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Abstract

This paper develops and applies a spatially explicit bioeconomic model to study trans-boundary nutrient pollution of the Baltic Sea. We combine catchment, marine and economic models covering the entire Baltic Sea region to weigh the costs of nutrient abatement and the benefits of improved water quality and solve for the socially optimal level of water protection. The overall benefits of the Baltic Sea Action Plan, the present convention on nutrient abatement, clearly outweigh the costs. Nevertheless, the total cost could be almost halved if the mix of measures and the regional targets were planned in a spatially cost-effective manner and if the consequent reductions of nitrogen and phosphorus, the two nutrients causing eutrophication, were better balanced. Policy optimizations, however, suggest that the socially optimal level of nutrient abatement is somewhat lower than the more ambitious level envisaged by the convention. The welfare gains from cost sharing that makes the socially optimal level of nutrient abatement worthwhile for all littoral countries would be 100 million euros annually.

Key words: *cost-effectiveness, environmental valuation, eutrophication, integrated assessment modelling, nitrogen, optimization, phosphorus*

1 Introduction

Marine ecosystems throughout the world are in poor condition due to anthropogenic pressures and insufficient protection efforts. Altered ecosystem functioning jeopardizes the provision of ecosystem services necessary for human well-being (Batabyal et al 2003). The Baltic Sea stands as an alarming example of poor management that has led to severe pollution. The sea is susceptible to eutrophication due to its low mean depth, limited water exchange with other seas, and large catchment area, which sustains a population of 85 million people in Russia and eight littoral EU countries (Figure 1). Despite the continuing attempts of the Helsinki Commission, an inter-governmental body in the Baltic Sea region, progress in combating eutrophication has been slow and meagre.[1] Notwithstanding, the latest convention to that end, the Baltic Sea Action Plan (BSAP), aims to reach a good environmental status of the sea by 2021 by assigning country-specific targets for reducing nutrient loads (HELCOM 2007).

Due to the immense political challenges in protecting international common-property resources, knowledge of the economic impacts of protection is a prerequisite for successful implementation of any international agreement. In such contexts, economists have increasingly applied cost–benefit analysis to address pressing environmental problems, one example being global climate change (Nordhaus 1993, Tol 2001, Stern 2007). A major difficulty in such analyses is predicting the societal consequences of human intervention: long-term impacts of measures on the state of the natural system and, ultimately, the value of changes in the provision of ecosystem services that contribute to human welfare. Integrated assessment models of climate change fulfil these tasks by explicitly linking descriptions of natural and societal systems (see, e.g., Weyant et al 1996 for a review). Common to protection efforts targeting atmospheric and marine environments are interaction between human and natural systems, long delays in the impacts of measures and trans-boundary pollution.

Aquatic ecosystem services have typically been studied using what is known as the shallow lake model, with a focus on non-convexities, ecological thresholds and irreversible changes (e.g. Mäler et al 2003, Kiseleva and Wagener 2010, Chen et al 2012) or by integrating metapopulation models to investigate the management of aquatic resources (e.g. Sanchirico and

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[1] Since the first Helsinki Convention in 1974, the littoral countries have agreed to reduce their loads of phosphorus and nitrogen, the main nutrients contributing to plant growth in aquatic ecosystems. The target of reducing both loads by 50 per cent, defined in the Ministerial Declarations of 1988 and 1990, was never met and was replaced by the revised set of targets in the Baltic Sea Action Plan in 2007.

Wilen 2005). A few studies have made use of empirically estimated models and applications to evaluate environmental policies. Massey et al (2006) developed a bioeconomic model of a coastal recreational fishery to evaluate water quality changes in Maryland's coastal bays. Smith et al (2009) applied a spatially explicit metapopulation model for a reef-fish fishery in the Gulf of Mexico. In the Baltic Sea, the costs of nutrient abatement are based on static cost-and-effect models (Gren et al 1997a, 2008, Elofsson 2003, 2010) or dynamic sub-basin models (e.g. Laukkanen and Huhtala 2008, Ahlvik and Pavlova 2013); the benefits have been calculated based on studies done in the mid-1990s (Gren et al 1997b, Turner et al 1999), after which some Baltic Sea countries, as well as the marine environment itself, have undergone substantial changes.

We expand on previous studies examining the costs and benefits of nutrient abatement and develop a spatial and dynamic integrated modelling framework for the entire Baltic Sea that is based on a consistent set of ecological and economic data. Of course, integrated assessment models can be - and are - criticized for poor linking of ecological feedback loops and economic modeling (see, e.g., Pindyck (2013) in the context of climate policy). Our specific contribution is to establish two key physical feedback mechanisms in the marine and economic models. The first translates decreases in nutrient loads into decreases in nutrient concentrations in the sea. The second translates decreases in nutrient concentrations into economic impacts. The anticipated ecological improvements, that is, the effects of reduced eutrophication, allowed us to describe alternative scenarios for the state of the Baltic Sea and, finally, to carry out a valuation study eliciting people's preferences. The express purpose of describing the causal chain of these feedback mechanisms was to produce spatially explicit benefit functions applicable in cost-benefit analysis and optimization (cf. Turner et al 2010). Integration of state-of-the-art biogeochemical marine models in economic analysis provides a direct link between nutrient load reductions and their societal consequences and is necessary to project the development of water quality in different parts of the Baltic Sea. To the best of our knowledge, our study is a pioneering attempt to conduct policy optimization using an integrated assessment model that covers an entire sea and its catchment area.

Our contribution to the literature is a science-based cost-benefit analysis to evaluate and identify practicable solutions to a trans-boundary environmental problem (e.g. Stern 2007). A relevant concern is whether a cost-benefit analysis on such a large scale is possible. One of our major findings – based on ecological-economic modelling – is that if the protection measures are designed in a socially optimal manner, the costs of the measures amount to a mere 0.04 per cent of the total GDP in the nine littoral states. This is such a small proportion that no meaningful economy-wide effects on prices or behavioural responses can be detected in any general-equilibrium model. Our results underscore the importance of political negotiations on the spatial and regional allocation of abatement measures and burden sharing. With this in mind, we assess the economic efficiency of implementing the latest water protection convention, the Baltic Sea Action Plan (BSAP), in comparison to a socially optimal level of nutrient abatement for the sea. Moreover, we take into account the potential political constraints on trans-boundary collaboration, and derive a Pareto-efficient solution in which the net benefits of water protection are non-negative for each country. Our results and modelling framework also serve a pragmatic goal in that the littoral EU countries can use them when designing and assessing the economic impacts of their environmental policies with a view to the requirements of the Marine Strategy Framework Directive.

