Chapter 19

A Study of Climate Change and Cost Effective Mitigation of the Baltic Sea Eutrophication

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Additional information is available at the end of the chapter

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1. Introduction

Eutrophication of coastal marine waters is globally considered to be a serious environmental problem [1, 2]. The Baltic Sea is the world's largest brackish-sea and damages from eutrophication have been documented since the early 1960s by a large number of different studies [e.g. 3, 4]. In response to eutrophication of the sea the riparian states formed the administrative body HELCOM in charge of policies for improving the Baltic Sea and entered ministerial agreements on nutrient reduction in 1988 and 2007. Although nutrient reductions have been made, the 50 percent reduction agreed upon in 1988 has been far from reached and the ecological status of the sea continues to deteriorate. In order to reach the ecological goal of "clear water", which is one main objective of the 2007 treaty, large reductions of both phosphorous and nitrogen are necessary. The cost of these nutrient reductions can be substantial, not the least since many low cost abatement options have already been implemented. In this respect it is important to evaluate if and how future nutrient loads will change and how this will affect costs for achieving stipulated targets.

Climate change and structural changes in the agricultural sector are considered to be the major drivers of future nutrient loads to the Baltic Sea [5]. Climate change is expected to change the precipitation pattern in the drainage basin. This is expected to lead to an increase in mean annual river-flows in the northen drainage basins of the Sea and a decrease in mean annual river-flows in the southern part of the catchment [6, 7]. Changes in run-off and river flows explain 71-97 percent of the variability in land-sea fluxes of nutrients [6]. Climate change will therefore affect the magnitude of future nutrient loads to the Baltic Sea. The purpose of this paper is to calculate cost-effective solutions to reductions of nutrient loads stipulated by the Baltic Sea Action Plan (BSAP) [6] under different scenarios with respect to impacts of climate change on nutrient loads. Since climate change is not occurring in a vacuum we will also take the effect of agricultural change and demographic changes on future nutrient loads into consideration. This is carried out by means of a numerical dynamic discrete model of control costs for abatement in the riparian countries of the Baltic Sea.

Similar to several other international water bodies, the Baltic Sea contains a number of interlinked and heterogeneous marine basins. The ecosystem conditions in these basins differ, and the BSAP therefore suggests different nutrient load targets for the basins. However, since the basins are coupled, nutrient load reduction to one basin affects all the other basins. This means that both dynamic and spatial distribution of abatement need to be taken into account when identifying cost effective timing and location of nutrient abatement. Starting in mid 1990s there is by now a relatively large economics literature on cost effective or efficient nutrient load reductions to the Baltic Sea e.g. [8-21], but most of these studies calculate cost effective or efficient allocation of abatement among the riparian countries in a static setting [8-10, 12-14, 17, 21].

A majority of the few studies accounting for nutrient dynamics considers only one marine basin, disregards the heterogeneity among marine basins, and/or restrict the number of nutrient related activities [15, 16, 10, 18, 19]. The focus is often on optimal nutrient management in one drainage basin including only agriculture [15, 16] or this sector together with sewage treatment [10, 18, 19]. The only study covering the entire drainage basin of the Baltic Sea, accounting for coupled heterogeneous marine basins with respect to dynamics of both nitrogen and phosphorus, and including several nutrient-emitting sectors is [20]. However, none of the studies applied on eutrophication in the Baltic Sea or in lakes evaluate consequences on optimal cost paths under different climate changes scenarios and future development with respect to demography and agriculture. In [21] they addresses the same question as in this paper i.e. impacts of climate change on cost effective management of eutrophied water, but applies a static approach to a sub drainage basin of the Baltic drainage basin. In order to calculate impacts on total abatements costs and associated allocation among the riparian countries the dynamic model in [20] is developed to account for the different scenarios of future nutrient loads. This paper therefore extends earlier literature on dynamic management of eutrophied seas and lakes by adding scenario analysis of climate change to the spatial and temporal perspectives on cost effective nutrient management.

The paper is organised as follows. First the numerical model underlying the calculations of effective solutions is presented, i.e. the allocation of abatement among drainage basins and during time which minimizes total cost for achieving nutrient load targets within a specific time period. Derivation of the climate change scenarios is carried out in section 3. In section 4 the cost effective achievement of the BSAP under different scenarios is presented and the paper ends with some tentative conclusions.

2. A brief presentation of the numerical model of dynamic and spatial nutrient management

The discrete dynamic model builds on [20], but adds a climate change dimension by alterations in business as usual (BAU) nutrient loads from different future changes in nutrient load; *i)* climate change induced impacts on nutrient leaching from given emission sources in the drainage basins, *ii)* the development of nutrient emissions from agriculture and *iii)* demographic impacts on nutrient loads. A scenario is then defined as a combination of these types of causes for changes in nutrient loads to the Baltic Sea, which are further described in Section 3.

The effect of any climate change scenario is calculated as the impacts of minimum costs for achieving predetermined nutrient concentration targets in the future compared to the reference case. The basis for target setting is the most recent ministerial agreement on nutrient load restrictions to the different marine basins presented in the HELCOM Baltic Sea Action Plan (BSAP) [22, 23], which are shown in Table 1. Since the targets are determined for marine basins and costs of nutrient load reductions are born by the nutrient emitting sectors in the drainage basins of the Baltic Sea four connected but different spatial layers are included in the numerical model; sub-catchments (24), countries (9), marine basins, (7) and the entire catchment (see Figure A1 in the appendix). The dynamic scale is captured by the responses to nutrient loads in each marine basin. A simplification is thus made by disregarding the dynamics of nutrient transports in the drainage sub catchment. The reason is the lack of harmonized data on nutrient dynamics for all sub-catchments and for both nitrogen and phosphorus. Such data is available only for the dynamics in the marine basins [24] and for nutrient transports between marine basins. On the other hand, there exist no quantifications of climate change on nutrient dynamics in the sea but only on nutrient transports from the catchments to the marine basins. It is therefore assumed that the climate change impacts on nutrient loads can be described as a proportional changes in nutrient loads from the emission sources in the reference case, see Appendix A. For given emissions at the sources such as agriculture land, climate change affects leaching and transports of nutrients to the sea which can either increase or decrease loads to the sea.

