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BONUS briefing
SCIENCE FOR A BETTER FUTURE OF THE BALTIC SEA REGION

HYPER
Hypoxia in the Baltic Sea

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HYPoxia mitigation for Baltic Sea Ecosystem Restoration

The drastic expansion of hypoxia (oxygen depletion) from less than 10,000 km^2 before 1950 to over 60,000 km^2 in recent years is one of the most profound effects of eutrophication in the Baltic Sea. Increasing nutrient input from land and atmosphere is the main cause for this trend. The expansion of hypoxia has significantly altered nutrient cycles. Over the years, denitrification, which is the most important removal process for nitrogen, has shifted from mainly taking place in the sediment to the water column. Hypoxia can be reversed, but only if nutrient inputs are reduced. The recovery process can, however, be further enhanced by benthic animals that bio-irrigate the sediments and increase ecosystem resilience towards perturbations from hypoxia. Targeting hypoxia as part of the Baltic Sea Action Plan also addresses other ecological objectives of HELCOM.

OVERVIEW

The drastic expansion of hypoxia over the last century is one of the most profound effects of the increase of nutrient inputs from land and atmosphere.
Bottom water oxygen concentrations are strongly influenced by physical factors, especially the inflow of saltier, denser water. These inflows are governed by large-scale and local meteorological forcing, and have large variations in frequency and magnitude over time-scales of decades. Saltwater inflows bring new supplies of oxygen to bottom waters, but at the same time enhance stratification creating larger bottom areas that experience hypoxia. However, it is the increased sedimentation of organic material to the bottom water and sediments due to nutrient enrichment, that has disrupted the balance between oxygen supply through physical processes and oxygen consumption from decomposition of organic material. Subsequently, large parts of the Baltic Sea ecosystem have experienced functional changes in biogeochemical processes and in food-web interactions. Moreover, changes in the benthic community can have significant effects on nutrient feedbacks from the sediments, characterised as regime shifts. A reduced capability of removing nutrients from the system releases nutrients back to the water column and thereby enhances algal growth. Nutrient releases from the sediments are substantial, particularly phosphorus mobilisation can exceed the land-based loading by factors up to 3. These mechanisms are believed to be self-sustaining, maintaining a state with widespread hypoxia and algal bloom that is also known as the "vicious cycle" of the Baltic Sea.

The ecological problems of the Baltic Sea are inter-linked and hypoxia is a focal point for restoring a healthy ecosystem.
Hypoxia changes the functioning of the benthic community and enhances internal nutrient fluxes, and this will consequently affect nutrient levels, algal blooms and water transparency. Therefore, mitigating hypoxia will indirectly also address the other ecological objectives of HELCOM. Reversing hypoxia in the Baltic Sea can only be achieved by proper management of the nutrient inputs from land and atmosphere. Failure to accurately quantify nutrient feedbacks under various hypoxic conditions and extrapolate these to the entire Baltic Sea may lead to inappropriate reduction measures being taken, and may ultimately jeopardise the HELCOM's Baltic Sea Action Plan objective for good ecosystem health by 2021.

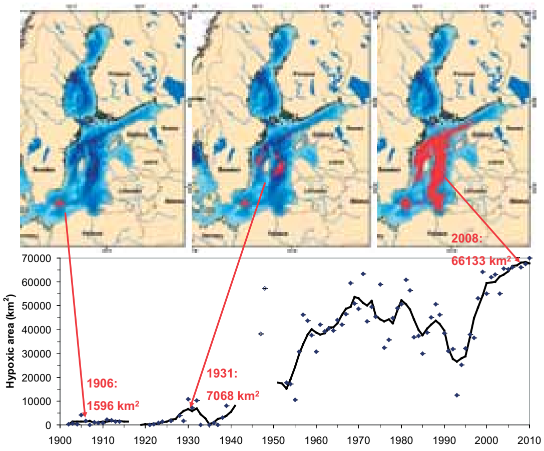

Figure 1. The hypoxic area in the Baltic Sea has increased more than 10-fold during the last century. Solid line is 5-year moving average.

HYPER is an interdisciplinary project with the aim to improve the understanding and quantification of the mechanisms underlying hypoxia in the Baltic Sea.

