Estimation of additional load reductions and costs to obtain the BSAP environmental targets in a warmer future climate

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Bo G. Gustafsson[1]

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[1]Baltic Nest Institute, Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden

Contents

1 Introduction

In the HELCOM Baltic Sea Action Plan explicit, but provisional, reductions of nutrient loads to the Baltic Sea was agreed based on calculations indicating how large the reductions need to be for certain environmental goals on eutrophication indicators in the Baltic Sea HELCOM (2007). These quantitative goals, denoted here targets, where limited to Secchi depths for seven separate sub-basins of the Baltic; Bothnian Bay, Bothnian Sea, Baltic proper, Gulf of Finland, Gulf of Riga, Danish Straits and Kattegat. The marine model Sanbalts within the Baltic Nest system(Savchuk and Wulff, 2007) was used to find the maximum allowable loads to reach the Secchi depth targets. At present a process revising the load reductions set in the agreement is on-going, with the aim of a new decision in 2013. For the revision extensive work has been undertaken to improve the scientific basis of the environmental targets and improving the modeling tools. In a preliminary report to HELCOM, the TARGREV project delivered recently a proposed table of new environmental targets (Carstensen et al., 2011), primarily setting Secchi depths but also targets on oxygen in basins with oxygen depletion problems. The Baltsem model are being used to calculate the maximum allowable loads from these targets and finally the necessary reductions to reach maximum allowable loads will be allocated to countries and sub-basins. This work will continue during 2012.

Within the ECOSUPPORT project a series of combined nutrient load and climate change scenarios where explored using a three coupled physical-biogeochemical Baltic Sea models (Meier et al., 2011a, 2012). The results showed that climate change will cause a deterioration of major water quality indicators, such as Secchi depth and oxygen conditions, and that the load reductions given in the BSAP will not be as efficient as anticipated (Meier et al., 2012). Another complicating factor is that probably nutrient loads will increase due to higher runoff in the future climate (Gustafsson et al., 2011) and as the Baltic Sea Action Plan provides maximum allowable loads at the river mouths additional efforts would be necessary at source to maintain the load to the Baltic Sea.

The ECOSUPPORT projects ends before the revised BSAP maximum allowable loads are calculated, but still it would be interesting to get a first indication how much additional reductions that would be necessary in a warmer climate compared to present. There are several options on how to do the calculation, either use the Sanbalts model and compare with the BSAP as it was in 2007 or use Baltsem and compare to what is obtained with the new targets from TARGREV in present and future climate. The problem with the first approach is that it is not straightforward how to implement climate change in the Sanbalts model because it is semi-empirical and does not explicitly calculate the physical response of the Baltic Sea to climate change. The second approach has the problem that the calculation of maximum allowable loads is not fully developed, especially for the Secchi depth targets. An additional complications could be biases due to deficiencies of the forcing from the climate models. A major uncertainty that arise is how the colored organic matter (CDOM) concentrations will change in future climate. That has not explicitly been investigated in ECOSUPPORT and may have a significant influence on the the results, since a large increase in CDOM may prevent any possibility to reach the targets of the BSAP. Given these constrains, we reside to a simpler approach. We make the assumption that a simulation of the Baltic Sea in present climate using the loads of the BSAP provide the definition of good environmental status. Using this we can define some simple constrains or targets that should be obtained also in future climate, so instead of the difficult transparency, phytoplankton biomass can be used. Another climate sensitive indicator would be oxygen concentrations in the deeps of the Baltic proper.

In the companion BONUS+ project RECOCA, new estimates of the costs for management of nutrient loads according to BSAP was presented using the BALTCOST model (Smart et al., 2012). These cost estimates take into account retention in the drainage basin which significantly increase the costs compared to previous modeling. The nutrient reduction measures taken into account were: reductions in fertilizer application, catch crops, reduction in livestock numbers, restoring wetlands and improved wastewater treatment. The results showed that under the limitations of the abatement measures, the model could reach all reductions of the BSAP except for the phosphorus reduction to Baltic proper (74% was reached) and the nitrogen reduction in Danish Straits (88% was reached). The total cost for implementation of BSAP is according to BALTCOST is 4689 million Euro or on average, 21.9 Euro (kg N)$^{-1}$ and 85.4 Euro (kg P)$^{-1}$, respectively. Here, we use these figures to put an extremely uncertain price tag on the climate change impact on the Baltic Sea environment.