Based on simple analysis of the model accounting for the four different spatial layers in the Baltic Sea and its catchment it is shown that the net effect of climate change on costs for achieving predetermined nutrient concentration targets in different marine basins are determined by two counteracting factors: change in target stringency through impacts on the BAU loads in the reference scenario and the effects of abatement on nutrient loads (see Appendix A). If we consider only the impacts on the BAU loads proportional increases (decreases) in nutrient loads will increase (decrease) costs for achieving an unchanged nutrient concentration target compared with the reference case. On the other hand, higher nutrient loads also imply larger impact on nutrient loads from given abatement by a measure, which lowers costs of achieving the given targets. The combined net impact of these counteracting factors on the resulting abatement costs can be determined only by numerical analysis, which is carried out in Section 4.

Minimum costs are calculated by means of a dynamic discrete optimisation model including the four spatial layers, the structure of which is presented in Appendix A. Data on nutrient loads from the drainage basins, transports among marine basins, nutrient pools and dynamics in each marine basin are obtained from [20], and constitute the reference scenario. Gren et al. [20] applies an oceanographic model with transport among basins described by coefficient matrixes (Tables A3 and A4 in [20]) for calculating carry over rates of nutrient among periods (Table 1 in [20]), nutrient pools and concentration. The oceanographic model allows for individual description and simulation of different forms of nutrients occurring in the sea: inorganic, labile organic and refractory organic fractions. Inorganic and labile organic fractions are together considered as biologically available fraction that mainly determines eutrophication and is readily affected by human activity, while dynamics of refractory organic compounds driven mainly by natural processes are hardly significant for eutrophication. Nutrient loads, pools and concentrations in the reference case are therefore expressed in terms of bio-available fractions, see Table 1.

	Nutrient load, kton/year[1]		*Nutrient pools, kton*[2]		*Nutrient concentration μM* [3], *reference*		*Nutrient concentration μM* [3], *target,*	
	N	*P*	*N*	*P*	*N*	*P*	*N*	*P*
Bothnian Bay	25	2.5	183	7.4	8.73	0.16	9.93	0.15
Bothnian Sea	36	2.3	457	71.2	6.67	0.47	7.43	0.34
Baltic Proper	333	17.8	1330	435	7.31	1.08	6.28	0.55
Gulf of Finland	73	6.3	143	25.9	9.29	0.76	9.36	0.51
Gulf of Riga	61	2.1	86	12.7	14.51	0.97	22.81	0.64
Danish Straits	59	1.3	34	6.7	8.50	0.75	7.30	0.51
Kattegat	70	1.5	55	8.7	9.14	0.65	8.42	0.57
Total	657	33.8	2288	567				

1. Table B1 in Appendix B; 2. [20] Table 1; 3. [20] Table 5

Table 1. Bio-available nutrient loads/year, pools, and concentrations in the reference and target cases, N=nitrogen, P=phosphorus

The Baltic Proper receives that largest loads of nutrients every year and contains the largest pools of both nutrients. It also faces the relatively most stringent phosphorus reduction target; the concentration needs to be reduced by approximately 50 per cent. This is in contrast with the nitrogen concentration targets, which are more close to or even above those in the reference case. It can also be noticed that one country, Poland, accounts for 38 per cent of total phosphorus loads and for 30 percent of total nitrogen loads, see Table B1 in Appendix B.

Costs of nutrient load abatement are estimated by means of a pseudo data approach (see e.g. [25]). Unlike traditional sources, such data sets are not constrained by historical variations in, for example, factor prices and yields from land affecting land prices. Observations on costs and nutrient reductions are then obtained by using the static optimisation model in [26] for calculating minimum cost solutions for different levels of nutrient reductions to the coastal waters from each drainage basin. The static model in [26] contains a number of different measures for reducing water and airborne nitrogen and phosphorous loads from agriculture, industry and sewage. In total, the static model includes 14 measures affecting nitrogen loads and 12 measures changing phosphorous loads. These measures can be divided into three main categories: reductions in nutrients at the source, reductions in leaching of nutrients into soil and water for given nutrient emission levels, and reductions in discharges into the Baltic Sea for given emissions at sources and leaching into soil and water. Examples of the first class of measures include, among others, reductions in nitrogen fertilizers and reductions in livestock. The second type of measure can be exemplified by cultivation of catch crop or other land use measures such as increased area of grassland. The third type of measure consists of wetlands near the Baltic coast. For a detailed description of method and abatement measures in the static model, we refer to [26]. Based on data obtained from [26] ordinary least square estimator is applied for the estimation of coefficients in a quadratic cost function for nitrogen and phosphorus for each drainage basin, see Table B1 in Appendix B. This approach for deriving cost functions in each time period assumes that cost effective reductions of nitrogen and phosphorus are implemented in each drainage basin.

