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Tackling Hypoxia in the Baltic Sea: Is Engineering a Solution?

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To mitigate the formation and spread of the Baltic hypoxic zone, scientists, engineers, and regulators must work together.

Hypoxia, the lack of dissolved O_2 in bottom waters, reduces the habitat for living resources. Hypoxic regions in the Baltic Sea enhance P release from sediments and increase N loss. This chemical scenario supports favorable growth conditions for cyanobacteria which contribute to the hypoxia and ultimately sustains eutrophication. The hypoxic conditions are insufficient to support multicellular life, having affected regions referred to as "dead zones". The Baltic Sea contains the largest anthropogenic dead zone in the world (*1*). The long-term average area impacted by hypoxia (O_2 < 2 mL/L) is 42,000 km^2 (Figures 1 and 2), and over the past few years near record areas of hypoxia (~60,000 km^2) have been reported by monitoring authorities (*2*). Physical factors, especially the inflow of saltwater from the North Sea (*3*), are important determinants of the annual extent of hypoxia (*4*). Although hypoxia has occurred in the Baltic Sea during previous climatic warm periods (*5*), nutrient-driven eutrophication is believed to be the primary cause of increases in hypoxia over the last 50−100 years (*6*).

Since the late 1980s, the Convention on the Protection of the Marine Environment of the Baltic Sea (Helsinki Commission [HELCOM]), representing the countries surrounding the Baltic, has been working to implement a 50% reduction target for anthropogenic nutrient loads (*7*). In 2007, HELCOM reached an international agreement to reduce the effects of eutrophication, with targeted nutrient reductions for each country (*8*). The effects of eutrophication in the Baltic Sea have been well described (*9*). As a result of improved treatment of industrial point sources and municipal wastewater treatment plants, some nutrient discharges from point sources have been reduced, improving local conditions. Despite the pledges of governments there has, however, been little progress in total nutrient reductions (*2*).

Frustration over the lack of progress in achieving improvements in water quality has led to calls for rapid and radical remediation efforts. Several private foundations have been established recently to combat eutrophication in the Baltic Sea, especially following the record bloom of cyanobacteria in 2005 (*10*). For example, Baltic Sea 2020 was established in 2005 through a private donation (500 million SEK = $83 million USD) made by Björn Carlson in order to promote concrete measures to improve the Baltic Sea environment (*11*). The John Nurmisen Foundation has led efforts to implement P reductions from wastewater treatment plants in St. Petersburg, Russia (*12*), and is currently pursuing similar goals in Poland. The Swedish government has pledged

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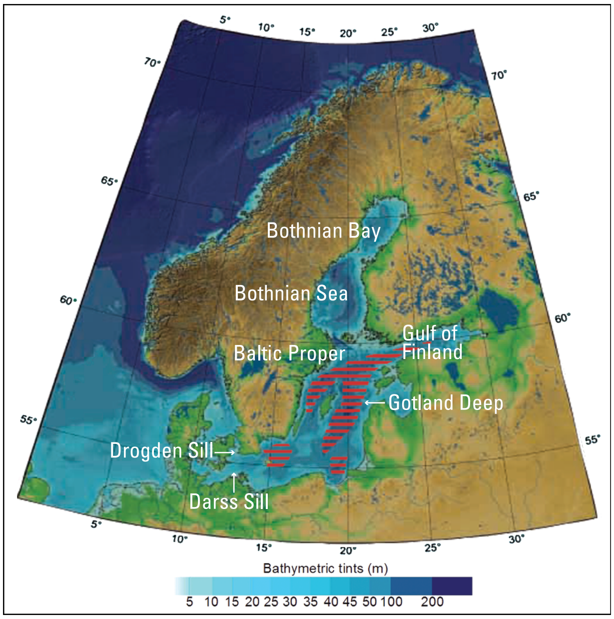

FIGURE 1. Map of the Baltic Sea identifying its major basins and sills governing the inflow of saltwater. The red lines designate the maximum hypoxic area that occurs in the Baltic Sea.