The report consists of a Method section, were the model, forcing and the targets are presented, thereafter in the result section, the model estimates of new load reductions and the estimation of the costs are presented. A brief discussion concludes this report.

2 Method

2.1 Baltsem model

The Baltic Sea is divided into 13 sub-basins each with its own hypsographic features (Gustafsson, 2003). Horizontal contractions and/or sills separate the horizontally homogeneous sub-basins and regulate dynamically the water exchange between the sub-basins. The flow dynamics are forced by wind, varying sea levels (Carlsson, 1998) and densities between the seas and controlled by frictional resistance and dynamical flow contraction due to Bernoulli and Coriolis effects (Stigebrandt, 1990; Gustafsson, 2000). The parameterizations of flows between sub-basins and through open boundaries differ due to different dynamic characteristics. The vertical stratification is resolved by a variable number of layers where the layers are created by inflows and kept below a maximum by fusion (Gustafsson, 2000). Vertical mixing is described by a mixed layer model for the Baltic Sea (Stigebrandt, 1985) and a deep water mixing parameterization where the coefficient of vertical diffusion varies with the stratification (Stigebrandt, 1987) and mixing wind (Axell, 1998; Stigebrandt and Aure, 1989). The sea-ice model follows the model of the Arctic sea ice by Björk (1992, 1997), with dynamics adapted to the Baltic Sea (Nohr et al., 2009). Heating/cooling and evaporation at the sea surface is calculated using bulk formulas (Björk, 1997; Gustafsson, 2003). The deepwater inflows are described by a mixing sub-model of dense gravity currents (Stigebrandt, 1987). In the northern Kattegat open boundary conditions are implemented. The biogeochemical model (Savchuk, 2002) describes dynamics of nitrogen, oxygen and phosphorus including the inorganic nutrients nitrate, ammonia and phosphate, and particulate organic matter consisting of phytoplankton (autotrophs), dead organic matter (detritus) and zooplankton (heterotrophs). Autochthonous organic matter is produced from the inorganic nutrients by three functional groups of phytoplankton: diatoms, flagellates and others, and cyanobacteria. Organic material sinks and enters the model sediment as benthic nitrogen and phosphorus. Hydrogen sulfide concentrations are represented by negative oxygen equivalents (1 mol H_2S = 2 mol O_2).