Finally there is a need for defining the time period when the targets in Table 1 are to be achieved, and to choose the level of the discount rate. Helcom BSAP suggests 2021 to be the deadline for implementation of nutrient load reductions. As was estimated from the "flushing out" scenario in [27], nutrient stocks in the entire sea have a response time scale of about 60-70 years. However, running the "flushing out scenario" in [27] indicate that even after over 130 years the sea did not come to a new nutrient balance with the nutrient loads reduced to "pre-industrial" levels [28]. Therefore, we assume that the nutrient concentration targets are to be achieved at the latest in year 2100 and then sustained for additional 70 years. With respect to the choice of discount rate, it can be noticed that there is no consensus in the large literature on the appropriate level of social discount rate. It is agreed that it is determined by a number of factors such as people's general time preferences, economic growth and utility from consumption. In practice, the long run economic growth rate is usually applied. This differs among the riparian countries, which would suggest different discount rates for the countries. However, this would create arbitrage possibilities of abatement between countries which is not consistent with a cost effective solution. We therefore apply a common discount rate of 0.03 which is in line with long run economic growth in several riparian countries.

3. Description of different climate change scenarios

We focus on climate change impacts and investigate their effects on cost effective solutions in isolation and in combination with future changes in nutrient loads due to development in demography and the agricultural sector. In the following, the derivations of impacts on nutrient loads from different climate change scenarios and changes in population and agriculture are presented.

3.1. Climate change and nutrient outflow

Climate change is expected to impact the hydrological water balance in the Baltic Sea region, leading to changes in river discharge to the sea. The general trend predicts an increase in precipitation and river outflow in the northern part of the drainage basin and a decrease in precipitation and river outflow in the southeast parts of the drainage basin [7].

To the best of our knowledge, there is no study analyzing the impact of climate change on nutrient outflow to all basins of the Baltic Sea, which is needed in this study. Furthermore, most studies calculate the impact of climate change only on nitrogen load to the Baltic Sea. Data from [5, 29] is therefore used to simulate the impact of climate change on nutrient outflow in the dynamic nutrient abatement model. Both [5] and [29] use the same four climate change scenarios, which are described in [7]. All of the four climate change scenarios are produced from a coupled regional atmosphere – Baltic Sea climate model, the so-called Rosby Centre Atmosphere Ocean Model (RCAO). Data from two different global general circulation models, from Hadley Centre, United Kingdom (HadAM3H) and Max Planck Institute for Metrology in Germany (ECHAM4/OPYC3), are used for setting the boundary conditions which drive the regional RCAO-model. Each of these model combinations applies two different CO_2 emission scenarios, high and low emissions, obtained from the Intergovernmental Panel on Climate Change (IPCC). The high emission scenario corresponds to a change in CO_2 equivalent content from the 1990 level of 353 ppm to 1143 ppm in the future. Correspondingly the low emission scenario implies an increase to 822 ppm [30]. This results in four different climate change scenarios with a high or a low future CO_2 level and with boundary conditions from one of two different global general circulation models. The time period for these scenarios stretches over a 30-year period 2071-2100 and is compared to a reference period of 1961-1990. These four climate change scenarios are labeled in the following way: "Climate change scenario 1"=RCAO-H/A2, "Climate change scenario 2"=RCAO-H/B2, "Climate change scenario 3"=RCAO-E/A2, "Climate change scenario 4"=RCAO-E/B2. Where RCAO=Rosby Centre, H=Hadley Centre, E=Max Planck Institute for metrology, A2=high emission scenario, B2=low emission scenario.

In [5] the predicted change in water discharges from [7] is used to model impacts of climate change on nitrogen outflow to five of the Baltic Sea marine basins; Bothnian Sea, Bothnian Bay, Baltic Proper, Gulf of Finland and Gulf of Riga. Corresponding nitrogen loads to the Danish strait and the Kattegat marine basins are obtained from [29]. However, neither [5] nor [29] model the impact of climate change on phosphorous loads to the Baltic Sea. This is made by [31] who shows that for the Finnish catchment Kokemäenjoki, climate change has an equally large impact on both nitrogen and phosphorous loads to the sea. Kokemäenjoki can be considered a representative catchment for the Bothnian Bay and Bothnian Sea basins with regard to climate and other characteristics [32, 7]. It is therefore assumed that the relationship between nitrogen and phosphorous loads due to climate change in Bothnian Bay and Bothnian Sea follow the same pattern as in Kokemäenjoki. In [33] the impacts of climate change on hydrology and nutrients in a Danish lowland river basin is analysed. Their results indicate that climate change reduces phosphorous loads to about 80 percent of the total change in nitrogen loads. It is assumed that this relationship applies also to the Baltic Proper, the Gulf of Finland, the Gulf of Riga, the Danish strait and the Kattegat.

Given these assumptions and the relationship between climate change and nutrient outflow as described in [5] and [29] the changes in nutrient loads under the four different scenarios are as presented in Table 2.

	Climate change-scenario1		**Climate change-scenario 2**		**Climate change-scenario 3**		**Climate change-scenario 4**	
	N	***P***	***N***	***P***	***N***	***P***	***N***	***P***
Bothnian Bay, Bothnian Sea	8	8	9	9	28	28	22	**22**
Baltic Proper	-32	-26	-17	-14	-61	-49	-19	**-15**
Gulf of Finland, Gulf of Riga	21	17	26	21	30	24	38	**30**
Danish Straits, Kattegat	11	9	15	12	33	26	31	**25**

Table 2. Changes in nitrogen, N, and phosphorus, P, loads to different marine basins from different climate models and assumed carbon dioxide emissions, in % from the reference case.

An interesting result in Table 2 is that climate change leads to calculated increases in nutrient outflows to all marine basins but the Baltic Proper. This is noteworthy since the size of the Baltic Proper basin and the stringency of the abatement goals for this basin (see Table 1) makes it important in any cost effective abatement scheme. As will be shown in Section 4 this turns out to have a major influence of climate change effects on cost efficient abatement solution.

