July, 2012

REFERENCE GROUP EVALUATION OF THE BOX AND PROPPEN PROJECTS AIMED AT OXYGENATION OF BOTTOM WATER AND SEDIMENTS IN THE BALTIC TO IMPROVE PHOSPHORUS RETENTION

Summary of reference group evaluation

The reference group has evaluated the BOX and PROPPEN projects, largely based on final reports delivered in the end of March 2012 after a three years project period (2009-March 2012).

We acknowledge the pioneering work done in BOX and PROPPEN, showing that oxygenation of below-pycnocline water in stagnant (Byfjorden) or semi-stagnant (Lännerstasundet) brackish-water coastal basins is technically feasible with cable-powered pumping of oxygenated water downwards. Increased oxygen content in sediment-near water was accompanied by a reduction in phosphorus mobilization from formerly anoxic sediments.

The time available for the projects was too short to allow for a re-colonization of oxygenated sediments with benthic macro fauna. Thus the effects of benthic fauna uptake and mobilization of toxic compounds in the sediments, as well as effects on phosphorus exchange could not be established *in situ*. Long-term effects on phosphorus mobilization from sediments after oxygenation are thus still unknown. The projects have also not been able to identify more closely the mechanism(s) responsible for reduced phosphorus mobilization under oxic conditions, although laboratory experiments indicate that iron and possibly manganese are important regulators.

The projects had also the task of up scaling from the pilot projects in sheltered inner archipelago bays to the outer archipelago and the open Baltic Proper deep-water basins. Work with dimensioning of a full-scale wind-powered pumping system was not concluded in BOX. Modelling has been performed at various scales, including the full Baltic Proper. This modelling effort, although rather ambitious, is based on many uncertain factors. Modelling indicates that oxygenation of Baltic deep-water basins through large-scale pumping of below halocline water should increase oxygen content over large areas. However, long-term effects from pumping on phosphorus immobilization have not been modelled or investigated experimentally. Large-scale pumping according to BOX and PROPPEN should, under some assumptions, be economically cost-effective, and acceptable by the public. However, calculations are at least partly based on the assumption that the external load of phosphorus and internal phosphorus mobilization from sediments and deep-water are ecologically equivalent. We have the opinion that this is wrong and that external loading is driving internal fertilization. There is thus no substitute for a decrease in external nutrient loading.

The benefits from a permanent oxygenation of stagnant and anoxic/hypoxic basins in the Baltic Sea could potentially be substantial: 1) Decreased algal

blooms due to immobilization of the vast pool of deep-water phosphorus, which in turn would decrease the risk for oxygen deficiency in deep water (due to diminished sedimentation of oxygen-consuming algae), 2) Colonization of presently "dead" sediments with macro fauna, greatly increasing potential food resources for demersal fish, including cod, and 3) Improving spawning conditions for cod. In an idealized case large-scale pumping would flip the Baltic Proper ecosystem into a new state, without enormous blooms of cyanobacteria and oxygen deficiency, and pumping could then be terminated. However, we believe such a scenario is overly optimistic. The Baltic Sea has inherent conditions for stagnation and deep-water anoxia even without an elevated external load of nutrients. If pumping is terminated, large areas may quickly become deoxygenated, releasing phosphorus accumulated during the pumping period.

The projects have in our opinion not treated the potential ecological risks with pumping in an adequate way. The pilot projects were too short and the systems too open to allow for studies of e. g. mobilization of toxic substances, up-transport of nutrients through pumping and ecological effects from changes in salinity and temperature. These are real risks in case pumping should be tested on a larger and more prolonged scale.

It has not been the task of the reference group to weigh pumping against other measures or to recommend a next stage in the eventual development towards full-scale Baltic Sea pumping. Our opinion is that available information even after conclusion of BOX and PROPPEN is insufficient for a decision on full-scale experiments.

Background information

The Baltic Sea has since the 1950-ies shown clear and increasing signs of eutrophication: high N and P concentrations, algal blooms and hypoxia in deep-water. Eutrophication has caused extermination of benthic fauna over large areas, adverse effects on fish populations, especially cod, and loss of aesthetic and recreational value. The external load of nutrients, especially P, has been reduced, but conditions in the Baltic Sea have not improved. Although external loading is still too high, part of the problem is also thought to be the large pool of P in deep-water and sediments, equivalent to several years of external loading. This P pool seems to be regulated by, or at least to vary inversely proportional to oxygen conditions in deep-water. P is binding to the sediments when deep-water is oxygenated, and is mobilized from the sediments under hypoxic or anoxic conditions. Since the flushing of anthropogenic P from the Baltic Sea system through Öresund and the Danish straits is limited, the large internal pool of excess P is thought to delay recovery of the Baltic Sea for several decades, even with a drastic decrease in external loading.

