for methods to early detect substances that may become environmental contaminants. Research on general environmental properties of substances, biomarker methods and models that quantify flows of chemicals in society and nature are essential components. Climate change is likely to influence the species composition and the food web structure, thereby also affecting the transport of contaminants. Changed food web transport can also be caused by non-indigenous species (e.g. establishment of the deep-burrowing *Marenzelleria* that potentially can remobilize historic deposits of contaminants). The effect and metabolism of contaminants in the natural microbial community is largely unknown and many of the organisms are not identified. The occurrence and effects in nature of nanoparticles, microscopic plastic particles and complex mixtures in low concentrations but with additive effects are to a great extent also unknown.

Some advances in ***climate change*** research in the last decade have been the development of Regional Climate Models (RCMs) and regional assessments and scenarios of the current and future effects of climate change through the work of e.g. IPCC and the BACC-project. It is clear that climate changes are likely to have considerable impacts on the marine environment through changes in the hydrological and biogeochemical cycles, temperature and salinity regimes, sea level, pH etc. Such changes may directly and indirectly affect species distribution, community composition and biodiversity and thus ecosystem functioning. Some observed shifts in dominance of e.g. biomass and distribution of fish, and zoo- and phytoplankton during the last decades have been shown to have direct or indirect connections to climate changes.

There are however still large *knowledge gaps* regarding what the overall quantitative impacts of climate change will be on a Baltic Sea-wide level. There is also insufficient knowledge on the physiological tolerance ranges of different species and their intra- and interspecific couplings to be able to estimate how species-specific effects will translate to a community and ultimately an ecosystem response to climate change. There is need for improved RCMs, with better data and climate statistics to understand biogeochemical feedbacks and circulation patterns, including quantification of the hydrological cycle and heat balance, gas exchange between land and atmosphere, effects of aerosols and changes in land use, understanding of the carbon cycle and the system's capacity to buffer acidification. There are still large knowledge gaps regarding the interactions and feedbacks between drivers such as climate change, eutrophication and overfishing, and how these complex interactions may affect species distribution, biodiversity, food webs, ecosystem functioning and the provisioning of ecosystem services.

Research in the last decade has led to improved understanding of ***fish and fisheries***, not least regarding the reasons for some of the large-scale changes detected in fish populations. There has been increased cooperation between different research fields and the combination of e.g. climate change, eutrophication and overfishing have been shown to lead to changes in species composition, biomass and distribution. Several of the most important fish species have been shown to have genetically distinct populations, with local adaptations of e.g. egg buoyancy and natal homing. It is also clarified that sustainable fishing management can lead to recovered stocks and higher yield.

Important *knowledge gaps* include understanding trophic interactions, diet composition and benthic-pelagic coupling. It is still unclear if there is a direct relationship between primary productivity and fish biomass, and how fish populations are structured and affected by migration patterns and recruitment. Moreover, there are large uncertainties regarding the impacts of multiple and interacting pressures, and how e.g. hydrographic regimes and climate change will influence stocks and food webs. For these and other knowledge gaps, there is need for more and better data, including e.g. field data on fish population size and age structure, as well as continued and increasing integration of ecosystem modeling with experimental and observational science.

Advances regarding ***biodiversity*** research include the finding that species diversity in the Baltic Sea is higher than previously known. A number of species have been shown to have undergone specific adaptations to the brackish environment, harboring unique genetic variations. Examples of such species are cod, herring and blue mussels, as well as the newly found endemic species narrowwrack (*Fucus radicans*), which have undergone rapid speciation during the last 400-1000 years. It has been shown that over 120 non-indigenous species (NIS) have entered the Baltic since the 1800s, mainly as an effect of human activities. The establishment of NIS is, to some extent, also a natural on-going process of succession and so far it has not been reported that NIS in the Baltic have resulted in the extinction of naturally occurring species. It is even possible that some NIS have increased functional diversity. During the last decade knowledge regarding the importance of functional diversity and biological traits coupled to ecosystem functioning has increased.

There are considerable *knowledge gaps* regarding biodiversity, including functional diversity and NIS. It is still unclear how the cumulative and synergistic effects caused by human pressures (e.g. pollution by hazardous substances and excessive nutrients, high fishing pressure, climate change, loss of habitat and potentially NIS and invasive species) will affect Baltic Sea biodiversity. Today, over 60 species and 16 habitats are classified as threatened and/or declining. These biodiversity losses threaten the functioning and resilience, as well as provisioning of ecosystem services. It is thought that the relatively simple food webs and low biodiversity renders the Baltic vulnerable since key functions may be upheld by single species. The preservation of biodiversity, both at the levels of genes, species, functional groups and habitats, through proper management is therefore vital for the future of the Baltic, not least under changing environmental conditions. There is need to genetically map adapted local populations and understanding essential ecological functions, to identify and maintain communities that have high functional diversity and perform quantitatively important ecological functions. Studies should include the linkages between functional traits of the entire range of organisms in the Baltic Sea to the food web-concept. It is still unclear how species and functional groups will respond to perturbations and interactions, including how anthropogenic pressures affect intraspecific genetic diversity.

A frequent question in Baltic ***food web*** research in the last decade has been if regime shifts have altered the Baltic food web and stabilized it in an alternative state. This has been suggested for the interaction between sediment release of phosphorus and cyanobacterial nitrogen fixation, and for changed top down control by cod, causing increased sprat populations. No conclusive answers have been reached and there is information both supporting and contradicting regime shifts to alternative stable states. No dramatic long-terms changes in phyto- or zooplankton have been reported for the last decade, however information about zooplankton is very scarce and retrospective studies of preserved material are currently performed. Monitoring shows no clear long-term increase in cyanobacterial blooms in the open Baltic Proper other than in the Gulf of Finland. In the benthic community the oxygen deficiency has greatly reduced the potential benthic habitats in the Baltic Proper and diversity has decreased with an increase in hypoxia tolerant species, most notable a dramatic increase in *Marenzelleria*. A strong focus in benthic research has been on the ecological functions performed by different organisms emphasizing the importance of functional diversity. The depth distribution of bladderwrack in the Askö area has increased from around six meters in the 1970s to 9.5 meters, which is the depth it reached in the 1940s, which has increased the extent of this important habitat.

The *knowledge gaps* regarding the food web are many and substantial. Some important gaps include the interactions between the communities in the sediment and the pelagic community (benthic-pelagic coupling), the importance of benthic species in fish diet, the role of the coastal zone for reproduction in pelagic species, the causes of decline in *Monoporeia*, lack of zooplankton data, causes and consequences of cod concentrating in the southern Baltic Proper and of sprat in the northeastern Baltic Proper.

Our understanding of the Baltic Sea has increased greatly in the last decade. Many processes have been quantitatively better known and models have been developed to describe them. Our greatest and most important knowledge gaps are in understanding of the food web and the general biogeochemical cycles of the nutrients and carbon. There is still a great need of fundamental scientific interdisciplinary work, both in the field, laboratory and theoretic work. Since most of the large-scale processes in the Baltic Sea can only be studied at the spatial and temporal scale that they occur, the value of quality assured, high frequency, long-term monitoring cannot be overstressed. Connecting long-term monitoring with long-term ecological research, including experimental work and modeling, is a strong mechanism for providing efficient data flow, quality assurance, preserving methodological and taxonomic skills and providing modeling with new ideas for conceptual understanding.

3 Intentions and approach

The report gives examples of progress or changes in scientific knowledge of the Baltic Sea during the last decade and identifies some important knowledge gaps. Very briefly some major trends in the environment are discussed, but these are easily available in greater detail and in a condensed form with graphics in the annual reports from national monitoring programs “HAVET” and “Fiskbestånd och miljö i hav och vatten”. The thematic assessments of HELCOM also give synthesizing overviews of trends and HELCOMs Baltic Sea Environment Fact Sheets give the most recent information.

The area considered is the waters defined as the Baltic Sea Area by the Helsinki Commission (HELCOM), which includes the Kattegat. The report deals only with findings in the natural sciences and has been conceived and produced in a very short time frame. The time frame for the project has only allowed reading of summarizing reports and precluded extensive analysis of original sources. The selection of advances and knowledge gaps has been aided by interviews with 24 leading scientists from Sweden, Finland and Great Britain (see Acknowledgements) and discussions with the associated Expert Group (see chapter 15).

The authors want to stress that neither the scientific findings nor identified knowledge gaps in any way are proposed to cover all, or necessarily be the most important, findings and gaps. They are an attempt to find issues where we have learned considerably more, changed views or have very insufficient information. As such we consider the identified issues important, but there may well be other, potentially more important ones that we have failed to identify.

The Baltic Sea is one of the most intensively researched marine areas in the world. It is also one of the marine areas most affected by human activities, as more than 85 million people live in the drainage basin. The approach is therefore rather to give an overview of some major recent research findings and some current environmental trends than to cover the entire scientific field. The focus of the synthesis is on the environmental fields where negative anthropogenic influence is most pronounced. The purpose is also to identify major knowledge gaps that are likely to be obstacles for the work to minimize anthropogenic effects on the Baltic Sea. The report is focused on six main environmental fields:

- Eutrophication
- Environmental contaminants
- Climate change and ocean acidification
- Fish and fisheries
- Baltic Sea biodiversity, including genetic diversity and non-indigenous species
- Food web interactions (incl. changes in seabird populations and the degraded state in Hanö Bight)

This report is produced for a general reader, not for scientific experts. Nomenclature that requires extensive scientific expertise or concepts that have many potential interpretations are avoided as far as possible. Some terms, like ecosystem, are used so routinely that it becomes unclear what they actually mean. The ambition here is to use as uncomplicated and clearly defined terms as possible to avoid misunderstanding. We hope that the balance will be agreeable to most readers.

It is desirable to consider ecosystem aspects in management in the sense that we should consider all ecological interactions. What we actually can do is to address all that we have information about. This is not necessarily the same thing as addressing what is most important. If we put a substantial effort into managing a process that we have misunderstood, the result may be ineffective or at worst detrimental. Managing the Baltic Sea and its organisms based on theoretical ecological concepts is an attractive and potentially powerful idea, but also carries considerable risks. Models of the interrelations between organisms are at best uncertain and actions taken in accordance with theoretical concepts are likely to give unexpected results. It is therefore a good strategy not to overestimate our knowledge about the function of the Baltic Sea, but primarily strive to decrease the identified stressors rather than attempting to modify the system at a large scale according to yet uncertain hypotheses. An extensive monitoring with good resolution in time and space is the only reliable way of evaluating the efficiency of our actions.

Since the ambition is to manage the entire Baltic Sea there is no control system to compare with. We have to interpret changes where and when they occur and try to separate them from natural variations. This is a formidable task since intermittent events connected to the exchange with the North Sea can have very extensive effects. Most of our understanding needed to take appropriate action in order to improve the environmental state of the Baltic Sea is therefore dependent on long time series. Most processes have time perspectives of one or several decades. We are now at a stage where for some variables we have fragmentary information from a 100 years back in time and high quality data from about 20 to 40 years back. Our understanding of fundamental processes has improved considerably and continuous to grow. Continued adequate monitoring is of paramount importance for understanding and model development.

This report focuses on knowledge gaps and remaining and future problems, but our knowledge has also increased greatly in the last 20 years and many problems have improved. The open waters show little recovery from eutrophication yet, but improved sewage treatment has greatly improved water quality in many coastal waters, the concentrations of the classic environmental contaminants have declined drastically and many are now below threshold values, the populations of top predators like eagles and seals have increased strongly and cod has recovered. The lesson is that when we become aware of a problem and understand it, coordinated and resolute action can give results in a relatively short time for many problem areas.

A short description of some of the specific conditions in the Baltic is included, with focus on the issues discussed below. The text for each main subject area has a short introduction, a number of examples where our knowledge has expanded substantially or our perceptions have changed in the last decade, and some important knowledge gaps. These sections do not claim to be complete and are not ranked according to their relative importance. A comparatively large amount of text has been spent on eutrophication since this is currently the human activity that most fundamentally changes the Baltic and greatly affects most other issues. In the future climate change may well be an even more influential process, and according to most scenarios it is more likely to augment eutrophication effects than to mitigate them.

4 Brief background on the Baltic

4.1 Some general descriptions available on the net and in print

The Baltic Sea is one of the most extensively studied water bodies in the world and the background information is substantial. There are a several excellent and easily available background descriptions (e.g. Elmgren 2001, Bernes 2005, Feistel et al. 2008, Läpperanta & Myrberg 2009). No extensive description will therefore be included here and the general properties of the Baltic Sea are assumed to be reasonably well known to the reader. Some fundamental characteristics of the Baltic Sea that are essential to the concepts discussed in this report are however still included.

4.2 Some aspects on water dynamics and oxygen

According to the HELCOM definition Kattegat is part of the Baltic Sea Area, but when discussing general properties of the brackish Baltic Sea it is more natural to concentrate on the waters inside the Danish Straits. The Baltic Sea is a relatively shallow fjord-like brackish water body with several basins separated by sills, which restrict the movement of deep-water between the basins. The water has a sharp increase in salinity (and thereby also in density) at approximately 60 to 80 meters in the central Baltic Proper, called the halocline. Because of density differences the water below and above the halocline have a limited exchange. During the spring - summer season the surface water is heated by sun insolation, causing a sharp increase in density at 10–20 meters depth that is called the thermocline. Water exchange across the thermocline is also limited.

Early in the production period the stock of the main limiting inorganic nutrient (nutrients available to plants) in the surface water is used up by growing phytoplankton (plant plankton) in a spring bloom and its concentrations become very low. The nutrients are however rapidly circulating and available to phytoplankton by excretion from microorganisms and zooplankton (animal plankton) that consume the phytoplankton and one another. The production of phytoplankton can therefore be maintained at a high level throughout the production period. During summer the paradoxical situation arises that the phytoplankton production is high while the biomass is comparatively low and the nutrient concentrations are often below detection level. When the thermocline breaks down in the autumn the water mass becomes mixed and relatively homogeneous down to the halocline. The concentrations of nutrients during midwinter are therefore most representative for the stocks of inorganic nutrients in different forms.

The Baltic Sea is connected to the North Atlantic through a number of narrow straits with a maximum depth of 18 meters, severely restricting the exchange of water with the ocean. The exchange of water is driven by the freshwater outflow through the southern sounds, causing a compensatory inflow of saline water from the Kattegat. The salt water entering the Baltic Sea this way is usually of intermediate salinity and is a mixture of outflowing Baltic water and Atlantic water. These inflows occur more or less continuously during the year and spread in the Baltic Sea at depths where water of the same density occurs, usually somewhere between the bottom and the halocline.

Compared to most lake systems the turnover of water is very slow. The residence time for water in the whole Baltic Sea has been calculated to be in the order of 30 – 50 years depending on calculation method (e.g. Stigebrandt & Gustafsson 2003, Leppäranta & Myrberg 2009). There are large differences in turnover times between the basins. The water residence time in the Bothnian Sea was for example recently estimated at 4 years (Yi et al. 2013). Because of its large volume the Baltic Proper has the lowest turnover rate. Substances and molecules involved in biological processes can circulate at much shorter time scales. It is however important to remember that the turnover time by water transport is very long.

The total annual inflow of fresh water from rivers and precipitation minus evaporation to the Baltic Sea has been approximated to 480 km^3 per year (Leppäranta & Myrberg 2009, Stigebrandt & Gustafsson 2003). Which annual compensation inflow this translates to depends on the current mixing situation and the salinity of outflows and inflows. Water of considerably higher salinity (and thus density) can enter the Baltic Sea from the Kattegat in specific weather conditions with strong westerly winds. This water is salter than the deepest and most saline water in the Baltic Sea, causing it to flow along the bottom and replace the deepest water in the Baltic Sea. Such cold oxygen-rich inflows are termed major inflows and occur sporadically during major winter storms, and cannot be forecasted in the long-term. The major high salinity inflows can vary approximately between 100 km^3 and 250 km^3 (Feistel et al. 2008), but are characteristically in the range of 100 to 150 km^3. Since 1996 a number of inflows have also occurred in summer with transport of saline warm water. Warm water inflows bring less oxygen, since warm water holds less oxygen than cold water. The warmer water also stimulates oxygen-consuming biological activity.

As mentioned above, the Baltic Sea inside the Danish Straits has a very restricted water exchange with the ocean and the deep water a very limited exchange with the surface water because of the halocline. Production in the surface waters continually produces organic material that sinks out of the water and settles on the sediment. Part of that material is consumed and decomposed in the water while sinking, but much is processed by bottom dwelling (benthic) animals and microorganisms. Both the digestion and bacterial decomposition of this material requires oxygen. Oxygen is produced by photosynthesis in the surface waters and can therefore only be renewed below the halocline by inflowing saline water or by the limited water exchange across the halocline. Since both these transports are restricted, the supply of oxygen is often reduced or even totally exhausted in the water below the halocline. The Baltic Proper therefore periodically experiences periods of low oxygen levels (hypoxia) in the deep water.

When the oxygen levels become too low, multicellular animal life disappears and only some specific microorganisms are able to function. At total lack of oxygen (anoxia) microbial processes form the toxic substance hydrogen sulfide. When oxygen is resupplied it is consumed by the oxidation (reaction with oxygen) of the stored hydrogen sulfide, so that oxygen will not become available to organisms until the hydrogen sulfide is eliminated. In this way oxygen is not only depleted but there is also an “oxygen debt” to be paid. The size of the oxygen debt depends on the concentration of hydrogen sulfide and the affected volumes, which both increase with the length of the anoxic period.

The major inflows have always been crucial for oxygenating the deep waters of the Baltic Sea. They usually have a dramatic effect on the nutrient dynamics and the distribution of benthic organisms (bottom dwelling organisms). In the last 25 years these major inflows have become less frequent than in the preceding 100 years, which is as far back as they can be estimated with reasonable certainty. Between 1880 and 1983 approximately 28 such inflows of varying intensity occurred intermittently but reasonably evenly distributed over the period (Feistel et al. 2008). Since 1983 only four have occurred, the latest of which was in 2011. No improvement of the conditions in the deeper central parts of the Baltic Proper could be seen after the last inflow in November/December 2011 (Hansson et al. 2013).

The causes for this change are not well understood, but changed atmospheric conditions, wind patterns and precipitation are considered potentially important factors (Hansson et al. 2011, Feistel et al. 2008). The major inflows are comparatively easy to quantify but the continuous inflows are much more difficult to estimate. These transports occur when water with relatively small salinity differences moves back and forth through the sounds. Net transports must be estimated by differences between large volumes of water and therefore become uncertain. The relative importance of variations in these two processes for the oxygenation of the Baltic Sea is therefore difficult to evaluate.

4.3 Oxygen and nutrients interact

An extended period of anoxia, which affects large areas of sediment below the halocline, has profound effects on the nutrient dynamics. Very large quantities of nitrogen and phosphorus are shifted between different pools when the oxygen levels are significantly changed. These shifts are, with delays, reflected in surface concentrations and can seriously complicate our interpretations of how surface concentrations and external nutrient loads are interrelated.

Both dissolved nitrogen and phosphorus occur in forms where they are part of organic matter (particles and molecules containing carbon) and in inorganic forms (molecules without carbon). Both organic and inorganic forms of these nutrients are carried to the Baltic Sea by riverine transport. The inorganic forms are instantaneously available for uptake by phytoplankton. A fraction of the organic forms are, through decomposition in the Baltic Sea, transformed to inorganic forms. Excretion of digested foodstuffs from consumers releases inorganic nutrients but also organic forms, which are rapidly transformed to inorganic forms. Production shifts nutrients from inorganic form to become included in organic matter while decomposition does the opposite. In general only the inorganic forms of nutrients are available to plants and algae, even though some organisms can assimilate and use nutrients in some organic forms. Both phosphorus and nitrogen are permanently removed from the Baltic Sea by export to the ocean through the southern sounds or by permanent burial in the sediments.

4.3.1 Nitrogen

When oxygen is present in the water nitrogen occurs mainly in the form of nitrate. Nitrogen is continually released by decomposition in the sediment (and in the water column) as the reduced form of nitrogen called ammonium, which occurs when oxygen is not present. In presence of oxygen ammonium reacts with oxygen (is oxidized) and forms nitrate. Both nitrate and ammonium are readily assimilated by plants and algae.

Under anoxic conditions, inorganic forms of nitrogen nutrients can be transformed into nitrogen gas by microbial processes broadly summarized as denitrification. Nitrogen gas is unavailable to plants and algae as a nutrient. Only some cyanobacteria (formerly incorrectly called blue-green algae) can use dissolved nitrogen gas as a source of nitrogen. Their use of nitrogen gas to build biomass (nitrogen fixation) annually adds as much nitrogen as about a third of the total external nitrogen load to the biological system. Denitrification removes nitrogen from production. This process is the main reason why the nitrogen concentrations in the Baltic Sea are lower in the water than could be expected from the load. Denitrification requires zones of both oxygenated and oxygen free water. Such conditions frequently occur when decomposition is intensive.

When oxygen is depleted in the water below the halocline a massive denitrification occurs and almost all other inorganic nitrogen below the halocline is transformed into nitrogen gas. The amount of nitrogen removed in this way can be a substantial part of the total nitrogen pool. Afterwards, ammonium starts to accumulate in the now oxygen-free water mass below the halocline. When a major inflow oxygenates the water, this ammonium is transformed to nitrate. Some of the nitrate is transported to the waters above the halocline by water movements, while most of the rest will later be denitrified, once oxygen is again consumed.

4.3.2 Phosphorus

Phosphorus differs from nitrogen in having no biological removal process equivalent to denitrification. It is only removed by export to the ocean or by burial in the sediment. When oxygen is present the inorganic form of phosphorus (phosphate) binds to the metals iron and manganese. Much of the phosphorus hereby settles out of the water mass on to the sediment and remains in the sediments as long as the water above the sediment is oxygenated. Decomposition of organically bound phosphorus in the sediment continuously supplies new phosphate and a balance between sedimentation and release is reached. In the waters above the halocline oxygen is always present at some distance from the sediment and wind causes the water to circulate. A large part of the phosphate from shallow sediments is thus kept in the water and available for production.

During periods when oxygen is present in the water below the halocline sedimentation of phosphorus dominates and phosphate concentrations are comparatively low in the water. Binding to iron and manganese keeps the phosphate in the sediments. When oxygen is depleted the metals lose their ability to bind phosphate and the phosphate is rapidly released to the water. During periods of anoxia water exchange below the halocline is low, causing phosphate concentrations to build up. Extended periods of anoxia can thus result in very high phosphate concentrations.

When an inflow causes replenishment of oxygen in the water below the halocline the metals regain their ability to bind phosphate. A significant part of the phosphate therefore sediments out of the water mass and settle on top of the sediment. However, water replacement transports some of it to the surface waters where it becomes available for production. The mechanism of release and resettling of phosphate below the halocline can potentially keep much of the phosphate at the sediment surface. In a renewed anoxic period it can be released again, which reduces permanent burial.

Eventually some of the deep water will reach the surface through water mixing. The periods with oxygenation and oxygen depletion below the halocline are therefore, with time delays, reflected in the surface waters. Therefore, the massive denitrification in the initial phase of oxygen depletion is generally reflected in the surface water as a decrease in inorganic nitrogen. The build-up of phosphate during the oxygen-free periods will cause surface concentrations of phosphate to increase. These processes affect a considerable part of the pools of nutrients and the resulting changes can mask the effects of reduced nutrient loads.