3.3. Demographic change

Population growth and shifts towards coastal zones in the Baltic Sea catchment add to the impact from other drivers e.g. climate change [34]. In this respect changes in the costal-zone population have larger impacts on eutrophication since nutrient emission sources located further inland are affected by retention through plant assimilation, sedimentation and in the case of nitrogen denitrification. Demographic change scenarios would therefore ideally be based on demographic projections that take the distance to the sea into consideration. However to the best of our knowledge, projections of population change that make a distinction between the costal-zone and inland areas do not exist for the entire Baltic Sea drainage basin. Data are, however, available that allow for a distinction between rural and urban areas [35]. It is also possible to relate the population density for rural and urban areas respectively as functions of the distance to the Baltic Sea [36]. Using this functional relation the different impacts from demographic movements to the costal-zone and inland areas respectively on nutrient loads can be taken into consideration.

The projected impact on future nutrient loads from demographic change in the riparian countries is based on estimates of the population in 2008 and projections for 2050 for urban and rural areas [35]. Data on population density in rural and urban areas and their distance to the Baltic Sea are obtained from [36]. Under the assumption that the population density distribution as a function of distance to the Baltic Sea stays intact in the demographic projections, we can construct a demographic scenario where the different impact from demographic shifts to the costal-zone and inland areas respectively on nutrient loads to the Baltic Sea can be taken into consideration. The large coastal population of the Baltic Sea drainage basin [37] can thereby be factored into the analysis. In order to translate the demographic projections into changes in nutrient outflow we assume an annual production of 4,38 kg N/PE and 1,095 P/PE and unchanged shares of the population connected to sewage treatment [38]. It is further assumed that nutrient emissions from people living 1-10 km from the coast are not affected by nutrient retention. Emissions further inland is affected by retention according to ([26], Table A1). Table 3 presents the percentage increase/decrease in nitrogen and phosphorous load compared to the business as usual load presented in Table 1.

	Nitrogen	Phosphorous
Bothnian Bay	0.7	6.7
Bothnian Sea	0.9	7.7
Baltic Proper	-1.6	-10
Gulf of Finland	-1.9	-13.6
Gulf of Riga	-1.2	-1.2
Danish Straits	-2.1	0.2
Kattegat	0.7	7.2

Table 3. Changes in nitrogen and phosphorus loads to different marine basins from demographic change, in % from the nutrient loads in Table 1.

For most countries demographic change makes a larger impact on phosphorous loads to the Baltic Sea than on nitrogen loads. This is because sewage discharges, which depend on population size, contribute to approximately 50 percent of the total phosphorus load to the Baltic Sea compared to approximately 12 percent of the total nitrogen load [26]. The largest part of the population increase will take place in urban areas, close to the shore and is therefore not affected by retention. The largest decrease in population on the other hand takes place in rural areas with a larger part of the population living further from the coast and thus affected by retention. This will enhance the effect of demographic increases/decreases on nutrient outflow.

3.4. Future nutrient loads from agriculture

The future nutrient loads from agriculture are projected in [5] and based on assumed increase in consumption of animal protein for the year 2070, which is assumed to increase substantially in [5]. If this increased protein demand is met by domestic increase in animal production it would result in large increases in nutrient outflow to the Baltic Sea [39, 5]. The future increase in protein consumption is estimated in [5] based on the assumption that all countries in the Baltic Sea drainage basin will have protein consumption in 2070 equal to the mean of the EU-15 countries. Under this assumption time series for 1970-2003 is used to estimate protein consumption for the EU-15 countries and this relationship is then extended until 2070 (see [5] for details). Using the estimated increase in protein demand as a proxy for increased animal stock size they estimate consequential increase in nitrogen loads [5]. The impact on phosphorus load to the Baltic Sea due to structural change in the agricultural sector is however not included in [5]. Changes in phosphorous load needed to achieve the increase in total nitrogen load described in [5], have therefore been calculated based on constant proportions of nitrogen and phosphorus in livestock manure reported in ([26], Table B1, B2). This rough estimate of the phosphorous load together with the nitrogen estimations from [5] generates the increases in nitrogen and phosphorous due to increases in the animal production presented in Table 4.

	Nitrogen	**Phosphorus**
Bothnian Bay, Bothnian Sea	21	**22**
Baltic Proper	35	**28**
Gulf of Finland, Gulf of Riga	24	**21**
Danish Straits, Kattegat	51	**20**

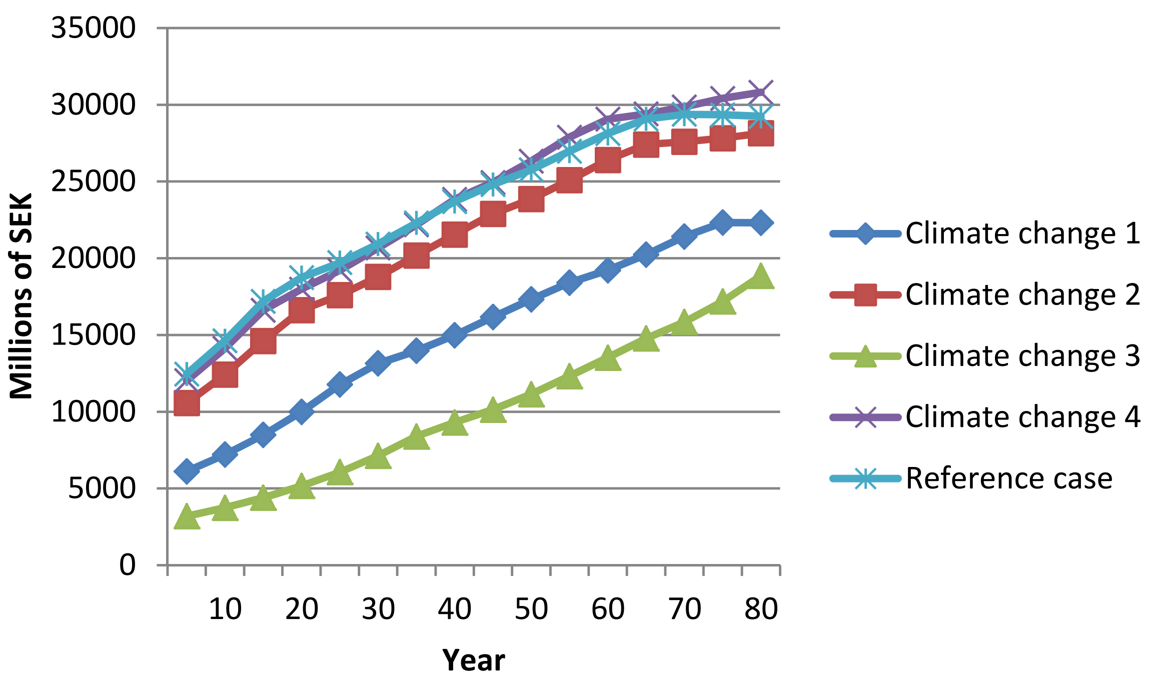
Table 4. Changes in nitrogen and phosphorus loads to different marine basins from increased demand for animal protein in % from the nutrient loads in Table 1.