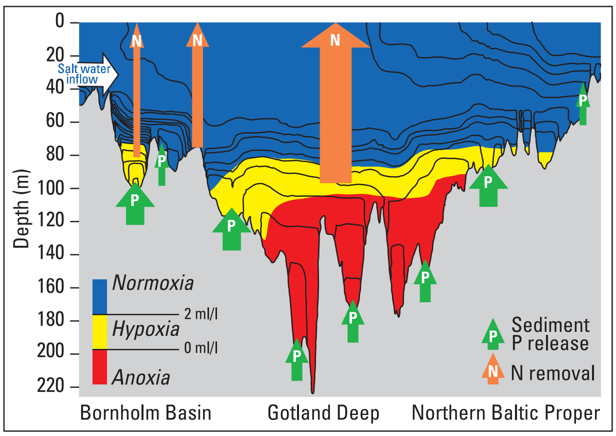

FIGURE 2. Diagram of hypoxia in the Baltic Sea. Saltwater enters from the Danish Straits and moves into the Baltic proper following depth contours. As the water ages it is depleted of O_2, with anoxia occurring in the deepest basins. As a result of hypoxia the amount of sediment removal of N through denitrification and anaerobic ammonium oxidation (anammox) decreases (smaller arrows) and is essentially zero in anoxic basins. N removal also occurs below the permanent halocline and above the zone of hypoxia. Sediment P release is highest in hypoxic area (largest arrow), low in oxic areas, and intermediate in anoxic areas. The anoxic areas tend to have low rates of P release because sediment P pools are depleted. The abundance, composition, and diversity of benthic communities are also strongly influenced by O_2.

another 500 million SEK for improvements in the Baltic Sea (*13*). More recently, the Swedish Environmental Protection Agency, in collaboration with several other national funding agencies, announced a call for proposals for pilot experiments to oxygenate bottom layers of the Baltic Sea or to increase the precipitation and sequestration of P in order to reduce its release from sediments.

Large-scale engineered remediation projects within the marine environment itself are receiving increasing attention, such as ocean enrichment to enhance carbon sequestration (*14*). Although experience from freshwaters demonstrates that nutrient reductions must occur for any mitigation measure to be effective (*15*), complementary engineering solutions may enhance or accelerate the recovery process provided that nutrient inputs are reduced simultaneously. Remediation through engineering is often presented as promising grand improvements in water quality as it is typically less expensive and far more rapid than nutrient reduction plans. These promises make large-scale, engineered remediation appear quite attractive to politicians. In this Viewpoint we examine and discuss some of the various options that have been suggested for the Baltic Sea (*13*).

Hypoxia in the Baltic Sea

Climate and anthropogenic pressures have both played a role as drivers of hypoxia over time in the Baltic Sea. Hypoxia was present in the Baltic from its formation ca. 6000−2000 BCE and again during the Medieval Warm Period 750−1200 CE (*5*). Bottom waters of the Gotland Deep became hypoxic ca. 1900 CE as recorded by the deposition of laminated sediments (*16*). Superimposed on this natural variability, anthropogenically induced hypoxia has become more widespread and prevalent in modern times, ca. 1950−present, in both the coastal zone (*17*) and the open waters (pelagic zone) of the Baltic Sea (*6*). Hypoxia not only destroys benthic communities (*18*), but also alters nutrient biogeochemical cycles. The amount of dissolved inorganic phosphate (PO_4^{3-}) released from sediments during hypoxia is approximately 1 order of magnitude greater than the anthropogenic total P loading (*4*). Removal of N through denitrification increases in the Baltic Sea with more hypoxia (*10*). High P and low N are favorable for blooms of N_2-fixing cyanobacteria, increasing the available nutrients leading to more eutrophication and more hypoxia. This internal acceleration of eutrophication in the Baltic has been termed a "vicious circle" (*10*). To combat this feedback cycle, different large-scale engineering methods have been suggested.

Large-Scale Engineering to Increase Oxygen in Bottom Waters

The majority of plans for remediation have focused on reducing the area of hypoxia and thereby reducing internal P loading. The many-suggested large-scale engineering solutions vary from bubbling to large-scale manipulation of the circulation (*13*). To evaluate a selection of the alternatives a number of numerical model experiments of generalized engineering solutions were made using the BALTSEM and RCO-SCOBI models (*19*). The total amount of O_2 needed to keep the deep waters above the threshold for hypoxia varied by 2−6 million t of O_2 annually. This is not a trivial amount of O_2: equal to 19,000−55,000 railroad cars of liquid O_2. Various strategies have been suggested for adding O_2 directly into deep water; however, at present there is no known technology that could transfer such an enormous amount of O_2 directly into bottom waters and disperse it into large hypoxic volumes.