HYPER investigates the interaction of physical, biogeochemical and biological processes, from the past to present, and integrates this knowledge into a nutrient management framework. This has been achieved through intensive field sampling where nutrient fluxes have been measured under various physical and biological conditions. Analyses of these data have allowed scaling-up flux rates from discrete measurements to the entire Baltic Sea by means of advanced biogeochemical models. The improved process understanding will be used to advance present-day models used for nutrient management and in support of the Baltic Sea Action Plan.

OUTLINE OF KEY RESULTS

RECONSTRUCTING THE HISTORY OF HYPOXIA

It is important to understand how hypoxia has developed in the past to be able to predict for the future. Oxygen has been measured in the Baltic Sea since the start of the 20th century using the same method, but data before 1960 have been too scarce to interpolate and produce basin-wide estimates of hypoxia. A statistical model has been developed to estimate the core characteristics of salinity and temperature profiles and analyse the temporal and spatial variations of these. Using this developed methodology trends of hypoxia for the last 110 years have been reconstructed (Figure 1).

Before 1950 hypoxia was confined to a spatially restricted area, but in the following two decades hypoxia increased its extent to about 50,000 km^2. The situation improved from 1982 to 1993 which was the so-called stagnation period without any major saltwater inflows. During the stagnation period stratification became weaker and the depth of the halocline moved from 70 m to 80 m depth. However, saltwater inflows after 1993 strengthened stratification again and the area of hypoxia doubled. In the last decade between 60,000 and 70,000 km^2 of bottom area were hypoxic.

Trends of hypoxia are consistent with trends in nutrient inputs developed in ECOSUPPORT project up to 1990, but the reduced inputs of nutrients from land during the last two decades have not yet had a positive effect on hypoxia in the Baltic Sea. This decoupling of hypoxia from nutrient input trends suggests that a regime shift may have occurred, with internal nutrient inputs playing an increasingly larger role in more recent years. Our results confirm that increased nutrient inputs are the cause of the expansion of hypoxia over the last century.

OSCILLATIONS IN HYPOXIA ERODES THE CAPABILITY OF SEDIMENTS TO STORE PHOSPHORUS

Phosphorus is buried in the bottom sediments when Baltic Sea bottom waters contain oxygen. Most of the phosphorus is buried with iron which binds phosphorus tightly. However, phosphorus and iron is rapidly released from the bottom when oxygen in bottom water is depleted during periods of hypoxia. The phosphorus is then available during summer to support blue-green algal blooms. Thus, the Baltic Sea has less blue green algae when the bottom water contains oxygen.

HYPER has discovered that phosphorus can also accumulate in bottom sediments in organic matter. During periods of hypoxia phosphorus in organic matter is the major form of phosphorus burial. If the system becomes oxic again the sediments will start to accumulate iron and phosphorus (Figure 2). Oxygen is more corrosive to the organic matter and the organic phosphorus will be released, although it rapidly reacts with iron and is buried.

With oscillating periods of oxic and hypoxic conditions, as is observed today, the ability of the sediments to store organic phosphorus is greatly reduced. Ultimately, this reduces the capacity of Baltic Sea sediments to store phosphorus in the bottoms and makes phosphorus more available to cause harmful algal blooms.

This result also has implications for the engineering approaches to add oxygen to the Baltic Sea. If the engineering system fails because of a storm for example, phosphorus will be rapidly released from the bottom creating a "phosphorus bomb" to the ecosystem. A massive release of phosphorus from sediments over a short period would be a catastrophe to the Baltic Sea ecosystem.

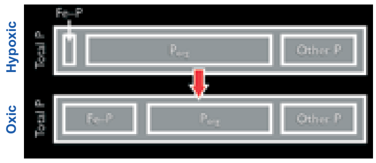

Figure 2. When oxygen conditions change from hypoxic to oxic organic phosphorus is remineralised and becomes iron-bound. The iron-bound pool will be released from the sediments to the water if sediments become hypoxic again (P-bomb).