4.4 Some aspects on biological conditions in the Baltic Sea

4.4.1 Salinity gradients and diversity

The Black Sea and the Baltic Sea are the two largest permanent brackish environments in the world. From a biological point of view the Baltic is an environment characterized by a low number of species (low diversity). Including the Kattegat the number of known species have been estimated to 6 065 (Ojaveer et al. 2010). Of these a little more than a third each are plants and benthic animals, a fifth are zooplankton and about three percent are fish.

The number of marine species quickly drops when passing the Danish Straits and going from south to north in the Baltic Proper and Gulf of Bothnia. Compared to other aquatic environments, such as streams, rivers, lakes and the ocean, brackish environments are often relatively rare, isolated and from an evolutionary perspective of short duration. Species richness (high diversity) often occurs in environments that cover large parts of the world, have existed for geologically long time and where organisms are able to spread between different areas of such environments. There are therefore few species specifically adapted to the brackish environment. From a geological and evolutionary time perspective the present brackish Baltic Sea was just formed about 8 000 year ago and is still being populated by adaptable organisms from both marine and freshwater systems. The flora and fauna of the Baltic is thus a mixture of freshwater species, marine species and a few true brackish water species. Some of them have been there as long as the Baltic Sea has existed, whereas others appeared later.

Organisms in the Baltic Sea have to adapt to a geographic salinity gradient from the Danish Straits in the south to the Bothnian Bay in the north and to a salinity that also varies slightly over time. The internal salt concentration in the cells of an organism is vital to its survival and can generally not vary to any greater extent. Aquatic organisms have to actively maintain the internal salt concentration, a process that is energy demanding. Marine and many freshwater organisms in the Baltic therefore have to allocate more energy to this regulation than they would in their original environment. A substantial part of their food consumption could otherwise have been used in growth, reproduction and general cellular maintenance.

This cost of living in the Baltic causes many marine organisms to become smaller in size than their counterparts in their original environment. Many of the species present in the Baltic also occur at the border of the salinity they can endure, which can make them vulnerable to other pressures. On the other hand the Baltic is a highly productive system. The large drainage area in relation to the water volume causes intensive nutrient loading, which can compensate for some of the energy cost of adapting to the salinity of the Baltic. Organisms in the Baltic are generally adaptive species that can tolerate variable conditions.

A specific problem related to the limited water exchange and unfavorable metabolic conditions for marine species has been the very high load of environmental contaminants in the Baltic. Harmful substances that are excreted at a slow rate and accumulate in organisms are called persistent contaminants. In many texts they are termed PBT substances (Persistent Bioaccumulating Toxic or vPvB very Persistent very Bioaccumulating). If the main exposure is through the ingested food, organisms that use a smaller proportion of their food for growth will eat more per unit of body weight. They will therefore end up with higher concentrations of persistent contaminants in their tissue. The salinity stress thus makes the Baltic organism community potentially sensitive to such accumulation. The combination of 85 million people in the drainage basin, a high level of industrialization, slow water exchange and an unfavorable energy balance for organisms makes environmental contamination in the Baltic Sea particularly unfortunate.

4.4.2 Geographic isolation

From a genetic aspect the Baltic organism community is very vulnerable. The limited exchange with the ocean has caused most marine species in the Baltic to become isolated from their source populations in the Atlantic. Not only the number of marine species but also the genetic diversity within species decreases rapidly when passing the Danish Straits. Even if the geological history of the Baltic is short some of its populations are genetically unique and have adapted to the special conditions of life in the Baltic Sea (Johannesson & André 2006, Wennerström et al. 2013). Many of these populations are local and in some cases clones (a group of individuals that do not reproduce sexually i.e. all individuals have identical genetic material). If such locally adapted populations go extinct they are unlikely to be replaced by immigration of the same species for a very long time. In a low diversity system like the Baltic, many central ecological functions may depend on one or a few species (see also chapters on Biodiversity and Food web).

Human activities also cause an increasing number of non-indigenous species (NIS) to become established in the Baltic Sea. Since the beginning of the 19th century approximately 120 NIS have been recorded in the Baltic Sea including the Kattegat (HELCOM 2009a). It must however be remembered that essentially all species in the Baltic are “new” in a longer time perspective since the Baltic inside the Danish Straits is a young sea. The Baltic organism community is a succession where new species will continuously find their way to the Baltic also without human assistance.

It is impossible to reliably predict how NIS may affect the system and other species. So far no one of the NIS have had very dramatic adverse effects on other Baltic species. In some cases they have become important parts of the invaded organism community (Ojaveer et al. 2011). There is however a concern that an aggressive invasive species sooner or later may establish itself and cause substantial negative changes in the Baltic Sea. A precautionary principle has been to limit the introduction of NIS where possible.

New non-indigenous species will also in the future become permanent members of the flora and fauna in the Baltic. In geologically old environments most ways of living are used organisms ("niches") and competition is strong, but in the young Baltic it is likely that there are ways of living that have not yet been exploited (empty niches). Some NIS may therefore be able to establish themselves without seriously affecting already present species, whereas others may potentially have negative effects on species already present in the Baltic. The biological monitoring programs are potentially very important for detecting dramatic changes in the population sizes of present and new species.

5 Eutrophication

5.1 Current trends

There are six main factors that currently are assumed to strongly determine the future trajectory of Baltic eutrophication: the current load of nutrients, the frequency and magnitude of water exchange with the ocean, the mobility of the large amounts of nutrients sequestered in the sediment during more than 60 years of extensive nutrient load, the blooms of nitrogen-fixing cyanobacteria, climate change and potentially the absence of big predatory fish.

The Baltic Sea has since a very long time been affected by human activities. Recent studies suggest that it has been affected by human perturbation during the last two millennia (Zillén & Conley 2010). The sediments in the deepest parts of the Baltic have, since more than 100 years, for long periods been oxygen free (anoxic) or had oxygen levels too low (hypoxic) to sustain life (Jonsson et al. 1990, Hille et al. 2006, Zillén & Conley 2010). Only some microorganisms can live under anoxic conditions and since the animals die the sediment remains undisturbed.

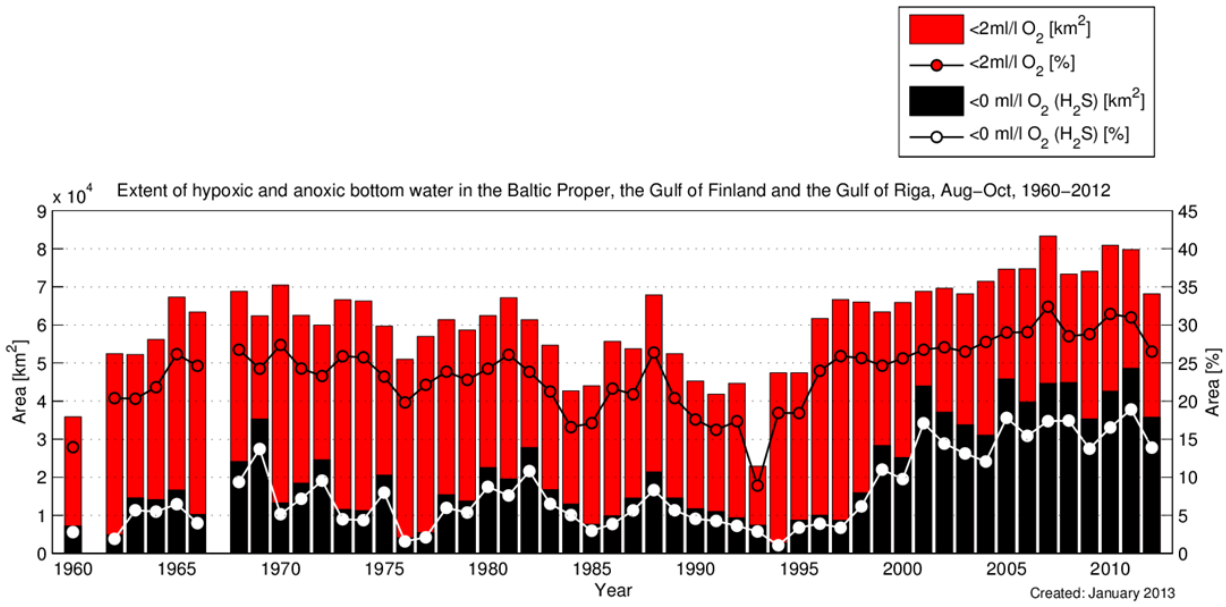

Figure showing areal extent of anoxic and hypoxic conditions in the Baltic Proper, Gulf of Finland and Gulf of Riga. Results from 1961 and 1967 have been removed since sufficient data from the deep basins are missing (from Hansson et al. 2013).

In sediment cores, layers from anoxic periods can be identified by being dark, whereas oxygenated conditions produce greyish layers. Jonsson et al. showed already in 1990 that such dark layers have occurred since more than 100 years in the open Baltic Proper. There was however an increase in areas showing such dark layers beginning in 1940 and a dramatic increase from 1960. The area covered by laminated sediments was calculated to have increased by a factor of 4 from 1960 until 1990 (Jonsson et al. 1990).

In recent years the lack of oxygen in the deep water of the Baltic has reached record proportions. More than 30 percent of the bottom area in the Baltic Proper, Gulf of Finland and Gulf of Riga are now below hypoxic water and some years almost 20 percent was below anoxic water. The areal extent of hypoxia increased from about 9 percent in 1993 to 32 percent in 2007. The mean extent of anoxic bottoms have increased threefold from 5 percent in the period 1960-1998 to 15 percent in the period 1999-2011 (Hansson et al. 2013).

5.2 Examples of scientific progress and changed views

Our view on the Baltic eutrophication process has not changed substantially concerning the main driving pressures during the last decade. The fundamental problem is still considered to be the excessive load of nitrogen and phosphorus. The historically large extent of oxygen depleted bottoms is generally considered to be a result of decreased frequency of major inflows, degradation of accumulated sedimented material from a long history of eutrophication, as well as still elevated levels of chlorophyll. Our understanding of the Baltic eutrophication has however expanded in a number of ways in the last decade. As is often the case with increased understanding of complexity, a number of new potentially important processes have been identified.

Even if substantial reductions in nutrient loads have been achieved in the last 20 years the only potential effect that can be seen in the open waters of the Baltic is an unclear trend of reduction in the winter concentration of inorganic nitrogen in the Baltic Proper. Whether this is an effect of reduced atmospheric and riverine loads, or of intensified denitrification due to the exceptionally bad oxygen conditions in the Baltic Proper is unclear. Open Baltic phosphorus concentrations remain at near all-time high values, even though the external load has been cut by half since the 1980s (Gustafsson et al. 2012). There are two major ways of interpreting this. One is simply that the time perspectives are very long in a water body with more than 30 years turnover time. The other is that the Baltic has changed from one stable state of functioning at low nutrient levels to another stable state of functioning at more nutrient rich conditions.

The first view is supported by the fact that since the late 1970s the Baltic has experienced three long periods of severe oxygen depletion in the deep water. The longest of these lasted for almost 16 years. In the deep sediments of the Baltic Sea a huge amount of organic material has accumulated during the history of eutrophication. The organic matter consumes oxygen at a higher rate than what would occur in a less eutrophic state. The oxygen situation affects internal processes that can release or remove very large amounts of nutrients from being available for production. The nutrient amounts shifting between available and unavailable pools can exceed the annual external loads (e.g. Conley et al. 2002, Savchuk 2013 and references therein).

The arising fluctuations in nutrient concentrations caused by major deep-water inflows and the subsequent potential effects on production makes it difficult to separate the effects of internal processes from effects caused by changes in external load of nutrients. Reliable and detailed measures of most of the relevant variables have only been available for approximately 30-40 years, with an increased precision in the last 20 years. For oxygen the first reliable measurements were made over a 100 years ago. The internal cycles, driven by major inflows from the ocean, occur on the timescale of decades. They can only be studied at the spatial and temporal scale at which they occur, which is the entire Baltic Sea. It is therefore likely that the time scale will be comparatively long for finding reliable trends in open waters that can be tied to changes in the external load.

Population sizes of organisms also undergo considerable changes due to natural processes. Dramatic changes frequently occurs in e.g. phytoplankton, which can unpredictably bloom over vast ocean surfaces. Blooms can effect the entire organism community of consumers and thereby cause fluctuations in abundance for many species. Sometimes the mechanism behind drastic changes in population size is known, as with the El Niño oscillation in the Pacific ocean, but mostly the changes are not well understood. In the Baltic the human impact is extensive and it is often difficult to separate natural population fluctuations from those potentially caused by human influence. The most drastic changes we are aware of have probably been caused by interactions between natural processes and nutrient load, release of toxic substances, fishing or unintentional introduction of new species. For example the Baltic blooms of nitrogen fixing cyanobacteria are a well known phenomenon which appears to have occured for a very long time, perhaps since the brackish Baltic Sea was formed (e.g. Bianchi et al. 2000). The small benthic crustacean *Monoporeia affinis* is an important part of the benthic community and can undergo drastic population changes for reasons which are not fully understood. Here the role of human activities is unclear, whereas the decline of the cod population can be attributed to overfishing and anoxia and the previous decline of seal and eagle populations to hunting and the effect of environmental contaminants.

The long time frames and internal processes may explain why no long-term decreasing trends in the nutrient and chlorophyll concentrations have been found in open waters, but a large part of recent discussions regarding Baltic eutrophication has been concerned with the question “Has there occurred one or several regime shifts?” In recent years a number of articles have discussed potential regime shifts in the Baltic Sea (e.g. Alheit et al. 2005, Hagen & Feistel 2005, Österblom et al. 2007, Casini et al. 2008, Möllmann et al. 2008, 2009, Cardinale & Svedäng 2011, Kraberg et al. 2011, Dippner et al. 2012). The term regime shift is generally used for describing that many state variables (e.g. nutrient concentration, production, species composition and relative abundance of species) have changed substantially from one state to another and that the system remains in this alternative state without further change in external pressures. In this use the term regime shift just means that with a new set of pressures the system has a new set of characteristics and may function differently. If a return to the original pressures occurs, the system will theoretically return along the same path to its original state. If the set of pressures changes permanently from the original (e.g. climate change) the system will not move to its original state, but remain in an altered state according to the new pressures.

A distinct difference between this general use of the term “regime shift” occurs if the change of state causes a situation where a return to the original pressures does not cause the system to return to its original state, or to do so by a different path because of internal mechanisms stabilizing it in an alternative state. This effect is sometimes called “hysteresis”. In general it is expected to require greater changes in the pressures to return to the original state than was required to reach the alternative state. A simple analogy for hysteresis is the thought that a person presently stays in a small depression on top of a small hill with a steep slope. It requires little effort to cross the rim of the hill and tumble down. It also requires little effort to remain on the plain ground below, but returning to the top of the hill requires considerable effort.

In nature such shifts can appear as results of substantial changes in the physical environment or in species composition and are familiar from environments on land. After a minor forest fire in a northern conifer forest a new forest similar to the one that burnt will establish itself, since those are the seeds most likely to reach the area and be competitive. If the fire is large enough the physical properties of the soil may change and another type of vegetation like a heath may establish itself. To restore it to a forest in a limited time frame may require substantial measures and cannot be achieved by simply reseeding the first stages of the forest succession.

In aquatic systems the research on potential regime shifts has increased greatly in recent years (se references above and therein). On land such events can be studied in detail. A large number of measurements of species composition, abundance and other state variables can be obtained by observation and frequent sampling. In the sea however observation and sampling is generally much more complicated. We are therefore often limited to studying complicated processes through “key holes” with a very limited number of observations and shorter time frames. Originally most of the concepts of regime shifts in aquatic environments have their origin in experimental work in small lakes.

> An example is a relatively nutrient poor shallow lake made eutrophic by loading of nutrients. Phytoplankton production increases, sinks and accumulates in sediments. In deep lakes sedimented material to a great extent remains in the sediment. In a shallow lake wind action can cause the entire water body to circulate and parts of the nutrient rich sediment to be re-suspended in surface water causing

new production. Removal of the external nutrient load may not result in a return to a low productive state in a time frame comparable to the change from low to high productivity. The sediment will become an active part of the production and resettle on the bottom during calm periods.

Another well-known lake manipulation is reduction or removal of large fish-eating fish leaving only fish that feed on zooplankton (animal plankton) and plants (plankton and submerged vegetation). A large proportion of zooplankton feed on phytoplankton. When zooplankton eating fish become more numerous they will consume more zooplankton. Zooplankton will become fewer and the phytoplankton will increase in numbers, causing water quality in terms of clarity to deteriorate and sedimentation to increase. The now numerous zooplankton feeders may also be predators of the juvenile stages of the fish-eating fish. The return of the latter will therefore be hampered.

In small lakes the turnover time of water is often short and the conditions in the water are relatively homogeneous over the whole lake. It is therefore comparatively feasible to confirm that a shift in state has occurred and that pressures can produce effects that fundamentally change the properties of the lake and moves it to a state that is not easily reversed by removing the pressures. In marine environments however changes generally occur on the time scale of decades or several decades. It is therefore very difficult to judge if large changes are reversible on the same timescale, or if a regime shift with a fundamentally different return path has occurred.

The view on potential regime shifts has far-reaching implications for management. If a change is believed to be a reversible process where the return occurs on the same timescale, a return to the original levels of pressure can be assumed to produce a predictable rate of return to the original state. If however the return path occurs on a very different time scale it becomes difficult to predict the rate of return or endpoint of change and, even more seriously, how large effort will be required to sufficiently decrease pressures. Whether some of the processes we observe in the Baltic are results of regime shifts or only processes with a very long time scale affects how we would plan to manage them.

The following subsections present a non-exhaustive list of changed views or new insights in the field of eutrophication. Some of these have been known to a limited number of people for more than a decade but have come to be more widely recognized, which does however not mean that there is a clear consensus on their relative importance.

5.2.1 Better quantitative understanding of loads, processes and mechanisms

The load pollution compilations (PLCs) of HELCOM have given a considerably better understanding of loads and their sources (HELCOM 2004, 2011, 2013a). The methods used to calculate loads have also improved substantially, become more standardized and consequently also gained higher precision. We therefore now have a considerably better understanding of the sources and amounts of nutrients and where they enter the Baltic Sea. The organized load compilations have, together with model development, also given a quantitatively clearer picture of how the loads change over time. A number of studies of nutrient pools and flows between them have greatly increased the general quantitative understanding of the fate of nutrient loads and the quantitative importance of internal processes (e.g. Savchuket al. 2005, 2006, 2008, Conley et al. 2007. 2009a, b, c, Morth et al. 2007, Savchuk & Wulff 2007, 2009, Vahtera et al. 2007, Wulff et al. 2007. 2008, Zillen & Conley 2010, Gustafsson et al. 2012). A number of large research projects have also substantially contributed to this increased knowledge (Bonus 2013).

The transfers between pools by internal processes such as denitrification, nitrogen fixation and phosphate release from sediments are very large and may in some cases considerably exceed the external loads. Particularly these internal shifts between pools may become accentuated and shift direction in connection with the inflow of oxygenated saline water. In the last decade this information has however become more generally known, more reliably quantified and identified as one of the main causes for why trends in open waters do not yet appear to be significantly affected by management actions.

The rapid development of models for the Baltic Sea coupled with load models for the drainage area has developed the research into how different processes are interconnected. The Baltic Nest Institute’s Nest-model has been developed into a management tool to calculate required nutrient reductions to fulfill the political goals of the Baltic Sea Action Plan and there are parallel model developments at the Swedish Meteorological and Hydrological Institute (SMHI RCO-SCOBI) and The Leibniz Institute for Baltic Sea Research (ERGOM). Existing models have been used in combinations to develop a multi-model system tools and to analyze uncertainties by combining and comparing different models (ensemble modeling). In this context attempts have been made to co-evaluate combined effects of climate and eutrophication scenarios. One of the conclusions reached was that "Nutrient load reductions and sustainable fishery may even be more important in future climate than in present climate" (http://www.baltex-research.eu/ecosupport/).

5.2.2 Severity of oxygen deficiency may cancel effects of major inflows

The oxygen deficiency in the deep water of the central Baltic Proper is extensive and strongly affects most biological processes (Conley et al. 2002, 2009). As mentioned above anoxia has spread to very large bottom areas and hypoxia almost reaches the halocline in the Baltic Proper (Hansson et al. 2011). Almost the entire water body below the halocline is therefore hypoxic and in 2011 anoxic conditions affected 20 percent of the bottom areas in the Baltic Proper, including parts of the Gulfs of Finland and Riga (Hansson et al. 2013).

The halocline restricts water exchange between the deep water and the surface water. The water from the surface down to the halocline is well mixed during the winter period and is therefore oxygenated. The area affected by hypoxia is therefore likely to have reached almost its maximal extent since it now has reached the halocline. The anoxic area can however still expand if no major inflow occurs and eutrophication continues (Hansson et al. 2011). Within the BONUS program the inflows to the Baltic Sea and their consequences have recently been studied (http://www.bonusportal.org/about_bonus/bonus_and_era-net/bonus_2009-2011/bonus_projects/inflow).

A worrying view on oxygen depletion is presented in a recent HELCOM report concerned with setting the targets for management in the Baltic region (HELCOM 2013b). In the report an "oxygen debt" is calculated and defined as: "the missing oxygen relative to a full saturated water column". This does not only mean to "fill the water with new oxygen" but also to oxidize the hydrogen sulfide that accumulates in the deep water. Also ammonium, which now accumulates, will require oxygen to be transformed into nitrate. A retrospective calculation suggests that this debt is now considerably greater than previously recorded. Infrequent inflows may therefore to a large extent be consumed without causing any fundamental improvement in the conditions for life in the water below the halocline, and could potentially also aggravate anoxia by strengthening the halocline. The duration of the hypoxic/anoxic period thereby has a memory that will affect the time frame for recovery.

5.2.3 Why load reductions have not led to improvements in the open waters

Despite substantial efforts to reduce nutrient loads the open surface waters of the Baltic Sea shows no clear trends of decreasing nutrient or chlorophyll concentrations (Fonselius & Valderrama 2003, HELCOM 2009b, Havet 2012). The most recent historic reconstruction of loads indicates that a peak level was reached at around 1980 (Gustafsson et al. 2012). The reconstruction indicates that from 1850 to 1980 the total load of phosphorus increased from 13 to 75 kton/year and the load of total nitrogen from 400 to 1 250 kton/year.

Since the peak in the 1980s the phosphorus loads have been estimated to have decreased to approximately half of the peak loads (Gustafsson et al. 2012). The main reduction has been achieved in coastal point sources by improved sewage treatment, but the riverine loads have decreased by less than 10 percent. For nitrogen a minor reduction in load can be seen but annual data is highly variable and the uncertainties are large. For the load reconstruction and modeling of development in the Baltic Sea the model BALTSEM (Baltic Nest Institute) was used. The results from modeling suggest that further reductions are required for both nitrogen and phosphorus to improve the water quality (Gustafsson et al. 2012 and references therein). The finding that many internal processes are of the same size or greater than the external loads has changed the perspectives of time frames for recovery due to decreased external loads.

5.2.4 Lack of data for determining background values

For many central variables (e.g. complete nutrients, chlorophyll, etc.) there is only reliable data with good coverage approximately 20 to 40 years back. Information on organism abundance is scarce but reasonably reliable in older data particularly for benthic animals, partly due to the low diversity and small changes in sampling methods and taxonomy. In plankton however there has been a substantial development in species identification (taxonomy) and many organisms previously identified as one species have now been separated into different species. It is thus in some cases difficult to compare data on historic abundance with modern data. We can therefore not with certainty say what the Baltic looked like before humans made a significant impact.