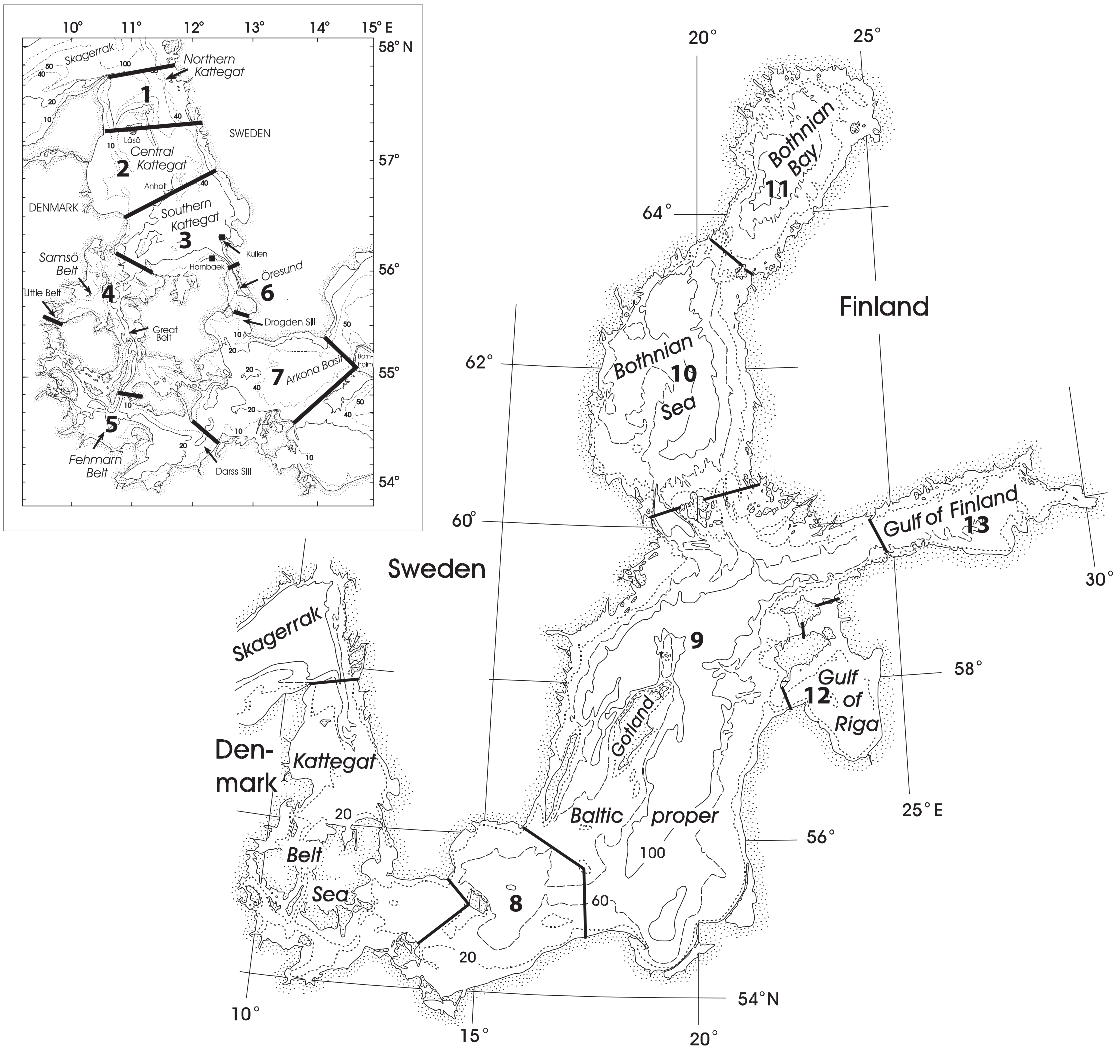

Figure 2.1: Outline of the Baltsem sub-basins.

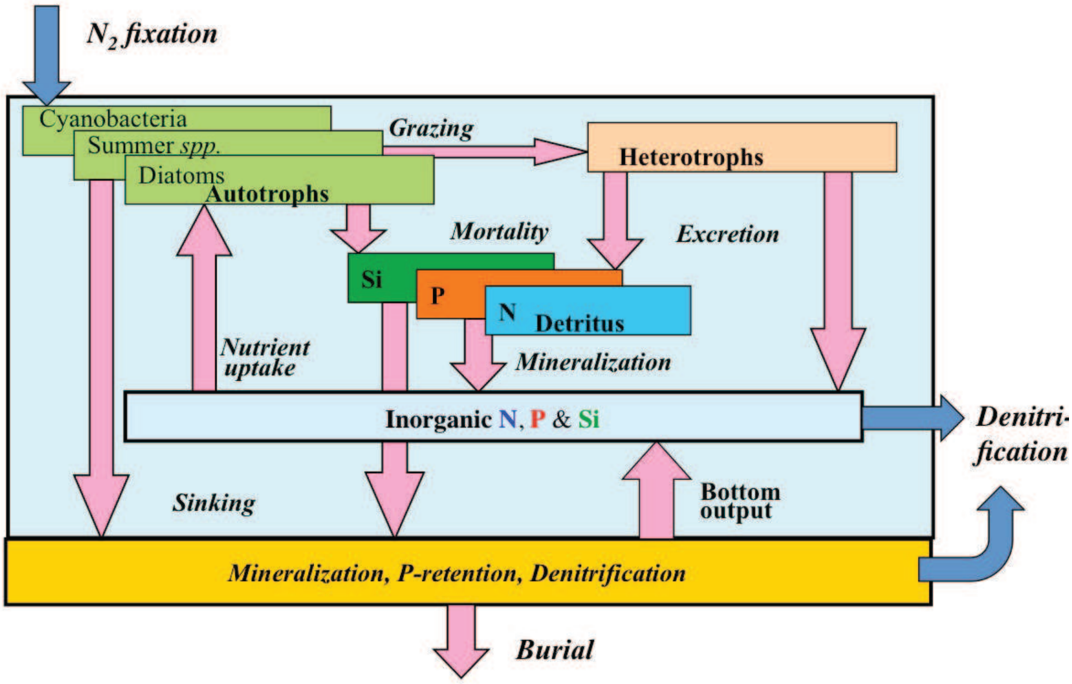

Figure 2.2: Schematic of the processes and state variables of the biogeochemical module in Baltsem.