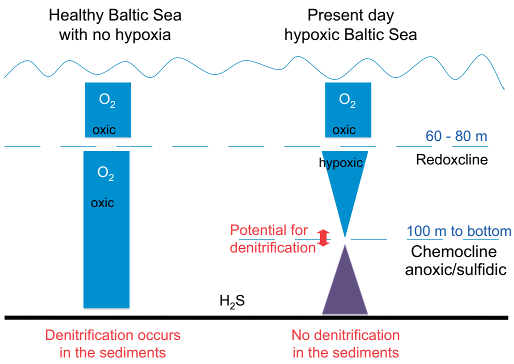

Figure 3. The position of the redoxcline affects the denitrification potential.

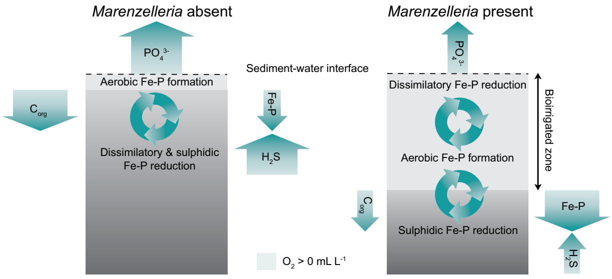

Figure 4. Bio-engineering species such as Marenzelleria *has a positive feedback on the P-cycle.*

HYPOXIA HAS MOVED DENITRIFICATION FROM SEDIMENTS TO WATER COLUMN

It is well known that nitrogen is an important nutrient in the Baltic Sea regulating the growth of algae in the water. However, there are large uncertainties about how nitrogen nutrients are converted to dinitrogen gas and lost from the ecosystem through a process called denitrification. In a healthy ecosystem the most important losses of nitrogen occur at the interface between the sediments and the water where nitrate-nitrogen, an important nutrient for algal growth, is converted to dinitrogen gas (Figure 3). Most algae cannot use dinitrogen gas, so this process is an important pathway to remove nitrogen from the system.

During periods of hypoxia denitrification does not occur in the sediments because the process requires that oxygen is present. In fact, the results demonstrate that for oxygen levels below 2-2.5 ml/l another process, dissimilatory nitrate reduction to ammonium, becomes more important than denitrification. This is generally bad for the ecosystem because it means that nitrogen is not lost from the system and can remain to trigger growth of more algae.

In the Baltic Sea it has been hypothesised that there is another possibility that denitrification can occur in the water at the interface between bottom water with no oxygen and the hypoxic bottom water. Very careful measurements of denitrification were made using very specialised techniques in the water and significant rates of denitrification were found. The results confirm that the water column has become an important sink for nitrogen removal during periods of hypoxia, but the magnitudes and variability are not yet understood. Moreover, low oxygen concentrations reduce the capacity to permanently remove nitrogen by denitrification.

A WELCOME CAN OF WORMS?

Just as the loss of macrofauna can have a negative feedback on nutrient cycles, there can be a positive feedback from bio-irrigating species colonising an area under restoration. There is recent evidence that improved bottom-water oxygen conditions in coastal areas of the northern Baltic Sea coincide with increased abundances of the invasive polychaetes *Marenzelleria spp*. HYPER has documented significantly lower phosphate concentrations in the Stockholm Archipelago after *Marenzelleria* became abundant, demonstrating that bio-irrigating organisms can affect the sedimentary phosphorus dynamics on a system-wide scale.

These results were further confirmed using a reactive-transport model, demonstrating that the long-term bio-irrigation activities of dense *Marenzelleria* populations may facilitate the switch from a seasonally hypoxic system back to a normoxic system by reducing the flux of phosphate from the sediment to the upper water column (Figure 4).

Invasive species are generally considered to have a negative impact. Results of HYPER show that one of the main recent invaders in the Baltic Sea may provide important positive ecosystem services. The results suggest that a rapid ecosystem recovery is possible, provided that oxygen conditions are improved to a level allowing bio-irrigating species to colonise the system.

NEXT STEPS AND FUTURE PLANS

Results of HYPER have advanced the scientific understanding of how oxygen conditions affect the nitrogen and phosphorus cycles on both short and long terms, as well as the role of the benthic fauna in modulating these processes. Although introduction of bio-irrigating species may speed-up the recovery process, a precondition is that oxygen must first reach levels for these organisms to (re)colonise and consequently the solution to mitigate hypoxia in the Baltic Sea is to reduce the organic loading by reducing inputs of nutrients from land and atmosphere. The estimated process rates obtained in HYPER are being used to improve the parameterisation of the NEST model which will be used for revising the Baltic Sea Action Plan.