Lack of data on the baseline for human impact is a serious problem when setting target levels for different environmental variables. Estimates of nutrient concentrations, primary production, organism abundance, species composition etc. must in most cases be estimated by extrapolation, regressions, modeling or educated guesses. The complexity of the baseline identification has become more palpable during the development of Environmental Quality Standards (EQS) and in modeling. It is not only difficult to say what the levels would be at a baseline, but also which combinations of baseline values that can occur simultaneously.

An example of this is the abundance and biomass of sediment dwelling organisms. With increasing eutrophication more food will fall out of the water to the sediment. As long as this does not cause oxygen deficiency it will be good news for the organisms feeding on the sediment and their abundance will increase. When oxygen deficiency appears they may be drastically reduced. Another example is cyanobacterial nitrogen fixation and fish production. The Baltic Proper is likely to have been reasonably productive also prior to significant human impact. It is likely that the cyanobacteria are partly the cause of this. They introduce biologically available nitrogen during the summer period when nitrogen is limiting phytoplankton growth, which is the base for the zooplankton food web. During summer zooplankton grow vigorously as do fish larvae and fry feeding on zooplankton. In this way the nitrogen fixation of cyanobacteria is likely to be to a substantial part channeled into fish production.

In general we consider low nutrient levels and high biomass of benthic animals, zooplankton and fish to be desirable. It is however unlikely that very low nutrient levels, absence of cyanobacterial blooms and high biomass of animals would occur simultaneously, since eutrophication is the most likely cause for high benthic biomass (e.g. Cederwall & Elmgren 1980, Bernes 2005, HAVET 2011) and cyanobacterial blooms introduce nitrogen to the pelagic food web (e.g. Rolff 2000, Woodland et al. 2013). To evaluate within which boundaries different variables can vary simultaneously is a substantial scientific challenge. There has therefore been a growing interest in using historic datasets and try to interpret them in relation to modern data.

5.2.5 Improvement in many coastal areas but also signs of oxygen deficiency

In contrast to the open sea many coastal areas in Sweden show decreasing trends in nutrient and chlorophyll concentrations as a result of improved sewage treatment, starting with phosphorus removal in the 1970s and improved nitrogen removal in the late 1990s. In for instance the Stockholm archipelago the improved sewage treatment has caused considerable improvements in water quality. Concentrations of nitrogen and phosphorus in the water, transparency (Secchi depth), chlorophyll and oxygen levels in bottom water have all improved substantially during the last 40 years following improved sewage treatment (Lännergren 2012), which is reflected in the water quality, particularly in the inner parts of the archipelago. The benthic fauna has also recovered as a result of improved oxygen conditions in the bottom water (e.g. Karlsson et al. 2010). Also in Denmark many coastal waters are recovering from eutrophication (Carstensen et al. 2006).

Some coastal waters have improved, but there are also signs of increasing occurrence of oxygen deficiency at other coastal stations (Conley et al. 2009). Severe oxygen conditions do generally not prevail all year around in coastal areas since most coastal sediments are above the halocline and therefore affected by circulation. Oxygen deficiency therefore occurs periodically, making it difficult to detect and quantify. Generally the late autumn produces the most oxygen depleted conditions but it is also more sensitive to wind conditions than anoxia below the halocline. The sporadic occurrence of hypoxia/anoxia in coastal sites and the complex topography of archipelago areas make it difficult to evaluate large-scale time-trends.

There is also an increased interest in the general large-scale function of the coastal areas for several reasons. It is generally believed that the coastal zone act as a "filter" for nutrients and that a substantial amount of production generated in the coastal zone is also deposited there, but on a large scale this effect is to a great extent quantitatively unknown (Heiskanen & Tallberg 1999, Lampe 1999, Pastuszak et al. 2005, Selig et al. 2006, Worm et al. 2000). Coastal waters are also important spawning grounds for many organisms and many important organism communities occur only here, such as coastal fish and organisms associated with macroalgae like bladderwrack. A substantial part of the soft bottoms that have macroscopic life are also in the coastal zone. There are several positive signs in many coastal areas in Sweden, where management has reduced nutrient loads. The coastal waters are the first to respond to management and it is also here that most people meet the sea and form their opinion on its state.

5.2.6 Potential regime shift may alter ecosystem functioning

A number of articles have discussed the potential feedback mechanisms of internal processes. A potentially very strong such feedback is the interaction between sediment release of phosphate and the nitrogen fixing cyanobacterial blooms. When phosphate released from sediments during hypoxia/anoxia reaches the surface it can potentially fuel nitrogen fixing cyanobacterial blooms in the Baltic Proper. Cyanobacteria can, through nitrogen fixation, access gaseous nitrogen which is unavailable to phytoplankton and thereby utilize a surplus of phosphorus when phytoplankton are limited by low availability of inorganic nitrogen. Inorganic nitrogen is virtually exhausted down to 50 meters depth by the spring bloom giving cyanobacteria a competitive advantage during the summer season. The cyanobacteria transform nitrogen from its biologically inert gaseous form to bioavailable nitrogen, part of which will be in the form of cyanobacterial biomass. Some of the produced bioavailable nitrogen is also released to the surrounding water where it can be assimilated by other organisms. The new biomass generated by the cyanobacteria and the production caused by their excretion of nitrogen increases the sedimentation and can thereby increase oxygen consumption in the sediment.

Release of phosphate from sediments occurs both under good oxygen conditions and during oxygen deficiency. When oxygen is present oxidized iron binds phosphate causing it to decrease in the water and to a greater extent stay in the sediment. Bad oxygen conditions therefore increases the phosphate concentration in the water. A potentially vicious circle can be the result where: oxygen depletion causes phosphate release, which fuels cyanobacterial blooms, which sediment and consumes oxygen and so on. The large release of phosphorus from sediments (e.g. Conley et al. 2002) and extensive nitrogen fixation (e.g. Rahm et al. 2000, Larsson et al. 2001, Rolff et al. 2007) can potentially lead to a considerable amplification of eutrophication problems (e.g. Vahtera et al. 2007).

The two main species responsible for large summer cyanobacterial blooms in the Baltic are the filamentous forms *Nodularia spumigena* and *Aphanizomenon* sp. Unlike phytoplankton that sink in calm weather the filamentous cyanobacteria float to the surface. This is especially characteristic of *Nodularia*, which forms large surface scums, sometimes covering much of the Baltic Proper. Wind and water movements aggregate them in large scale patterns visible from satellite. The number of filaments per volume can vary by orders of magnitude over very short distances. It is therefore very difficult to get a reliable estimate of their abundance and consequently also very difficult to investigate potential time trends or how the size of the bloom is interrelated to other environmental variables (e.g. Kononen et al. 1996, Finni et al. 2001, Larsson et al. 2001, Vahtera et al. 2005, Degerholm et al. 2006, Rolff et al. 2007, Walve & Larsson 2007, Wasmund et al. 2012).

The information on trends in cyanobacterial blooms is conflicting. Previous studies (e.g. Finni et al. 2001, Poutanen & Nikkilä 2001) found that the intensity and frequency of cyanobacterial blooms had increased in the Baltic Sea during the latter half of the last century. Kahru et al. (2007) found a correlation to remaining phosphate after the spring bloom when analyzing satellite data for the open sea in the entire Baltic Proper and Bothnian Sea. There is however also information that contradicts a direct coupling between phosphate release and cyanobacterial blooms. The concentration of inorganic phosphorus in the surface water has increased strongly since the mid-1990s as a consequence of the oxygen deficiency in the deep water of the Baltic Proper. This would be expected to increase cyanobacterial blooms. Recent analysis of long-term monitoring of the biomass of nitrogen fixing cyanobacteria does however not show any increase in the summer blooms in the open Baltic Proper. This has been shown both for the southern and the northern part where they were even found to decrease in the southern Baltic Proper (Suikkanen et al. 2007, Wasmund et al. 2011, Hällfors et al. 2013). In the Gulf of Finland and at many coastal sites there have however been increases in abundance (Suikkanen et al. 2007, Jaanus et al. 2011).

5.2.7 Insights on interaction between eutrophication – fishery – climate change

The traditional view of the eutrophication process has been a bottom-up regulation, where the loading of nutrients causes production to increase and the effects of increased production are propagated upwards in the food chain. There has always been awareness that food web interactions can cause feed backs and unexpected effects. It has however been assumed that the state of the system should generally be governed by the combination of external load and accumulated historical load in combination with major inflows. It has also been assumed that some sort of proportional relation could be expected with time delays, between levels of load and observed nutrient levels and phytoplankton production. It has been widely accepted that the time frame for response could be long, but at the turn of the millennium many found it surprising that no consistent trends showing improvement could be seen in the open waters, in spite of more than 20 years of substantial reductions made by improved sewage treatment.

In general the assumption that load reductions will eventually affect the nutrient levels and thereby the phytoplankton production remains, but it has become clear that the time perspective can be longer than previously expected. The expectations on the relation between load and response has been complicated by changing views on the persistent decrease in major inflows, variations in river runoff, potential regime shifts altering fundamental processes and the potential of fishery induced top-down effects etc.

Basically there is no disagreement amongst scientists on the direction of management actions. Decreased loads of both nitrogen and phosphorus and a fishery that allows the return of big predatory fish is by most seen as steps to recovery. It is however not clear how strong the relative impacts of these different factors will be. How to balance the effort between reductions of phosphorus and nitrogen is strongly dependent on assumptions concerning how efficiently cyanobacteria can utilize a phosphorus surplus and how denitrification responds to changing nitrogen concentrations. It is also widely accepted that return of big predatory fish is likely to have a positive effect on the growth rate of herring and sprat. The latter are today growing slowly, which is likely to be caused by food limitation. Potentially a reduced biomass of herring and sprat could also affect phytoplankton by reducing zooplankton biomass and hence grazing on phytoplankton.

Long-term fluctuations in river runoff, wind-driven mixing and long-term temperature increase in the surface water complicate the interpretation of eutrophication effects. The net benefit of major inflows has also been discussed when they, as now, occur more sporadically. When they occur relatively often they continuously oxygenate the water below the halocline, causing phosphate to remain in the sediment and enabling benthic fauna to return to dead areas. In the current regime, with few inflows, oxygen deficiency is only temporarily relieved since the oxygen contained in the inflow is soon consumed. The inflow also has the effect of increasing the salinity of the deep water. With greater difference in salinity between surface and deep water the exchange between them decreases and the potential for such transport of oxygen decreases. How these two effects balance each other is not clear since water mixing across the halocline is not well understood.

With such substantial uncertainties there is no general consensus about the time frame for recovery in relation to management actions. Our best educated guesses are those made by models but it must be remembered that the model results are scenarios and not predictions. There are also many uncertainties in potentially very large-scale processes. It is therefore important to look for signs of recovery also in the coastal areas which are likely to respond much faster, but they also present a sampling problem by being more variable on a short term basis.

5.2.8 Attempts to reach holistic assessments of ecosystem health

The EU Water Framework Directive (WFD) has stimulated the development of tools which aim at summarizing the ecological status of water bodies. Essentially they are reductionist methods to summarize complicated information to a single value reflecting the ecological status of the water and its organism community. Such descriptors are legally required to fulfill EU-directives, assess the relative importance of environmental variables and identify what can be assumed to be ecologically safe limits. They are also a legal requirement to enforce action where it is needed and to distribute the costs to the responsible parties. The reductionist approach also helps in communicating complex information that is otherwise only comprehensible to experts. For eutrophication a set of quality elements for the classification of ecological status have been developed for the WFD and quality elements are under development for the EU Marine Strategy Framework Directive (MSFD).

HELCOM has also developed a tool to characterize eutrophication in the Baltic called HEAT, which has been used in the HELCOM holistic assessments of Baltic (HELCOM 2006, 2009, 2010, 2013c). In the HELCOM Initial Holistic Assessment (HELCOM 2010a) the status for the Baltic Sea eutrophication is summarized as follows: "Eutrophication, caused by nutrient pollution, is of major concern in most areas of the Baltic Sea. The Bothnian Bay and the northeastern parts of the Kattegat are the only open-sea areas of the Baltic Sea not affected. The only coastal areas not affected by eutrophication are restricted to the Gulf of Bothnia".

The development of descriptors and quality elements has advanced the study of what can be considered reference levels and an acceptable ecological status. This has not previously been done in a systematic and consensus based manner. The work has also advanced the knowledge of how to construct holistic concepts for entire communities of organisms. There are however also substantial risks with communicating only such holistic information. To a great extent we do not understand food web interactions and fluctuations in relative abundances. What we consider as reference conditions will change with increasing knowledge and there is no permanent "good state" since nature is continuously changing by itself and particularly with the strong pressures induced by human activity. The requirement of the directives to describe all waters also forces a focus on geographical coverage to identify where management action is needed and the time cycle for sampling is long (e.g. six years in the WFD). There is a substantial risk that the focus on coverage and holistic approaches with limited resources in monitoring will compete with the long-term and high frequency monitoring. Such a development would be detrimental for the efforts to alleviate eutrophication.

The long time series in national and regional monitoring are the only sources of data that can help construct and validate models to understand the processes behind changes, which is a requirement for meaningful management decisions. Scientific field-research programs are short term activities and do not generate long-term data. The reductionist information of the descriptors gives no further understanding of the causes of poor ecological status. There is a risk of ending up with "knowing that something is wrong but not what and why" if monitoring is focused only on variables needed for descriptors and performed with long time intervals between campaigns. Most of the eutrophication processes can only be scientifically studied at the large geographic and time scales at which they occur. It would therefore be highly desirable and efficient to link scientific long-term ecological programs and long-term monitoring more strongly than they are at present. This would increase the scientific use of monitoring data and facilitate efficient use of infrastructure.

5.2.9 *Marenzelleria* dramatically changes the organism community in the sediments

During the last decade the invasive benthic polychaete worm *Marenzelleria* spp. has established itself and in many places become a dominant benthic animal. It can occur in very high densities and digs deep in the sediment where it circulates water through the created passages (Norkko et al. 2012). The circulation of water has been reported to improve bottom-water oxygen conditions in coastal areas, which was expected to reduce benthic phosphate release (Norkko et al. 2012). Another study however questions this effect (Bonaglia et al. 2013).

Marenzelleria has so far not been found to compete for resources with already present species (e.g. Karlson et al. 2011). There are however concerns that the extensive digging by *Marenzelleria* may remobilize environmental contaminants that are presently buried in the deeper horizons of the sediment. The organism community could thereby become exposed to historical deposits of contaminants from periods when the loads were higher or to chemicals that have been banned (e.g. Granberg et al. 2008, Josefsson et al. 2010). There is unfortunately also very little information on the value of *Marenzelleria* as food for benthic fish.

5.3 Some major knowledge gaps

The mechanisms of the eutrophication process have a number of knowledge gaps. This does however not pose a problem for the direction of management actions. It is from all points of view clear that a reduction of nutrient load and a fishery that allows large predatory fish to reach safe population size will lead in the right direction. Knowledge gaps can however cause uncertainties in relative allocation of management measures and quantitative predictions of expected results and their time frames. Listed below are some gaps that are important but there may be many others just as important or possibly even more so.

- *What controls the major inflows of oxygen rich sea water?* The large seawater inflows have a major influence on bottom water oxygenation and thus on almost all processes in the Baltic Sea. We do not understand why the frequency of such inflows has decreased dramatically and can therefore not efficiently make educated guesses on the future of inflows.

- *The relative effectiveness of potential management measures in agriculture must be better understood.* There are a substantial number of potential measures to reduce losses from agriculture (e.g. Malgeryd et al. 2008) and other land uses (e.g. wetlands, forestry etc.). For several reasons the relative effectiveness of these measures is however poorly understood, partly since the effectiveness must often be evaluated for the long-term effect which is time consuming and costly. It is also difficult to generalize the effects of many measures since they vary with soil properties, slope, precipitation, crop etc. There is a need to identify the most cost efficient measures and evaluate what to start with and where.

- *We do not know how nutrient reductions can be achieved as cost efficiently as possible.* It is clear that the efforts to reduce nutrient load will have to be substantial. Today we have considerably better information on which areas that contributes most to eutrophication and also which water bodies that are most sensitive. There are also a considerable number of potential management actions available, particularly in agricultural landscapes. Even if the long-term efficiency of many of these actions is unclear, an analysis of the potential costs and effects of different national strategies would help to evaluate the cost efficiency of different approaches.

- *Many processes in the nitrogen cycle are still poorly understood, at least from a quantitative perspective.* Which relative quantitative role is played by denitrification, permanent burial in the sediment, nitrogen fixation and release by decomposition from the sediment (mineralization)? How does the load affect these processes? Does denitrification increase in proportion to the nitrate concentrations? Is nitrogen fixation strongly coupled to the phosphate surplus or are other factors (e.g. temperature, wind, timing of stratification etc.) stronger regulators? How efficiently is the nitrogen fixed by cyanobacteria transferred into the food web and fish production?

- *Transport of phosphorus is to a great extent unknown*. Phosphorus is transported from land to the sea mainly in particles with organics constituting a large part, and is often due to intensive rain causing strong water flow over soil. Measurements of transport in collecting water streams can differ extremely between days due to different amounts of precipitation. The estimates of losses under different conditions are therefore uncertain and better descriptions are needed.

- *How is the release and binding of phosphate in the sediments regulated?* How much can be released, how much is returned when oxygenation occurs and how large is the pool? The regulation in many processes that transforms organically bound phosphorus to phosphate also need further investigation, both under oxidized and anoxic conditions.

- *Many uncertainties in the general carbon cycle.* Climate change research has highlighted the need for better understanding the carbon cycle. How is dissolved organic matter (DOM) utilized in the food web? How will an increased load of DOM affect the role of the microbial community? How will potential acidification be affected by increased DOM load and increasing temperature?

- *How much nutrients can the sediments release?* The sediments contain large deposits of nutrients in organic form, remains of dead organisms and other sedimented organic material. By release to the water mass such deposits will eventually be drained and the released amounts will come to reflect current loads rather than historical accumulation. Material that is deep down in the sediment is unavailable to biological activity and becomes permanently buried. Little is however known about how large parts of the entire deposits that can be remobilized. Since this internal source is very large it is essential to assess how long the sediments can continue to release nutrients from historic deposits.

- *The role and regulation of nitrogen fixing cyanobacterial blooms.* What causes large nitrogen fixing cyanobacterial blooms? It is often assumed that a large surplus of phosphorus causes a large cyanobacterial bloom but the extent of such blooms cannot be predicted from data. The regulation is likely to be a complex interaction between water temperature, development and stability of the thermocline, size of the seed population, stability of the surface water during bloom, wind speed and available phosphate. Considering the extent of nitrogen fixation this is likely to be a key process in the Baltic.

- *The role of the coastal zone in retaining nutrients*. There is a large uncertainty concerning how efficiently nutrients are retained in the shallow coastal areas of the Baltic Sea. For the open sea it is often reasonable to make generalizations over large areas both for the water column and for sediments. In contrast coastal zones and particularly archipelago areas with complex topography, are often very heterogeneous environments. For modeling of open waters it is important to get better quantitative estimates of this function. A major question is: "How much of nutrient load is retained in the coastal zone, how much of this is permanent losses (e.g. denitrification) and how much is only a delay in transport to the open sea"? An expected climate driven temperature increase is also likely to affect the shallow waters and sediments most. As mentioned above the coastal zone is where the effects of management actions will be visible first. In Sweden the investigation of many coastal areas has to a great extent been performed by industry and municipalities. Such programs have in many places not been optimally designed and performed (among a few others the Stockholm area is an exception from this and has excellent data series). The knowledge of how the coastal zone works is therefore less extensive than could be expected.

- *How well can we attribute the loads to sources*? Monitoring rivers and point sources give good estimates of how much nutrients actually reach the Baltic Sea. The rivers carry a mixture of loads from many sources and there are still large uncertainties in estimates of their relative contribution. Uncertainties in the release and retention (what is lost or retained in the freshwater environment on the way to the sea) are therefore important in estimating how efficient different management measures will be. A better knowledge of these factors could make management more cost efficient.

- *How available are organic forms of nutrients?* Nutrients enter the Baltic Sea in both inorganic and organic forms. A rough estimate is that between half and a third of the load is organic with a higher organic proportion for phosphorus than nitrogen. The loads are usually measured as total nitrogen and phosphorus, which includes both organic and inorganic fractions. The organic part is mainly in the form of living or dead organisms or large molecules derived from decomposing organisms (humus). The inorganic forms are immediately available for plant photosynthesis (nitrogen gas excepted). The availability of organic forms of nutrients is much less known and more variable. Some plankton and microorganisms take up and utilize small organic molecules and most bacteria live by extracting carbon and nutrients from large organic molecules. Organic molecules are also broken down by UV light from the sun. Very little is known about the proportion of nutrients in different organic materials that will eventually be available for production in the sea and there are large differences between basins.

- *Models must be developed that can handle eutrophication in combination with other pressures like climate change.* Everything in nature is interconnected and multiple pressures calls for models to evaluate the combined effects. This can be done by developing models that attempt to address several issues. In most cases the relevant biological interactions are incompletely known, calling also for experimental analysis of multiple drivers, to guide and validate the models.

- *Models must become able to handle natural variation.* Most models generally work with averages or other forms of central values. In nature all variables have considerable variation, which is particularly true for biological processes. Such aspects must be considered in models and discussed in the output.

- *The processes causing exchange of material between the bottoms and the open water need further research and quantification (benthic-pelagic coupling)*. How much material sediments? How much of the settling material reaches the bottom and how much is decomposed in the water? How much nutrients are released by the sediments under different conditions? Processes such as sedimentation, benthic filter feeding predation by pelagic organisms living in the water on benthic organisms (and *vice versa*), mysid shrimps moving between bottom and the open water both as predators and prey, and habitat shifts of organisms in different development stages all cause material flows between the sediment and the free water. Little is known quantitatively about these processes, known collectively as benthic-pelagic coupling.

- *Importance and description of continuous inflows.* The major Baltic inflows are fairly well estimated. The intermediate inflows are more difficult to quantify and will, in the absence of major inflows, become more important for water renewal. They therefore also need a better quantitative description.

6 Environmental contaminants

6.1 Current trends

The history of many classic environmental contaminants in the Baltic is an encouraging example of how awareness, management actions, legislation and well performed monitoring can turn a negative development around. For most of the classic environmental contaminants the concentrations have decreased considerably in organisms and sediments and for many the concentrations continue to decrease. A description of trends for individual environmental contaminants would be outside the scope of this report and there is an admirably short and concise English summary available in chapter 2 of the annual report from the national Swedish monitoring program (Bignert et al. 2013). In the extensive report detailed information for each monitored contaminant is also available. A summary of central parts of the results is also available in HAVET 2012. Also in the recent HELCOM (2010b) is the status and trends summarized in chapter 2.

In general most trends are encouraging and the populations of fish eating top predators like eagles and seals are increasing. There is however also some indications that cause concern and also a number of new and unknown contaminants that require attention, some of which will be briefly discussed below. A HELCOM screening study of substances identified in the Baltic Sea Action Plan (2008–2009) was focused on the eastern Baltic but also had a reference station in southeastern Sweden. HELCOM concluded that ”The results of the screening studies showed that relatively high concentrations of several hazardous substances were found in areas that had originally been chosen as reference areas and initially considered to be unpolluted. The substances that were found in the “reference areas” were generally those with PBT properties (persistent, bioaccumulating and toxic) and known to be subject to long-distance atmospheric transport.” (HELCOM 2010b) The report also summarizes information for some substances not monitored on a regular basis (nonylphenol, octylphenol, bisphenol A, short-chain chlorinated paraffins, phthalates and pharmaceuticals).