4. Cost effective achievement of the BSAP under different scenarios

Minimum costs are calculated for the impacts of the four different climate change scenarios presented in Section 3. For each climate change scenario the impact of demographic change and agricultural change occurring at the same time as climate change is also investigated. In Section 4.1 the impact of the four climate change scenarios on the cost effective implementation of the BSAP is presented in isolation. In Section 4.2 other future drivers of eutrophication are included in the form of changes in the demographic structure and structural changes in the agricultural sector in addition to climate change. These scenarios are then compared to the cost effective solution in the reference case (Section 2, Table 1). The GAMS Conopt2 solver is used for solving the problem [40]. In order to obtain tractable solutions, the entire period is divided into 30 periods where each period corresponds to 5 years. For all scenarios it is assumed that the full effect of the impact on future nutrient loads occurs from period one.

4.1. Climate change scenarios

As described in Section 3, climate change leads to increased nutrient outflow for all scenarios and all basins but the Baltic Proper. It might therefore be expected that climate change should lead to increased abatement costs. Inspection of Table 1 shows that the abatement targets are very stringent for phosphorus reductions to the Baltic Proper. This is the reason why total abatement costs decrease for all the climate change scenarios compared to the reference case except for scenario 4, see Figure 1.

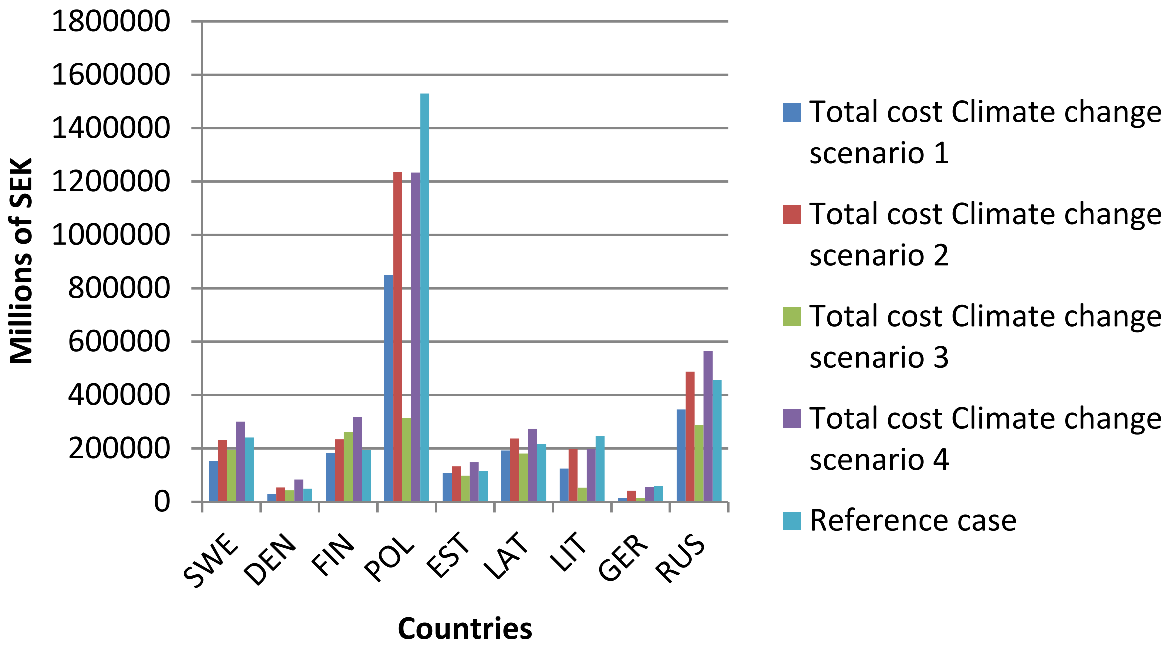


(SEK 1=€ 0,11; 2012-03-07)

Figure 1. Optimal paths of discounted abatement costs under different scenarios, Mill SEK/year.

The highest costs emerge under the fourth scenario with the lowest reductions in phosphorus loads to Baltic Proper and the largest increases in nutrients to the other basins. As expected, abatement is delayed as long as possible due to the discounting of future costs.

The abatement costs are also largest under Scenario 4 for most of the countries, see Figure 2. Climate change scenario 3, which results in the largest decrease in abatement costs, represents high future CO_2 emission scenario, as was shown in chapter three, and climate change scenario 4 represent a low future CO_2 emission scenario. This trend that abatement costs decrease with the severity of climate change is observed for all climate change models used in this paper. The reason is, as discussed in Section 2, that the cost reducing impact obtained by higher impact of abatement exceeds the cost increasing effect due to the need for large nutrient loads.