Nutrients from land are mediated through the coastal zone before entering the open Baltic Sea. The coastal zone has an important role of retaining nutrients, i.e. acting as a coastal filter to reduce nutrient exports to the open waters. However, this filter becomes percolated when coastal systems experience hypoxia, and as a result nutrients inputs to the open waters increase. HYPER has reported wide-spread occurrences of hypoxia along the coastal zone of the Baltic Sea (Figure 5), which could indicate an increasing leakage of nutrients from the coastal zone. As a consequence, there could be no change in the nutrient export from the coastal zone over the last 2-3 decades, despite reductions in nutrient inputs from land, because the coastal filter capacity has been diminished. Understanding the role of the coastal zone in retaining nutrients, particularly in relation to oxygen conditions, is crucial to understand the cause-effect chain from nutrient inputs to hypoxia in the

Baltic Sea and to estimate consequences of nutrient management of the ecosystem health.

HYPER has demonstrated the importance of bio-engineering organisms on the nutrient cycles, but exploring this research field has only begun. Particularly, there is a need to study the dynamical interaction between fauna and biogeochemical processes during different phases of ecosystem recovery to assert the resilience of the new system. This will allow assessing the long-term effect of recovered ecosystems which will be crucial for decision support models to describe the likely outcome of nutrient management plans at all levels of the Baltic Sea ecosystem.

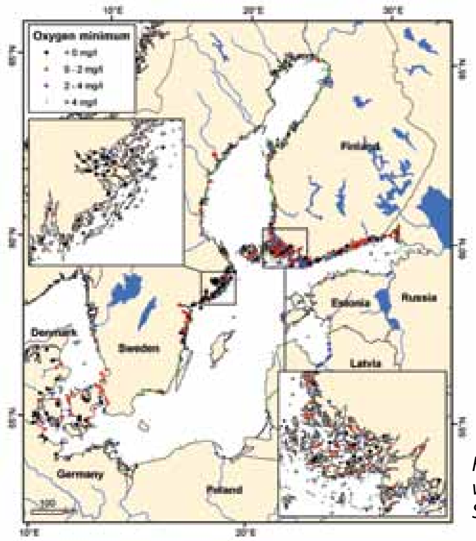

Figure 5. Hypoxia is widespread along the Baltic Sea coastline.

IN BRIEF

HYPER
Hypoxia in the open waters of the Baltic Sea

KEY RESULTS

- Oxygen trends constructed by the project over the last 110 years show that hypoxia was confined to a spatially restricted area before 1950. Since then the hypoxic area has increased drastically to a present level around 60,000 km2. Trends of hypoxia are closely linked with nutrient inputs.

- Significant amounts of phosphorus are buried in the sediments in organic forms, when hypoxic conditions prevail. This pool of phosphorus will be remineralised during oxic conditions and bound to iron. If the system becomes hypoxic again the iron-bound phosphorus is released to the water, potentially sustaining large harmful algal blooms. Thus, the Baltic Sea contains a potential "P-bomb" that can be released with alternating hypoxic-normoxic conditions.

- Denitrification is the most important pathway for removing nitrogen. Low oxygen levels induce a shift from denitrification to another process (DNRA), which recycles nitrogen back the water column. Moreover, the increase in hypoxia over time has displaced the zone of denitrification from the sediment to the water column.

- Benthic invertebrates play an important role modulating nutrient cycles and enhancing ecosystem recovery. Hypoxia can be reversed, but it requires that nutrient inputs are first reduced to achieve oxygen levels suitable for these species to colonise. Bio-irrigating benthic organisms will speed up and maintain the recovery process after colonising the area.

WHO NEEDS THE INFORMATION

These results will give more precision to the Baltic Sea Action Plan revision process, involving stakeholders from environmental ministries, HELCOM, NGOs. HYPER results have advanced our scientific understanding of processes in the Baltic Sea.

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