The large human population, high level of industrialization, relatively low biodiversity and long residence time of water will also in the future make environmental contaminants a major threat to the Baltic, and most likely cause elevated concentrations in biota in relation to conditions in coastal areas of the ocean.

6.2 Examples of scientific progress and changed views

Even if many of the classic environmental contaminants are now approaching comparatively safe levels some of them have not and a multitude of old and new industrial substances with unknown effects are continuously discharged into the sea. Some of these have already been identified as new problem substances in nature (emerging pollutants). Only for a very limited number of these do we have knowledge regarding their environmental fate and potential detrimental effects in nature. The worldwide production of chemicals is continuously increasing. It has been estimated that approximately 7 million tons per year were produced in the 1950s, which had by 2000 increased to 400 million tons (Naturvårdsverket 2012). The total number of chemical substances are by the Swedish Chemicals Agency estimated to exceed 140 000 (Kemi 2013). For economic and practical reasons we can only monitor a very limited number of substances. It is also clear that we in the future cannot become aware of the hazardous properties of some substances by waiting for detrimental effects to manifest themselves in nature. To early identify which new substances that can cause environmental problems and limit their transport to the sea is a major challenge for the future.

In a number of ways we are better equipped to address such problems today than we were a decade ago. For many high-quality Baltic time series of environmental contaminant data the studied time period has almost doubled. Time trends that were often uncertain ten years ago have now become much clearer. The statistical strength of many programs has been evaluated and conclusions are therefore more reliable. Analytical methods have become more standardized and the precision of analytical instruments is continually increasing. The observed development of concentration changes in organisms gives insights into the time perspective of recovery from high loads. General properties of the classic environmental contaminants (e.g. fat or water solubility, chemical structure, metabolism, excretion rates, toxicity etc.) can be helpful in predicting the behavior of previously unstudied contaminants in nature. The data from time trends in monitoring can thus also give hints on the relevant time perspectives from management action to effect and the potential magnitude of effects.

6.2.1 Development of ecologically relevant threshold levels for contaminants

In the last decade there has worldwide been a strong development in methodology to establish ecologically relevant threshold values for environmental contaminants. The goal is to find safe concentrations that can be assumed not to cause serious harm to any organism in the food web or to humans by consumption of aquatic organisms. The objective is to evaluate all exposure routes including transport in the food web. For most of the classical environmental contaminants we now have a preliminary set of ecological threshold values and quality standards protecting the most sensitive organisms that were not available ten years ago (HELCOM 2010b, HAVET 2012).

In the EU Water Framework Directive (WFD) such limits were primarily estimated for water concentrations for a limited number of prioritized environmental contaminants. They are being further developed to be applicable to sediments and organisms, and the number of included substances has also increased. The general strategy was to use information from a wide range of studies to identify levels where the most sensitive organisms in the organism community would not be seriously affected and then apply additional safeguards to this level. The Environmental Quality Standards (EQS) of the WFD are set to protect aquatic organisms and humans both from direct exposure via water and for bioaccumulating substances from food (e.g. Lepper 2005, European Commission 2011).

For the Baltic Sea threshold levels have also been adopted from work within OSPAR (e.g. OSPAR 1997, 2004, 2009) and will be further developed for the Baltic. A set of threshold values are used to assess the levels of Baltic environmental contaminants in HELCOMs thematic assessment of hazardous substances (HELCOM 2010b) and in the publication of the national Swedish monitoring program (HAVET 2012).

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To develop threshold values that take food web effects and different exposure routes into consideration is a much more complex issue compared to establishing safe concentration for exposure from water concentration. The efficiency of material transfer and pathways in the food web are to a great extent unknown and must generally be approximated by literature values, rather than actual measurements from the food web in question. Biomagnification is a food web effect where the consumer ends up with higher concentrations than the prey. Some of the effects we have seen were caused by such processes (e.g. DDT – reproductive failure in eagles, PCB – reduced health and reproduction in seals). Our knowledge on food web dynamics is much more fragmentary than what is desirable and the work with developing threshold level need to continually adapt to new insights into material transport through the food web.

6.2.2 Integrating the state for several environmental contaminants

In the last decade there has been a development towards integrating complex ecological information into one estimate of environmental state. The information used generally contains a very large set of individual measurements of physical and chemical variables, species composition, abundances and biomasses. To absorb this complexity and evaluate it is often not possible for non-experts and becomes a serious problem in legal issues. The WFD has therefore had an approach where individual variables are integrated into hierarchies leading to an overall estimate of ecological and chemical status.

Also with the aim of synthesizing the overall status of hazardous substances in the Baltic Sea HELCOM has developed a tool called CHASE. CHASE is a multimetric indicator-based tool that from a large set of data evaluates the condition of an area on a five level scale from “bad” to “high”. The tool is used in the HELCOM assessments of Baltic ecosystem health and of hazardous substances in Baltic Sea (HELCOM 2010a, b).

The approach of synthesizing complex environmental data has advantages in communication but also contains considerable risks of oversimplifying information. The level of uncertainty in the information behind the integrating estimates can differ substantially between different substances and water bodies and differences between laboratories can be substantial. It is also not evident what principle should be used to synthesize potential effects. A hierarchical method that lets the worst case decide can give a very standardized negative picture, which is particularly serious is if the worst case potentially has lower reliability compared to the other cases. Average approaches can underestimate the importance of a single variable that may be crucial. Notwithstanding the communication advantages it is therefore important that the communication of detailed information is not replaced by integrating approaches that can potentially contain heterogeneous information.

6.2.3 What should we aim for?

As in most other fields of environmental science there are uncertainties concerning the preindustrial background concentration of chemicals in organisms. For synthetic industrial chemicals it is easy, they would not have occurred in an environment unaffected by humans. For other substances and elements, such as dioxins and metals, there is a natural occurrence with geographic variation to take into account. In some cases historic biological material can be analyzed, but in most cases background levels must be estimated from current material or a limited number of often unsuitably preserved historic materials.

For many substances, sparsely populated and unindustrialized areas provide the most reliable background data at the current level of industrialisation. Some organic environmental contaminants such as PCB and pesticides can however also occur in comparatively high concentrations in the arctic region because of long range atmospheric transport, which can obscure the relation to local load. A potential mechanism called “grasshopper effect” has been proposed for such transport (e.g. Gouin et al. 2004 and references therein). According to the hypothesis contaminants emitted in warm regions can revolatilize back into the air and condense in colder areas. During warm weather in the cold areas the process can be repeated and potentially cause persistent chemicals to accumulate in cold regions.

Reaching natural background levels of naturally occurring substances is not likely to be achievable in an area where 85 million people live in a highly industrialized society. Because of time lags in long and short-range transport and food web transfer it can also be difficult to relate organism concentrations to current loads. Setting goals that are environmentally safe and economically possible thus becomes heavily dependent on our assessments of risk. For the classical environmental contaminants a vast experimental and observational material gives guidance, but for new substances and combination effects from complex mixtures the terrain is often unknown. It is therefore essential to develop methods detecting potentially problematic substances and predicting possible effects to set goals that ensure ecological sustainability.

6.2.4 Monitoring and sample bank provides new opportunities

The Swedish monitoring system for contaminants contains some of the longest and best data series in the world. This has given unique insights into the environmental chemistry of several classic environmental contaminants and the construction of the monitoring provides a preparedness to address new environmental contaminants. The availability of long-term frozen samples now enables us to retrospectively create time series for new substances suspected of causing environmental problems.

The monitoring system has four pillars. The base is a statistically designed program for repetitive sampling of several biological matrices in which a defined set of environmental contaminants are analyzed. The program is complemented with campaigns where unmonitored substances with unknown or suspected effects are mapped with wide geographic coverage and in several matrices (screening). A central component is a large bank of frozen or otherwise suitably preserved samples both from the repetitive sampling programs and other matrices (sample banking). The system also contains a program that monitors a wide range of health status variables in a defined set of organisms (biomarkers).

The power of the system lies in its flexibility. Known environmental contaminants are monitored and the time series provide guidance on the efficiency of management efforts. The long time series also provide scientific information on the long-term ecological behavior of environmental contaminants, which can often be used to predict the behavior of substances with similar properties. The screening can give an indication of the occurrence in nature of potentially new environmental contaminants. The monitoring of biomarkers can be used to reveal health disturbances in organisms that are potentially related to environmental contaminants.

If there is a suspicion that a specific substance, or group of substances, may have caused an observed effect, or just occurs in unexpectedly high concentrations, the preserved material can be used to create a retrospective time series. A long monitoring series can thus rapidly be created to evaluate a time trend. Such trends often requires one or more decades of sampling to be reliably interpreted. In many ways the availability of properly sampled, well preserved and long-term historical biological material is a new situation that provides new opportunities. The difficulties lie in identifying which substances that may be responsible for an observed effect.

6.2.5 Eutrophication and environmental contaminants

Nutrient and contaminant load are two major current pressures on the Baltic Sea. The limited water exchange makes it particularly susceptible for both. How these two processes interact is however still unclear. A major research project (EUCON) during the latter part of the 1990s revealed the complexity of the issue and increased the available information substantially (Skei et al. 2000 and references therein).

There are a number of potentially important processes that interact. Many organic contaminants accumulate in organisms because they have an affinity to lipids (lipophilic) and are slowly metabolized. Increased primary production leads to increased sedimentation, which potentially removes such substances from the water to the sediment. Potentially a greater proportion of contaminants would thus be permanently buried in the sediment. With a greater biomass of all organisms it is also logical that contaminants should occur in lower concentrations in organisms. With higher individual growth rates a growth dilution occurs where the accumulation of persistent contaminants is balanced by a faster production of biomass.

If the material sediments on oxygen rich sediments a greater proportion of the contaminants may end up in the benthic organism community. If the increased sedimentation causes oxygen depletion, the material may instead be sequestered in the sediment. In improved oxygen conditions the sediment may be recolonized by organisms and persistent substances become remobilized. There is concern that the newly arrived worm *Marenzelleria*, which is tolerant of low oxygen levels and digs deeper than indigenous worms in the sediment, can remobilize buried contaminants (e.g. Hedman et al. 2008, Josefsson et al. 2011 and references therein)

The dissolved organic matter in the water is also an important matrix that affects both organic contaminants and metals. The chemistry of these reactions is highly complex and in many aspects still unclear. It is therefore not possible to with certainty evaluate if reduced nutrient load will overall increase or reduce the availability of contaminants to the organism community. It is not only dependent on the present situation but also of the future trajectory of the eutrophication process. The results may also differ between different contaminants and organisms. The still elevated concentration of dioxin in herring and sprat is potentially both dependent on the remaining load and slow growth rate (Miller et al. 2013 and references therein).

6.2.6 Complex mixtures, nanoparticles and microscopic plastic particles

Industrial substances and pharmaceuticals continually increase in numbers and often become used in large volumes in a comparatively short time after they have been introduced. Many of these substances sooner or later end up in the sea and some of them are likely to become tomorrow's substances of concern. Many of them occur in the environment in low concentrations and sometimes below detection levels. It has however been shown that a mixture of chemicals may have a substantial effect even if the concentration of each of the individual substances in the mixture are below what is considered safe toxicological limits (Backhaus & Faust 2012 and references therein). Many substances are also designed to be persistent in order to make low dosage possible. This property can also cause them to become persistent in nature and thereby potentially have a long lasting effect. Some essential parts in addressing the problem of complex mixtures are: increased effort in identifying new groups of problem substances which can cause adverse effects in organisms; better descriptions of usage, transport and loads; development of biomarkers to identify effects in nature and relate them to the relevant mixtures.

Nanoparticles are extremely small particles, some of which are produced in large quantities. They generally have properties that are related to their high surface to volume ratio and can in many processes act as links between bulk materials and structures on the molecular and atomic scale. Their occurrence and long-term effect in aquatic systems is essentially unknown. Some of them have been shown to have adverse effects but there is a very limited number of studies (e.g. Moore 2006, Handy et al. 2008, Klaine et al. 2008, Canesi et al. 2010, Fabrega et al. 2011, Canesi et al. 2012, Wright et al. 2013).

It has also relatively recently been shown that the concentration of microscopic plastic particles is very large in the oceans (e.g. Wright et al. 2013) and also in the Baltic Sea (Norén et al. 2009). Many are small enough to be consumed by zooplankton and benthic animals but the extent and effect of this is essentially unknown. It has been speculated that they can cause malnutrition or increase the transfer of certain environmental contaminants.

6.2.7 Reduced health in some coastal organisms

White-tailed eagle (*Haliaeetus albicilla*) and seals have previously been severely affected by organic pollutants but now show a strong increase in numbers. Also a number of fish-eating sea birds have increased in the Baltic Sea (Ottvall 2012). From a food web perspective this is encouraging signs. There are however also some worrying signs of declining health in some eagles and coastal fish in spite of the generally sinking levels of most monitored environmental contaminants. Mussel eating sea birds have for unknown reasons also decreased dramatically (Ottvall 2012), which is further discussed in connection with food web interactions.

Monitoring of the White-tailed eagle has during the last 30 years shown a strong recovery of the population. The population and reproduction were in the 1970s critically low as a consequence of high DDT and PCB levels in combination with previous hunting. The eagles in some parts of the Bothnian Sea have recently shown poor reproduction results with a higher proportion of dead eggs, particularly in the northern part. The results are further investigated, but so far no clear connection to the classic environmental contaminants has been found. However the damaged eggs have similarities to those found in the 1960s and 70s and have higher concentration of PCB and DDT compared to eggs from other coastal areas.

In monitoring of coastal fish a large number of health variables are measured. During the last decade some of these variables have shown signs of decreasing fish health at monitored reference sites in the Baltic Sea. The interpretation is complex and no clear relation can be shown for contaminants monitored in coastal fish. There is also no measurable effect on the population level at the monitored sites. The response in health variables does however show similarities with those found in areas polluted by complex mixtures, such as in Gothenburg harbor. It cannot be ruled out that other factors than environmental contaminants are involved, but the results are worrying and are currently further investigated.

6.2.8 Multiple stressors climate change–eutrophication–environmental contaminants

There is a growing awareness that different stressors cannot be viewed isolated, and environmental contaminants are no exception. As previously mentioned their effects can differ in mixtures compared to the individual substances. Changes in the food web can cause different transfer routes for both known and unknown contaminants. Introduction of non-indigenous species may alter the length of the food chain and thereby increase the load on top predators. Increased temperature may increase the occurrence of oxygen depleted sediments but can also cause generally greater biological activity that can in turn increase metabolization of contaminants. A change in acidity of the water may have considerable effect on the viability of many organisms. A combination of contaminant load estimates, experimental work, field studies and modeling of transport is likely to be the best way to scientifically address the contaminant problem in relation to other large-scale processes.

6.3 Some major knowledge gaps

- *The general transport and fate of most environmental contaminants and their metabolites is to a great extent unknown*. There is a substantial need for basic research in the field of ecotoxicology. Most of our knowledge is centered on the original substances discharged in the environment. When they are metabolized in an organism they are transformed to modifications of the original substance (metabolites). These metabolites often have similar properties as the original substances and are in some cases even more toxic. Also physical and chemical processes may cause modification of the original substances. With exceptions for some well investigated metabolites (e.g. for DDT and tributyltin), the concentrations of metabolites and degradation products in the environment is essentially unknown.

- *What are ecologically acceptable and achievable contaminant concentrations?* There has been a fast development in methodology to set ecologically safe limits for contaminants. The unknowns are however still large and the methods need development to address food web transport and effects. The vast majority of substances will also in the future lack proper toxicological information. How can we proceed in estimating acceptable environmental concentrations for them?

- *How can collected information on use and properties of substances be used to identify new substances of concern?* ECHA (European Chemicals Agency) now has database containing the use, toxicity, chemical and physical properties for a substantial number of substances used in Europe. How can this information be most efficiently used?

- *Transfer and effects of contaminants in the microbial organism community.* Are specific species of microorganisms more important than other and how are microorganisms affected? Which important ecological processes carried out by microorganisms may be affected by contaminants and to what extent?

- *How can we identify new chemical substances or complex mixtures with adverse effects in nature before they become large scale problems?* To identify problem substances by large-scale effects in nature is not a realistic method for the future. Enrichment of a substance in the food web is a strong warning signal in itself. How can ecologically relevant tests, models and monitoring be developed to generate “early warning” signals? Some substances are however not enriched since they are efficiently metabolized, but nonetheless cause serious adverse effects during this process (e.g. Polycyclic Aromatic Hydrocarbons, PAHs).

- *How can we relate biological warning signals to specific substances or mixtures of substances?* Biological indicators of the environmental state can provide warning signals that one or several unmonitored substances are adversely affecting the organism community. Such indicators can be drastic changes in abundance, symptoms of bad health, malformations or behavioral changes.

- *How can safe limits be defined for complex mixtures with combination effects?* How can we address the issue of a potentially endless combination of additive, synergistic and antagonistic effects in complex mixtures? Can entire groups be identified as mixtures that commonly occur in nature? Can groups of contaminants causing similar effects be quantitative comparable (e.g. by developing Toxic Equivalent Factors like for dioxins, furans and dl-PCBs).

- *How will changes in the food web affect the transfer of contaminants?* Can some contaminants affect the entire structure of the food web? Can introduction of NIS lengthen the food chain from phytoplankton to top predators or change the bioavailability and thereby increase the contaminant concentration in top predators?

- *Can Marenzelleria cause a large scale remobilization of previously buried contaminants?* As mentioned above the invasive worm *Marenzelleria* has been shown to be able to transport contaminants from deeper sediment layers to the sediment surface in experimental conditions (Hedman et al. 2008, Josefsson et al. 2011). Will this also occur in large scale in natural environments? Will *Marenzelleria* become important fish food and thereby potentially expose benthic fish to historic deposits?

- *How will increased load of dissolved organic matter from rivers affect the load and distribution of contaminants in the Baltic?* Many environmental contaminants become associated with dissolved organic matter. The binding to organic matter can potentially reduce the uptake in plants and animals. A greater microbial activity that utilizes the dissolved organic matter may on the other hand provide a more efficient way for contaminants to enter the food chain.

- *Will the potentially contaminated fiber banks of the Bothnian Sea coast become a problem as crustal uplift brings them closer to the surface?* The fiber banks outside pulp industries along the Coast of the Bothnian Sea are currently being investigated by the Geological Survey of Sweden (SGU) since there is concern that environmental contaminants in these deposits may expose organisms if they are disturbed (http://www.sgu.se/sgu/sv/produkter-tjanster/nyheter/nyheter-2010/fiberbankar.html). There are also experimental research projects initiated to address these issues.

- *Are there methods to generally decrease loads of entire mixtures?* The reduction of load from point sources has been very successful. There is also research on methods to treat sewage to reduce large groups of contaminants. Can sewage be generally treated to reduce a wide variety of contaminants to a realistic cost and without moving the problem from the effluent water to the sludge?

- *There is a need to improve the description for transport of contaminants in the environment.* Both models and comprehensive data sets for the occurrence of contaminants in the environment need development. One type of models is flow analyses to describe and quantify the flow of chemicals in society: Where are they used? Where will they end up? How do they reach the water? The other types of models are those that describe the physical and biological transport and fate of contaminants in nature like: Which organisms are likely to be exposed? How will the contaminant accumulate in organisms and various compartments in the food web? How fast will it be metabolized? How much will be permanently buried? There are many models in use but there is substantial uncertainty in many assumptions and the available data sets are limited. A critical aspect is the assumptions of food web dynamics and trophic transfer.

7 Climate change and ocean acidification

7.1 Introduction to trends and projections of climate change

During the last decade the knowledge and evidence base regarding climate change and its impacts has increased vastly, not least as a result of the work by the IPCC (Intergovernmental Panel on Climate Change) on a global level, and that within BACC (the BALTEX Assessment of Climate Change in the Baltic Sea Region) on a regional level. The work of integrating new scientific evidence and climate models has made substantial progress and increased the awareness of global warming and it's likelihood to be a result of anthropogenic activity.

The BACC-project combined this evidence of climate changes with related impacts on the marine, freshwater and terrestrial ecosystems in the entire Baltic Sea catchment area. The assessment has clarified how climate changes can lead to considerable impacts on the marine environment of the Baltic by changes in the hydrological cycle, temperature and salinity regimes, sea level, pH etc. These changes may be non-linear, and future climate changes may counteract the BSAP load reductions (e.g. BACC 2008, HELCOM 2013d and references therein). There is now on-going work with a second assessment (BACC II), building on and extending the first BACC in order to provide the scientific and decision-making community with an update regarding on-going and future climate variations. The BACC II book will be published during 2014 and its conclusions can therefore not be cited in this report.

7.2 Some aspects of climate change in the Baltic: current trends and scenarios

The projections of possible future changes on a global level are based on IPCC-models and for the Baltic Sea based on regional climate models (RCMs). For the latter the majority of changes from scenarios presented here are projected to be seen in the end of the 21st century. It is also of great importance to keep in mind that these are scenarios. There are substantial uncertainties and biases within the current models, e.g. with regards to heat and water balances and the hydrological cycle, including major inflows, effects of land use change, aerosols and the gas exchange between land and atmosphere, alkalinity etc., making the outcome of scenarios uncertain (BACC 2008 and references therein).

Warming

IPCC has shown that the global mean temperature (averaged combined land and ocean surface temperature) has increased by 0.85 °C since 1880 (IPCC 2013). These increases in temperature are clearly detected also for the Baltic Sea region and are likely to continue throughout the century. Over the past 140 years a significant increase in surface air temperatures has been detected for the region, with between 0.08 and 0.11 °C increase per decade, to be compared to the global mean of 0.05 °C. Other changes include the daily temperature cycle and an increase in temperature extremes, which has caused an increased length of the growing season and a decreased length of the cold season. There has also been an increase in sea surface temperature (SST) since 1985, with annual mean SST estimated to have increased by up to 1 °C/decade from 1900 to 2008. The largest increases have been seen in the northern Bothnian Bay, Gulf of Finland, Gulf of Riga and the northern Baltic Proper (BACC 2008, HELCOM 2013d, and references therein).

Scenarios based on regional climate models (RCMs) show that temperature by the end of the 21th century will be higher than any time since 1850. Summer SST is projected to, by the of the 21th century, increase with approximately 2 °C and 4 °C for the southern and northern parts respectively, and the temperature is estimated to increase 1 °C more in the surface layer than in the deep layer. This is in turn expected to affect the stratification and thermocline, although there is no scientific consensus on how this will affect the overall vertical stratification and thus also the oxygen content (BACC 2008, Meier et al. 2012a, b, HELCOM 2013d).

Precipitation, river discharges and salinity

There is a tendency of increasing precipitation in winter and spring during the second half of the 20th century. Despite large variations between regions and seasons, there are no significant long-term changes detected regarding total river runoff during the past 500 years (BACC 2008, HELCOM 2013d).

Precipitation is projected to increase 12-18 percent, potentially causing increased river runoff to the Baltic Sea basin with 4-22 percent, with the largest increase found in the northern parts of the region, and possibly a decrease in the southern cultivated watershed. The Gulf of Bothnia would thus receive significantly higher freshwater inflows, also affecting the loads of nutrients and organic matter from soils, forests and wetlands (BACC 2008, HELCOM 2013d, and references therein).