(SWE Sweden; DEN Denmark; FIN Finland; POL Poland; EST Estonia; LAT Latvia; LIT Lithuania; GER Germany; RUS Russia)

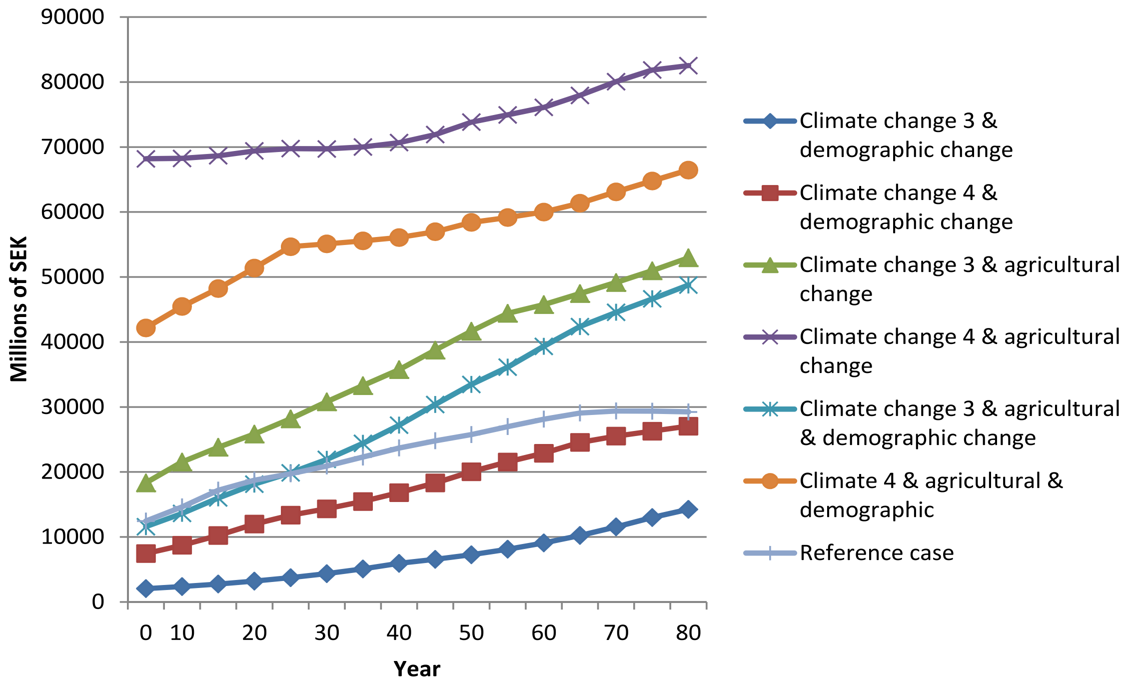
Figure 2. Total cost of abatement per country, under different climate change scenarios. (SEK 1=€ 0,11; 2012-03-07)

Common to all scenarios is the relative large abatement costs for Poland. This is because Poland is the largest polluter of nitrogen and phosphorous loads into the sea basins with the highest stringency in nutrient targets, the Baltic Proper. It is noteworthy that abatement cost for Poland decreases considerably under all climate change scenarios, in particular under climate change scenario 3, where the total abatement costs decrease by approximately 80 percent. Climate change also generates lower abatement costs for Germany and Lithuania but not as much as for Poland.

The impact of climate change on abatement costs creates a more diversified picture for the other riparian countries. For Russia, Latvia, Estonia, Denmark climate change scenario 2 and 4 lead to increases in abatement costs. For Sweden it is only climate change scenario 4 that implies larger abatement costs under a cost efficient implementation of the BSAP. For Finland all climate change scenarios except climate change scenario 1 leads to increases in abatement costs, this follows from the fact that Finland emits into the Bothnian Sea, Bothnian Bay and the Gulf of Finland where the largest increases in nutrient outflow due to climate change occur.

4.2. Combined scenarios

Climate change scenarios are combined with projections of development in the agricultural sector and demographic structure. Since the number of possible combinations is quite large, we focus on the climate change scenarios 3 and 4 which generated the lowest and highest abatement costs. The highest total abatement costs are now generated under climate change scenario 4 in combination with that on nutrient loads from agriculture, and the lowest costs are obtained under climate change scenario 3 in combination with demographic development, see Figure 3.



(SEK 1=€ 0,11; 2012-03-07)

Figure 3. Optimal paths of discounted abatement costs under different scenarios, Mill SEK/year

The inclusion of demographic change in the climate change scenarios results in a further decrease in abatement costs under all scenarios. This follows from the calculated decrease in population of approximately 15 percent for the entire Baltic Sea drainage basin (see Table B2 in the Appendix B). The decrease in total discounted abatement costs compared with the reference case then varies between 18 and 64 percent. The agricultural change scenario implies large increases in both nitrogen and phosphorous fluxes to the Baltic Sea. When agricultural change is simulated at the same time as climate change it results in an increase in total discounted abatement costs ranging between 65 and 200 percent depending on scenario.

Climate change and agricultural change are considered to be the major drivers of the future eutrophication of the Baltic Sea and demographic change will have an impact on future nutrient loads. It can therefore be argued that the most interesting scenario to consider is when all these drivers occur at the same time. When we include both agricultural change and demographic change in the climate change scenarios we observe an increase in abatement costs of 40-150 percent compared to the reference case. The agricultural change simulated here results in a very large increase in nutrient outflow to the Baltic Sea, and it might be argued that an increase of this magnitude is unlikely. It is however interesting that the major drivers work in different directions and that climate change and demographic change could counteract some of the increased abatement costs due to agricultural change.