The idea has therefore emerged to try to fix the deep-water P pool to the sediments by ecotechnological measures, e g by artificially improving deep-water oxygen conditions, or by adding substances that would bind P to the sediments. Such methods have been extensively tested in lakes, with varying success, but their effect in and applicability to marine or brackish-water systems have not been evaluated. These ecotechnological measures are not an alternative to reductions in external nutrient loading, which is the cause of the problem; they are complementary actions that could speed up recovery. This is important to bear in mind: a kg of P removed from the water mass through binding to the sediments is not ecologically equivalent to a kg reduction of the external P load. Binding does not remove any phosphorus from the system, but only immobilizes the already existing phosphorus in it for a shorter or longer period depending on the success of the method used. The timescale of phosphorus immobilization in sediments is unknown.

Call for letter of interest 2008-02-15

The Swedish Environmental Protection Agency, FORMAS, Vinnova and Baltic Sea 2020 jointly in 2007 decided to finance "*Pilot experiment to oxygenate bottom layers of the Baltic Sea or to increase the precipitation of phosphorus in order to reduce the leakage of phosphorus from the sediment*" (revised Call for Letter of Interest 2008-02-15). "*The pilot experiment(s) is primarily to be carried out in the laboratory, in mesocosms or in a defined coastal area. Letters of Interest aiming at restoring the retention of coastal areas are also welcome*".

BOX and Proppen proposals

Fourteen Letters of Interest were submitted in March 2008. After a scientific evaluation six were selected to develop full proposals. These six proposals were evaluated by a review panel (Wilhelm Graneli, Thomas Aabling, Johanna Mattila, Matti Perttilä, Ingemar Cato, Sverker Evans, Bertil Håkansson, Cecilia Lindblad, Håkan Westerberg; of these Graneli, Aabling, Mattila and Håkansson, are also members of the Scientific Reference Group responsible for the present evaluation of BOX and PROPPEN) which met November 10, 2008 for a final recommendation to the funding authorities and Baltic Sea 2020 (Erik Bonsdorff was observer at the meeting, representing Baltic Sea 2020). The review panel recommended funding of three proposals, of which BOX (project leader Anders Stigebrandt, Gothenburg University) and PROPPEN (project leader Heikki Pitkänen, SYKE-Finnish Environment Institute) were chosen by the funding consortium. Both BOX and PROPPEN have as main goal to test at a pilot scale (in coastal bays) if pumping of oxygen-rich water to greater depths with hypoxia could prevent long-term leakage of phosphorus from the sediments.

The two projects got funding with 20,2 MSEK (BOX) and 13,3 MSEK (PROPPEN) in December 2008. Formal project end was 31 March 2012 (delivery of final versions of the final reports), although BOX is still running. The project period has thus been approximately 3 years.

For an evaluation of the two projects it is essential to refer to the aims, goals and hypotheses as set out in the original applications, and added tasks, as required by SEPA:

BOX project proposal:

Summary copied from original proposal text

"By a natural event during the 1990'ies the phosphorus content decreased by one third in the Baltic proper! It coincided with a decrease of the deep-water volume, manifested in a lowering of the halocline from 60 to 90 m, which increased the oxygen contents between 70 and 120 m depth. After a few years, the halocline rose, and the oxygen content below 70 m depth decreased. The Baltic proper went back to a state with high phosphorus content and strong summertime blooms of cyanobacteria.

This event demonstrated that it should be possible to counteract hypoxia and kick the Baltic proper into a less eutrophic state using artificial oxygenation of the deep water by enforced mixing, without addition of chemicals with unknown long-term effects. However, it is not known if it would be possible to keep the Baltic proper in the less eutrophic state by continuous supply of oxygen to the deep-water. This will be investigated in the pilot experiment suggested in this application. The main question is *what happens with the long-term retention efficiency of phosphorus in earlier mainly anoxic deep-water sediments when the overlying water is kept permanently oxic*.