For the Baltic Sea as a whole, there are no significant, long-term, changes in mean salinity for the 20th century (BACC 2008, Havet 2012, HELCOM 2013d). Model projections suggest that salinity may decrease by 2–2.5 PSU by the end of the 21st century. The changes in sea-surface salinity are projected to be largest in the Belt Sea and smaller in the northern and eastern Baltic. In the Gulf of Finland and Bothnian Bay, which are more weakly stratified, the salinity changes are projected to be larger, leading to a reduction in the vertical stability (Meier et al. 2012a, b, Gustafsson et al. 2012, Neumann et al. 2012, HELCOM 2013d).

Ice extent

The annual maximum ice extent of the Baltic Sea (MIB) has decreased 20 percent over the past century, and the length of the ice season has also decreased. Shipping is also increasing strongly in the Baltic, which can influence the ice extent via ship-induced waves preventing the formation of a permanent ice cover and enhancing break-up of ice cover (HELCOM 2013d and references therein).

The extent and duration of ice cover is projected to decrease mainly as a result of increases in winter air temperatures. This may affect nutrient dynamics in and under the ice. Loss of sea ice will affect the ringed seal since they depend on ice for rearing their pups (HELCOM 2013d and references therein).

Sea level changes

Sea level changes on the Baltic Sea coasts are a result of the combined effects of post-glacial rebound (especially in the Northern Baltic), global sea level rise (thermal expansion of seawater in combination with increase of global ocean mass due to melting of glaciers) and the contribution of regional factors. Potential sea level changes in the Baltic Sea are more affected by the melting of Antarctic ice than the Greenland Ice Sheet. Relative sea level is decreasing in the north (where the continental crust is rising) and rising in the south (where the continental crust is rising) (BACC 2008, HELCOM 2013d and references therein).

Although there is considerable uncertainty in the scenarios of future sea level rise, the Baltic Sea is projected to see a 0.6 – 1.1 m rise by 2100, with large regional differences due to e.g. rising and sinking of the continental crust, varying between 0 m/century in Denmark and 0.8 m/century in the Bothnian Bay (BACC 2008, HELCOM 2013d and references therein).

Acidification

As a result of human activity, today's atmospheric CO_2 concentration is 395 ppm (with peaks of over 400 already measured). It has been calculated that on a global level the oceans have taken up approximately one third of the anthropogenic CO_2 produced in the past 200 years, resulting in 26 percent more acidic water during the last 150 years. The major driver of global ocean acidification is the uptake of atmospheric CO_2, with pH decreasing as a result of increasing partial pressure of atmospheric CO_2. There are two additional known or potential causes; coastal acidification due to additional pollutants and release of methane hydrates which are currently stored in the sediments, although it is unclear how much these may affect the Baltic Sea. In addition, alkalinity and biological production can "buffer" against acidification (Favry et al. 2008, Feely et al. 2010, IPCC 2013, Billé et al. 2013 and references therein).

In the Baltic Sea region, CO_2 in the atmosphere has increased from 280 ppm (parts per million) to 390 ppm since 1750, causing concern for potential effects on pH in the Baltic. Baltic pH is controlled by alkalinity (affected by the dissolution of limestone in the catchment area) as well as biological primary production (photosynthesis reduces carbon dioxide in the water) (BACC 2008, Havet 2012, HELCOM 2013d, Edman & Omstedt 2013). There are however also variations in pH on smaller spatial and temporal scale. For example, the pH in the Kiel fjord varies by 0.7 pH units seasonally, and studies of temporal variations in macrophyte meadows (with e.g. *Fucus serratus* and *Zostera marina*) in the western Baltic Sea have shown that pCO_2 and pH can vary on a daily basis due to photosynthesis and respiration (Havenhand 2012, Saderne et al. 2013). For some *Fucus*-belts in vegetated, shallow soft-bottoms, pH can fluctuate between 7.5 and 11 daily (L. Kautsky pers. comm). pH can also vary regionally depending on differences in delivery of fresh water, since it has a lower pH than marine waters. So far, no general or significant trends regarding Baltic Sea acidification have been detected during the last century (BACC 2008, Havet 2012, Havenhand 2012, HELCOM 2013d, Saderne et al. 2013).

Atmospheric CO_2 concentrations are projected to continue rising but there is also a regional and local dimension, as e.g. shipping and local power plants may contribute to regionally elevated CO_2 emissions. According to the climate scenarios there is a higher risk for acidification in the Baltic Sea by 2100, especially at lower salinities and alkalinities. The effects of coastal pH are more variable and difficult to predict compared to that of open water (Favry et al. 2008, Havenhand 2012, HELCOM 2013d). Forthcoming results (Omstedt et al. forthcoming) from modeling within the BONUS Baltic-C project show that the atmospheric CO_2 concentrations are the main controlling factor for the direction and magnitude of future Baltic Sea pH changes.

Increasing acidification poses an additional stress on organisms in the Baltic Sea, many of which are already living at their physiological limits in the brackish Baltic Sea. Acidification can affect key physiological processes such as reproduction, growth and not least shell formation in calcifying organisms such as bivalves and crustaceans. There are few studies of acidification effects on Baltic species. Some benthic macroalgae with so-called CO_2 concentrating mechanisms are likely to be unaffected by, or even benefit, from increased CO_2 levels. The eelgrass *Zostera marina* is also likely to benefit and has in Kattegat been shown to increase shoot biomass under elevated CO_2. It is likely that there will be negative effects on bivalves and crustaceans and one study has shown that even slight reductions of pH have significant negative effects on larvae of *Macoma balthica* by both decreasing growth and survival. The tolerance to acidification of blue mussel (*Mytilus edulis*) and barnacle (*Balanus improvises)* increased if food was abundant, lowering "acidification stress" (Havenhand 2012 and references therein, L. Kautsky pers. comm.).

On an ecosystem level the rate of change and the effects of multiple stressors are likely to be critical. Seen from an evolutionary perspective, changes in pH have been fairly slow. The rapid change now seen in the ocean is likely to make it difficult for many species to adapt. However, pH can fluctuate on shorter temporal scales due to e.g. photosynthesis and respiration and therefor some organisms are already adapted to high variability in pH. The effects of future acidification of the Baltic Sea are hence difficult to predict, and general conclusions are hard to draw from the few studies available (Havenhand 2012, Saderne et al. 2013, and references therein, Jansson et al. 2013, L. Kautsky pers. comm.).

7.3 Some examples of how climate changes may influence the Baltic Sea

There is an increasing awareness that climate changes can lead to considerable impacts on the marine environment affecting both biotic and abiotic conditions. Variations in temperature, salinity and pH have the potential to affect all aspects of marine life, from physiology and reproduction to food web structure and ecosystem functioning and services (BACC 2008, HELCOM 2013d and references therein).

For example, warmer temperature may have large impact on biological processes, species composition and length of phytoplankton bloom seasons. A mis-match of the temporal production of phyto- and zooplankton has the potential to cause cascading effects affecting top predators in the ecosystem. Changes in salinity can lead to decreased growth rates and loss of habitat for some organisms. If these are keystone and habitat-forming species such as bladderwrack, seagrasses and blue mussels, then substantial changes in distribution patterns of their associated flora and fauna will follow. Evaluation of changes in physical and chemical variables is dependent on regular sampling with high geographical coverage. Ferry-boxes can provide valuable integrating information (also on phytoplankton) complementing regular monitoring (BACC 2008, Answorth 2008, MacKenzie et al. 2012, Havenhand 2012, HELCOM 2013d, Ferry-box 2013).

7.4 Some major knowledge gaps

Despite considerable progress and intensive research regarding climate change and its impacts, many important knowledge gaps remain. Some of these are listed below.

- *What are the effects of climate change on a Baltic Sea basin-wide scale?* It is still difficult to quantify the potential effects of climate change (and extreme events) on a Baltic Sea basin-wide scale. What are the effects in the coming 20-50 years and 50-100 years respectively?

    - There are large uncertainties and biases in the regional climate models (RCMs), not least due to the lack of robust long-term data and climate statistics.

        - We need to quantify e.g. the hydrological cycle and heat balance, gas exchange between land and atmosphere, clouds and radiation. What are the effects of aerosols? What are the effects of changes in land-use? What are the biogeochemical feedbacks and circulation patterns; salinity regime and fluxes between open water and coastal areas, wind patterns, role of Northern Atlantic Oscillation (NOA) etc.?

        - How will changes in e.g. temperature and salinity affect the ecosystem? There is need for more research on how biodiversity, from the level of genes, species and populations up to the ecosystem level will be affected. Which species or genetic groups are likely to be able to adapt and which are likely to perish?

    - *There is need for improved models (coupled atmospheric and oceanographic models) and scenarios on a basin level.* Recent research and ensemble modeling have shown that when using the same IPCC scenario, different models show different responses in different basins.

    - *What will be the impacts of acidification?* There is need for better understanding of the carbon cycle; will pH decrease as projected, or will acidification be buffered by e.g. production? What is the role of shipping for acidification? What is the effect of increasing humus and bacterial degradation for the pH? What will be the implications for biogeochemical cycling (and thereby eutrophication) if pH decreases?

        - What are the effects and responses of Baltic Sea biota, including competition, predation and mutualism, as a result of acidification (on species and community/ecosystem level)? There are very few studies and measurements on how species and communities will be affected, hence there is need for further research on different populations and species, but also between life cycles of the same species, especially since changes in some species can have cascading effects on the rest of the food web. How will shallow benthic areas (abundance, diversity and functioning of benthic communities) react to changes in pH? There is need for more data from Baltic Sea populations, particularly from environmentally diverse regions and from controlled mesocosm experiments.

        - Will some species disappear and will the conditions improve for other species, perhaps NIS, which will replace them? Will new species fill essentially the same functions in the ecosystem, or will a different type of ecosystem be established?

- *What are the interactions and feedback* between climate change (including acidification) and e.g. eutrophication and overfishing, i.e. multi-stressors and cumulative impacts? These are all interlinked, but how will e.g. primary production and mineralization of organic matter interplay? How will climate changes affect our health – e.g. what are the risks for spreading of hazardous substances as a result of increased precipitation and runoff? How can fisheries adapt to climate change?

8 Fish and fisheries

At the end of 2013 the report from the project ”PLANFISH” (SLU) will be presented. As we do not have access to the report, there might be additions to what has changed in our perception, and what the major knowledge gaps are regarding fish and fisheries. In recent years, there has been repeated reporting regarding low catches and fish disease in Hanö Bight and Kalmarsund on the Swedish east coast, but despite recent studies by the Swedish Marine and Water Management Agency and the Baltic Sea 2020 Foundation, no clear explanations have been found.

8.1 Introduction to Baltic Sea fish and fisheries

There are around 100 fish species in the Baltic Sea (excluding Kattegat), which is a relatively low number compared to the North and Black Sea, with approximately 230 and 170 species respectively. This is mainly due to environmental characteristics such as the brackish water, which has resulted in a mix of species; marine, freshwater, migratory and glacial relicts, some of them non-indigenous. The distribution and composition of fish communities is affected by habitat characteristics such as salinity, temperature and nutrient availability, with both number of species and individuals decreasing in size with declining salinity (e.g. MacKenzie et al. 2007, HELCOM 2009a, Ojaveer et al. 2010).

Fish are important parts of the ecosystem, providing a link between lower and higher trophic levels. By consuming planktonic and benthic invertebrates they structure the lower levels of the food web. By serving as food for top predators such as mammals, birds and big fish they facilitate exchange of material between the organism communities in the water and the sediment (benthic-pelagic coupling). Their importance for the Baltic ecosystem and human welfare is addressed in several policies, not least the EU Common Fisheries Policy (CFP) and the HELCOM Baltic Sea Action Plan (BSAP) (HELCOM 2006a, 2009b).

Baltic Sea fisheries have for centuries been an important economic and social activity, with species such as cod, herring, sprat, salmon and sea trout being valuable catch since the 1500s. Until the middle of the 20th century, this fishery was carried out on a fairly small scale and with simple methods, but technical advances in fishing methods (including open sea fishery and trawling) lead to substantial increases in landings. Between 1974-1984 some 850 000-990 000 tons of fish (all species included) were caught annually (Casini et al. 2008, MacKenzie et al. 2012).

According to assessments by the UN Food and Agriculture Organization (FAO) over 30 percent of global fish stocks are overexploited, and the productivity of many fish stocks has declined during the last decades. In Europe, over 75 percent of the stocks are overfished and landings have decreased by over 25 percent since 1999, with overcapacity of the fishery fleet identified as a key driver behind this overexploitation (FAO 2012). However, over the last decade the situation in EU waters has dramatically improved, with decreased fishing intensity and an increasing number of stocks managed to deliver according to the Maximum Sustainable Yield (MSY) directive (Cardinale et al. 2011). This positive development is true also for the Baltic Sea, where catch quotas for the “three big” (cod, herring and sprat) are set to provide MSY (ICES advice).

A number of fish species are included in the HELCOM Red List (2013). According to it, the sturgeon (*Acipenser oxyrinchus*) is regarded as Regionally Extinct, four species (including the eel, *Anguilla anguilla*) are classified as Critically Endangered, and three are listed as Endangered. The list further includes nine species listed as Near Threatened, the status of eight is unknown as there is insufficient data, and some, such as the cod (*Gadus morhua*), are listed as Vulnerable (HELCOM 2013e).

Many factors directly and/or indirectly influence fish stocks, often with synergistic interactions. The largest direct threat is fishing above biologically safe limits, both with regards to target species and by-catch. The effects of eutrophication are more complex, favoring some species and negatively impacting others (e.g. Hansson 1985, Hansson & Rudstam 1990). Some species, like cod, have been impacted both positively (more food) and severely negatively (reduced reproduction volume) by eutrophication (Eero et al. 2011). A potentially important factor is also the recently increased predation by seals and fish-eating birds. Climate variations, affecting e.g. water temperature, runoff and salinity (for example affecting growth, survival and production rates), are also potentially important factors behind changes in Baltic fish communities (e.g. Margonski et al. 2010), and climate changes are likely to be of increasing importance in the future. It is expected that marine-tolerant species (some 70 percent of Baltic fish species) will be disadvantaged due to climate-induced changes, while fresh water species will likely expand their distribution (MacKenzie et al. 2007, ICES 2008, 2013a HELCOM 2013e).

8.2 Examples of scientific progress and changed views

There have been substantial efforts by the research community to understand the causes and effects of the observed large-scale changes in the pelagic fish community during the last decades, which has led to increased cooperation between different research fields. A central theme has been the role of cod as a top predator with the potential to assert top-down effects on the food web, leading to trophic cascades and potential regime shifts. Recent research has described these reorganizations, where the ecosystem in the central Baltic Sea changed from being cod- to sprat-dominated, also potentially affecting the zooplankton community (Casini et al. 2008, 2009). The changes are likely to have been caused by a combination of hydrographic changes, overfishing, eutrophication and potentially changes in predation pressure by seals (Eero et al. 2012). There are different ways of viewing the changes and the role of food web processes. It has been argued that a cod-hostile situation has arisen as the result of impaired reproduction and overfishing, and that food web changes maintain this situation. That cod has recovered in the last decade has been seen as an argument for questioning the importance food web changes and stressing the importance of reduced fishing pressure (e.g. Alheit 2005, MacKenzie et al. 2007, Österblom et al. 2007, Möllmann et al. 2008, Cardinale & Svedäng 2012). For a detailed description of these changes, we refer to chapter 10.2.3.

8.2.1 The status of cod in the Baltic Sea

Cod *(Gadus morhua)* is a demersal, marine cold-water species divided into three stocks in the Baltic; the Eastern Baltic Cod (EBC), Western Baltic Cod (WBC), and the Kattegat cod stock. The eggs, and thus reproduction, are dependent on saline (> 11 PSU – practical salinity units) and cold water with high enough oxygen concentrations (min. 2 ml/l). Cod mainly preys on sprat, herring and benthos (such as *Saduria entomon),* and to some extent cannibalistically on juvenile cod. It is the most economically important species and fishing peaked in the mid-1980s with annual landings of 344-442 ktons (thousand tons), corresponding to 22 percent of global landings. A few years after reaching the historically high levels caught (650 ktons in 1982-1982), the EBC stock collapsed. This was a result of high fishing pressure in combination with decreasing reproductive success due to limited inflow of oxygenated, high-salinity waters (e.g. MacKenzie et al. 2007, 2012 and references therein, ICES 2008, 2013a).

During the next 30 years, EBC stocks decreased by almost half, and it was feared that the stocks would never recover. Decades after the collapse, the stocks was still assessed as vulnerable, and the population considered to be outside biologically safe limits. In 2000-2007, Baltic cod landings were at their lowest levels since the 1950s, with 63 000-105 000 tons caught yearly (ICES 2008, 2013a, HELCOM 2010c, SEPA 2011).

New research and analysis of fish landings during the last couple of years show that the EBC stock has now recovered, with substantial increases in the spawning stock biomass and total biomass increasing from 120 to 350 kton between 2005 and 2009. This recovery seems to be a result of substantial reductions in fishing mortality, helped by increased strong recruitment in 2003 and 2005 (Eero et al. 2011, 2012, ICES 2013a).

The WBC stock has also decreased during in recent decades, with spawning biomass now at less than 10 percent of the levels in the 1970s. Recruitment has also decreased since the 1970s, with historically low numbers during the last years. The stock is classified as overfished, and ICES recommended a fishing ban in Kattegat during 2012. The situation for the population in the Sound is fortunately better. Due to the long upheld ban on trawling, fishing is only done with nets, which has proved sustainable. This has led to higher production and a more diverse population structure with a higher proportion of larger individuals. Compared to the Kattegat, the Öresund population is 100 times more productive, and there is a natural distribution in age and size classes (ICES 2008, 2013a, Svedäng 2010, SLU 2012).

Although cod biomass is mainly controlled by fishing mortality, new research indicates that in the latter part of the 21st century the combination of climate change and eutrophication may also result in a decline of cod biomass due to deterioration of reproductive conditions. There is even a risk of local extinction (MacKenzie et al. 2012, Niiranen et al. 2012).

8.2.2 Short descriptions of the status of sprat, herring, flounder, perch and salmon

Sprat (*Sprattus sprattus*) is found throughout the Baltic (less common in the Bothnian Bay) where it occurs in schools in the open water as well as in coastal areas. They migrate, seeking warmer waters, as they cannot tolerate temperatures below 2-3 °C, and feed mainly on zooplankton, but also eat cod larvae and eggs. Sprat is a pelagic spawner, with eggs and larvae that drift in the offshore pelagic environment (Köster et al. 2005, HELCOM 2006a).

Recent research that tried to reconstruct the population dynamics of sprat in the 20th century has identified peaks in the 1930s, 1960s and 1970s, reaching approximately 900 ktons. Before the development of pelagic sprat fisheries in the 1960s, the exploitation rate was low (Eero 2012b). In the 1980s, sprat biomass was low, but a sharp decline in cod biomass and favorable conditions for sprat recruitment led to high biomasses in the 1990s. In the past, sprat abundance was low in the northern Baltic Proper, but today about 80 percent of the biomass is found in this area. In the southern Baltic Proper, where sprat was formerly abundant, it is now scarce. The spawning stocks have also decreased since 1997, probably as a result of decreasing cod stocks resulting from fishery (HELCOM 2006a, 2013, MacKenzie et al. 2012, Eero 2012b, Havet 2012, SLU 2012).

Baltic Sea herring (*Clupea harengus membras*, considered a subspecies of the Atlantic herring) is a pelagic species widespread in the Baltic and divided into several biological stocks. According to ICES there are five stocks; one in each of the areas the central Baltic, Gulf of Finland, Bothnian Sea and Bothnian Bay, and a fifth Western stock that spawns around the Rügen Island and migrates between the Baltic and North Sea. Herring make seasonal feeding and spawning migrations between coastal archipelagoes and the open sea, staying near the coast in spring and autumn, but spending the summer in open sea-feeding areas (HELCOM 2006a, ICES 2013a).

Herring has been commercially important for centuries, but due to overfishing, changes in zooplankton communities and increasing food competition, their numbers have decreased. The average size of adult herring has also halved in the last 40 years, and it is hypothesized that this is a result of increased food competition for zooplankton. ICES estimated that the Western and Baltic Proper stock spawning biomass (in individual biomass, not numbers) has decreased with more than 50 percent and 25 percent respectively during the last 20 years. In contrast, there is an increase in the Bothnian Sea and Riga Bay. Compared to the objective of the high long-term yields, the herrings stocks are still overexploited (HELCOM 2006a, SLU 2012, ICES 2013a).

Flounder (*Platichthys flesus*) is a flatfish found on sandy bottoms in the entire Baltic. The flounder can survive and reproduce at lower salinities than other flatfish and can therefore live in a greater variety of habitats and has a larger biomass than other flatfish in the Baltic. The size of the flounder stocks varies between the regions, and total landings have fluctuated between 8 400 – 19 400 tons between 1975 and 2012 (HELCOM 2003a, ICES 2013a).

Perch (*Perca fluviatilis*) is a freshwater fish occurring among aquatic vegetation but also at deeper bottoms in e.g. the Swedish coastal areas. The Baltic perch travels between feeding, wintering and spawning grounds. Depending on size they feed on different prey: zooplankton, benthic crustacean and/or other fish (HELCOM 2006a, HaV 2012).

Since 1994 Swedish commercial landing have shrunk by half (from 149 to 77 tons). Perch is popular in recreational fishing and estimates indicate that recreational landings are up to 9 times greater than the commercial. There are large geographical and temporal stock variations, due to e.g. recruitment, predation and food competition. Perch stocks have declined in some coastal areas of the western Baltic Proper, often substantially, and in many areas recruitment has failed. The causes for these decreases are unknown. In the Archipelago Sea perch abundance has instead increased significantly (HELCOM 2006a, HaV 2012). Research has shown that the abundance of juvenile perch is negatively related to the abundance of adult stickleback (*Gasterosteus aculeatus*), and the decreased recruitment success might be due to larval starvation, predation and competition for food (SLU 2012). Locally, predation from cormorants has been suggested as a significant cause (Vetemaa et al. 2010).

Salmon (*Salmo salar)* is an open sea fish, migrating long distances from the open Baltic Proper feeding areas back to the rivers they were born in for spawning. In their feeding area, the central-southern Baltic Proper they mainly feed on sprat and herring (Hansson et al. 2001). As a result of the construction of hydroelectric power plants (large scaled damming of rivers) after the 1940s, much of the natural reproductions areas for salmon have become inaccessible. The M-74 syndrome, caused salmon fry mortalities of 50-90 percent in the 1990s, but the causes of the disease are still not clear. The production of wild Salmon has however increased substantially from very low levels in the 1990s. In Skagerrak and Kattegat the Baltic salmon parasite *Gyrodactylas salaris*, found to cause high death rates in Norwegian salmon, have been observed but it is yet unclear how large effect it has on the Baltic salmon populations (HELCOM 2006a, 2011a, Havet 2012, SLU 2012, ICES 2013b).

In 2011, as a reaction to reduced stocks and the loss of genetic diversity, the EU Commission proposed a multiannual plan for sustainable management of Baltic salmon (EU COM 2011) There have also been other attempts to promote the recovery of the salmon stocks, including reductions in the fishery, phasing out of driftnets and closed seasons. The latest HELCOM stock assessment for salmon (2011), found that there have been some general improvements, and reported recovery also for some populations (HELCOM 2011b).