The next section presents the biogeochemical models and the data and methods used for deriving the cost and benefit functions of nutrient abatement. The results are provided in Section 3 and discussed in Section 4. Section 5 presents the conclusions to be drawn.

2 Integrated modelling framework for weighing the costs and benefits of nutrient abatement

2.1 Ecological-economic framework

A spatially explicit ecological-economic modelling framework was developed to evaluate the costs and benefits of nutrient abatement in the Baltic Sea. The marine area covers seven sub-basins, and its catchment area is divided into 23 sub-catchments comprising land areas within a single country and draining to a single sub-basin (Figure 1). A reduction of nutrients and the costs of abatement measures would mainly affect agriculture and water treatment, which account for an average of some 2.5 per cent of GDP in the countries involved. In light of this fact, we consider it plausible to assume that nutrient abatement measures in the nine Baltic Sea countries would not affect the world market prices in agriculture or induce major changes in other sectors either. Hence, our modelling results emphasize the political aspects of solving what is an international common-property problem with moderate economic burden sharing.

Figure 2 depicts the ecological-economic modelling framework in a nutshell. The black boxes represent the model components needed in policy optimizations, that is, an iterative search for the socially optimal level and combination of nutrient abatement activities. The catchment model is first used to describe the effects of various nutrient abatement measures on future loads. When these have been determined, a cost function is employed to draw the respective cost projection, with a marine model then applied to predict the impacts of nutrient loads on the state of the sea. Finally, a benefit function translates the developments in the marine environment into a monetary estimate of improvements in human welfare. The white boxes in Figure 2 represent the model components (biogeochemical models and survey data on citizens' willingness to pay for improvements in water quality) that were needed to derive the benefit functions. In the following, we explain the role of each model component, element by element, in our analysis and the underlying assumptions.[2]

2.2 Catchment model and cost function

The catchment model projects at yearly time steps the riverine nitrogen, N, and phosphorus, P, loads to the sea from the 23 sub-catchments of the Baltic Sea (see Figure 1). The loads are projected over a period of 40 years, after which they are assumed to remain constant. The initial loads are based on the most recent statistics available (HELCOM 2011, Kondratev 2011).

The catchment model is first used to project the baseline development of nutrient loads in light of the expected developments in agriculture and municipal wastewater treatment[3], the two main sources of nutrients to the sea. Then, alternative policy projections involving different combinations of nutrient abatement measures are produced for comparison. Deterministic projections enable numerical cost minimization and optimization[4].

The cost function specifies the costs and effects of ten nutrient abatement measures on N and P loads for each of the 23 sub-catchments (see Figure 3 for a description of the cost model and Table 1b for marginal costs and ranges of application). Some of the measures, such as reducing the application of inorganic fertilizers and decreasing the number of production animals, reduce

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[2] We focus on the model components that are critical for the purpose of the cost-benefits analysis carried out here. More details on the catchment model, cost function and the marine model can be found in Ahlvik et al (2013) and on the survey eliciting citizens' willingness to pay for reduced eutrophication in Ahtiainen et al (2013).

[3] According to the baseline scenario, nutrient loads will decrease slightly during the next 40 years (0.5% and 2.5% of N and P loads, respectively) if the present infrastructure is maintained and no new investments in water protection are made.

[4] The analysis can also be extended to probabilistic load projections, including seasonal weather-driven variations in the load. However, yearly variations tend to cancel each other out, making them relatively unimportant over a time horizon of several decades.

the loads at their source, before they enter the soil. Other measures, such as creating wetlands, building sedimentation ponds and increasing cultivation of catch crops, improve the nutrient retention capacity of agricultural soils and inland waters. Improvements in wastewater treatment increase the capacity of the existing plants and bring additional households within the sphere of municipal waste management. Increased use of phosphate-free detergents – not as yet required by law in all the littoral countries – reduces P emissions to the sewage system and, consequently, into water bodies.

The costs of agricultural measures such as reductions in fertilizer or manure inputs reflect foregone farm profits due to deviation from the present level of application. Improvements in wastewater treatment and the creation of additional wetlands include both initial investment and maintenance costs. The cost of phosphate-free detergent reflects the increased purchase price to consumers. Retention of nutrients in rivers and other inland water bodies was modelled as a spatially explicit, but time-independent constant coefficient.

A novel feature of our model in comparison to earlier cost models on nutrient abatement is that it introduces soil P as a state variable. This enhancement enables us to account for the long delays and gradual reductions in riverine loads in response to reduced fertilization and manure application. The measures selected for optimization are amongst those with the most promise, but it must be noted that many of the focal countries and regions have a number of other measures available, and the palette of potential measures is specific to each sub-catchment. The number of measures was constrained to ten here to keep the non-linear optimization problem solvable.

2.3 Marine model

A marine basin model was used to predict the future developments of water quality in the Baltic Sea for alternative nutrient load projections. The model describes the exchange of water and the nutrients between the seven basins and the North Sea at a yearly time interval and produces an estimate of the average, basin-specific nutrient concentrations during the winter period. It also translates concentrations of N and P into estimates of annual phytoplankton biomass, that is, the most conspicuous manifestation of eutrophication, which, in excessive amounts, diminishes recreational opportunities and degrades the overall health of the marine ecosystem. Phytoplankton biomass is divided into two groups: cyanobacteria, or blue-green algae, which typically bloom during late summer and produce toxins harmful to humans and animals; and other algae, which bloom abundantly during the spring. Figure 4 shows a demonstration of the impacts of the baseline nutrient load projection and the consequences of two policy scenarios on the phytoplankton biomass in one Baltic Sea basin.

2.4 Benefit function

Spatially explicit functions were developed to estimate, in monetary terms, the overall benefits that the citizens living in the Baltic Sea countries would realize from improvements in water quality. For this purpose, a contingent valuation study was conducted comprising identical surveys in all littoral countries. The study was designed as a collaborative international effort during the period 2010-2011, and implemented in all nine Baltic Sea countries between October and December 2011. Identical questionnaires, translated into the national languages, were used to collect the data. Significant effort was devoted to ensuring that the questionnaire was equally relevant and accurate in all nine countries, both in describing the effects of eutrophication and in providing information on the valuation scenario. In the design and implementation of the survey, we adhered closely to the tailored design method (Dillman et al 2009). Pre-testing included expert reviews, cognitive interviews and focus group discussions, with these followed by a pilot survey in all the countries. In collection of the data, Internet panels were used in Denmark, Estonia, Finland, Germany and Sweden, and face-to-face interviews in Latvia, Lithuania and Russia; in Poland, both face-to-face interviews and an Internet panel were employed. The final data set comprised geographically representative national samples totalling 10 564 respondents.