We will investigate the efficiency of phosphorus retention under various conditions, with and without artificial oxygenation, in two inshore coastal basins with lower and higher salinities, respectively, than in the upper deep-water of the Baltic proper. Different approaches will be used, from budget calculations of the water – sediment exchange based on monitoring of the state of the basins and water exchange, to measurements with benthic landers and other small-scale hi-tech methods. In addition we will also do laboratory investigations of phosphorus dynamics in bottom sediments from Baltic proper. The efficiency of a prototype of a wind-driven pump will be investigated in both basins and we will also investigate design criteria for a full-scale pumping system in the Baltic proper with respect to efficiency of wind-driven pumps, optimal pumping capacity, the total need of pumping and the geographical distribution of pump capacity."

Additional requirements from SEPA were monitoring of ecological effects of the pilot project pumping, including oxygen conditions, colonization of formerly oxygen deficient basins, potential eutrophication effects, and mobilization of toxic substances. Also a technical, social and ecological risk analysis for the application of the method tested to the open Baltic Sea.

PROPPEN project proposal:

Summary copied from original proposal text

"Bottom sediment release of bioavailable nutrients, especially phosphorus (P), extensively controls eutrophication and cyanobacterial production in the Baltic Sea. Exceeding the threshold, which leads to enhanced sediment phosphorus release ("internal loading"), is dependent on a variety of physical, chemical and microbial processes, in addition to the availability of oxygen. However, in eutrophic sulphate-rich systems the fundamental issue for the ability of the sediment to retain phosphorus is the maintenance of cycling of iron by oxygen and bottom animals. Here we suggest a series of coastal and laboratory scale experiments (artificial pumping oxygenation, chemical additions) and modelling from laboratory to coastal and open sea scales to test whether it would be possible to maintain deep water oxygen reserves and the coupled cycling of iron and phosphorus instead of sulphate reduction detrimental for iron cycling and sediment release of P. The effect of artificial oxygenation is tested by pumping of oxygen rich water into near-bottom depths under well-monitored conditions in semi-enclosed coastal basins with and without iron additions. In laboratory sediment samples are manipulated with various combinations of salinity and oxygen concentrations and additions of montmorillonite clay containing lanthanum, and iron oxides. The results of coastal and laboratory experiments will be extrapolated to larger coastal and open sea areas with the aid of physical/biogeochemical models. The coastal pumping oxygenation experiments will be performed in two seasonally anoxic basins in Sweden and Finland. Quantification of the results regarding both oxygen conditions and benthic phosphorus release is based on frequent monitoring of these areas by both automatic and by conventional sampling and laboratory analyses. Cost efficiency and risk analyses of the different procedures for different coastal and open sea scales will be made by using real costs and results of the coastal experiments, monetary valuation of improved water quality, as well as simulated results from ecosystem modelling**.** The results and conclusions of the study will be published and let to wider audience in high standard peer reviewed scientific journals, as project report publications, as well as in articles published in other professional journals and in widely read newspapers."

The additions concerned monitoring of ecological effects of pumping and a technical, social and ecological risk analysis on the use of the methods at the full Baltic Sea scale.

Comments on the main idea on which the two projects are based

Both BOX and PROPPEN are based on the concept of pumping oxygen-rich water to greater depths, with the aim to oxygenate hypoxic/anoxic deep-waters and the surface of underlying sediments, thereby increasing the capacity of sediments to sequester phosphorus (theoretically through the Fe mechanism). By keeping P in the sediment, surface water P concentrations will eventually decrease and eutrophication symptoms as algal blooms will also decrease.

Oxygenating an anoxic deep-water body to reduce P is, as other restoration techniques, only a treatment of symptoms, if the external loading is not at the same time reduced. Roughly speaking, only three major factors determine the long term P-concentration: The external loading, the flushing rate, and the input of P-binders. Restoration techniques can for a time offset the P-concentration from this equilibrium, but it will always in the long run return to the P-concentration determined by the three factors. If the goal is a permanent change of the P-concentration, then one of the three factors has to be influenced, e.g. reducing the external loading.

P-binding techniques in lakes, such as oxygenation, alum-treatment, or lanthanum-treatment, will for some time reduce the P-concentration by binding a pool of P in the sediment. In contrast to addition of P-binding agents, oxygenation has an inherent risk as the extra P-binding following oxygenation is redox-liable and therefore not permanent, i. e. the bound P will be released once anoxia returns, especially in sulphur-rich environments as sea- or brackish water.