8.2.3 Changes in spatial distribution, including transitory spill over effects

Research during the last ten years has shown that there has been a redistribution of the Eastern cod stock. The cod stock contracts into the southernmost area of the Baltic. The reasons for this are unknown, but it could possibly be a result of low salinity and low oxygen levels at the bottom, coupled with low stock size. But, at high stock sizes cod expands (“spills over”) its geographical range, from the central Baltic (“source area”) into more northern areas and coastal systems (“sink areas”). These expansions and contractions into adjacent ecosystems can affect the local ecosystem, as have been shown in the Gulf of Riga. Here, the presence/absence of cod, have affected the local food web, from herring to zoo- and phytoplankton through so-called top-down processes and trophic cascades. These expansions and contractions are examples of so called source-sink dynamics (Casini et al. 2012, ICES 2012, SLU 2012). The study of source-sink dynamics of cod (Casini et al. 2012) add to the intense scientific debate on the role of top predators, here cod, and their potential to structure food webs.

During the last decade, Baltic sprat stocks have become concentrated in the northern Baltic Proper. Sprat stock distribution is believed to be governed by exploitation rates and through predator-prey relationships with cod, competition with herring over food resources and by trophic cascades (MacKenzie et al. 2007, Eero 2012b, ICES 2012, SLU 2012). Using fragmentary and qualitative information on historical stock developments, Eero (2012b) has provided a quantitative estimate of sprat stocks for the whole Baltic Sea during the whole 20th century. Assessments of historical trends are valuable in understanding past variations in abundance and distribution, how fish are affected by different pressures and drivers and how future changes might affect important species and the food webs. Such assessments are also important in developing baselines for distribution and abundance.

8.2.4 Potential changes in the food quality in the Baltic Sea ecosystem

There has been a large decline in mean individual weight of sprat and herring during the last decades, possibly explained by changes in the lower levels of the food chain causing increased food competition. The mean weight of sprat has e.g. decreased by about 40 percent between 1992 and 1997 and the fat content has also decreased. Some researchers argue that this has resulted in sprat becoming "junk food diet" for some marine top-predators. For example, the weight of common guillemots chicks (*Uria aalge)* were shown to decrease in the 1990s when sprat stocks were large, and increase between 2000 and 2004 when the commercial sprat fishing increased. It thus seems that when the number of fish went up, the nutritional value of each fish instead went down, and as guillemots deliver one fish at the time to their chick, the quality of the each fish is important (Möllmann et al. 2005, Österblom et al. 2008, Eero 2012a, b, ICES 2012).

8.2.5 New findings regarding genetic diversity in Baltic Sea fish

Our knowledge of the genetics of our most common and commercially important fish species has improved greatly in the last decade. Below we shortly mention some of the research findings from the last ten years. See also section 8.2.6 regarding how commercial fishing may influence the evolution of fish.

The Baltic Sea cod has two main, genetically distinct local populations (the Eastern and Western stock) with separate spawning areas east and west of Bornholm. The Eastern stock is especially well adapted to the brackish Baltic, with e.g. eggs that float closer to the surface compared to those of Western cod (e.g. Larsen et al. 2011, 2012, ICES 2008, 2013a). Studies also indicate that cod has specific migration behavior, with strong natal homing (i.e. they swim back to their spawning areas) and thus little mixing of populations. This adds to the reproductive isolation between the stocks, where the Eastern population cannot be restocked by inflow from the Western population. If conditions in the Bornholm Deep are unfavorable, the recruitment will thus not succeed (Svedäng et al. 2007, 2010, Havet 2012).

Recent genetic studies have confirmed Linnaeus' assumptions that Baltic populations of herring are genetically distinct from those of the Atlantic (e.g. Lamichhaney 2012, Teacher et al. 2013). The Baltic Sea flounder is divided into several populations, and has been proposed to have two reproductive types depending on egg buoyancy; 1) six populations of demersal spawners that spawn in shallow water and have eggs that develop on the bottom (found mainly in the north and central Baltic Sea), 2) five populations of pelagic spawner, that spawn in the open sea and have free-floating eggs (found in west, south and central parts of the Baltic) (e.g. Lamichhaney 2012, Teacher et al. 2013).

Research on salmon shows that when cultured salmon escape to breed with wild salmon, the genetic diversity decreases, leading to lower survival rates. The replacement of naturally produced salmon smolt, with those produced in hatcheries, has reduced the genetic diversity of Baltic salmon and stocked smolt have a lower survival rate in the sea. Approximately 80 percent of Baltic Sea salmon have their origin in aquaculture. The remaining 20 percent are wild and with a unique genetic diversity, but a large proportion of wild stocks (approximately 2/3) are threatened and many have disappeared, with approximately 20 wild salmon rivers in the Baltic outside safe biological limits and at risk of genetic depletion. Between 1990 and 2010 the Baltic catches of salmon declined from 5 636 to 881 tons, the lowest registered since 1970. The last 2-3 years have seen slight increases in catches and in smolt production (HELCOM 2006a, 2011b, Havet 2012, ICES 2013b, S. Hansson, pers. comm.).

8.2.6 Some new findings concerning fisheries management

Increasing interest and efforts regarding fisheries management during the last ten years have resulted in better understanding of the importance of sustainable fisheries management. Below we present a few examples.

Knowledge regarding profitability of fish stocks with the help of bio-economic modeling, where simulations of different management scenarios are coupled to the ecosystem, show that changes in fishing effort can affect profits, but also the ecological condition of the fish stocks. Recent studies show that fisheries in the central Baltic Sea may potentially only be profitable (i.e. profits > subsidies) given current stock size and fishing fleet structure if the fishing effort is low (SEPA 2011).

Sustainable fishing management (especially in combination with favorable conditions for reproduction and egg survival) could lead to drastic increases in the cod stock. Retrospective research has shown that responsibly managed cod stocks, where e.g. discards and illegal and unreported catches are removed, would have generated substantially larger catches and thus additional income (e.g. BS2020 2009, Zeller et al. 2011).

There has been increasing realization that under-reporting by-catches and discards have an impact not only on the fish populations, but also on the economic sustainability of the fisheries sector, in terms of jobs and profits. According to ICES estimates from 2010, discards of Baltic cod are in the order of 6 – 7 percent by weight of the total catch (SEPA 2011, ICES 2013a).

A recent study argues that commercial fishing (here cod) might control the evolution of fish. When fishing targets at a particular size of fish, it can be a key driving force behind changes in characters such as body size and age at maturation. In short, fishing exerts as a strong selection pressure and causes genetic changes in fish potentially with cascading effects in the ecosystem (Belgrano & Fowler 2013 and references therein).

See Gårdmark et al. 2013 and Huss et al. 2012 for more on modeling multi-species interactions and management of multi-species systems.

8.3 Some major knowledge gaps

- *Need for better understanding of trophic interactions/food web dynamics, diet composition and benthic-pelagic coupling.* Is there a direct relationship between system productivity (e.g. production of benthos and plankton) and fish biomass? What are the couplings between open water and benthic systems? How do different species and sub-groups of species interact? What is the relative importance of benthic and pelagic prey for cod in different size classes? What is the extent of cod cannibalism? There is need for stomach samples for different species.

- *How are fish populations structured? How are they affected by migration patterns and recruitment? What is the role of the coastal zone for important fish species?* Fish are mobile organisms in an open system, and it is important to get better descriptions of where they are and what they eat during different phases of their lifecycles. How long distances do they move and in what time frames? What role do different habitats in the coastal zone play for spawning? Population structure of the main species (e.g. sprat) is not well understood. What are the reasons for changes in spatial distribution and what is the relative importance of migration, predation and reproduction for spatial distribution? Why doesn´t cod spread from the Bornholm Basin to areas where there is more food (e.g. to northern Baltic Proper) and why does sprat concentrate in the northeastern part of the Baltic Proper? Will large predatory fish return to the Kattegat?

- *How will hydrographic regimes and climate change influence fish stocks?* Reproduction, stock size, recruitment and growth are dependent on hydrographic and climatic processes. How are they likely to be affected by predicted climate changes? How are different species and life stages affected by projected climate changes (e.g. temperature, salinity, pH and increased load of DOC) and how is the prey affected, e.g. different species of zooplankton? What are the reasons behind the strong cod recruitment during the last 5 years? Is cod really restricted by the 11 PSU salinity limit for spawning?

- *What is lacking in current fisheries management?* How should we integrate knowledge for sustainable fisheries – currently there are differences in how fisheries and other environmental areas (e.g. eutrophication, climate change) are managed. How can we integrate different aspects of the fish ecology in fisheries management, e.g. account for benthic-pelagic coupling? What are the MSY (Maximum Sustainable Yield) levels for Baltic Sea fish stocks? There is a need to develop multi-species, multi-fisheries models that include food web dynamics. More reliable information is needed on IUU (Illegal, Underreported and Unregulated fishing) and natural mortality in order to reduce uncertainty in fish stock assessments. What is the relative importance of different drivers (e.g. fishery predation, food supply) for different species of fish? Need for continued development of selective fishing gears. A spatial component in research and management is missing. An improvement would be to calculate fisheries mortality (F) on sub-stock level and setting TAC (Total Allowable Catch) quotas on the same scale to structure the harvesting spatially. For Salmon (due to their homing behavior) this is clearly not in the sea basins, but rather in the individual streams. However, how far up in a stream are the genetic signals from different streams mixed?

- *There is need for more and better data on fish populations.* Considering the high mortality induced by fishery it is important to improve the field data on fish population sizes and age structure to improve management. It is also desirable to make data collection more independent of the fishery since fishery data contains biases not related to the fish population. There is also a need for population estimates for flounder. There is little information on the relation between flounder and cod. Are they competitors or prey for cod in different life cycle stages? Also stickleback has substantial populations that are currently not quantitatively assessed.

- *What is lacking with regards to modeling?* Need of continued and increasing integration of ecosystem modeling with experimental and observational science to include e.g. food web dynamics, genetic aspects, hydrographic and physical aspects in models.

- *What are the reasons for low mean weights in many fish species?* Is it possible that there are genetic reasons – e.g. that cods with genes for fast growth have been fished out, leaving a population dominated by genes for slow growth? Fish health (e.g. growth, condition, wounds etc.) in some cases appears to deteriorating but the reasons are unknown.

- *Are there several spawning populations within the Western cod populations, and are there spill over effects from the Eastern stock?* Is it possible that there are metapopulations (i.e. spatially separated populations that interact at some level) in the Eastern stock? We need empirical data on individual basis and cannot rely on modeling studies. Although tagging experiments are expensive, they are often the only alternative.

- *What is the effect of other top predators for fish biomass?* There is still no consensus regarding whether seals and cormorants have a major impact on fish biomass, or if the effects are small.

- *Can more information be extracted from historic material?* There is a substantial amount of historic fish material available for analysis in the form of scales and otholits (structure in the balance organ of fish). Improved analytical precision and reduced cost of analysis can facilitate extraction of retrospective information.

9 Baltic Sea biodiversity, genetic diversity and invasive species

9.1 A general introduction to biodiversity

Biodiversity is a term commonly used to describe the range of variation of living organisms and their habitats. There are a number of ways to define biodiversity; the one widely used divides it into three levels - genetic, species and ecosystem (habitat/biotype) diversity, corresponding to the three fundamental and hierarchically related levels of biological organization. During the last decade(s), a fourth definition, functional diversity, has gained increasing attention. The level of biodiversity is the result of natural evolution but increasingly also by human activity ("anthropogenic evolution").

Genetic diversity: Each species consists of one or more populations of individuals that reproduce, and genetic diversity represents the heritable variation within and between different individuals and populations of each species.

Species diversity: Species diversity refers to the variety and abundance of different types of organisms that inhabit an area/region (community) and includes the number of species, species richness (the number of species in a site or habitat) and the evenness of species' abundance.

Ecosystem diversity: Ecosystem diversity refers to the range of habitats (biotopes/landscapes) present in a region, forming the basis for a community of species. Habitats naturally differ between regions due to the abiotic and biotic characteristics of that region/area, a hard bottom community is thus likely to be different in the Baltic Proper compared to one in the Bothnian Bay.

Functional diversity: Another aspect of biodiversity is the diversity of functional groups; a group of species with common characteristics or functions in the ecosystem, e.g. feeding and reproductive behavior, mobility, size, productivity and capacity to conduct certain biogeochemical processes. Functional diversity can also include differences between populations or species to respond to various stress factors.

9.2 Introduction to Baltic Sea biodiversity

In principle, the coastal and offshore zone of the Baltic Sea is comprised of three types of plant and animal habitats: the benthic community with soft and hard bottoms (the most dominant and species-rich habitat types respectively), and the pelagic (i.e. open water) community. These three types of habitats can further be divided depending on light availability; if they are in the photic or aphotic zone, which determines the ability to include primary producers. Species composition includes species with both freshwater (limnic) and marine origin. Species biomass generally follows the salinity gradient, with a 20-40 times higher biomass of both fauna and flora in the Baltic Proper compared to the Bothnian Bay (e.g. de Jong 1974, Voipio 1981, Jansson & Kautsky 1977, Fuhrman et al. 2004).

Compared to other seas the Baltic is considered to have low species diversity because few species are adapted to the brackish environment, primarily due to its short evolutionary history. Despite the relatively low number of species, the Baltic Sea is as productive as the North Sea, which is much richer in species. A handful of species dominate biomass and abundance, e.g. keystone species such as the habitat forming blue mussel (*Mytilus* spp.) and bladderwrack (*Fucus vesiculosus*). A keystone species is a species that, relative to its abundance, has a disproportionately large effect on its environment. It plays a critical role in maintaining the organization and diversity of its associated community, and changes in its abundance and distribution leads to dramatic changes in the habitat affecting many other organisms in the food web. Blue mussels have e.g. been shown to be islands of high biodiversity in subtidal habitats (Elmgren & Hill 1997, Johannesson & André 2006, Norling & Kautsky 2008, HELCOM 2009a, 2010a, Ojaveer et al. 2010).

A range of present and future pressures and activities threaten biodiversity in the Baltic Sea, including eutrophication, fishing, harmful substances, maritime activities (e.g. shipping and construction), introduction of NIS and climate change. The relatively simple food webs and low biodiversity renders the Baltic vulnerable since key functions may be upheld by single species, making the genetic diversity of such species crucial (HELCOM 2009a, 2010a).

9.3 Examples of scientific progress and changed views

The research community has shown an increasing interest in biodiversity, not least in its role for the functioning of the Baltic Sea. Recent research shows that species diversity is much higher than previously thought, with over 6000 species in total for the Baltic Sea including Kattegat, and an unexpectedly high diversity (>4000 taxa) of phyto- and zooplankton communities. The Gulf of Finland is a well studied “hot spot”, where over 1500 of the 1700 known Baltic Sea species of phytoplankton are found, possible reasons being the high variance over short distances in the Gulf of Finland, and the large number of fresh water species. The long tradition of taxonomic studies in this area may also, at least partly, bee a reason that many species have been identified (Ojaveer et al. 2010, Telesh et al. 2011, Törnroos & Bonsdorff 2012).

The interest in functional diversity is increasing, as biological traits couple species to ecosystem functioning. It has been shown for larger invertebrate bottom-dwelling animals that the number of functional groups decreases from 20 in the Kattegat-Skagerrak to 1-2 in the Bothnian Bay. The number of species within each group is 4-5 in the former compared to 1-2 in the latter region (e.g. Bonsdorff & Pearson 1999, HELCOM 2009a). An increasing number of studies aim to link biodiversity and ecosystem functioning, and to investigate how these are affected by different disturbances and/or specific habitats. It has for example been shown that hypoxia resulted in loss of abundance and biomass, gradually impairing the structural and functional composition of a benthic community; with altered ecosystem functioning (e.g. oxygen consumption and nutrient fluxes) as a result (Villnäs et al. 2012). Traits (e.g. size) in different species have also been shown to be coupled to ecosystem functioning (Norkko et al. 2013).

There has also been an increasing understanding of microbial diversity, including patterns of bacterial biogeography and seasonal community succession, as well as the identification of key species and their functional traits, showing that there is a strong coupling between the microbial community composition and function and the surrounding environment (Andersson et al. 2010, Herlemann et al. 2011, 2013).

9.3.1 Genetic aspects of some common species in Baltic Sea biodiversity

Due to its short evolutionary history the Baltic Sea is seen as a geographically and ecologically marginal area, with low bio- and genetic diversity and a large share of genetically atypical, and locally adapted, populations. In recent years there has been a considerable increase in the description and understanding of genetic subgroups in different Baltic populations (not least thanks to method development and analysis of genetic material), increasing our knowledge of genetic diversity and local adaptations. There is evidence that a number of species from different taxonomic groups have undergone adaptations to the brackish environment of the Baltic despite its very short evolutionary history. A species consists of one or more populations with local adaptations. Several species show large genetic differences north and south of the Danish Straits and there are further so-called “genetic barriers” near the Island of Åland. The genetic diversity of these locally adapted species is important for their ability to respond to changes in the environment. A population with high genetic diversity is more likely to have some individuals that are able to adapt to environmental changes. Preserving the genetic diversity of Baltic species is therefore a safeguard for maintaining the functions of these species. Below some recent results of genetic studies of common species in the Baltic Sea are briefly presented (Johannesson & André 2006, Pereyra et al. 2009, Johannesson et al. 2011, Wennerström et al. 2013). More information of new findings regarding genetic diversity in some fish species is found in chapter 8.2.5.

Narrow wrack *(Fucus radicans*) is a recently described brown macroalgae. It was previously thought to be a dwarf morph of the bladderwrack (*F. vesiculosus*), but has been proven to be a separate species. It is the only endemic (restricted to a certain area) species in the Baltic Sea, separated from bladderwrack during the last 400-1000 years through rapid speciation. It is only found in the Bothnian Sea and around the Estonian Islands Saaremaa and Ösel. In contrast to other macroalgae of the genus *Fucus*, which reproduce sexually, the narrowwrack has been shown to have a very high level of clonality (i.e. reproducing asexually and thus have an identical set of genes), a trait that is thought to have contributed to its ability to disperse over a large geographical area. Among Swedish populations up to 80 percent of individuals are dominated by one female clone, found over a range of 550 km, and in some populations >90 percent belong to the same genetic individuals (Bergström et al. 2005, Pereyra et al. 2009, Johannesson et al. 2011).

Baltic Sea blue mussels have been shown to belong to two species/subspecies *Mytilus edulis* and *Mytilus trossulus* (both called blue mussels). Genotypes of the former are most common at the entrance to the North Sea, while the latter is predominant in northern and eastern populations of the Baltic Proper. Recent studies have shown that today’s populations of Baltic Sea blue mussels are often a mix of hybridizing *M. edulis* and *M. trossulus*. Hybridization occurs mainly in the Danish Straits, but to some extent also east of the Straits. *M. trossulus* is, although closely related to *M. edulis* native to the North Sea, shown to be indigenous to the Baltic and unique compared with populations in the North Atlantic and Pacific. *M. trossulus* are distinct from blue mussels in the North Sea and Skagerrak, with comparatively thin shells and small sizes at maturity, likely as a consequence of suppressed growth due to the low salinity (Reginos & Cunningham 2005, Kijewski et al. 2011, Wennerström et al. 2013).

Baltic Sea cod has through genetic studies, been shown to have two main, genetically distinct stocks; one large, which spawn east of Bornholm (Eastern stock), and one to several populations spawning west of Bornholm (Western stock). These populations have been isolated for a long time, and adaptations to the Baltic by the Eastern stock include adaptations to the low salinity and differences in egg buoyancy, spawning period and hemoglobin type (e.g. Larsen et al. 2011, 2012).

Baltic herring (*Clupea harengus membras*) was, based on its distinct phenotype with smaller size and lower fat content, classified as a subspecies of Atlantic herring by Linnaeus already in 1758. Recent genetic studies confirm that Baltic populations are genetically distinct from those of the Atlantic (e.g. Lamichhaney 2012, Teacher et al. 2013).

9.3.2 Non-indigenous and invasive species in the Baltic Sea

Non-indigenous species (NIS) (also known as alien species, non-natives) are species that intentionally or accidentally have been transported across a major geographical barrier and now occur outside their natural range. If these species threaten biodiversity, cause harm to the environment, economy or human health, they are referred to as invasive species. An NIS is thus not automatically an invasive species. Introductions of NIS and/or invasive species are caused by human activities such as e.g. shipping (through ballast water and hull fouling), building of canals, aquaculture, ornamental and live-food trade etc. (UNEP 2006, HELCOM 2009a).

The brackish water of the Baltic makes it prone to invasions by both freshwater and marine species. Increasing research and analysis of time trends and monitoring during the last decade show that from the 19th to the beginning of the 21st century about 120 NIS have entered the Baltic Sea, of which a majority have remained permanently. Between 1800-1900 the Baltic Sea were colonized by 17 NIS, of which 13 (e.g. the barnacle *Balanus improvisus*, the bivalve *Dreissena polymorpha* and the fish *Salvelinus fontinalis*) established themselves in the Baltic Sea ecosystem. The numbers increased between 1900 and 2000, when 61 of the 89 species that entered the Baltic became established. Species include crustaceans (e.g. *Acartia tonsa*, *Gammarus* spp.), fish (e.g. round goby, *Neogobius melanostomus*, and different species of salmonides, *Oncorhynchus* spp.), as well as the polychaete worms *Marenzelleria* spp., which have become one of the dominant benthic invertebrates in the northern Baltic Sea. Potentially harmful invaders, such as toxic dinoflagellates (*Pfiesteria piscicida*), American comb jelly (*Mnemiopsis leydii*), Asian clam (*Corbicula fluminea*) and the fishhook water flea (*Cercopagis pengoi*) have also been identified (e.g. Elmgren 2001, HELCOM 2009a, Baltic Sea Alien Species Database 2012, Norkko et al. 2012).

Trade and the increase in sea and canal traffic have contributed significantly to the migration of species to new areas, as well as the accelerated rate of introductions. The invasion rate and dispersal for the Baltic Sea is considered rapid and effective (approximately 1.3 new NIS/year over the period 1961-2007), with some, like *Marenzelleria*, spreading up to 480 km/year. The survival of the introduced species depends on their biological characteristics and of the environmental conditions faced. High biodiversity is known to enhance invasion resistance (e.g. Tilman 1999, Stachowicz et al. 2002). The relatively low biodiversity of the Baltic Sea could perhaps explain the high invasion success of many invasive species. To a certain extent the establishment of NIS in the Baltic Sea also is a natural on-going process of succession, as the Baltic Sea is very young and post-glacial succession of its ecosystem is on-going. So far, no reports have been found where NIS in the Baltic result in extinction of naturally occurring species. It is possible that some NIS add to the functional diversity, e.g. affecting the cycling of nutrients and providing a new food source (Leppäkoski et al. 2002, Leppäkoski 2005, Bonsdorff 2006, Baltic Sea Alien Species Database 2012). Invasive species are however increasingly recognized as serious threats to aquatic ecosystem and biodiversity. They have been claimed to be the second biggest factor of biodiversity loss globally (Vitousek et al. 1997, UNEP 2006). It is thus reasonable to expect that biodiversity, ecosystem functioning and ecosystem services of the Baltic Sea may be affected, not least if climate change increases water temperature, potentially making the ecosystem suitable for a larger number of non-indigenous and invasive species.