The surveys elicited citizens' willingness to pay (WTP) for improvements in water quality based on visual representations of three scenarios describing the state of the sea in 2050 (See Figure 5a): a baseline scenario assuming that the present infrastructure in agriculture and wastewater treatment is maintained and that no new investments in nutrient abatement are made; 50 per cent (half) fulfilment of the original reduction targets of the Baltic Sea Action Plan (HBSAP scenario); and complete fulfilment of the plan (BSAP scenario). The payment vehicle specified was a special Baltic Sea environmental tax that would be collected from each individual and business in all the Baltic Sea countries and earmarked for reducing eutrophication. As previous results indicated that earmarked payments were, in general, preferred by the citizens of the nine countries in funding actions concerning the sea, the tax was deemed credible. Prior to the valuation question, respondents were reminded that the payment would be yearly and permanent, that the programme would not ameliorate other environmental problems in the Baltic Sea, and that substitute water bodies could exist (see e.g. Bateman et al 2002).

The results of the contingent valuation study were carefully analysed, with WTP responses also estimated by alternative econometric models such as spike and interval regression, as well as numerous model specifications. Table 2 shows OLS regression results for a model with explanatory variables including individual mean monthly net income in the focal country, the respondent's age and gender, a binary variable describing his/her level of education, and variables describing the approximate distance between his/her place of residence and the Baltic Sea. The results show that WTP responses by country are related to the explanatory variables in an economically meaningful way. In particular, income level and distance to the sea figure substantially in the WTP in most of the countries.[5]

The water quality maps used in the survey provided a link between the nutrient abatement measures and the corresponding response in the ecological status of the sea, a feature which is crucial for the cost-benefit analysis. The maps were based on marine basin model outcomes generating the developments of nutrient loads for the three scenarios. In addition, spatially and temporally even more detailed 3D biogeochemical models were used to study the spatial and intra-annual variations of algae blooms and other descriptors of the state of the marine health.[6] Figure 5b displays the outcome of the 3D model for the distribution of phytoplankton biomass in the northern Baltic Sea during the summer months. As a next step, the 3D biogeochemical model outcomes were translated into a single descriptor, the ecological quality ratio (EQR), which represents the overall state of the marine ecosystem with regard to a reference condition, or a desired state of the sea (cf. Andersen et al 2011). The results of the assessment were discretized into a five-step eutrophication ladder. Each of these levels was described in terms of its association with five separate ecosystem characteristics: water clarity, blue-green algal blooms, underwater meadows, fish species, and oxygen conditions in deep sea bottoms. The results indicate that a good status (green and blue colours) would be reached within the next 40 years in all sub-basins except for the northern parts of the Baltic Proper (Figure 5a panel on the right side).

To derive spatially explicit benefit functions for the cost-benefit analysis from the survey data (cf. Luenberger 1992), we asked respondents in a debriefing question whether they were thinking about the whole Baltic Sea or merely certain sub-basins when they expressed their WTP. On this basis, we could classify the respondents in each country $i = 1, \dots, 9$ into $n_i = 1, \dots, nmax_i$ groups based on the combinations of the sea sub-basins they had considered when

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[5] For complete documentation of the study, see Ahtiainen et al (2013).

[6] Two biogeochemical marine models with high temporal and spatial resolution were used: EIA-SYKE (Kiirikki et al 2006) and ERGOM (Maar et al 2011).

giving their WTP responses. We computed the mean WTP and aggregated the benefit estimates for each country and group for partial (half) and complete implementation of the BSAP. The corresponding improvements in the eutrophication status of sea sub-basin were expressed in terms of annualized reductions of algae and cyanobacterial biomasses. These annualized reductions were obtained by discounting the differences in annual biomasses between the policy and baseline projections to the present and multiplying the sum by the interest rate (see Figure 4 for a demonstration of alternative developments of algal biomasses). The observations of annualized biomasses and WTP for three scenarios (baseline, half and complete implementation of BSAP) were then used to derive the spatially explicit benefit functions:

$$B_{in_i} = \sum_{t=1}^{\infty} \sum_{l=1}^{2} \vartheta_l Q_{in_i} \alpha_{in_i} \left(1 - e^{-\beta_{in_i} x_{n_i lt}}\right) e^{-rt} \quad for\ all\ i\ and\ n_i, \qquad [1]$$

where B_{in_i} represents the overall benefits from improvements in water quality and α_{in_i} and β_{in_i} are parameters for country i and group n_i. The rate of interest is denoted by r and time in years by t. The parameter ϑ_l denotes the relative weight of algal (l = 1) and cyanobacterial (l = 2) biomass, and Q_{in_i} represents the estimated aggregate benefit of reaching the state targets of the BSAP. Annual biomass reductions in comparison to the baseline projection are described by $x_{n_i lt}$. The benefit functions were derived for all groups with more than 20 respondents, and the functional form of the most common response (people considering the whole sea, or all sub-basins) was applied for other groups with smaller numbers of respondents. Based on responses to survey items eliciting preferences for water quality and reactions to the inconvenience caused by algae, a weight of $\vartheta_1 = 0.47$ was assigned to algal biomass and a weight of $\vartheta_2 = 0.53$ to cyanobacteria. The entire WTP was assigned to algal biomass in those basins where nutrient reductions did not reduce cyanobacteria.

2.5 Optimization

We used the modelling framework iteratively to determine least-cost solutions to given environmental targets and to determine the socially optimal level of water protection and the respective least-cost combination of measures. To start with, we solved the cost-effective set of abatement measures for meeting the BSAP targets. In order to achieve a good environmental status, the BSAP establishes two targets for nutrient loads. First, it sets annual quotas $\bar{L}_{jp}$ by sub-basin (j = 1,...,7) for loads of N ($p = 1$) and P ($p = 2$) such that

$$\sum_{i=1}^{9} L_{ijpt} \leq \bar{L}_{jp} \quad for\ all\ j, p\ and\ t \geq 30, \qquad [2]$$

where L_{ijpt} refers to riverine nutrient loads from littoral country i to sub-basin j in year t. Second, the BSAP sets country-specific provisional targets, $\bar{L}_{ip}$, for nutrient reductions:

$$\sum_{j=1}^{7} L_{ijpt} \leq \bar{L}_{ip} \quad for\ all\ i, p\ and\ t \geq 30 \qquad [3]$$

To account for time lags and the full effects of measures initiated at present, we allow 30 years for the load target in each sub-basin to be reached.