An oxygenation program of the Baltic Sea will sooner or later end due to e.g. technical, financial, environmental or political reasons; and the outlook for the deep waters of the Baltic to naturally sustain an oxic environment is not likely, even if oxygenation has been going on for many years.

The build-up of a large redox-unstable P-pool in the sediment during oxygenation can be seen as a potential phosphorous “bomb”, which may partly or fully be released once anoxia returns. With the prerequisite that the redox-unstable P-pool is fully released from the sediment once anoxia returns after some decades of oxygenation, simple mass balance shows that the P-concentration in a post-oxygenated Baltic Sea will be higher than if oxygenation never had taken place. This is due to the fact that export of P from the Baltic is proportional to the P-concentration, and during oxygenation the Baltic will have a lower P-concentration and thus a lower P-export, while having an unchanged P-import from external loading (unless extern P-loading is reduced during pumping).

On the other hand, according to current aquatic ecosystem theory, if the anthropogenic external load of nutrients is radically reduced in parallel with an elimination of the internal loading (e g through pumping), the system may flip into a new, less productive, stable state, with oxygen in deep waters even without pumping, preventing internal P loading. Thus recovery, which would eventually occur even in the absence of pumping, would be substantially speeded up. However, paleoecological studies show that the Baltic Sea seems to experience hypoxic periods without excess anthropogenic eutrophication. The same studies also demonstrate that the Baltic Sea is sensitive to hypoxia and that past oxygen conditions have been controlled by external forcing (climate and morphological changes). This means that, in the light of global warming, there is a real risk for hypoxia and P mobilization from sediments, even with current cuts in external nutrient loads. It also means that pumping activities, if they increase the salinity and/or temperature in bottom waters, may catalyse further expansion of hypoxia.

Evaluation of project results

Although BOX and PROPPEN had somewhat different approaches, we have tried to draw general conclusions. Thus the two projects are in most cases not evaluated separately.

Experimental design

The BOX and PROPPEN pumping pilot studies can be seen as ecosystem scale scientific experiments. These types of experiments are much more realistic than mesocosm and small-scale laboratory experiments, as they involve the whole system under more appropriate time-scales than for traditional more reductionistic experiments. In freshwater research whole-lake experiments have been extensively used, especially for applied questions (eutrophication, biomanipulation, acidification etc.). However, what is gained in realism is partly lost in control and replication. It is difficult to replicate in this type of experiments, but often it is possible to have an un-manipulated control system and/or extend the studies with a Before, a During (manipulation) and an After monitoring (BACI analysis). Due to inertia in the systems (e. g. colonization, long life cycles of organisms) and large natural climatic variations between years, such studies have to be performed during several years. BOX and PROPPEN have not (probably because of time constraints) applied a BACI or similar approach, which makes evaluations of treatment effects difficult.

BOX and PROPPEN were originally designed (according to proposals) with each 2 coastal bays manipulated, and with monitoring in adjacent un-manipulated control bays. Studies should according to the call be performed in the Baltic Sea. However, BOX chose (according to the approved project plan) to work in Byfjorden on the Swedish west coast, with appreciably higher salinity (around 30 psu in deep-water, in contrast to less than 10 in the Baltic Sea), and for BOX the additional study in the Baltic Proper was never realized. PROPPEN had two locations in the Baltic Sea, one in the Finnish Bay and in one in the Stockholm archipelago. However, due to insufficient pumping capacity in Sandöfjärden, in reality only one location remained for each of the projects (Byfjorden and Lännerstasundet in the Stockholm archipelago).

In addition to the lack of "replication" and a location quite different from the Baltic Sea, the time frame of the projects did not allow for any more extensive before treatment studies, and no after treatment. This was a limitation imposed by the funding agencies, but together with infrequent pumping and varying pumping intensity due to technical problems, the site and time limitations make it difficult to draw firm conclusions from the projects. Certainly the time frame was insufficient to say anything about long-term effects of pumping on sediment phosphorus binding capacity.

Another problem with studies in coastal bays is that they are open systems, especially with respect to surface water. Thus, it would be difficult to establish effects of pumping on surface water nutrients and phytoplankton. And indeed no statistically significant effects were found.