2.2 Forcing

The standard forcing used to run Baltsem comprise of atmospheric forcing variables (temp, wind, humidity, precipitation, cloudiness and air pressure), daily averaged sea level observations from southern Kattegat and of S, T, O2 and nutrients profiles at the boundary to Skagerrak. In addition also river runoff and nutrient loads are necessary. In order to calculate equilibrium response to load change long-term forcing data sets for different climate regimes are necessary. These are constructed from the transient forcing used in the climate experiments (Meier et al., 2011b,a). There are two main requirements, the new forcing data set need to be spatially consistent for different parts of the Baltic and covariances between variables needs to be maintained. In addition, unrealistic jumps in the sea level time series must be avoided since such would cause unrealistic inflow events to the Baltic proper. A simple method of random selection is used to create new forcing time series. First, the original forcing time series are sliced at each instant of zero sea-level in Kattegat. The time of year is noted for each slice. Then, new long time series of forcing are created by random selection of the slices, with only constrain that the slice should originate from the same time of the year (within a three month interval). The periods 1976-2005 and 2069-2098 are chosen to be representative for present and future climates, respectively. The calculations focus on the emission scenario A1B and the simulation with ECHAM5.

Potential increase in loads due to climate change is not taken into account at this stage. Concentrations of nutrients in Skagerrak is assumed to be constant.

2.3 Basic nutrient loads

Here, we used the loads data set that was used in the model experiments in the TARGREV project (Carstensen et al., 2011), and these are not perfectly identical to the BSAP maximum allowable loads. A reference was established by averaging the standard Baltsem loads for the period 1997 - 2006 (Gustafsson et al., 2012) and from that the reductions given in BSAP was drawn from this reference (see Table 2.1). In the experiments, loads from all land based and for nitrogen also atmospheric sources are changed in proportion to contemporary loads, that is, the refractory loads will take a part of the reduction.

Table 2.1: Land loads plus atmospheric nitrogen loads for the reference (REF) and BSAP (tons yr^{-1})

	REF		BSAP	
Basin	N-load	P-load	N-load	P-load
KT	82376	1570	62376	1570
DS	65279	1269	50280	1269
BP	441519	18560	347519	6060
BS	82065	2434	82065	2434
BB	62386	2613	62386	2613
GR	80602	4054	80602	3304
GF	113354	8008	107354	6008

2.4 Evaluation of targets

Initial conditions for all simulations are created by an initial 100 year run with forcing from the control climate and The model is run in control climate with BSAP loads and the average surface concentrations of nitrate, phosphate and phytoplankon is evaluated. Also the average deep-water oxygen concentration in Baltic proper + Gulf of Finland and Bornholm basin is computed according to

Carstensen et al. (2011). These averages will form our set of targets and the values are summarized in Table 2.2. Targets of individual nutrient concentrations has to be considered with some care since limiting nutrient may change causing an increase in the other nutrient even if biomass and production may decrease. Thus, we make the assessment on plankton biomass and oxygen concentrations primarily, but we will present the resulting nutrient concentrations as a reference.

To give a starting point for the search for a new set of loads, a simulation with BSAP loads in future climate is performed. In Table 2.3, the absolute changes in the indicators compared to targets are given. Plankton concentrations increase in all basins except for Bothnian Bay, and to a lesser degree in Kattegat compared to the other basins. Both nitrate and phosphate decrease in the Kattegat, phosphate only in Gulf of Bothnia. Largest increases in phosphate is in the Baltic proper basins and Gulf of Riga. It is evident that there is a decoupling between the response on average nutrient concentration and biomass, probably due to changes in the stratification and biological process rates. Deep-water oxygen concentration decreased with about 1 g m^{-3}. It seems however, that a good starting point is additional nutrient load reductions in the Baltic proper and Gulf of Riga.