The marine basin model describes the state of the marine basins as a function of current loads and past state, $S_{jt} = f(S_{j,t-1}, L_{ijpt})$, thus allowing us to search for the combination of abatement measures that leads to an identical or better state of the sea at the minimum cost in comparison to the BSAP load reduction targets, that is,

$$S_{jpt} \leq \bar{S}_{jp} \quad for\ all\ j, p\ and\ t \geq 40, \qquad [4]$$

$$S_{jlt} \leq \bar{S}_{jl} \quad for\ all\ j, l\ and\ t \geq 40. \qquad [5]$$

where $\bar{S}_{jp}$ are the target levels for the concentrations of *N* and *P* and $\bar{S}_{jl}$ are the target levels for algal and cyanobacterial biomass. These target levels were specified by simulating the state of the sea with the loads allowed by the BSAP (defined in equations [2] and [3]) for 40 years. The target year was set at 40 years hence to account for lags in the realization of the impacts of measures in the marine ecosystem and to be consistent with the BSAP, in which the reference year for load targets (2015) is somewhat earlier than that for water quality targets (2021).

The first step in developing cost functions was to solve for the cost-effective combination of measures for each sub-catchment (denoted here by country i draining into sub-basin *j*). This entailed selecting the levels of $k = 1, \dots, 10$ nutrient abatement measures,m_{ijk} such that

$$\min_{\{\mathrm{m_{ijk}\ for\ all\ k}\}} \sum_{t=1}^{\infty} \sum_{i=1}^{9} \sum_{j=1}^{7} c_{ijkt}(m_{ijk})\,(1+r)^{-t} \ , \ for\ all\ i\ and\ j, \qquad [6]$$

where r denotes the rate of interest[7]. We assume that all nutrient abatement measures start immediately. Of course, the temporal distribution of their costs varies; for example, the investments in wastewater treatment are concentrated in the first years while the costs from reduced fertilization remain constant over time. Upper levels were imposed for each measure[8] to ensure that the measures would be practicable and not entail major impacts on other economic sectors (Table 1b).

$$0 \leq m_{ijk} \leq \bar{m}_{ijk} \; for \; all \; i, j \; and \; k. \qquad [7]$$

The second step was to solve [6] with respect to [7] for different combinations of N and P reduction targets for each sub-catchment. As the third step, cost functions were derived for each sub-catchment by using the data obtained:

$$C_{ij} = \varphi_{ij}^{1} + \varphi_{ij}^{2}\widetilde{N}_{ij} + \varphi_{ij}^{3}\widetilde{P}_{ij} + \varphi_{ij}^{4}\widetilde{N}_{ij}^{\;2} + \varphi_{ij}^{5}\widetilde{N}_{ij}\widetilde{P}_{ij} + \varphi_{ij}^{6}\widetilde{P}_{ij}^{\;2} + \varphi_{ij}^{7}e^{\varphi_{ij}^{8}\widetilde{N}_{ij}} + \varphi_{ij}^{9}e^{\varphi_{ij}^{10}\widetilde{P}_{ij}} \quad [8]$$

where $\widetilde{N}_{ij}$ and $\widetilde{P}_{ij}$ denote the reductions of N and P loads in comparison to the baseline loads at year 30, and $\varphi_{ij}^{1}, \ldots, \varphi_{ij}^{10}$ are parameters (see Ahlvik et al 2013 for parameter values and other details).

Having elaborated continuous and twice-differentiable functions for both costs [8] and benefits [1], we were able to solve numerically for a socially optimal level of trans-boundary water protection for the Baltic Sea. The optimal solution was obtained by adjusting the abatement measures in each country and sub-catchment such that the difference between the overall benefits of improved water quality and the overall costs of nutrient abatement was maximized:

$$\max W = \sum_{t=1}^{\infty}\sum_{i=1}^{9}\left[\sum_{n_i=1}^{nmax_i} B_{in_i} - \sum_{j=1}^{7} C_{ij}\right](1+r)^{-t} \quad [9]$$

In each simulation, benefits and costs were projected for the first 40 years, after which the difference between the benefits and costs was assumed to remain constant.

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[7] The choice of interest rate is often decisive when evaluating long-term environmental investments, with a lower rate tending to favour measures with long lags (Nordhaus 2007). Here, a 3.5 per cent real rate of interest was chosen for discounting to accord with the rates typically used for evaluating public projects (e.g. HM Treasury 2003)

[8] For example, upper limits were imposed on the reductions in production animal numbers to accord with national food security requirements

A social optimum for a trans-boundary pollution problem may be difficult to implement if the net benefits are unevenly distributed between countries. To best inform policymaking we derive the level of water protection that leads to the highest overall utility by guaranteeing that benefits outweigh the costs for each littoral country:

$$\sum_{j=1}^{7}\sum_{t=1}^{\infty}\left[B_{in_i} - C_{ijt}\left(m_{ijk}\right)\right] \geq 0 \quad for\ all\ i \qquad [10]$$

Compared to the social optimum, this Pareto-efficient solution provides an estimate of how much can be gained from international negotiations and whether there is room for side-payments between countries. Non-linear optimization problems were solved using Knitro® solver.

2.6 Policy goals

Economic analysis may assist policy-makers by examining market failures to identify politically practicable solutions that improve social welfare and promote its fair distribution (see e.g. Acemoglu and Robinson, 2013). To offer policy advice on reducing eutrophication in the Baltic Sea, an analyst must account for several complexities, such as the common-property nature of the sea, the spatially heterogeneous marine and social systems and the past and present institutions established to promote water protection.

We computed solutions for five alternative policy goals to analyse the economic consequences of the present institutional settings in contrast to the socially optimal solution. Table 3 summarizes the policy goals as explicit optimization problems solved in the modelling. Since the Helsinki Commission has advocated intergovernmental collaboration and enhanced water protection during the past 40 years, a natural point of departure was to examine the cost-effective implementation of the existing international convention, the Baltic Sea Action Plan (Policy Goal I). We then studied the potential for cost savings by accounting only for ecologically determined nutrient reduction targets by sub-basin (Policy Goal II) and, further, by taking the state of the sea - rather than the load reductions - as a goal and letting the littoral countries jointly adjust their efforts to minimize the overall cost (Policy Goal III). Furthermore, a welfare-maximizing optimum was solved for the Baltic as a whole (Policy Goal IV) and, additionally, with a political constraint guaranteeing that the benefits outweigh the costs for each littoral country (Policy Goal V).