To what extent Byfjorden, with its more marine conditions, is biogeochemically representative of the Baltic Proper is uncertain. According to current understanding of sediment-water P exchange, at higher salinities P should be more easily mobilized from sediments due to high sulphur concentrations and thus immobilization of the potentially P-binding iron as sulphides. Thus, if increased oxygen supply to deep-water and sediments by pumping causes decreased mobilization of P from sediments in Byfjorden, the effect should also be seen in the less saline Baltic Sea with lower S availability. However, whether Byfjorden, or indeed the coastal sites in the Baltic Proper, are representative of the deep basins in the Baltic Proper with respect to availability of iron and other metal oxides, as well as organic matter loading, is unknown.

Technical solutions

The PROPPEN Project used commercially available and reasonably well-tested (mostly in lakes) pumping systems. Still there were some problems with bio-fouling and wind-stress. Such pumps would naturally not be useful in deeper and more open conditions. According to BOX the intention was to test the efficiency of a prototype wind-driven pump and also to investigate design criteria for a full-scale pumping system in the Baltic proper with respect to efficiency of wind-driven pumps, optimal pumping capacity, the total need of pumping and the geographical distribution of pump capacity. The use of a wind-driven pump had, however, to be abandoned, which is a clear drawback of the project, since development, building and use of windmill as energy source was one of the basic ideas of the project and also motivation for funding. As for PROPPEN, electric energy for the pump was furnished through a cable from land.

Effects from pumping on hydrography and nutrients

As has been remarked above there are problems with establishment of effects from pumping in BOX and PROPPEN due to severe time limitation, lack of replication/too few sites, and intermittent and uneven pumping capacity. All this was foreseen before the start of the project and was mostly outside the control of the projects. Nevertheless there has been in both projects an intensive monitoring of hydrographic parameters (currents, salinity, temperature, oxygen, nutrients etc.). These data have been used to analyse effects from pumping on the investigated bays. It should be born in mind that conclusions are mostly of the "Black Box" type, since the mechanism whereby increased oxygen and decreased P are connected has not been properly established. This is of course a major problem with the projects.

Pumping seemed technically to work well, after some initial problems, and in Byfjorden and Lännestasundet effects were seen on oxygen (increase) and P (decrease). In Sandöfjärden the number of pumps was not sufficient to increase oxygen and no effect was seen on P. Budget calculations, in situ landers (with chambers that incubate a small sediment surface and a portion of overlying water for some hours), as well as other small-scale methods show similar results with respect to the magnitude of sediment-water P exchange under oxic and anoxic conditions in Byfjorden. The net mobilization of P from the sediment under anoxic conditions was much higher than indicated by the mineralization rate and the Redfield ratio (relation between C and P in e. g. sedimenting algae), while under oxic conditions much less P left the sediment than should have been the case if P was mineralized and release according to the Redfield ratio. Thus oxygen in sediment overlying water had a clear short-term effect on P exchange.

Some of the decrease in deep-water P was, however, not caused by vertical processes (sediment-water exchange), but by out transport due to exchange of deep-water with less P-rich water. This means that the P will be exported to some other system, potentially causing increased algal production there.

Salinity decreased after pumping in several cases, and this was the cause of increased deep-water exchange. The effects on P and water exchange per se are positive, but a decrease in salinity may be an ecologically unwanted effect of pumping. Since organisms of marine origin in the brackish Baltic Sea live under strong salinity stress, a decrease in salinity is negative. More severe, however, was the increase in deep-water and sediment temperature during and after pumping, especially in Sandöfjärden. An increased deep-water temperature is unwanted, because oxygen consumption increases exponentially with increasing temperature. This may offset some of the potential improvement in deep-water oxygen concentrations and increase the risk for anoxia with P mobilization from the sediments. Also increased sediment and deep-water temperature is negative for several benthic animals, adapted to low temperatures.

Phosphorus removal mechanisms and laboratory experiments
Although in both BOX and PROPPEN (Lännerstasundet) pilot studies with pumping reduced sediment mobilization of P after oxygenation of deep water, the actual mechanism remains unknown. PROPPEN had the intention to falsify the hypothesis that *"artificial oxygenation cannot be targeted to the oxidation of iron (capable to bind phosphorus) in the sediment, but is used by the oxidation of hydrogen sulphides"* and that *"high enough amounts of oxygen cannot penetrate into sediment to oxidize iron and maintain the coupled iron-phosphorus cycling there"*. However, although P release decreased after oxygenation in situ, there were no studies of the Fe-P-S system in sediments and/or the penetration of oxygen (using oxygen microelectrodes or redox measurements) into the sediment after deep-water oxygenation.