In principle, the calculations should have been done using an objective optimization method to find the least reduction necessary to obtain the targets. However, given the enormous computational task this would imply, with 14 unknown and about 20 minutes of simulation time for each estimated we chose a manual sensitivity approach. In addition, the purpose of this exercise is not to give true management options, but rather to illustrate the consequences of climate change, which also point to that a simpler approach is sufficient.

Table 2.2: Target concentrations obtained by modeling with BSAP loads for present climate.

Basin	NO3 (mg m^{-3})	PO4 (mg m^{-3})	Plankton (mgN m^{-3})	O2 (g m^{-3})
1	19.6	5.9	4.6	
2	17.5	6.0	5.0	
3	16.1	6.2	5.4	
4	14.9	6.3	7.5	
5	12.0	4.9	6.0	
6	13.9	4.5	5.1	
7	10.5	4.2	2.8	
8	12.4	4.7	2.7	6.2
9	15.7	7.4	2.4	2.8
10	20.2	6.3	1.2	
11	85.9	1.8	0.3	
12	28.2	10.0	6.3	
13	34.8	13.0	6.0	

Table 2.3: Change in concentrations running with BSAP loads in future climate. Positive indicate higher value than for present climate.

Basin	NO3 (mg m^{-3})	PO4 (mg m^{-3})	Plankton (mgN m^{-3})	O2 (g m^{-3})
1	-2.62	-0.53	0.33	
2	-1.94	-0.35	0.37	
3	-1.42	-0.24	0.69	
4	-0.45	0.15	1.40	
5	0.12	0.26	0.86	
6	-0.43	0.15	0.56	
7	0.98	0.43	0.75	
8	1.68	0.53	0.76	-0.80
9	2.55	0.62	0.54	-1.00
10	4.25	-0.26	0.41	
11	2.91	-0.08	-0.02	
12	-1.32	2.85	1.02	
13	-1.10	0.34	1.76	

3 Results

3.1 Estimation of necessary additional load reductions

First, the sensitivity to changes in loads to the Baltic proper (Baltsem basins 7-9) are investigated using present BSAP as a starting point. From the results presented in Figure 3.1, it is evident that plankton biomass to reduce with phosphorus load reductions, while there is a small increase with nitrogen reductions. However, oxygen conditions improve for both nitrogen and phosphorus reductions. Already reducing phosphorus loads to the Baltic proper to 6000 tons yr^{-1} as in the BSAP has proven to be a challenge so reducing it to close to zero would be totally unrealistic, so to meet targets on oxygen, additional phosphorus reductions in adjacent basins, or nitrogen reductions are necessary. Thus, we continue to explore reductions in Gulf of Riga and Gulf of Finland in addition to the case where loads to Baltic proper are 3500 tons yr^{-1} and 250000 tons yr^{-1} for phosphorus and nitrogen, respectively, chosen so that targets are approximately met in Baltic proper. In the Gulfs, we focus on phosphorus load reductions since nitrogen reduction proven less efficient in reducing biomass also in these seas (not shown). In Figure 3.2 we see that reducing the phosphorus load to Gulf of Riga to about 2900 tons yr^{-1} and to Gulf of Finland to 4250 tons yr^{-1} would cause the target plankton biomass to be reach in these two basins.

Given the reductions in Baltic proper, Gulf of Finland and Gulf of Riga, targets are met everywhere except in Bothnian Sea, Kattegat (Baltsem basin 3) and Danish Straits (Baltsem basin 4). Thus, additional reductions are needed to these basins. Bothnian Sea biomass is primarily phosphorus limited while plankton biomass in Kattegat and Danish Straits seem to react strongest to nitrogen reductions. The phosphorus loads to the Bothnian Sea, needs to be reduced to 1600 tons yr^{-1} for the plankton biomass to reach the target levels (Figure 3.3). Reducing the nitrogen load to the Danish Straits to 30 000 tons yr^{-1} is enough to lower the biomass to almost what is needed as shown in Figure 3.4.

Through this iterative procedure, we obtained a set of load reductions that would satisfy the BSAP targets in the future climate. In Table 3.1, the necessary additional reductions compared to BSAP is presented. The resulting concentrations for all Baltsem sub-basins together with deviations from the target concentrations are given in Table 3.2. All targets are obtained for plankton and oxygen, but also the target on phosphate is now reached in all basins except Gulf of Riga. Nitrate concentrations has also been reduced although it is still higher than targets in basins 8 - 11.