Inspection of Table B3 in appendix B show that although total abatement cost increases under all climate change scenarios when both demographic change and agricultural change are included in the climate change scenarios, abatement cost decreases for Poland by 30 percent compared to the reference scenario under climate change scenario 3. It is thus possible that climate change could ease the cost burden for Poland, which carries the largest cost burden in all cost effective nutrient abatement schemes. Only Poland and Lithuania experience a decrease in abatement costs under climate change scenario 3, when agricultural change and demographic change are included in the climate change scenario analysis. For all other scenarios and countries abatement costs are larger than the reference scenario when agricultural change and demographic change are simulated at the same time as climate change.

5. Conclusions

The purpose of this paper has been to estimate impacts on costs for achieving the HELCOM targets for the Baltic Sea of different climate change scenarios in isolation and together with nutrient loads caused by future changes in agriculture and demography. Four different climate change scenarios, which are classified with respect to climate change model and projections of future carbon dioxide emissions, are investigated. The results indicate that impacts of climate change may facilitate the implementation of BSAP because of lower abatement costs. This occurs in spite of projected increases in nutrient outflow to the Baltic Sea for all marine basins but the Baltic Proper. The reason for this is the size of the Baltic Proper and the stringency in the abatement goals for this basin, in particular for phosphorus. An interesting feature of the scenario analysis is that abatement costs decrease with the severity of climate change, regardless of which climate change model is being used. These results are in line with the results found by [21] for the Baltic Sea sub-drainage basin Mälaren.

When we include both agricultural and demographic changes in the climate change scenarios we observe an increase in abatement costs corresponding to 40-150 percent compared to the reference case. In this scenario the major drivers of future nutrient loads to the Baltic Sea work in different directions. Climate and demographic changes both lead to lower total abatement costs while agricultural change leads to an increase in abatement costs. The increase in nutrient outflow from agricultural change is thus very large and the underlying assumptions that increased protein demand is met entirely by an increase in domestic animal production should be kept in mind. The magnitude of the increase in nutrient outflow caused by an increase in protein demand will be affected by this assumption and an increase in protein demand will to some extent be met by imported meat. The calculate cost increase from the agricultural change scenario can therefore be somewhat upward biased.

One should note that there are several limitations to the study; consideration has not been taken to the fact that the abatement targets as such might be altered by climate change. Another limitation is that uncertainty is not included in the climate change analysis, despite the fact that climate change most probably will lead to a change in the variability of nutrient loads to the Baltic Sea. An important factor in any future nutrient abatement scheme is development in abatement technology and, over a long time horizon, changes in preferences could also occur. Another limitation is the exclusion of response in the sea to climate change where e g. changes in water temperature and salinity level can affect the ecosystem in a manner that influence eutrophication and/or the environmental goal of clear water. These factors have not been considered in this study due to lack of data, but are important future developments of the analysis when data are available. Finally it is important to keep in mind that the results presented are scenarios and not predictions and should not be treated as such.

Appendix

A: Numerical discrete dynamic model and climate change scenarios

The numerical dynamic model is obtained from [20], with the inclusion of climate change parameters. In the following, we give a brief presentation of the model, and use it for analytical derivation of climate change impacts on optimal nutrient abatement.

Symbol	Explanation
s, $s=1,\ldots,v$	drainage basin
g, $g=1,..,n$	country
i, $i=1,\ldots k$	marine basin
E, $E=N,P$	nutrient loads, nitrogen (N) and phosphorus (P)
t, $t=0,..,T$	time period
I_t^{Eisg}	business as usual (BAU) nutrient load
M_t^{Eisg}	nutrient load
A_t^{Eisg}	nutrient abatement
$\phi^{HEsg}, 0 \le \phi^{HEsg}$	proportional impact on BAU load under scenario H
L_t^{HEi}	nutrient load to a marine basin
$a^{Eji} = \dfrac{L^{Eji}}{L^{Ej}}$	transport coefficient in nutrient load from marine basin j to basin i
S_t^{HEi}	nutrient stock in a marine basin
$\alpha^{iE} \in (0,1]$	share of self cleaning of nutrient stock per period
W^{iE}	nutrient atom weight
K_T^{Ei}	nutrient concentration target in period T
$C^{sg}(A_t^{sg})$	abatement cost functions
$\rho_t = \dfrac{1}{(1+r)^t}$	discount factor with the discount rate r

Table A1. Definitions and explanation of symbols

Discharges from a specific sub-catchment into a marine basin in each time period is written as BAU loads minus abatement according to

$$M_t^{Eisg} = I_t^{Eisg} - f^{Eisg}(A_t^{sig}) \qquad \text{(A1)}$$

Our climate change quantification is assumed to have a multiplicative impact, on the reference loads, M_t^{Eisg}, so that nutrient loads in the scenario H is written as

$$M_t^{HEisg} = \varphi^{HEsg} M_t^{Eisg} \qquad \text{(A2)}$$

The nutrient load to a marine basin is the sum of loads from its catchments and transports from other marine basins

$$L_t^{HEi} = \sum_s \sum_g \; M_t^{HEisg} + \sum_{j \neq i} \; \alpha^{Eji} L_t^{HEj} \qquad \text{(A3)}$$

Stock dynamics of nutrient in a marine basin is

$$S_{t+1}^{HEi} = (1-\alpha^{iE})S_t^{HEi} + L_t^{HEi} \qquad \text{(A4)}$$

$$S_0^{Ei} = S^{Ei}$$

The ecological targets are expressed in terms of nutrient concentrations as these are indicators of different types of ecological conditions e.g. [28]. The marine basin targets to be achieved in period T are then expressed as

$$((1-\alpha^{iE})S_Y^{HEi} + L_t^{HEi})W^{Ei} \leq K_T^{Ei} \qquad \text{for} \quad i = 1,..,k \qquad E = N, P \qquad \text{(A5)}$$