There were laboratory experiments performed in the BOX project. The aim in one was to study the effect on P mobilization from a re-colonization of an earlier anoxic sediment with benthic macro fauna. This experiment showed a substantial outflow of dissolved organic P, which raises the question what will happen with the P bound in sediment organic matter in a longer time perspective? After mineralization to inorganic P it will in the first run probably be redistributed to the now oxic surface sediment with a therefore higher chemical P-binding capacity. But what will happen to the former organically bound P if the oxygenation stops? Will this P add to the potential "phosphorous bomb"? Another similar experiment, but with an exotic polychaet, also involved Fe and Mn dynamics. This experiment does indeed indicate that Fe and possibly Mn are important for P binding in Baltic sediments, and that irrigation by tube-dwelling macro fauna can enhance Fe oxidation. However, most of these more mechanistic studies have only been reported in a very preliminary state. Thus it is difficult to draw any conclusions with regard to P-binding mechanisms, effects from macro fauna re-colonization and the long-term P binding capacity of Baltic deep-water sediments.

Experimental results compared to proposals
Although not all of the goals as described in the proposals have been reached, due to technical problems and suboptimal experimental design, still the projects have reached one of the major goals: to show that downward pumping of oxygen-rich water in coastal basins at scales of several km2 is possible and will cause at least short-term immobilization of P. On the other hand P binding mechanisms have not been identified and quantified, and it is still not known what will happen with the sediment-fixed P in a longer time perspective (decades). Neither have experiments with P immobilization using chemicals/clay been studied, as stated in the proposal (PROPPEN). No full-scale pumping equipment has been designed.

Modelling at various scales
Experimental results are based on manipulation of relatively sheltered inner

archipelago basins during limited time. This makes it questionable to scale up to an open Baltic Sea dimension, which is necessary if the goal of reducing internal loading of P from anoxic basins shall be possible. The presently available technology for artificial oxygenation is suitable for lakes and sheltered coastal waters, and not for marine coastal or open-sea conditions.

Modelling may close the knowledge gap by up-scaling the results from the coastal basin scale to the large-scale of the Baltic proper, given that technological, economic and juridical problems can be overcome. From the BOX project no such modelling activities have been reported. Within PROPPEN modelling of the Baltic proper was performed. However, the simulation period of 5 months is much too short to draw any conclusions because the response time scales of the stratification in the deep water and of biogeochemical cycles including the interaction with the sediments are much longer and amount to several decades. Consequently, only small changes in salinity were found.

Further, the experimental results of both projects suggest that as a consequence of reduced stability due to pumping, inflows into the deep water occur more frequently and have a larger potential to ventilate the deep water than the direct impact of oxygenation. The model setup has not considered this finding because only the impact of direct ventilation of the sea bottom was investigated. In the model experiment an unrealistic large pumping rate of water, pumped from 50 m depth down to 5 m above the bottom, was assumed. Though, the model results showed only a relatively small reduction of hypoxic area. In case of only coastal pumping the oxygen conditions in the deep basins did not improve at all. The impact of changing internal phosphorus loads on biogeochemical cycles and feedbacks have not been investigated.

Finally, there was no attempt to estimate the uncertainties of the model results due to unknown process descriptions, e.g. in nutrient fluxes from the sediments

Economic analysis

The projects socio-economic utility may be divided into two parts – user and non-user values. The former one includes consumption, which may be sub-divided into commercial and non-commercial values. The commercial values will increase in those branches dependent on God Environmental Status (GES). For example if no eutrophication is reached this will be beneficial for the fishery branch and for the tourism industry. The non-commercial values are also dependent on GES when the ecosystem can deliver at it most recreational services for the public domain.

The economic beneficial analysis of oxygen pumping, only addresses the increased value of less eutrophication and the willingness to pay for it. Instead it would have been beneficial to take on an integrated approach covering other socio-economic values be it negative or positive, taking into account either descriptive or quantifiable direct user on non-user values.

Within the concept of risk analysis, the calculation of present day WTP seem to be based on rough assumptions, and may thus be miss-leading up to 20%. Further, as no analysis of how the willingness to pay varies between the countries is presented, no real conclusions can be drawn.