Table 3.1: Additional load reductions needed to obtain BSAP targets in future climate (tons yr^{-1})

	Additional	reduction
Basin	N-load	P-load
KT	0	0
DS	20280	0
BP	97519	2560
BS	0	834
BB	0	0
GR	0	404
GF	0	1758
sum	117799	5556

3.2 Estimation of the cost of climate change impact on the Baltic Sea ecosystem

The additional measures needed to be taken to maintain the environmental status of the Baltic Sea as it was intended in the BSAP can be divided into two parts. First, additional measures to counteract an increase in loads because of increased runoff and second, to further decrease the loads to the Baltic Sea to counteract a deteriorating water quality because of direct influence of climate change. The average costs from the BALTCOST model are used to get order of magnitude estimate of the total costs of these to parts.

In Gustafsson et al. (2011), the increase in the loads for the ECHAM5-A1B realization 3 scenario of the loads in case of BSAP reductions are about 75 000 tons yr^{-1} and 2900 tons yr^{-1}, for nitrogen and phosphorus, respectively. Using 21.9 Euro (kg N $yr)^{-1}$ and 85.4 Euro (kg P $yr)^{-1}$ and assuming that nitrogen and phosphorus measures have to be taken separately, we get a total cost of about 1.9

Table 3.2: Concentrations obtained with the additional load reductions in future climate.Within parenthesis is the absolute deviation from the target given, negative value being better than target.

Basin	NO3 (mg m^{-3})	PO4 (mg m^{-3})	Plankton (mgN m^{-3})	O2 (g m^{-3})
1	16.5(-3.1)	5.2(-0.7)	4.5(-0.11)	
2	14.8(-2.7)	5.4(-0.6)	4.8(-0.21)	
3	13.6(-2.6)	5.7(-0.5)	5.3(-0.13)	
4	12.2(-2.7)	6.2(-0.1)	7.4(-0.05)	
5	9.8(-2.2)	4.7(-0.2)	5.5(-0.54)	
6	11.4(-2.4)	4.1(-0.4)	4.2(-0.90)	
7	10.2(-0.3)	3.6(-0.6)	2.4(-0.37)	
8	12.9(0.4)	4.1(-0.6)	2.2(-0.48)	6.4(-0.20)
9	17.2(1.5)	6.2(-1.2)	2.0(-0.39)	2.8(-0.03)
10	21.6(1.4)	4.6(-1.7)	1.2(0.00)	
11	90.0(4.1)	1.6(-0.2)	0.3(-0.04)	
12	26.3(-1.9)	10.5(0.5)	6.1(-0.27)	
13	29.4(-5.4)	9.4(-3.6)	5.9(-0.14)	

billion Euro yr^{-1}.

Above it is estimated that additional load reductions compared to the BSAP need to be about 118 000 tons yr^{-1} and 5600 tons yr^{-1} of nitrogen and phosphorus, respectively. Using the average costs from BALTCOST, this would correspond to an additional cost of about 3.1 billion Euro yr^{-1}.

Summing the cost for increased loads due to increased runoff and additional load reductions due to deteriorating conditions in the sea we get a total cost of 5 billion Euro yr^{-1}.