NIS (non-indigenous species) and invasive species can have both direct and indirect effects on the ecosystem and its structural and functional properties. Ecological impacts include increased predation pressure, competition for resources such as food or space, changes in food web and habitat, spread of diseases and parasites, production of toxins, genetic effects, as well as drastic reductions or even extinction of native species. These changes often lead to negative economic consequences as NIS can cause damage in fisheries, shipping, tourism and industry. Examples include biofoulers such as the barnacle and the hydrozoan *Cordylophora caspia*, common on boat hulls and underwater installations, the mussel *Mytilopsis laeucophaeata* in cooling systems in power plants, the fishhook water flee that cause clogging of gillnets, the zebra mussel (*Dreissena polymorpha*), which affects cooling systems and fouls beaches with sharp shells, and the shipworm (*Teredo navalis*), which can destroy wooden structures including historical shipwrecks (Ojaveer et al. 2002, Almqvist 2006, HELCOM 2009a).

The American comb jelly (*Mnemiopsis leydii)*, reported in Baltic waters since 2006, is a major predator on zooplankton, as well as on pelagic fish eggs and larvae. It has had major negative effects in other ecosystems, likely contributing to the collapse of Black Sea and Caspian Sea commercial fisheries in the late 1980s and early 2000s respectively (HELCOM 2009a, Florin et al. 2013). The invasive American polychaete worms *Marenzelleria* spp., invaded the Baltic Sea in 1985 and spread rapidly in soft-bottom habitats, and may compete with native benthic macrofauna for food and space, and as they have become numerically dominant they may also change the structure of the benthic community (Kotta & Ólafsson 2003). On the other hand it may have positive effects on the ecosystem as it has been reported to counteract eutrophication-related problems by increasing bio-irrigation, thus enhancing denitrification and potentially reducing the release of phosphate from the sediment to the water. This has potentially contributed to improved water-bottom oxygen conditions in the Stockholm Archipelago, counteracting seasonal hypoxic systems (Wallentinus & Nyberg 2007, Norkko et al. 2011).

9.3.3 Effects of biodiversity loss

According to the Millennium Ecosystem Assessment (MA), species vulnerable and prone to extinction have one or more of the following features: limited climatic ranges, restricted habitat requirements, reduced mobility, low genetic diversity, or isolated and/or small populations (MA 2005). The HELCOM Red List reports have categorized at least 60 species and 16 biotopes in the Baltic as threatened and/or declining, and the Swedish Environment Protection Agency lists 88 percent of biotopes as endangered, rendering the Baltic as one of the most threatened marine ecosystems worldwide (HELCOM 2007, 2013e, SEPA 2009). Human activities that cause habitat destruction or overexploit an individual species are serious threats to biodiversity. Research has shown that e.g. overfishing can lead to loss of genetic variation (e.g. Belgrano & Fowler 2013, Pimsky & Palumbi 2013).

Baltic Sea species and functional diversity is relatively low, and thus even minor changes in species biomass and/or occurrence may have large effects on ecosystem functioning. The loss of a single species therefore potentially has a higher impact in the Baltic Sea than in areas with high functional diversity. Biodiversity (including genetic and functional diversity) has been shown to play a vital role in the functioning and resilience of ecosystems (e.g. Bonsdorff & Pearson 1999, Diaz & Cabido 2001, Worm et al. 2006, HELCOM 2009a). In order to maintain biodiversity we need to preserve subgroups of species, as well as their habitats, as local populations constitute important genetic resources, housing unique genes and genotypes. For this, local management is essential.

9.4 Some major knowledge gaps

There is a substantial lack of knowledge and assessments regarding factors and processes affecting biodiversity at different taxonomic levels, including genetic and functional diversity. There is often focus on rare species, but from an ecosystem point of view it is also important to focus on the common ones; both with regards to understanding their functions in the ecosystem and their conservation (which will indirectly also benefit rare species).

What are the possible ecosystem impacts and societal consequences of non-indigenous and invasive species? How does biodiversity affect ecosystem functioning and resilience in the Baltic? There is need for fields and laboratory studies of functional groups and traits and the coupling between biodiversity, ecosystem functioning and resilience. Do common and rare species differ in response to different changes?

As biodiversity is threatened by the cumulative impacts of many stressors occurring at the same time, it must be studied and assessed using a multidisciplinary approach, preferably including all the levels of biodiversity; genetic, species, habitat and functional diversity.

What is the role of functional diversity in the Baltic Sea?

- What traits and functions are there in different trophic levels? How do we link functional diversity to the dynamics of food webs?
- What communities have the highest functional diversity, and what are the most desirable functions to safeguard? How many species and traits/functional groups are needed to uphold the balance/resilience and productivity of the Baltic, including its provisioning of ecosystem services?
- Is it possible to replace functions/species if they are lost? What are the mechanisms that underpin positive biodiversity-ecosystem function (BEF) relationships?
- Which type of characteristics or functions can signal changes in the ecosystem (early warning signals), e.g. sharp declines in growth, reproduction etc.?
- Are there differences in traits and functions between different parts of the Baltic, and do traits determine where and why species occur where they do? What will happen if key species or functional groups/traits are lost in one region?
- Are there traits and functions that non-indigenous and/or invasive species could provide that are currently lacking in the Baltic Sea?

What is lacking in knowledge with regards to genetic diversity?

- Increased efforts are needed to map and monitor Baltic genetic diversity and to identify functionally important genetic variation potentially important for future adaptation. Few species have enough levels of genetic data for proper management, and maintaining tissue and DNA archives for future monitoring is of central importance (historical sampling often used formalin, which damages the DNA).
- How fast can abiotic and biotic conditions affect genetic variability of species in the Baltic? Is strong evolutionary force created by different anthropogenic stressors, such as fishing, contaminants, eutrophication and different combinations?
- Is *Fucus radicans* the only endemic species? Which genetic populations have a high protection value? (e.g. we already now that some populations of *F. radicans* should be protected in Estonia). How should these populations be protected? Through local preservation/protection? Through relocation? Should they be cultured in laboratories or stored deep-frozen?
- Which are the genes controlling central processes in the nitrogen cycling and anoxic redox processes?

How will climate change and eutrophication affect Baltic Sea biodiversity?

- How will climate change affect the indigenous species? Will there be large changes in species composition, distribution etc.? How do organism groups, species or genetic sub-groups differ in their adaptations to projected changes in climate? How will different species (and functional groups) be affect by potential acidification?
- How will climate change affect non-indigenous and invasive species (e.g. promoting growth, and survival)? Will it make the Baltic more vulnerable and prone to new invasions, or less so, since they increase the over-all biodiversity and may contribute to higher adaptability to changing conditions? Are there non-indigenous species that could fill the functions of present Baltic species, should they decrease or become extinct as a result of climate change?
- Is a high degree of clonality (as seen in e.g. *Fucus radicans*) an important factor under future climate changes?
- What are the effects of eutrophication on biodiversity and important functions dependent on key organisms? (e.g. do current and increasing areas of hypoxia lead to a genetic change in benthic species?)

10 Food web interactions

10.1 Introduction to food web interactions

The food web is the network of trophic interactions that binds the organisms together, and many quantitative ecological processes can only be understood in that perspective. Our understanding of food web dynamics is unfortunately still rather fragmentary, and it is important to first of all acknowledge that there is a large need for basic ecological research. Understanding of food web processes will be crucial for managing the Baltic Sea with an ecological approach. At present, the best we can do is to address those aspects of which we have some knowledge, which is far from managing the whole ecosystem. This does not preclude taking action. We know that decreasing loads of nutrients and pollutants, maintaining diversity at all levels and maintaining healthy commercial fish populations will improve conditions. Unexpected effects and unforeseen situations will however inevitably occur, and require adaptive management as new knowledge is found.

Historically the food web in the Baltic has been seen as bottom-up controlled. The levels of nutrients determine the production level, which in turn regulates how much biomass can be supported in the upper levels of the food web. In the last decade there has also been a number of studies which have stressed the potential of top-down control, where the higher levels of the food chain regulates the lower levels. Much attention has been given to the disappearance of cod as pelagic and benthic top predator. It has also been intensely discussed whether the Baltic has ended up in a new, undesirable stable state in which internal mechanisms cause it to remain (regime shift with hysteresis).

Historically there has been a strong focus on rare species and environments with high symbolic value. The climate change and acidification research of recent years has renewed interest in the quantitatively important functions in the ecosystem, which are performed by the common species. Instead of looking upon the diversity in terms of species, the functions have been considered (e.g. producer, decomposer, transporter of resources etc.). If there are many organisms that perform a specific function it is more probable that functions will be maintained even if one species is lost. It is also possible that a specific function is performed by one species alone. The Baltic is likely to be particularly prone to functional losses since its diversity is so low. The number of identified functions, as well as number of species performing the same function, in the benthic community generally decreases with salinity in the Baltic (e.g. Bonsdorff & Pearson 1999, Norling et al. 2007, Nordstrom et al. 2010, Aarnio et al. 2011, Villnäs et al. 2011, Havenhand 2012, Törnroos & Bonsdorff 2012, Bryhn et al. 2013, Törnroos et al. 2013).

There are knowledge gaps about virtually every part of the food and the issues discussed below are just a few examples in some of the major organism communities. The division of subjects in this report has been made in a traditional way according to pressures, mainly because of the limited time frame available. A discussion of the pressures in a food web context very quickly reaches a level of detail that cannot be addressed in this report. For many processes and specific effects we also have a substantial bulk of knowledge. It is however clear that all processes and pressures interact and must thus be viewed in a food web perspective.

10.2 Examples of scientific progress and changed views

10.2.1 Large-scale and long-term information on phytoplankton

In recent years the long-term monitoring of phytoplankton has allowed a retrospective analysis of changes in the phytoplankton community. Phytoplankton constitutes the base of the food chain and its production supports the upper trophic levels all the way to seals and eagles. Two central issues have been if the chlorophyll concentration in the Baltic generally has increased and if the species composition has changed as a result of eutrophication. The taxonomical groups that have received most interest are cyanobacteria (formerly incorrectly called blue-green algae), diatoms and dinoflagellates.

The *cyanobacteria* attract attention since they fix large amounts of nitrogen, produce toxins and are a nuisance to the public during their holiday season. The potential changes in the occurrence of cyanobacteria have been discussed above under the chapter on “Eutrophication”.

Diatoms build an external siliceous skeleton by uptake of dissolved silica from the water. The diatoms have no means of movement but often have shapes and structures that reduce their sinking speed and enable them to remain longer in the water. They often occur in very large quantities early in the spring in an intensive spring bloom. Since there are relatively few zooplankton present in early spring, they are not heavily grazed, but sink down to the sediment to a large extent, where they are the most important food source for many benthic organisms.

Dinoflagellates are a heterogeneous group of algae, many of which are photosynthetic, with some able also to take up organic matter from the water (mixotrophic) or relying entirely on organic matter (heterotrophic). They move using two hair-like structures (flagella). They are therefore less prone to sinking and are often less common than diatoms in the material sinking out from the spring bloom. The dinoflagellates are more likely to be grazed since they often occur slightly later than the diatoms, when zooplankton have become more common.

Diatoms and dinoflagellates dominate the biomass of phytoplankton and their relative occurrence determines the amount and quality of the food reaching benthic organisms, as well as how much of the production that is degraded in the water (Heiskanen 1998, Klais et al. 2011). The dinoflagellates constitute a smaller part of the biomass in the Kattegat than in the Baltic Proper, where their biomass sometimes exceeds that of diatoms. The spring bloom in the Baltic Proper has an unusually high dinoflagellate biomass in relation to diatoms (Klais et al. 2011).

Long-term analysis shows an increase in the relative proportion of dinoflagellate biomass in several parts of the Baltic Proper (Suikkanen et al. 2007, Klais et al. 2011, Wasmund et al. 2011, Hällfors et al. 2013). The increase occurs in the northern Baltic Proper and particularly in the Gulf of Finland, whereas no change could be seen during the 20^{th} century in the Kiel Bight. Hällfors et al. (2013) could not find a convincing expalantion in terms of environmental factors. There does not appear to be continous change but rather ocillations in the dominance on a decadal scale (Wasmund et al. 2011, Hällfors et al. 2013). An analysis using consumtion of surface silicate rather than phytoplankton counts indicated a decrease in diatom occurrence in the 1980s in the Baltic Proper but not in the western Baltic. Diatoms were shown to generally reoccur after cold winters (Wasmund et al. 2013).

The causes and consequences of such shifts are not understood. The temperature of the water in spring, long-term changes in salinity, stratification, nutrient status and lifecycle traits are all potentially interacting causes. The food web consequences are also essentially unknown. There may be differences between phytoplankton species as food source, also between consumers. The greater ability of dinoflagellates to remain in the water mass may allow a greater proportion of the spring bloom to be consumed by zooplankton.

Fleming-Lehtinen et al. (2008) found the chlorophyll concentration to have increased by 150 percent in the northern Baltic Proper and the Gulf of Finland from the 1970s until the early 2000s. The same study reported an increase of 180 percent in the Bothnian Bay from 1970s until the late 1990s, followed by a decrease. Suikkanen et al. (2013) also report increased chlorophyll in the northern Baltic Proper. The HELCOM assessment of eutrophication in the Baltic Sea states: "During recent decades, chlorophyll concentrations have been increasing in most of the Baltic Sea sub-regions, although in the 2000s chlorophyll levels in many open sea areas showed signs of a decreasing tend" (HELCOM 2009c). Changes in the phytoplankton are likely to have effects on all levels of the food chain. A consistent strategy of long-term monitoring now allows us to begin analyzing such decadal pattterns and to separate them from long-term trends.

10.2.2 Zooplankton

There is too little information on the long-term development of Baltic zooplankton populations. Monitoring has been scarce and the variability is often large. There is however an awareness of the serious lack of data and its importance for fundamental understanding of the food web. A number of retrospective studies of preserved samples are under way and will hopefully shed more light on the development.

The zooplankton is dominated by three groups. Copepods are the most important food source for pelagic fish and juvenile stages of other fish and generally dominate the zooplankton biomass. Cladocerans (water fleas) and rotifers (wheel animals) are also important groups. The latter two groups are mainly of freshwater origin, and therefore constitute a greater proportion of the biomass in the northern basins than in the Baltic Proper. The rotifers are generally present already during the spring bloom and are an important food source for fish larvae, whereas cladocerans appear somewhat later. Mysid shrimps are also part of the zooplankton but may as well be counted to the benthic community since they move between the bottom and the water on a daily basis.

HELCOM (2009a) reported no general trends for zooplankton biomass. Copepods showed no trend in the northern Baltic Proper and the Gulf of Finland whereas cladocerans were found to decrease. There were however changes in the dominating species of copepods. A particularly important species is the saltwater copepod *Pseudocalanus acuspes*, a high-energy food item for herring. A dramatic decrease in *Pseudocalanus* occurred in the 1980s and other copepod species increased in abundance. The decrease of *Pseudocalanus* can at least partly be linked to decreased salinity during this period. Inflows in 1993 and 2003 caused increases in the population but it has not recovered to levels of the early 1980s.

Suikkanen et al. (2013) analyzed the long-term trends of the entire plankton community (both phyto- and zooplankton) in the northern Baltic Proper and found that rotifers had increased, whereas total zooplankton, cladocerans and copepods had decreased abundance in some basins. They also observed a general shift towards smaller organisms: "We conclude that the plankton communities in the Baltic Sea have shifted towards a food web structure with smaller sized organisms, leading to decreased energy available for grazing zooplankton and plankton eating fish. The shift is most probably due to complex interactions between warming, eutrophication and increased top-down pressure due to overexploitation of resources, and the resulting trophic cascades". In the southeastern Baltic however, Aleksandrov et al. (2009) found an increase in biomass of the dominant groups copepods and cladocerans for the last decade, concurrent with an increase in salinity and temperature.

10.2.3 The fish community

Fish play an important role in the ecosystem, linking lower and higher trophic levels through their predation on planktonic and benthic invertebrate and other fish (benthic-pelagic coupling), with an important structuring role in the food web and ecosystem. Assuming that the Baltic Sea pelagic fish communities are top-down controlled, large reductions (or increases) of their populations may have the potential to cause so-called trophic cascades, affecting the relative abundance of other species in the ecosystem.

In the last decade, there has been intensive research regarding changes in the abundance of our commercially most important species, for example showing that in the central Baltic Sea, the food web structure has gone through several large changes during the last century, most notably from a cod- to a sprat-dominated state.

Increasing primary production during the 1900s led to more food for fish, including cod. In combination with favorable hydrographic conditions (and possibly due to reduced top-down control through potentially lower predation pressure from seals; due to increased hunting and decline resulting from toxic pollutants, which e.g. impaired the immune system and reproduction), there were large increases in the cod populations (e.g. Ross et al. 1995, Swart et al. 1996, MacKenzie et al. 2002, Österblom et al. 2007, 2008, Eero et al. 2011).

In the late 1980s the cod stocks collapsed, mainly as a result of overfishing, combined with low reproductive success due to limited inflow of oxygenated, high-salinity water. The reduced cod stocks led to lowered predation pressure on its prey, the clupeid fish sprat (*Sprattus sprattus*). Some researchers have suggested that the large reduction of the cod population caused a trophic cascade (or even a regime shift) through loss of top-down control, when increased sprat populations lead to changes in the zooplankton community, and possibly even in the summer phytoplankton (e.g. Casini et al. 2008, 2009). Driven by changes in inflow regime, but also through trophic control by sprat, zooplankton composition changed, with copepods shifting from dominance by *Pseudocalanus acuspes* (the main food supply for cod larvae) to *Acartia* and *Temora ssp*. (e.g. Möllmann et al. 2009, Casini et al. 2009).

The combination of large sprat stocks, unfavorable conditions for cod spawning and recruitment and reduced abundance of *Pseudocalanus ssp.* has been proposed to stabilize the cod population at low levels, a new stable state termed “cod-hostile” (e.g. Köster & Möllmann 2000, Köster et al. 2005, Möllmann et al. 2008, MacKenzie et al. 2008).

This has however been disputed as the Eastern stock has actually recovered, with increases in both spawning stock biomass and total biomass since 2005 (Eero et al. 2011, 2012a), although the commercial fishery still cannot catch the TAC (Total Allowable Catch). This recovery contradicts the proposed “cod-hostile” state and suggestions of possible regime shifts, and Cardinale & Svedäng (2011) for example argue that the low cod biomass and productivity was mainly the result of overfishing, as demonstrated by the recovery seen when fishing mortality was reduced.

10.2.4 Benthic sediment communities

The benthic communities of deep (and sometimes hypoxic or anoxic) soft bottoms below the halocline in the Baltic Sea have low diversity. HELCOM (2009a) estimates the average and maximal number of species in the southern Arkona basin to 13.7 and 27 respectively. The number of species decreases when going north and the corresponding numbers for the Bothnian Bay are 1.4 and 3. With so few species it is clear that population fluctuations may have substantial effects on the processes in the whole community.

Some characteristic species found in the central Baltic Proper are the Baltic clam (*Macoma balthica*), the blue mussels (*Mytilus edulis* x *trossulus*), the amphipods *Monoporeia affinis* and *Pontoporeia femorata* and in recent years the polychaete worm *Marenzelleria* spp. (the latter mainly in coastal areas). The numbers of marine species decreases with decreasing salinity and species with freshwater origin dominate in the northern part. Generally mussels are more tolerant to oxygen deficiency than crustaceans. In the inner archipelago areas the presence of freshwater species creates a taxonomically more diverse community.

The Swedish biologist Christian Hessle was the first to perform quantitative sampling of sediment-living organisms in the inner Baltic Sea communities in the 1920s. Since the dominating species are few we have a comparatively good background material. In 1976-1977 a number of Hessle’s stations located above the halocline and around the islands Gotland and Öland were revisited. The results showed that the biomass had increased between 4.3 and 5.7 times compared to the 1920s. The results were interpreted as a result of increased food availability as a result of eutrophication. Below the halocline, where fauna was present in the 1920s, less or no fauna was found in the 1970s (HAVET 2011).

In 2006-2007 most of these stations were again revisited to evaluate changes. The data was compared and the calculated number of taxa and biomasses were lower than in 1967-1970 but the difference was not statistically significant. Several species present in the 1970s could not be found. These were mainly species of marine origin and those that were recovered were less abundant than in the 1970s. The non-indigenous *Marenzelleria* was the only new species. A substantial decrease was also found for the crustacean *Monoporeia affinis,* an important prey for fish (HAVET 2011).

Stations in the Gulf of Bothnia were also revisited in the 1980s. In the Bothnian Bay no changes were found, but in the Bothnian Sea the biomass had increased (as in the Baltic Proper), here by a factor of 5 over the 1920s. When stations in the northern Bothnian Sea were revisited 2008-2010 the number of individuals was only a third of that in the 1980s. The community was dominated by *Monoporeia* in the 1980s but by *Marenzelleria* spp. in 2008-2010. The loss of marine species in the Baltic Proper was most likely due to the decrease in salinity between the two samplings. This cannot, however, explain the decrease in *Monoporeia,* which is of freshwater origin (HAVET 2011).

A long-term investigation (1964-2007) of a coastal soft sediment community in the northern Gulf of Finland also showed a decreasing trend for crustaceans and an increase for the Baltic clam and *Marenzelleria* spp. A long-term trend of rising near bottom temperature and decreasing oxygen concentration was also found (Rousi et al. 2013). In another recent study the benthic diversity was found to be severely reduced in most of the Baltic Proper (Villnäs and Norkko 2011).

In sediments of the open Baltic Proper, the level of oxygen is likely to be the most critical factor for the benthic community. Already in the 1920s Hessle reported hypoxia and anoxia in both coastal and open-sea areas, but he also found live animals down to 140 meters east of Gotland (HELCOM 2009a). Today hypoxia and anoxia reach the halocline and the deeper sediments in the Baltic Proper support little or no macroscopic life. A studi indicated that the benthic communities are degraded and abundances below the 40 year average in the entire Baltic Sea (Norkko et al. 2007 cited in HELCOM 2009a).

10.2.5 The macrophyte community and communities on hard bottoms

The macrophyte habitat and communities on hard bottoms in the Baltic Sea is a diverse community where changes often attract public attention. The variability of coastal environments along the Baltic Sea makes it beyond the scope of this report to give general descriptions and trends. The focus will therefore be on the two important species bladderwrack (*Fucus vesiculosus*) and the blue mussel (*Mytilus edulis x trossulus*).

The most visible species on hard bottoms is the bladderwrack, which provides an important permanent environment for a number of crustaceans and isopods. It also provides shelter for mysids and a number of juvenile stages of fish. There has been an increase in the depth distribution and abundance of bladderwrack for the last 20 years in the Askö area from low levels in the 1970s and 1980s. The depth distribution has increased from around 6 meters in the 1970s to 9.5 meters, which is the same as was found in historic data from 1940s (HAVET 2009). In the Karlskrona area no such strong recovery is seen, and the bladderwrack is far from that found in the mid-1990s (HAVET 2010, 2011, 2012). A major discovery during the period has been that the narrowwrack (*Fucus radicans*), which was previously believed to be a variety of bladderwrack, is a separate species and dominates the Bothnian Sea whereas the bladderwrack dominates in the Baltic Proper (see also chapter 9.3.1).

The blue mussel is the most dominating animal on the hard bottoms. They often constitute 90 percent of the total weight of animals. Investigations show that the biomass of blue mussels has decreased in the Askö area since the 1990s, but no corresponding trend was found for monitoring sites around Gotland. In the Askö area there was also a general increase in water filtering organisms and particularly the cockle (*Cerastoderma glaucum*). It has not been possible to verify if this is a general trend in the Baltic Sea or if it is valid only for the Askö area (HAVET 2011).