3 Results

3.1 Costs and benefits of meeting the BSAP targets

Table 4a shows the benefits and costs of meeting the BSAP targets for three cost-minimization formulations (Policy Goals I–III). The benefits and costs are expressed as average annual amounts in 2011 euros by country. The net benefits and the benefit–cost ratios (B/C) describe the economic feasibility of meeting the target.

The overall benefits of improved water quality (€3716 M annually) outweigh the costs of meeting the country-specific and sub-basin-specific load quotas of the BSAP (€2805 M annually) provided that the nutrient abatement measures are planned cost effectively in each country and region (Policy Goal I). However, even when the implementation of the BSAP is economically viable for the Baltic Sea region as a whole, and for Russia and the EU as an aggregate, the benefits and costs are unevenly distributed among the coastal states. The benefits outweigh the costs in Finland, Sweden and Germany. Germany alone contributes to almost half of the overall benefit estimate.

The costs outweigh the benefits in Poland, Denmark and the Baltic states. Latvia and Lithuania are not able to fully meet the reduction targets with the given set of abatement measures and constraints. Contrary to the trend in most other regions in the Baltic Sea catchment, the riverine loads in these countries have recently increased in comparison to the values that were used to define the BSAP targets (HELCOM 2011). These increases may be also due to trans-boundary riverine pollution from non-littoral countries, in particular Ukraine and Belarus.

Comparison of the costs of meeting the BSAP targets with more flexible arrangements (Policy Goals II and III in Table 4a), ones eventually leading to the same overall improvements in water quality, suggests that the present allocation of load reduction targets in the BSAP is not cost-effective. Substantial cost savings could be achieved by allocating the nutrient reduction measures cost-effectively across regions and countries and revising the targets by country accordingly. The overall costs can be reduced by 17 per cent through a cost-effective combination of abatement measures that meets the sub-basin-specific reduction targets (Policy Goal II in Table 4a). If the measures and nutrient reductions can be adjusted flexibly across all countries and sub-basins, the reduction in costs might be as high as 47 per cent (Policy Goal III in Table 4a).

3.2 Socially optimal level of water protection

Table 4b shows the benefits and costs for an unconstrained socially optimal solution (Policy Goal IV) and for a constrained solution in which the benefits are forced to outweigh the costs in each country (Policy Goal V). The socially optimal level of abatement effort is lower than the level of effort specified in the BSAP. The total benefits of the socially optimally solution, expressed in monetary units, are 94 per cent of the benefits of meeting the full BSAP targets, while the total costs represent only a fraction (17–31 per cent) of the costs of meeting the BSAP targets. Both benefits and costs are reduced for each country, and the welfare gains are more evenly distributed across countries. The lower cost is a consequence of two factors: a slightly lower level of effort and a spatially optimal distribution of water protection efforts that matches the preferences of the citizens of the littoral countries.

When imposing a constraint to enforce a Pareto improvement vis-à-vis the baseline (Policy Goal V), the optimal level of water protection is even lower than in the socially optimal solution (Policy Goal IV). The benefits are 89 per cent of those envisaged in the BSAP, whereas the costs are only 14 to 26 per cent. From the point of view of a social planner considering the Baltic Sea and its littoral societies as a whole, this solution leads to a welfare loss of around €100 M annually compared to the social optimum. This sum can also be interpreted as an estimate of the gains achievable from cost sharing.

Figure 6a presents the benefits and costs of meeting the BSAP targets (Policy Goals I–III) at all intermediate levels of water protection between the baseline and BSAP. The benefits and costs are expressed as a function of relative improvements in the state of the sea in comparison to the baseline (level 0) and the BSAP target (level 1), described in terms of load reduction (Policy Goals I and II) or state targets (Policy Goals III). Figure 6b provides the net benefits for Policy Goals I–III at intermediate levels of water protection and for the socially optimal solution (Policy Goal IV) at levels exceeding the BSAP target. The marginal costs increase steeply at ambition levels higher than those set out in the BSAP (values greater than 1.0 on the horizontal axis). This implies that all inexpensive measures are already in use, and additional improvements can only be achieved by including costly measures, such as reducing the number of production animals, in the mix of measures.

Figure 6b and additional sensitivity analysis revealed that the cost function, which describes the present technology and potential for nutrient abatement, largely determines the range of economically feasible and optimal levels of water protection. Variations in the shape of benefit functions and the overall level of benefits played a smaller role. We note that nutrient abatement has important positive externalities for inland waters and catchment areas, the assessment of which was beyond the scope of the present study[9]. Thus, our benefit function is only a partial representation of the overall societal benefits of nutrient abatement. Proportional increases in the benefits increase the optimal level of water protection. However, the optimal efforts remained at a lower level than those set out in the BSAP at any realistic level of estimates of improvements in the recreational value of inland waters and land ecosystems.

3.3 Optimal combination of measures and the respective load projections

Figure 7 illustrates the optimal allocation of nutrient abatement efforts across measures (Figure 7a) and catchment areas (Figure 7b). The socially optimal solutions (Policy Goals IV–V) predominantly consist of investments to improve the capacity of wastewater treatment and, to a lesser extent, of investments in reducing the P content of laundry wastewater and increasing wetland areas and the number of sedimentation ponds. These measures are optimally carried out in the sub-catchments draining into the Baltic Proper, the Gulf of Riga and the Gulf of Finland. These sub-basins are the most heavily eutrophicated areas of the Baltic Sea and worsen water quality in adjacent sub-basins as water is the transferred between them. Improving wastewater treatment is the principal measure, particularly in Poland, Latvia and Lithuania, where it is optimal to apply capacity close to its full potential (tertiary treatment involving 80- and 85-percent reductions of effluent N and P loads, respectively).