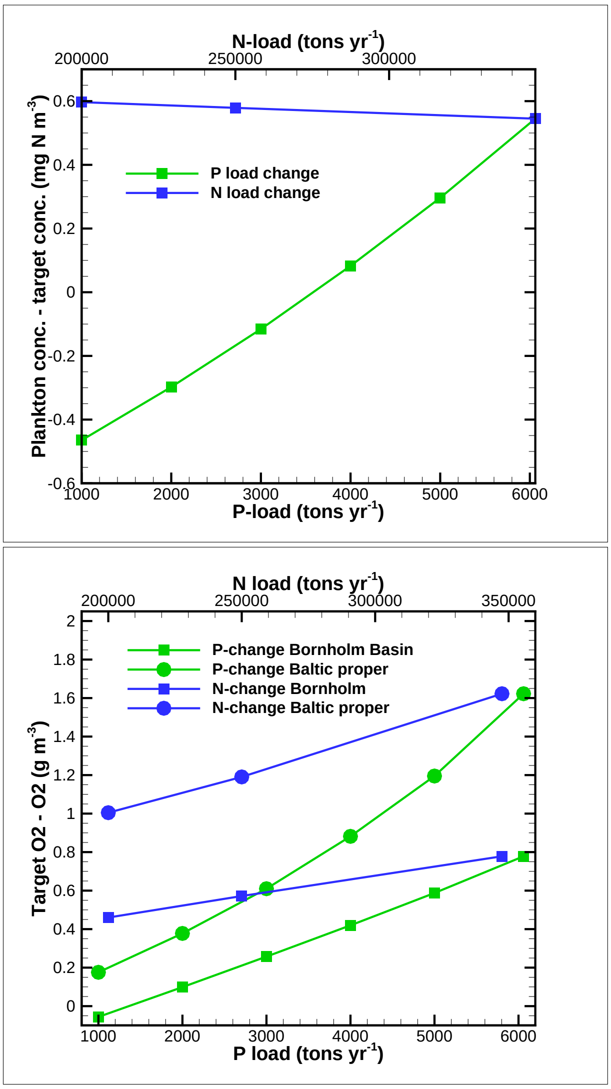

Figure 3.1: Sensitivity of the Baltic proper plankton concentration (top panel) and the oxygen in Baltic proper and Bornholm Basin (bottom panel) to changes in nitrogen (blue curves) and phosphorus (green curves) load changes to Baltic proper.

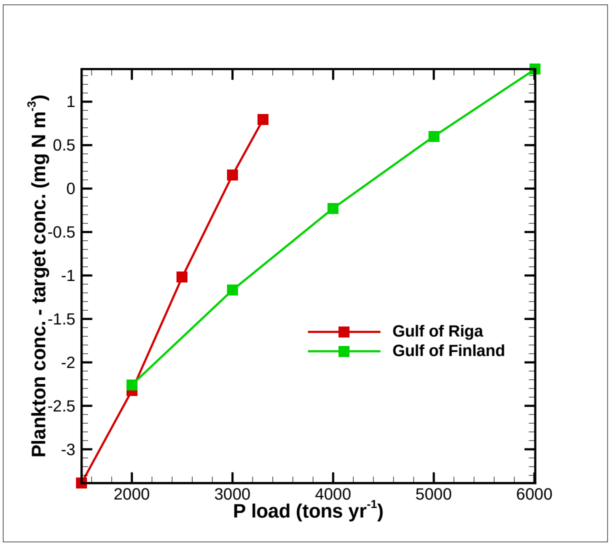

Figure 3.2: Sensitivity of the Gulfs of Riga and Finland plankton concentration to changes in the local phosphorus loads, under the circumstance that loads to Baltic proper are 3500 tons yr^{-1} and 250000 tons yr^{-1} for phosphorus and nitrogen, respectively.

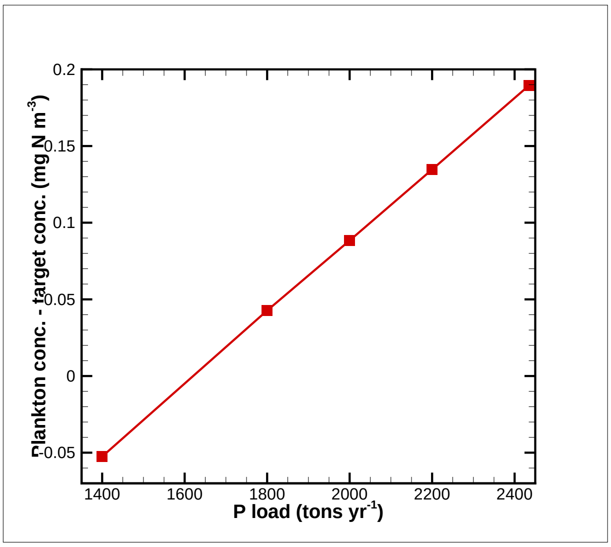

Figure 3.3: Sensitivity of the Bothnian Sea plankton concentration to changes in the local phosphorus loads, under the circumstance that loads are reduced in Baltic proper and the Gulfs of Finland and Riga.