10.3 Decrease in seabird populations and food web effects in Hanö Bight

Two current issues in Sweden are a dramatic decrease in mussel eating sea birds and complex signs of environmental problems in the Hanö Bight. In both cases changes in the food web have been proposed as one of several potential explanations. Both problems have been subject to special studies, but so far no clear causes have been identified.

10.3.1 Decreasing seabird populations

In a recent report to the Swedish government offices the drastic population decrease in Swedish mussel eating ducks was described and potential explanations discussed (Ottvall 2012). The overwintering population of diving ducks in the Baltic Sea decreased from approximately 7 million to slightly more than 3 million birds between 1990 and the period 2007-2009 (Skov et al. 2011 cited in Ottvall 2012). This dramatic decrease has caused concern and speculation of large-scale changes in the food web that may have affected their main food, the mussels. A factor stimulating speculation regarding causes is that many fish- and plant-eating ducks instead have increased in numbers in the same period.

In winter, 90 percent of the mussel-eating diving ducks concentrate in less than 5 percent of the total Baltic Sea area, in relatively shallow coastal and open sea areas rich in mussels. They are therefore all potentially affected by similar pressures. The best data available is for Eider ducks, which before the decline had increased in numbers for several decades, probably due to increased availability of food caused by eutrophication and reduced hunting. The report lists 8 potentially important factors for the recent decline, but states that it is presently not possible to identify the most important or likely. The proposed causes can be summarized as: changes in the food web and food quality, increased predation from eagles, reoccurring oil emissions from ships, ducks being caught by fishing equipment, hunting of approximately 10 percent of the Eider population, lack of thiamine in the food, unknown environmental contaminants and climate effects on salinity and water temperature (Ottvall 2012).

Ottwall (2012) discusses the arguments for and against these hypotheses. In particular the thiamin deficiency hypothesis has been intensively discussed in Sweden. The M-74 disease in salmon was found to be related to thiamin deficiency. It was however not conclusively clarified if the lack of thiamin itself was a cause or a consequence of other factors. Low thiamin levels in birds found in southern Sweden have fuelled a debate regarding the role of thiamin in the decline of birds.

A pilot study by Mistra EviEM (Mistra Council for Evidence-based Environmental Management) based on the present literature, found that there is presently not enough material to make an evidence-based evaluation of thiamin deficiency as the major cause of the population decline in seabirds, and that the subject requires further research (Söderberg 2013 and references therein).

10.3.2 Signs of degraded environmental state in Hanö Bight

During 2010 local fishermen reported that the fish avoided the inner parts of the Hanö Bight and that in the inner parts of the bight there was lower abundance of fish. There were also reports of increased frequency of wounds, signs of undernourishment in cod and brownish and foul smelling water. A report summarizing the available information was recently published (SWAM 2013). The analysis of available information was structured in four groups: environmental contaminants, water quality, fish and fishing and ecosystem effects.

No conclusive evidence for the problems was found for any of the investigated topics, but some of the information reported by local residents could be verified. Variations in the outflow of brownish freshwater can have caused variations in the bight and cod caught in the area were lean, which is the case also in other parts of the southern Baltic. In resemblance with most parts of the southern Baltic there was a decrease in benthic animals. As is the case for most food web studies SWAM found that there is a lack of information in many parts of the food web and has suggested an investigating monitoring program in order to disentangle underlying causes.

10.4 Some major knowledge gaps

It must be emphasized that our knowledge about the food web interactions remains fragmentary in spite of the impressive number of published articles on the Baltic ecosystem. We still have very incomplete models of the regulation of food web dynamics and a serious lack of data for most parts of the food web. The emerging view of considering food web functions (e.g. Törnroos & Bonsdorff 2012) rather than specific species also opens new perspectives. Individual species, or even genetic groups within a species, may fill fundamental functions of which we are not aware. In a low diversity community such as the Baltic the bulk of different functions is likely to be performed by a very limited number of species.

- *What is the food web role of mysid shrimp?* Very little is known about the abundance and quantitative food web importance of mysid shrimps. They are difficult to sample as they stay just above the sediment in daytime, and migrate up in the water column at night. They are important as predators of zooplankton, as food for fish and by coupling the benthic and pelagic habitats.
- *Has the population of three-spined stickleback (Gasterosteus aculeatus) increased dramatically in size and what may the consequences be?* There are indications of a dramatic increase in the population size of the three-spined stickleback in the central Baltic Proper and the Bothnian Sea (SLU 2012). The cause is not clear and this species is not monitored. Is stickleback an efficient food competitor to herring and sprat? There are also some indications that the stickleback may compete with perch for food.
- *Why does the growing population of cod remain in the southern part of the Baltic?* In recent years, cod appears to concentrate in the southern part of the Baltic Proper, while sprat, its main prey, has been abundant in the northeastern part (SLU 2012). Most of the cod caught in the southern parts are lean and appear undernourished. How much of the cod's food base is benthic organisms and how

much is sprat? What is the relative importance of the separation of cod and sprat populations and the loss of benthic fauna caused by the extensive oxygen depletion?

- *What causes strong sudden variations in populations of the benthic crustacean Monoporeia affinis?* The population of the important fish food *Monoporeia* has declined in the Bothnian Sea since the 1990s and only recently shows signs of recovery (HELCOM 2009a). The reasons are not clear, but *Monoporeia* has shown sudden population declines also in other areas. Sudden population declines occur naturally in many species, but *Monoporeia* is particularly sensitive to oxygen deficiency, which is the main problem for benthic organisms in the Baltic Proper.
- *How will the benthic organisms adapt to the dramatic increase of the invasive worm Marenzelleria* spp. *and the round goby (Neogobius melanostomus)?* These species have established strong populations in many parts of the Baltic Sea and are likely to affect other organisms in the community, but their appearance is so recent that no certain conclusions can yet be drawn.
- *How will an increased load of organic material from land affect the bacterial production and thus the food web?* In a warmer climate it is likely that more organic matter will be transported by rivers. In such a scenario it is also likely that bacterial production may increase and phytoplankton production decrease because brown coloring of the water reduces photosynthesis. There are indications that increased organic load in the Bothnian Sea stimulates bacterial production (Wikner & Andersson 2012). How important will this be in relation to eutrophication?
- *How does variation in the occurrence of bladderwrack affect the coastal organism community?* In many places round the Baltic the bladderwrack (*Fucus vesiculosus*) has been replaced by filamentous red algae. These do not provide the same habitat for protection and feeding as bladderwrack In some areas the bladder wrack has reestablished itself, but in others not. What are the effects of such large fluctuations in bladderwrack?
- *How do the benthic community and the organisms living in the open water interact and affect each other (benthic-pelagic coupling)?* The organism communities are often studied in isolation by different specialists. There is, however, a strong interdependence between the two communities, but little is known about the interactions between organisms and the flows of matter between sediment and water. There is some information on the material sinking down to the bottom, but flows in the other direction are largely unknown. How much of the production by benthic organisms is consumed by fish? What is the nutritional value of different organisms? How are fish affected by benthic population dynamics? Both *Monoporeia* and mysid shrimp swim daily in the water. How does this affect their distribution through transportation by currents? Are changes in their populations at particular stations a result of transport during such excursions in the water or are they resident in local areas? The movement of organisms in the sediment (bioturbation) enhances nutrient release to the water. How are such nutrient flows affected by changes in the organism communities?
- *How serious is the lack of long-term zooplankton data?* Monitoring of zooplankton has been neglected because of its cost. In the future it must be prioritized and preserved samples and historical records be evaluated. This is crucial for understanding variations in fish populations and their nutrition, as well as for evaluating the possibility of trophic cascades.

11 Overarching aspects with a food web perspective

The aim of this report has been to give a number of examples where new findings have altered or expanded our views regarding the Baltic Sea, as well as to identify a number of knowledge gaps. Since we have not attempted to prioritize between these neither will the conclusions. They attempt to summarize some of the major findings in the document and bridge over the different subjects rather than indicating what is most important.

All issues discussed in the report are different pressures or aspects of the food web dynamics, as are all our concerns for the Baltic. It is not a new conclusion that we have a very fragmentary understanding of the functions and quantitative flows in the food web, but it is nevertheless the most general knowledge gap in our understanding. With the exception of a few commercially important species of fish, and some birds and mammals, we have incomplete data on abundance, production, consumption, food composition and predator-prey relationships for almost all organisms in the Baltic Sea. Advancements in this field are crucial to improve our understanding of ecosystem functions and effects of pressures in the Baltic.

A central insight regarding the future development of the Baltic Sea is that there is no “stable state” for the Baltic Sea that we can return to. The presence of approximately 85 million people in the drainage basin will not allow a return to a reference state. To great extent management will have to decide what is desirable and achievable. It will neither be possible to have all desired properties at the same time; crystal clear water, absence of cyanobacterial blooms and anoxia, and high organism production are unlikely to occur simultaneously, but the goal must be a compromise that is achievable. What science can provide is educated guesses of the potential effects of different actions. This process of analysis and projections will always need to adapt to new situations since new species will inevitably establish themselves, climate and inflow regimes are likely to change, natural fluctuations will be better understood and the food web will continuously alter characteristics. Our knowledge base is, through the interactions between experimental and field research, modeling and long-term monitoring, considerably greater today than 20 years ago and we are at the beginning of a situation where we can separate natural variation on decadal scales from long-term trends.

For natural reasons a report of this kind focuses on problem areas and not the signs of recovery. The authors find it important to point out that in spite of the severe situation with extensive oxygen deficiency in the central parts of the Baltic Proper there are many positive signs. Because of improved sewage treatment and other measures to reduce nutrient load the water quality has improved greatly in many coastal areas and the loads have also decreased in some rivers. With a few exceptions the classic environmental contaminants have decreased dramatically in the last 20 – 30 years, many continue to decrease and are approaching, or are below, current estimates of safe levels. Sensitive top predators like seals and eagles have shown strong recoveries, and the cod has returned in the southern Baltic. The bladderwrack has, in the Askö area, returned to a depth distribution that approaches those found in the 1940s. No non-indigenous species has so far fundamentally altered the character of the Baltic Sea and no key species in the Baltic have gone extinct or been reduced to extinction levels in recent time.

Some large-scale processes in the Baltic have a fundamental effect on all parts of the food web. Eutrophication from historic deposits and current loads, inflow regime, fishing pressure and climate-driven temperature changes are likely to be the strongest forces presently acting on the food web in the Baltic Proper. The presently historically large areal covered by hypoxic or anoxic water and the possibility that inflows, in the current regime, may aggravate the situation further, has far-reaching implications. The extensive loss of inhabitable sediment for benthic animals causes food shortage and habitat loss for both cod and herring. The temperature increase potentially aggravates this by causing increased oxygen consumption also in shallow archipelago areas.

The relative importance of the historic deposits of organic material, current production and inflow regime for the present extent of oxygen deficiency is unknown. There is also a potential that top-down effects in the food web, induced by the decreased cod population, can aggravate the situation. The reduction in cod population was caused by too high fishing pressure and oxygen deficiency in the spawning area. Reduced predation by cod is likely to have caused the sprat to recover from a low population size during the 1980s. The strongly decreased abundance of the marine zooplankton *Pseudocalanus* since the 1980s makes it likely that this recovery has been achieved with less favorable food items compared to periods with higher salinity and greater presence of *Pseudocalanus.* Both herring and sprat are presently lean and have a comparatively low individual weight in relation to their age. Recent findings of shifts in the zooplankton size distribution towards smaller organisms could contribute to this. The low growth rate of herring and sprat may also be part of the reason why dioxin levels in herring do not continue to decrease in combination with a continued deposition by long-range atmospheric transport. Whether the increased predation on zooplankton by sprat has caused any changes in the zooplankton population is unclear, particularly since the herring population is small compared to historic levels (whereas the population is strong in the Gulf of Bothnia). The zooplankton community is perhaps the main organism community where our knowledge is most fragmentary. The few available data series, which do not show any clear trends in zooplankton biomass, and the available information rather shows a shift in species and size composition.

One step further down the food chain, to phytoplankton, there are no clear changes that can be potentially related to decreased zooplankton grazing. There appears to have been an increase in chlorophyll in most areas between the 1970s and the turn of the millennium, but thereafter the trends are unclear or slightly decreasing and one assessment suggested that the phytoplankton biomass has roughly doubled in the Kiel Bight in the last 100 years. In general there appears to have been an increase in the relative proportion of dinoflagellate biomass in relation to diatoms in all parts of the Baltic except the Kiel Bight. After a decline in the 1980s the diatoms in the southern Baltic have recovered and appear to increase following cold winters. Which of these two important groups that dominate phytoplankton appears to oscillate on a decadal scale. No clear conclusions can be drawn regarding the potential effects of such changes for the zooplankton community. A potential effect of more dinoflagellate biomass in relation to diatoms is a reduced sedimentation from the spring bloom, potentially causing a greater proportion of primary production to reach pelagic rather than benthic consumers. The nutritional aspects of changes between these two groups are not well known, but generally sub-arctic spring blooms are characterized by high levels of diatoms.

The most clearly observed effect of climate change in the Baltic Sea has so far been the increasing temperature in surface water. This is likely to affect archipelago areas substantially by increasing oxygen consumption and affecting the depth distribution of organisms. Potentially, the species composition can also change and thereby the functions in the ecosystem performed by the affected organisms. Many species of fish use the coastal areas for spawning and as nursery for their offspring. Changes in the food availability or major habitat change in the coastal environment is likely to have effects on a majority of species. In general there is a need to understand the material flows between the coast and open water better, as well as those between the sediments and the water.

Future projections of climate change show continuously increasing temperature and potentially decreasing salinity and pH in the Baltic. A major salinity change is likely to have dramatic effects on the distribution of marine species, where many already occur at the limits of their tolerance range. The genetic diversity is important in connection with such major changes. In the Baltic Sea many fundamental biological functions, such as primary production, material transport, trophic functions etc., are dependent on relatively few species compared to marine and freshwater environments. The genetic isolation of marine species in the Baltic makes it unlikely that they in a short time perspective will be replaced through re-colonization from the North Atlantic. Their ability to adapt to future changes is dependent on maintaining their genetic diversity.

It is also possible that NIS can fill lost functions, add new functions and contribute to a (from a human perspective) functioning and productive organism community in the Baltic Sea. It is possible that the young state of the Baltic causes it to have “empty niches” for new species that will not cause them to become harmful competitors to organisms already present. Will for instance the benthic polychaete worm *Marenzelleria*, which in a few years has become dominating in many areas, compete with indigenous crustaceans and mussels or will it coexist and through its tolerance to oxygen deficiency perform important biological functions in areas with hypoxic conditions? Will it become a useful food item for fish and will it also re-mobilize environmental contaminants from deeper sediment layers where they have been out of reach for currently present organisms?

Fishing is for some species likely to be the singular most important cause of mortality in adult individuals, which may also have genetic consequences. It is important that fishing and stocking activities do not reduce the genetic base for the commercial fish or causes a selection for undesired characters such as low growth rate or failed homing behavior. Other large-scale effects, such as widespread anoxia or other forms of substantial habitat losses, can potentially cause local populations to be drastically reduced or become extinct. The potential of top-down effects in the food web also puts the sustainability of fishing in a broader perspective than just the individual species concerned.

The regimes of inflow fundamentally affect most conditions in the Baltic Proper with time-lagged effects in the Gulf of Bothnia. The extended periods of wide spread anoxia in the central Baltic Proper causes considerable shifts in all major nutrient pools. Cyanobacterial blooms are central in the potential effects caused by these changes. They are major players in the nitrogen cycle in the Baltic and better insights into how their blooms are related to the phosphate release that occurs in periods of low oxygen levels, is crucial for the understanding of eutrophication. Cyanobacterial blooms are both a nuisance and probably a cause of high natural pelagic productivity in the Baltic Sea by introducing nitrogen into the pelagic system when the growth of zooplankton and fish is high. If their fixation of nitrogen is mainly governed by the availability of phosphorus it can cause a negative loop that decreases the value of nitrogen reductions. If they are instead mainly regulated by other factors the importance of reduced nitrogen loads is central. Nitrogen limits the size of the spring bloom in open coastal areas and open water, and the spring bloom to a great extent sinks to the bottom causing oxygen consumption and phosphate release (as well as food for benthic organisms). For future decisions it is important to know if cyanobacterial blooms increase or not as a result of phosphate availability, and how this is regulated in relation to other environmental factors, as well as how much of the productivity of zooplankton and fish that is related to nitrogen fixation.

Cyanobacteria excrete highly toxic substances in the water but these are also diluted in vast volumes to very low concentrations, but may reach higher concentrations in the sediment. Very little is known about the long-term effect of this on other organisms. Are they adapted to this? Are the concentrations with long-term exposure below effect levels? The problem is not different from the potential long-term and large-scale effects of discharges of a large number of industrial substances. How can we identify early effects and connect them to individual substances or mixtures? We are presently not aware of any effects on the scale of those caused by DDT, PCB and mercury in the latter half of the 20th century. There is however no guarantee that the more cautious attitude to new substances today will prevent similar large-scale effects in the future. There are a growing number of new substances used in industry and pharmacology. As they cannot all be monitored there is a need to develop efficient methods to identify biological effects in individual organisms and the community, and connect them to potential substances or mixtures of substances. The occurrence of a wide variety of nanoparticles and their potential effect in nature is essentially unknown.

It is important to acknowledge that we still have large fundamental weaknesses in our general scientific understanding of the nutrient cycles, food web dynamics and genetic description of the organism community. Many quantitative processes have however been substantially better described in the last decade and cooperation between different disciplines has increased substantially. As mentioned above, no attempt will be made to prioritize between knowledge gaps. It is however unlikely that there would be any dispute concerning the need to understand the cycling of material through the food web and how this is related to major abiotic factors such as inflow regime, current loading situation and potential future changes in these factors.

Future research must be addressed using interdisciplinary work and include interaction between observational studies, field studies, experimental work, laboratory work and modeling, as well as a better understanding of social drivers that affect our use and misuse of the Baltic Sea. High cost of fieldwork however causes students to spend less time in the field to acquire first-hand experience of the different habitats. Risks with failures in field seasons also cause doctoral students, and to a certain extent senior researchers, to limit their experimental work in favor of focused theoretical studies or limited field studies. Moreover the current uncertainties about infrastructure, particularly for work in open waters, limit the field experience of new researchers. There is a substantial risk that methodological and taxonomical knowledge, as well as hands-on field expertise, will decrease (and potentially be lost in some fields) in the future.

The focus on integrating estimates of environmental state has large value in communication, but also limits the presentation of data behind the communicated state, focusing the discussion on state rather than causes behind the changes. Since most of the large-scale processes in the Baltic Sea can only be studied at the spatial and temporal scale that they occur, the value of quality assured, high frequency, long-term monitoring cannot be overstressed. Connecting long-term monitoring with long-term ecological research, including experimental work and modeling, is a strong mechanism for providing efficient data flow, quality assurance, preserving methodological and taxonomic skills and providing modeling with new ideas for conceptual understanding.

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13 Word list

Anoxic conditions: Total absence of oxygen.

Benthic: Adjective of benthos (see below).

Benthos/benthic organism: Organisms that live associated with the sea bottom, including both mobile and non-mobile forms such as burrowing clams, sea grasses, sea urchins and barnacles.

Biomagnification: The occurrence of higher concentration of an environmental contaminant with increasing level in the food chain, sometimes exposing top predators to levels orders of magnitude higher than in plants or grazers.

Biomanipulation: To deliberately change an ecosystem by removing or adding species, especially predators.

Bottom-up control: Refers to food webs where a control of a population comes from change lower in the web (e.g., control of a population of mussels by abundance of phytoplankton food).

Cascading effects: See "Trophic cascade"

Demersal: Demersal species (such as cod) live in the water near the sea bottom (in contrast to pelagic species living in open water).

DOM (Dissolved Organic Matter): DOM consists of soluble organic materials derived from the partial decomposition of organic materials, including soil organic matter, plant residues, and soluble particles released by living organisms, including bacteria, algae, and plants.

Endemic: Describing a plant or animal species whose distribution is restricted to one or a few localities.

Eutrophic: Water bodies or habitats having high concentrations of nutrients.

Eutrophication: Defined as an increased input of nutrients causing an acceleratedgrowth of planktonic algae and macrophytes.

Functional diversity: Diversity of functional groups; a group of species with common characteristics or functions in the ecosystem, e.g. feeding and reproductive behavior, mobility, size, productivity and capacity to conduct certain biogeochemical processes.

Functional group: A group of species characterized by common traits or roles in the ecosystem. This applies to functions such as feeding behavior, occupation of a specific niche or the capacity to conduct certain biogeochemical processes.

Genotype: The genotype of an organism is the inherited instructions it carries within its genetic code..

Halocline**:** A strong vertical density gradient in the water mass caused by difference in salinity.

Hypoxic condition: Oxygen levels that become detrimental to aquatic animals. The exact level differs with the tolerance of the animals. Oxygen levels below 2 ml/l are often considered as hypoxic.

Keystone species: A keystone species is a species that, relative to its abundance, has a disproportionately large effect on its environment. It plays a critical role in maintaining the organization and diversity of its ecological community, and changes in its abundance and distribution thereby affects many other organisms in the food web.

Macrophyte: Macroscopic submerged aquatic plants and algae.

Niche: The niche of an organism is defined by e.g. what it eats, its predators, salt tolerances, light requirements etc., i.e. abiotic and biotic factors.

Oligotrophic**:** In this context a state where production is comparatively low because of low nutrient levels. The terminology comes from freshwater studies (limnology) and has no generally accepted scale in marine environments.

Oxic conditions*:* Levels of oxygen where animals can occur. The absolute value differs between different animal species. In general it is understood as oxygen levels exceeding hypoxia (in this context more than 2 ml/l).

Pelagic: Open sea; pelagic species live and feed in the open water column.

Phenotype: An organism´s observable characteristics or traits, resulting from the expression of an organism´s genes, the influence of environmental factors and the interactions between the two.

Phytoplankton**:** Plant plankton are tiny plants that drift in the water mass. Phytoplankton convert nutrients and carbon dioxide to biomass by the process of photosynthesis (photosynthetic primary production).

Practical Salinity Units (PSU): A measure of the salt content of seawater approximately equal to per mil salt.

Regime shift: An ecosystem regime shift is an infrequent, large-scale reorganization, marking an abrupt transition between different states of a complex system, affecting ecosystem structure and function and occurring at multiple trophic levels.

Retention**:** In a transport of material (e.g. nutrients) from one water body to another some of the transported material is usually lost along the way. If for instance nutrients are released in a lake some of the nutrients will be taken up by production in the lake and the rivers leading from the lake to the sea. Some of the material will become sediment in the lake and rivers and some may be lost in other processes like denitrification. The proportion of material lost from source to the sea is called retention.

Top-down control: Refers to food webs where control of a population is mainly explained by consumption by a species or group of species at higher levels of the food chain (e.g., population change of population fish controlled by seal predation).

Trait: A trait is a measurable property, phenotype, or characteristic of an organism; e.g. size, growth, tolerance and sensitivity to environmental conditions, motility etc.

Trophic cascade: Changes in the relative abundances of multiple species in an ecological community as a result of changes in abundance of one species.

Trophic level: In a food chain, a level containing organisms of identical feeding habits with respect to the chain (e.g., decomposers, primary producers, grazers, predators, top-predators).

Zooplankton**:** Animal plankton are tiny animals that drift in the water mass. Zooplankton can be predators, grazers on phytoplankton or consumers of decomposing material (detrivores).

14 References

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15 Appendix: Statement of the expert group