The Baltic Sea is naturally susceptible to hypoxia due to permanent salinity stratification and intermittent inflows of saltwater (*20*). Better O_2 conditions are observed in bottom waters immediately following major inflow events. Therefore, enhanced ventilation of deep waters through additional inputs of oxygenated saltwater has been suggested as a remediation method. In model experiments, an increased exchange through the Danish Straits was achieved by artificially doubling the depth of the Drogden Sill from about 8 to 16 m. However, based on our current understanding of the Baltic Sea (*21*) and from the model results (*19*), enhanced saltwater input into bottom waters is expected to increase stratification and *increase* the area of hypoxia (*3, 4*): Initially oxygenation of bottom waters is achieved with additional saltwater inputs, utilization of O_2 from sediment demand rapidly depletes the new O_2 brought into the system.

The scenario of closing the Drogden Sill to freshen the Baltic was also investigated (*19*). Model results demonstrated that there is a long transitional stagnation period following reduced saltwater inflow during which hypoxia increases in deeper waters. There are improvements in water quality in the long run (>30 years) at the cost of a drastic reduction of salinity. Any engineering solution that increases or decreases the overall salinity will lead to significant and unpredictable alterations of biodiversity, in both pelagic and benthic ecosystems. Changes in salinity may also be illegal under the EU Habitats Directive (*22*) and are most likely politically unacceptable to many of the countries with Baltic coasts. For example, when bridge construction linking Denmark and Sweden was planned, millions of Euros were spent to ensure that no net changes in salinity or deviations in water exchange would occur in the Baltic (*23*).

Stigebrandt and Gustafsson (*24*) suggested that ventilation by pumping intermediate O_2 rich midwater downward could alleviate hypoxia and reduce internal P loading. Enhanced ventilation was modeled by mixing water below the halocline between 50 and 125 m throughout the Baltic Sea and gave improved O_2 concentrations (*19*). Although the models suggest that midwater mixing has the potential to reduce hypoxia, more work is required to determine the technical feasibility and cost, and to evaluate the possible detrimental effects on organisms and environmental processes. One fear is that weakened stratification could negatively affect cod (*Gadus morhua*) recruitment, although that is presently not possible in higher salinity hypoxic water.

Uncertainties Regarding Impact of Oxygenation

Significant gaps remain in our understanding of the effects of large-scale remediation efforts to reoxygenate the Baltic Sea. A first important step is to evaluate the impacts of physical mixing and circulation processes. Whether halocline ventilation (*24*) is implemented or if oxygenated surface waters are piped below the halocline using wave-driven overflow columns (*25*), changes in salt distribution and circulation will occur. More detailed modeling efforts of the impact on physical mixing process and the response of salinity, temperature, and stratification must be made prior to any large-scale manipulation.

While we have a general understanding of nutrient biogeochemical cycles and the effects of hypoxia on those cycles, the effect of remediation efforts on the P, N, and SiO_2 biogeochemical cycles are only superficially understood with many basic questions remaining (*21*). If the Baltic Sea is reoxygenated, enhanced N loss processes in the water column will no longer occur and it is assumed that sediment N loss processes will be restored following oxygenation. However, no precedent for these large-scale changes exists. For P, the size and location of the mobile/bioavailable P fraction and permanent P sinks in Baltic Sea sediments need to be established. Oxygenation can potentially create a large pool of labile Fe−P in the sediments that could be potentially released if the system became hypoxic again—a highly undesirable condition. In addition, experience from fresh waters shows that increased Fe−P burial through artificial oxygenation may not be sufficient to significantly increase P burial. For example, although a number of lakes have been artificially oxygenated for years, changes in P release from sediments have not occurred (*26, 27*).

Chemical Removal of Phosphorus

Models show that P reductions will be necessary to alleviate hypoxia in the Baltic Sea (*28*). Chemical precipitation has been suggested as a method to remove P from the water column and enhance the permanent P burial in Baltic Sea sediments (*29*). Inactivation of P by the addition of Al and other chemical species has been used in lake restoration and sewage treatment plants to chemically bind and precipitate P (*15*). A variety of chemicals have been suggested including alum ($KAl[SO_4]_2 \cdot 12H_2O$), apatite ($Ca_5[PO_4]_3[OH,F,Cl]$), and rock flour from limestone quarries (*29*).