Ecologic risk assessment

The conclusion that "the ecological benefits by oxygenation are much larger than the risk" lacks a firm scientific base, although certainly a total elimination of hypoxic bottoms and their colonization with benthic fauna would greatly increase potential fish production if primary production is not reduced. However, one must also bear in mind that eutrophication of the Baltic Sea most likely has increased fish production (not necessarily of cod though) markedly. An oligotrophication of the Baltic Sea through reduced internal P loading in combination with a lower external P loading will thus most likely decrease ecosystem total production. Changes in the vertical distribution of temperature and salinity may not only change the living conditions for pelagic and benthic fauna, but also the water exchange between sub-basins including the Baltic and the North Sea. Such large-scale changes in hydrographic conditions may have negative effects on the marine ecosystem.

Nutrients and phytoplankton

The pumping of oxygen-rich water of lower salinity than bottom-near water can weaken or break the thermocline or halocline, and bring deep water nutrients into the surface layer and cause eutrophication. No such effects were noticed in any of the investigated bays, although some of the decrease in deep-water P was due not to fixation of P in sediments, but to horizontal water exchange. Because the investigated coastal bays are – at least with respect to the surface layer – rather open systems affected by water exchange with adjacent bays and the open sea, any nutrients brought to the surface were likely transported away and diluted. Thus no eutrophication was to be expected. A full-scale pumping is another story, since the Baltic Sea has limited water exchange with the Kattegat, Skagerrak and the North Sea. Thus any upwelled nutrients would tend to stay in the system for a long time.

Neither of the projects conducted a proper ecological risk assessment for their pumping experiments or for the modelled Baltic-wide scenarios. Thus, the ecological effects and risks were not satisfactorily evaluated. This is a clear shortcoming in the output of both projects, since ecological risk assessment was explicitly asked for in the call and specified project requirements from the Swedish EPA during the application phase.

Toxic substances

The transport to the Baltic Sea of many highly toxic substances, e. g. DDT and PCBs, has decreased substantially in the last decades, as has their accumulation in top consumers. However, herring and salmon from the Baltic Sea still contain high concentrations of dioxins. Sediments in the Baltic Sea do not only serve as a source/sink of phosphorous, but also as an important source/sink of these contaminants. There is a risk that re-oxygenation of the vast areas of anoxic sediments and subsequent re-colonisation of a burrowing fauna and associated bioturbation will result in mobilization of accumulated and buried toxins. The majority of the organic toxins do not "flux out" from the sediment surface but are "taken up" by burrowing biota and subsequently incorporated into the food web. There is no discussion of the ecological risk of artificial oxygenation of sediment on contaminant bioavailability in BOX and PROPPEN projects. On the other hand a re-colonization of presently anoxic sediments is what we expect and wish to happen even without ecotechnological means. The efforts to reduce external nutrient loading aims precisely towards the same goal as pumping: i. e. to eliminate anoxia and allow re-colonization of lifeless bottoms. The difference being that pumping is expected to have immediate effects on oxygen and re-colonization (a few years), while such effects are thought to take decades even after a substantial decrease in the excessive external nutrient load.

In the Box project, a control program was run to study changes in leakage of toxins from the seabed in Byfjorden. The conclusion in the final report was that *"No negative effects of oxygenation have been detected".* However, the reason for this may be that the bottom sediment redox conditions never changed due to the existing heavy debt of oxygen, as this is a main factor regulating fluxes of inorganic pollutants from the sediment surface. Thus, if the pumping had continued for a longer time, the fluxes of pollutants may have increased. This is critical, since the sediments in Byfjorden are among the most polluted in Swedish coastal waters, due to industrial activity (e. g. petrochemical) and shipping.

Conclusions made by the projects and reference group comments

The BOX Project concludes that if scaling the project up to the Baltic Proper the ecological benefits from oxygenating are much larger than the risks. Although the goal of artificial oxygenation is the same as the goal with a reduction of external nutrient loading (decreased eutrophication, including less algal blooms, smaller hypoxic areas and more benthic fauna and demersal fish) it seems premature to draw this conclusion based on the rather limited pumping projects (space and time). Neither have long term ecological risks been thoroughly identified or discussed.