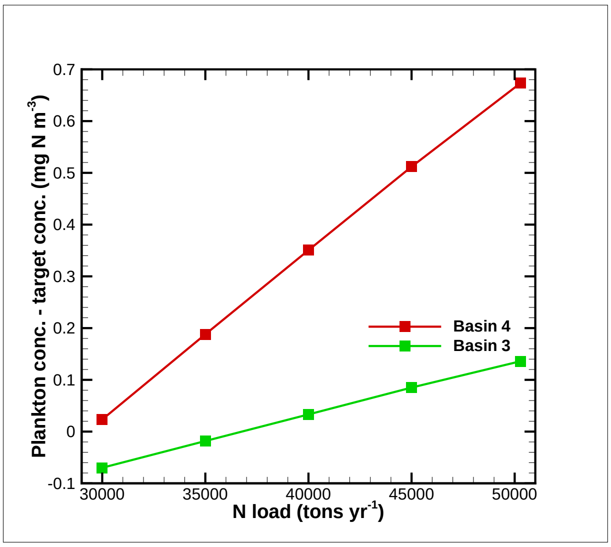

Figure 3.4: Sensitivity of the plankton concentrations in Southern Kattegat (Baltsem basin 3) and Northern Belt Sea (Baltsem basin 4) to changes in the nitrogen loads to the Danish Straits, under the circumstance that loads are reduced in Baltic proper and the Gulfs of Finland and Riga.

4 Discussion

There are many uncertainties associated with climate change scenarios and their representation through the chain from global to regional models, and further to the coupled physical-biogeochemical models as Baltsem which is used here. In addition, climate change as such can cause so large perturbations that the biogeochemical processes may change in unpredictable ways.

In the case of the scenario used here, salinity decrease is substantial throughout the Baltic Sea. In present formulations of phosphorus dynamics, salinity is used as a proxy for the processes that enables strong retention of phosphorus in primarily the Bothnian Bay. When salinity decrease this parameterization cause larger retention of phosphorus. In Baltsem, the effect was so strong that it got profound influence on the results when running the climate scenario forcing into steady-state. Because the actual effects from an increased runoff on phosphorus retention still is unknown, however, most likely it is not only dependent on the supply of iron and humic substances that can form complexes with phosphorus, but also on the redox state of the sediments, we decided to do the present calculations as a worse case with unchanged salinities in the sediment formulations. This should constitute a worse case in that retention would not change with increased runoff.

Additional uncertainty that could in a future analysis be taken into account are running with an ensemble of global climate models and emission scenarios. This was beyond the scope of the present first analysis, but can be pursued with the revised BSAP which is being developed during 2012.

The cost estimate of 5 billion Euro yr^{-1} is extremely uncertain. In one sense it could be considered a lower limit since the work on present BSAP presented in Smart et al. (2012) showed that costs increase drastically with increased reductions and the averaged figures should represent a lower estimate. Also the reductions would probably be extremely difficult to reach as the BALTCOST model did not manage to reduce fully to BSAP loads in its current setting, which is much because of large retention of nutrients in the catchments. A possibility of lower cost could be that we did not take into account that measures affect both N and P loads, which would be possible if a proper application of the BALTCOST model was done.

An educated guess is, however, that the present estimate should be regarded as the lower limit of cost. Despite all uncertainties, it is notable that a conservative estimate of the additional cost of obtaining good environmental status of the Baltic Sea in future climate is indeed larger than that for achieving the load reductions of BSAP.

The additional needed reductions to meet the environmental targets of the BSAP in a future warmer climate was large, in total about 118 000 tons yr^{-1} and 5 600 tons yr^{-1} for nitrogen and phosphorus, respectively. Given that already the undertaken reductions are difficult to meet for several countries and in addition that load reductions may be counteracted by increased water flows, the challenge of obtaining a good environmental status of the Baltic Sea seems tremendous and perhaps unreachable.

The resulting by basin load reductions is not the unique solution to the optimization problem of finding the maximum possible loads to obtain the environmental targets. However, the iterative approach taken here could easily be expanded to investigate more possibilities of load reductions, but the purpose here is not that the load reductions here should be basis for management action, but rather to illustrate consequences of climate change. However, for future research, it is important to develop methodologies that couples what can be obtained by measures on land with needed reductions at sea to find a more true optimal strategy to improve the Baltic Sea.

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