While we can use the successful experience gained in small lakes to remove P from the water column, there are significant gaps in our present knowledge with regard to P precipitation in the brackish waters of the Baltic Sea. Potential problems include reductions in the binding capacity of alum in seawater, toxicity to benthic organisms and fish, and the potential for cosequestration of dissolved silicate. Dissolved silicate is an important limiting nutrient in the Baltic Sea and is currently being sequestered in buried diatoms faster than it is being replenished (*30*), causing potential dissolved silicate limitation of diatom growth. All chemical engineering techniques to precipitate P require preliminary experiments to show that the P losses are permanent and stable under varying redox conditions. As a cautionary note, addition of any chemical will violate the principle of reversibility, i.e., once added a chemical cannot be removed, no matter if the obtained response is desirable or not. Addition of chemicals may also violate the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972 (the "London" Convention) and its amendments (*31*).

Biomanipulation

Biomanipulation is a method to alter the biological communities by altering the abundance of specific organisms, usually with the goal of reducing summertime chlorophyll concentrations (*32*). Biomanipulation generally entails the stocking of predatory fish to enhance the predation of fish feeding on zooplankton (planktivores) or by "fishing out" planktivorous fish (*33*). Although this method has been used frequently in lakes with mixed success (*34*), no large-scale biomanipulation, with the exception of commercial overfishing (*35*), has to our knowledge ever been performed in marine ecosystems. Recently, however, an experiment to reduce phytoplankton by increasing the population density of a predatory fish (pikeperch, *Sander* sp.) through stocking is being conducted in the Himmerfjärden estuary of Sweden (S. Hansson, Stockholm University personal communication).

The Swedish Fisheries Research Board is currently preparing a large-scale biomanipulation project in the Baltic Sea (*13*) with a proposed intensive fishing initiative on sprat (*Sprattus sprattus*). The goal is to reduce the predation pressure on herbivorous zooplankton potentially leading to increased grazing on algae and reduced chlorophyll concentrations with an additional goal to increase the numbers of cod. Although some success has been achieved in freshwaters, the enormous size of the Baltic Sea adds to the uncertainty of the effectiveness of biomanipulation on such a scale. Although fish reduction has been achieved even at large scales, e.g., cod overfishing in Newfoundland (*35*), there is a risk that alteration of the food web opens up a niche allowing species such as the comb jelly, *Mnemiopsis leidyi*, to take over as it did in the Black Sea (*36*). The comb jelly has been recently recorded in significant numbers in the Baltic Sea (*2*).

Conclusions and Recommendations

Virtually all engineering methods proposed to date for the Baltic Sea's pelagic waters seem unrealistic and/or not viable: At best they can only speed up recovery while nutrient reductions begin to have an effect. Although there are gaps in our understanding of hypoxia (*21*), remediation experience from lakes tells us that simply adding O_2 may not in fact help to mitigate eutrophication (*26, 27*). Pilot experiments with other types of manipulations are underway, with further projects planned. However, it is our evaluation that these large-scale attempts at remediation are unlikely to substantially improve the short-term conditions in the Baltic Sea and several pose substantial risk for the environment.

Implementation of pilot experiments must include an environmental impact assessment to gauge potential effects on biota and the (expected) impact on nutrient biogeochemical cycles, run a risk analysis of unintended consequences, and consider energy needs and costs. Additionally, implementation of large-scale remediation in the open waters of the Baltic Sea is not a decision for any one country and must conform to international conventions. From a scientific perspective, important knowledge can be gained from experiments and models that test large-scale experimental approaches on ecosystems (*37*). Engineered remediation on a local area with hypoxia and eutrophication could be instructive.

Any overall solution must include large reductions in the input of nutrients, despite difficulty and cost (*38*). It is our opinion that long-lasting improved water quality can only be achieved by reducing nutrient loads and we should refocus the energy and the will to this end. The recent HELCOM Action Plan (*8*) with agreed-upon country allocations, has renewed efforts to achieve nutrient reductions. To accomplish this accord, a sector analysis covering both the costs and effectiveness of nutrient reductions needs to be carried out to ensure the implementation of adequate reductions. In addition, innovative reduction measures should be tested and implemented to supplement traditional methods for reducing nutrients.

Management of the Baltic Sea through HELCOM has had a long tradition of science-based management (*7*). Science must continue to be an integral part of any remediation effort. Environmental monitoring is an important, but in some cases missing, part of any such effort. Experimental approaches and modeling, both on the land and in the sea, in addition to diverse expert scientific advice, are required for effective solutions and eventual reduction of eutrophication and hypoxia in the Baltic Sea.

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