Cost-effective combinations of measures to meet the BSAP targets (Policy Goals I–III) consist of investments in wastewater treatment and, in addition, substantial allocations for agricultural measures that reduce inorganic fertilizers and the number of production animals and improve the retention capacity of the soil and inland waters. The last include catch crops, wetlands and sedimentation ponds. Reductions in the number of production animals and application of inorganic fertilizers are expensive measures that are taken last, after other measures, to meet the country- and sub-basin-specific N targets (Policy Goal I). Under more flexible policies (Policy Goals II and III), the most costly measures can be replaced by less expensive ones in other sub-catchments. For example, essentially the same improvement in the state of the Baltic Sea can be achieved without reductions in production animals and with far smaller reductions in inorganic fertilizers when a spatially efficient allocation of measures is allowed (Policy Goal III). The cost

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[9] Nutrient abatement improves the quality of inland waters, and some of the measures, such as establishing wetlands, may enhance the biodiversity of agricultural lands and the scenic value of the landscape.

of nutrient abatement can also be substantially reduced by meeting some of the requirements set for sub-catchments draining into the Danish Straits through measures taken elsewhere. Measures implemented in sub-basins that are far from the North Sea are more important in that their effect is seen in the Baltic Sea for a longer period of time.

In the socially optimal solution (Policy Goal IV), both N and P loads are reduced, but the reduction of P is given more emphasis.[10] This result is an outcome of both ecological and economic processes and factors. First, some of the lowest-cost abatement measures - improving wastewater treatment and increasing the use of phosphate-free laundry detergents - focus on P reduction and are among the first to be included in the cost-effective combination of measures. Second, a significant P reduction is important, because it diminishes late-summer cyanobacterial blooms, hence also reducing the free molecular N fixed by cyanobacteria. Third, citizens consider the harm caused by cyanobacteria to be slightly higher than the problems related to other types of algae, which are determined by N loads in N-limited sub-basins[11]. Fourth, the retention time of P in marine ecosystems is longer than that of N.

The socially optimal level of water protection in the Baltic Sea can be reached mainly through improving municipal wastewater treatment in sub-catchment areas draining to the Baltic Proper, the Gulf of Riga and the Gulf of Finland, the three most eutrophicated sub-basins. In addition, some smaller investments are needed to establish wetlands and increase the use of phosphate-free laundry detergents. Meeting more ambitious water protection targets, such as those in the BSAP, would require that more costly agricultural measures be included in the mix of measures.

3.4 Impacts on national economies

Finally, we investigated the magnitude of welfare impacts from reduced eutrophication in the Baltic Sea. Figure 8 shows the aggregate benefits and costs by country of meeting the BSAP requirements under Policy Goal I as a proportion of Gross Domestic Product (GDP). The aggregate value of reduced eutrophication varies between 0.02 and 0.14 per cent of GDP. Improvements in the water quality of the Baltic Sea have the greatest effects on the welfare of Swedes, Finns and Estonians. These countries are characterized by relatively long coastlines, extensive archipelagos and good access to different parts of the sea.

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[10] Table 2a presents the initial loads, baseline development and targets for the five problem formulations.

[11] In our model, primary production in all the sea basins, except for the Bothnian Bay, are nitrogen-limited.

The costs are higher for those countries whose waters drain into the sub-basins that are initially in the poorest ecological state (in particular the Baltic Proper) and have thus been assigned the most ambitious nutrient abatement targets. The costs, as a proportion of GDP, are highest in the Baltic countries, that is, Latvia, Lithuania and Estonia. These countries are characterized by relatively small national economies and ambitious nutrient reduction targets. Moreover, from the point of view of the social planner, it is rational, to invest in water protection in the Baltic countries, Poland and Russia, as these countries have the greatest potential for additional nutrient abatement and improvements in municipal wastewater treatment.

In Denmark and Germany, the low-cost possibilities for nutrient abatement are already in use, and meeting the country-specific and sub-basin-specific targets (Policy Goal I) requires the inclusion of expensive measures such as reducing the number of farm animals. The ambitious load target set for the Danish Straits requires many high-cost measures to be implemented in Sweden and Denmark. In the most flexibly designed goal to meet the BSAP state target (Policy Goal III), load reductions are smaller and the associated costs lower for Denmark.

4 Discussion

Cost-benefit analysis shows that the aggregate benefits of implementing the Baltic Sea Action Plan clearly outweigh its costs, making it an economically justified and socially desirable environmental project for increasing the welfare of the citizens of the Baltic Sea countries. On the other hand, our numerical results have revealed several issues that should be given due consideration in the revisions of present policies and design of future international water policies. Our computations suggest that (1) the nutrient abatement targets of the BSAP are not cost-effectively specified across the littoral countries, (2) the current N and P reduction targets of BSAP are not well balanced, (3) the costs and benefits of meeting the BSAP targets are unevenly distributed across littoral countries, and (4) the socially optimal level of water protection is somewhat lower than the level envisaged in the BSAP. Next we discuss how these findings should be interpreted in light of the principal caveats and shortcomings relating to the model.

According to our results, the present allocation of nutrient abatement targets across littoral countries and sub-catchments of the Baltic is far from cost-effective. Embracing the ‘polluter pays’ principle, the BSAP set targets that are proportional to each country’s estimated nutrient input; yet, such an approach neglects any spatial variability in the availability, unit costs and effectiveness of nutrient abatement measures. Our analysis using an integrated dynamic model suggests that cost savings can be achieved that are even higher than those shown by earlier studies employing static cost-and-effect models (Gren et al 1997a, Elofsson 2003). An improvement in the state of the marine environment similar to that envisioned with the present allocation of targets can be realized at as little as 47 per cent lower costs if nutrient abatement efforts are allocated flexibly and cost-effectively across economic sectors, countries and regions.

Numerical computations also suggest that both N and P reductions are needed, but that P reductions are more important and urgent, particularly in sub-catchments that drain into the most eutrophicated sub-basins. Moreover, these reductions are more effective in sub-catchments draining to sub-basins relatively far from the North Sea. These results capture the interplay of ecological and economic factors in what is a spatially heterogeneous catchment area and sea. In doing so, they will inform the long-standing debate on the urgency and proper division of efforts to reduce N and P loads (e.g. Tyrrell 1999, Conley et al 2009), which to date has been based solely on ecological arguments.

Cost-effective allocation of abatement measures reduces the total costs of nutrient abatement and increases the incentives of all littoral countries to make additional investments to improve the water quality of the Baltic. Recent papers in the field (Gren 2008, Elofsson 2010) and our results give rather consistent estimates of the overall costs of nutrient abatement, but the optimal combination of measures varies considerably across studies. This suggests that the cost-effective combination of measures is sensitive to variations in the initial loads, effectiveness of measures and their unit costs. Thus, additional analysis using refined cost-and-effect models with higher spatial resolution and additional optional nutrient abatement measures may still be needed if research is to provide detailed ex ante guidance to decision-makers on cost-effective programmes of measures in the Baltic. It must also be noted that the effectiveness of agricultural measures in particular is often location-dependent and uncertain, a factor which calls for probabilistic analysis.