The decision problem is now specified as choosing the allocation of abatement among countries and time periods that minimises total control cost for achieving the targets defined by Eqs. (1)-(5), which is written as

$$\underset{A_t^{ig}}{Min} \qquad \sum_t \sum_s \sum_g \sum_E \; C^{ig}(A_t^{ig})\rho_t \qquad \text{(A6)}$$

s.t. (A1)-(A5)

The first-order conditions are obtained by formulating the Lagrangian which deliver

$$\rho_t \frac{\partial C^{ig}}{\partial A_t^{ig}} = \sum_j \sum_E \; \lambda_T^{jE} W^{jE} \sum_\tau \; (1-\alpha^{jE})^{T-t+1} a^{ijE} \phi^{HEsg} \frac{\partial f^{Eigs}}{\partial A_t^{ig}} \qquad \text{(A7)}$$

where λ_T^{iE} are the *k x 2* maximum number of Lagrange multipliers for the restrictions in *k* different marine basins with respect to two nutrient concentrations From (A1) to (A7) two counteracting impacts of climate change scenarios, i.e. ϕ^{HEsg} , can be identified; the effect on nutrient loads and associated impact on target achievement, and the effect of abatement measures on nutrient loads. The first effect can be seen from (A3) and (A5) where a higher proportional impact of the scenario on the reference nutrient load implies a larger nutrient load and accumulations. The second effect counteracts this cost increasing impact and is obtained from higher marginal effect of abatement on nutrient loads (see eq. A7). A larger impact from given marginal costs of abatement implies lower costs of achieving the targets. Another cost reducing effect is the delay of abatement which is increased since the impacts of later abatement is increased and can replace earlier abatement.

B: Tables and figures

Region	*Nitrogen*[1]: *Kton*	*% of total*	*Phosphorus*[2]: *Kton*	*% of total*	*Coefficients in quadratic cost functions*[3] *N*	*P*
Denmark:		10.0		5		
Kattegat	36		0.8		14.15	**4971**
The Sound	30		0.9		4.71	**2766**
Finland:		6.8		9.5		
Bothnian Bay	16		1.5		8.79	**4347**
Bothnian Sea	18		1.2		8.21	**2290**
Gulf of Finland	11		0.5		7.78	**2993**
Germany:		10.7		1.5		
The Sound	23		0.3		8	**61982**
Baltic Proper	47		0.2		8.04	**65525**
Poland:		30.3		38.4		
Vistula	118		7.26		0.54	**255**
Oder	65		4.45		0.99	**420**
Polish coast	16		1.28		4.75	**1483**
Sweden:		14.2		11.0		
Bothnian Bay	9		0.95		64.93	**10426**
Bothnian Sea	18		1.14		24.99	**2468**
Baltic Proper	26		0.81		6.49	**3230**
The Sound	6		0.1		6.38	**13118**
Kattegat	34		0.72		2.95	**6712**
Estonia:		3.7		3.6		
Baltic Proper	1		0.02		18.77	**20227**
Gulf of Riga	10		0.25		10.03	**9432**
Gulf of Finland	13		0.93		1.33	**2160**
Latvia:		9.0		6.2		
Baltic Proper	8		0.25		22.27	**5522**
Gulf of Riga	51		1.84		4.93	**1635**
Lithuania	42	6.4	2.35	7.0	39.55	**1268**
Russia:		9.0		18.0		
Baltic Proper	10		1.19		43.62	**5846**
Gulf of Finland	49		4.90		4.68	**734**
	657	100	33.8	100		

1.Tables B1 and B3 in [20]; 2. Table B2 in [20]; 3 $TC=a(N^{Bau}-N)^2+b(P^{Bau}-P)^2$ where *TC* is total cost, N^{Bau} and P^{Bau} in the reference case, and *N* and *P* are the optimal loads for achieving nutrient concentration targets [26].

Table B1. BAU nitrogen, N, and phosphorus, P, loads from different drainage basins of the Baltic Sea, kton and in % of total loads in the reference case, estimated coefficients in nutrient abatement cost functions

	Total population 2008, thousand	*Total population 2050, thousand*	*Demographic change, thousand*	*%*
Estonia	1341	1233	-108	-8
Finland	5304	5445	141	2,7
Latvia	2259	1854	-405	-18
Lithuania	3321	2579	-742	-22
Poland	38104	32013	-6091	-16
Russian federation	141394	116097	-25297	-18
Sweden	9205	10571	1366	15
Germany	82264	70504	-11760	-14
Denmark	5458	5551	93	2
Total	287309	244614	-42695	-15

Table B2. Demographic change in countries of the Baltic Sea drainage basin.

	Climate change scenario 3, & agricultural & demographic change	*Climatechange scenario 4, & agricultural & demographic change*	*Reference case*
Sweden	773325	1093329	241085
Denmark	369721	467326	48896
Finland	671922	901168	194423
Poland	1058937	2257641	1529647
Estland	183267	243281	114808
Latvia	353262	644229	216339
Lithuania	142966	439524	245249
Germany	144004	471943	59343
Russia	626599	1460392	456101
Total abatement cost	4324003	7978833	3105891

Table B3. Total abatement cost per country for climate change scenario 3 and 4, when demographic change and agricultural change is simulated at the same time. Millions of SEK.

Figure B1. Drainage basins of the Baltic Sea (originally from [41]). (Drainage basins in Denmark (2). Germany (2). Latvia (2). and Estonia (3) are not provided with names. but are delineated only by fine lines)

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