The PROPPEN Project concludes that the method (pumping) may be applicable in sheltered coastal areas, particularly where external loading is low or has been reduced. But in the Baltic proper or even on a lager coastal scale more information is needed on physical and ecological factors.

One of the most crucial questions, identified by BOX (see e. g. Fig I:7 in the final BOX report), is *what happens with the long-term retention efficiency of phosphorus in earlier mainly anoxic deep-water sediments when the overlying water is kept permanently oxic*? This question has not been answered in any of the projects. It has of course been impossible to observe such long-term effects after only a few years of intermittent pumping, as was the case for both BOX and PROPPEN. A short-term (weeks, months) reduction in sediment release of P was observed, but we still know nothing about the long-term fate of the (vast?) pool of P that oxygenation might divert to the sediment surface. Will increased bioturbation and mineralization of organic P in the formerly anoxic sediments offset some or the whole P immobilization caused by pumping oxygen-rich water to anoxic/hypoxic bottoms? There is also the question of a potential sudden release of the P pool accumulated in sediments during pumping brought up in the comments by the reference group to the underlying project idea (see above)?

What BOX and PROPPEN have shown is that it is technically feasible to improve below-halocline or below-thermocline oxygen conditions in brackish costal bays of several km2 sizes and with depths of a few tenths of meters. The effect is rather immediate (days/weeks), but not permanent: after terminating pumping the system reverts to its original condition. BOX and PROPPEN have also shown that pumping can affect P in deep-water: if deep-water is oxygenated P release from sediments is greatly reduced and P may actually be removed from the bottom water. These are unique ecosystem-scale experiments and findings in saline/brackish-water coastal ecosystems. What the projects have not managed to clarify is the mechanism(s) causing changes in P mobilization, e. g. the roles of Fe and S, and what are the long-term effects of pumping on P retention. A positive side-effect of pumping seems to be intensified coupled nitrification-denitrification, causing an increase in the permanent removal of fixed, bioavailable N from the system. Negative effects are elevated deep-water and sediment temperatures (at least in coastal pumping), as well as changes in salinity. However, the decrease in deep-water salinity caused by pumping is a cornerstone of the idea behind pumping and is the driver of increased deep-water exchange, transporting oxygen-richer water to stagnant basins.

When it comes to an up scaling of the pumping idea to the open Baltic Sea stagnant deep-water basins, or even an application to larger coastal areas, there are of course many uncertain factors. The projects have to some extent treated the technical and economic aspects, as well as public risk acceptance, and large-scale pumping has been modelled in the projects. It is, however, a substantial jump to extrapolate from the BOX and PROPPEN pilot projects to a full-scale pumping in all or even one of the deep-water basins in the Baltic Proper.

Reference group conclusions

The reference group acknowledges the pioneering scientific experiments conducted in the BOX and PROPPEN projects. Ecotechnological methods for use in the Baltic Sea have been discussed for some years, following the earlier development of similar techniques in lakes. However, the BOX and PROPPEN pilot pumping projects are some of the first worldwide to demonstrate at the ecosystem-scale that oxygen conditions can at least temporarily be improved in coastal basins by pumping downward of oxygen-richer water, and that an increase in oxygen has immediate effects on phosphorus. Unfortunately neither project answers in a trustworthy way the crucial question if pumping can be scaled up to the very much larger dimensions of the Baltic Proper with its stagnant deep-water basins, without causing mobilization of toxic substances or other ecologically negative effects. Even if up-scaling from the pilot experiments should be technically and economically feasible and have the desired large-scale effects on oxygen and phosphorus, the crucial question still remains if this kind of ecotechnology is the solution to eutrophication problems in the Baltic Sea, and if it can be accepted by all the Baltic states. It has not been the task of the reference group to discuss the issue of ecotechnology or not or weighing pumping against intensified efforts to reduce external loads of nutrients. This is partly a political question since the Baltic Sea will improve even without ecotechnology if proper actions against external nutrient loads are taken. However, in the absence of echotechnology the recovery may take many decades. The crucial question here is if ecotechnology, as e. g. pumping, has the ability to speed up the process at acceptable ecological and economic costs and risks. This question is still unanswered.

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Reference group meetings and other activities

The reference group met January 24, 2012, when BOX and PROPPEN presented their preliminary final reports. Reference group members delivered individual reviews of the projects by the middle of May 2012, and met again 25 May to produce a final reference group report.