Accounting for economic considerations in the design of nutrient abatement targets reduces the total cost of, and thus increases the economic incentives for additional efforts on nutrient abatement for all littoral countries. However, the costs and benefits still remain unevenly distributed even in the cost-effective and socially optimal solutions. This is a consequence of spatial heterogeneity in the population, land uses and past adoption of nutrient abatement technologies in the littoral countries as well as variations in the physical characteristics of the sea. The optimal course of action remains to implement nutrient abatement measures in countries and regions which offer the best return on investments in abatement. Uneven distribution of the net benefits undermines the prospects of success of any international agreement and calls for additional efforts to make marine protection mutually encouraging for all littoral countries. Our computations show that the welfare gains obtainable from a socially optimal solution with side payments can be as high as €100 M annually in comparison to the Pareto-efficient solution, in which the benefits outweigh the costs of water protection in each country. This sum can be interpreted as a ceiling for the transaction costs of mutually encouraging cost-sharing schemes (cf. Markowska and Żylicz 1999, Ahlvik and Pavlova 2013).

According to our computations, the socially optimal level of water protection is somewhat lower than the present target level agreed on by the littoral Baltic Sea countries. The total benefits of the socially optimal solution, expressed in monetary units, are 94 per cent of the benefits of meeting the full BSAP targets, while the total costs represent only a small fraction (17-31 per cent) of the costs of meeting the BSAP targets. Lower cost is a consequence of two factors: a slightly lower level of effort and the spatially optimal distribution of water protection efforts matching the preferences of the citizens of the littoral countries. However, this result should be interpreted with caution. Firstly, our benefit function neglects the positive impacts of nutrient abatement on the provision of ecosystem services in the inland waters and thus only partially represents the overall societal benefits. Second, our cost function, describing the present nutrient abatement technologies and potentials available is likely to overestimate the true cost. The identification of new, low-cost measures, particularly in agriculture, and the development of cost-effective water protection plans with spatially more detailed models are possible avenues for reducing the marginal cost at higher levels of effort and to make aiming at more stringent environmental targets worthwhile.

5 Conclusions

Although the costs and benefits of nutrient abatement are distributed unevenly across the littoral countries of the Baltic Sea, they play only a minor role in their national economies. This has implications for both research on and the design of international and national environmental policies. Research must acknowledge that general-equilibrium analysis may not bring additional insights and that sectoral analyses such as the ones presented in this paper are able to provide adequate estimates of the societal impacts of marine protection. The implication for policy-making is that the most important barriers to additional national efforts are political rather than economic. This realization calls for additional international collaboration and a search for burden-sharing mechanisms. Open and transparent sharing of research information on the present nutrient loads and the societal consequences of abatement also aid in increasing confidence. Recalling that eight out of the nine Baltic Sea countries are members of the EU, financing institutions such as the Structural Fund and the Cohesion Fund have an important role to play in promoting fair burden sharing.

The EU Marine Strategy Framework Directive poses a serious challenge for socio-economic research on marine areas by requiring member states to conduct cost-effectiveness and cost–benefit analyses to evaluate their water protection plans by the year 2015. Our integrated framework for addressing the issues relating to eutrophication in the Baltic Sea serves as an example of the tools needed to conduct such analyses. The framework can be adjusted for other regional seas and possibly also for some other descriptors of good environmental status provided that the information and quantitative models describing the relevant interactions between the ecosystem and society are in place.

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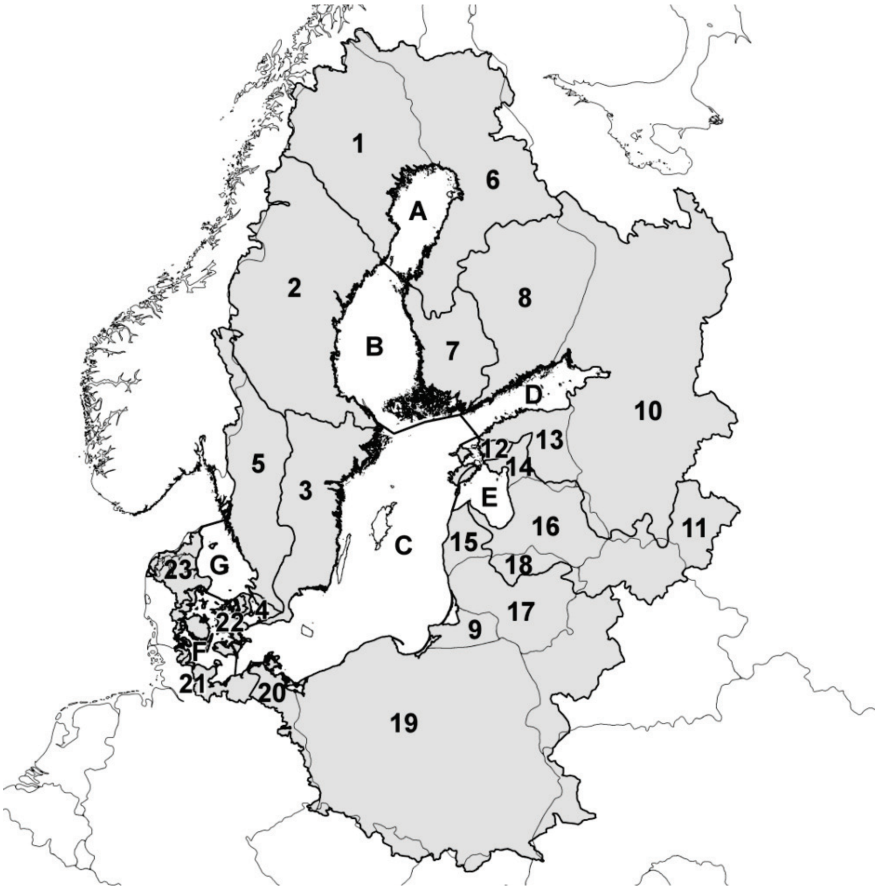


Figure 1. The Baltic Sea sub-basins (A–G) and sub-catchment areas (1–23). Sub-basins: A. Bothnian Bay, B. Bothnian Sea, C. Baltic Proper (northern and southern parts combined), D. Gulf of Finland, E. Gulf of Riga, F. Danish Straits, G. Kattegat. Source: Larsen (2008)

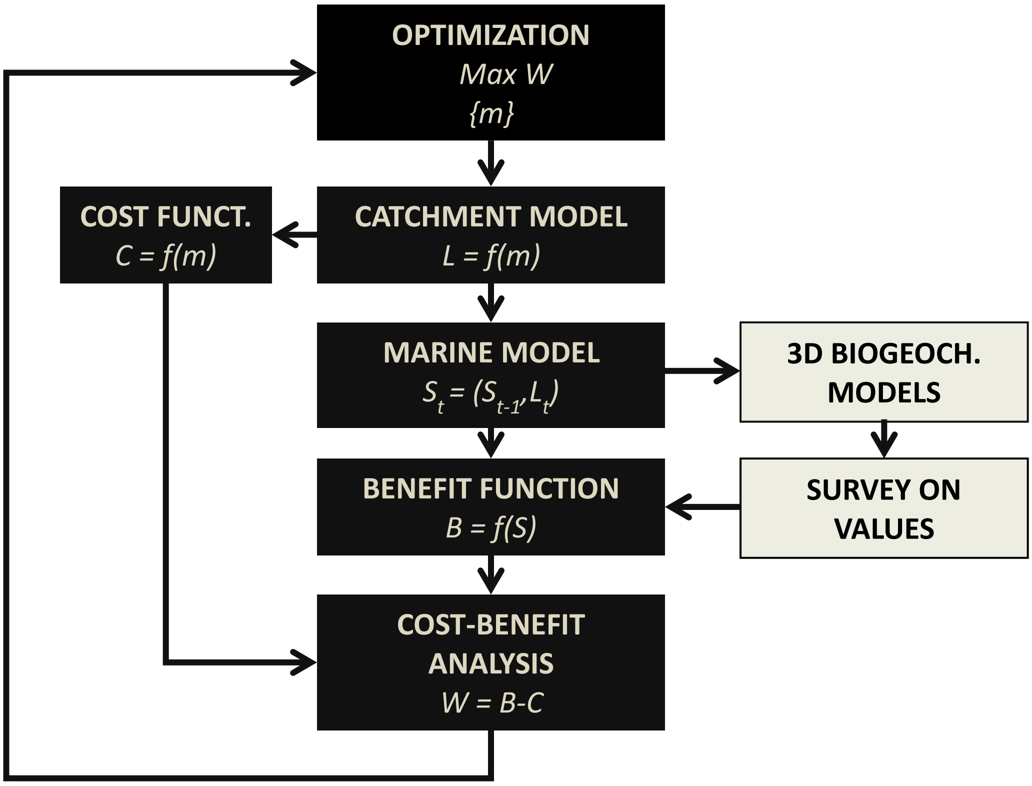


Figure 2. Integrated modelling framework to evaluate the costs and benefits of nutrient abatement in the Baltic Sea. The black boxes represent the model components needed in policy optimizations. The white boxes denote the elements that were needed to determine the benefit function. Symbols: W – net present value, m – measures, L – loads, S – state of the sea, B – benefits, C – costs

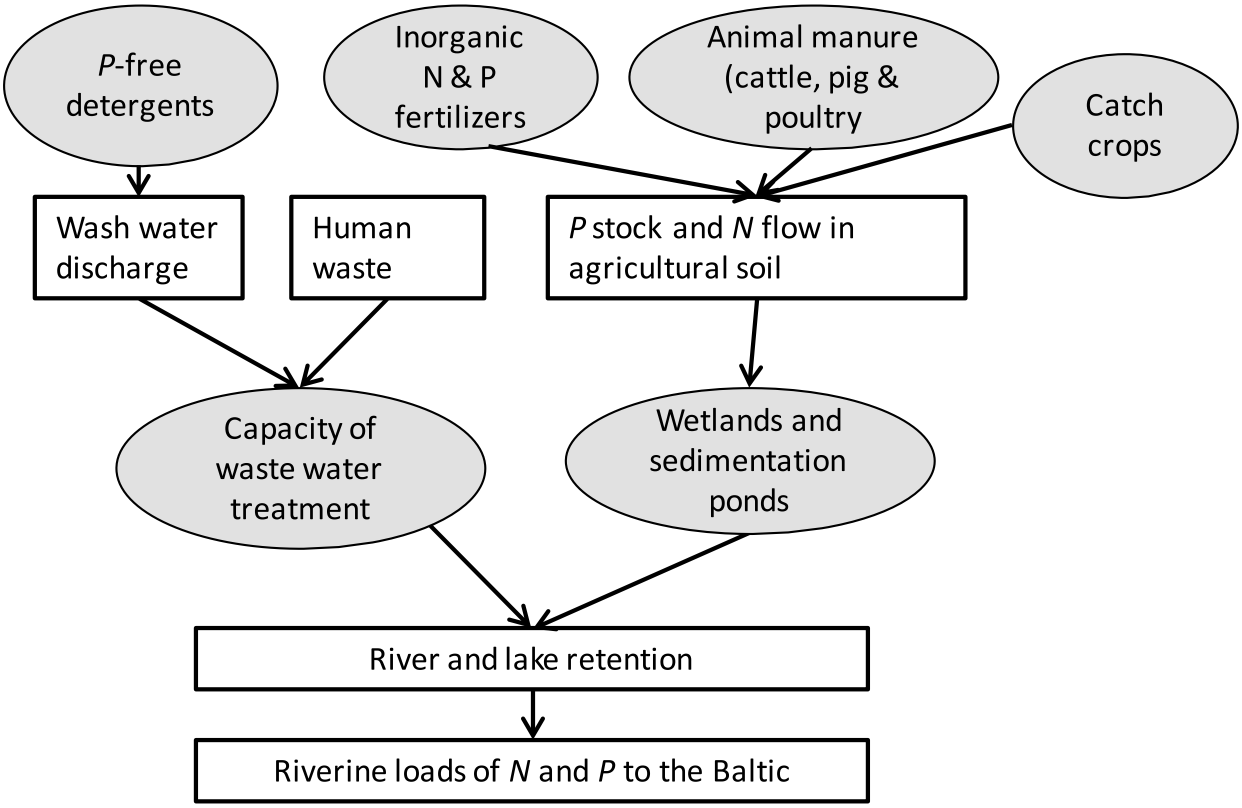


Figure 3. Interactions between the control variables (ellipses) and other variables (rectangular boxes) including a state variable for soil phosphorus stock and flows of nutrients into the Baltic Sea from waste water treatment and the agricultural sector

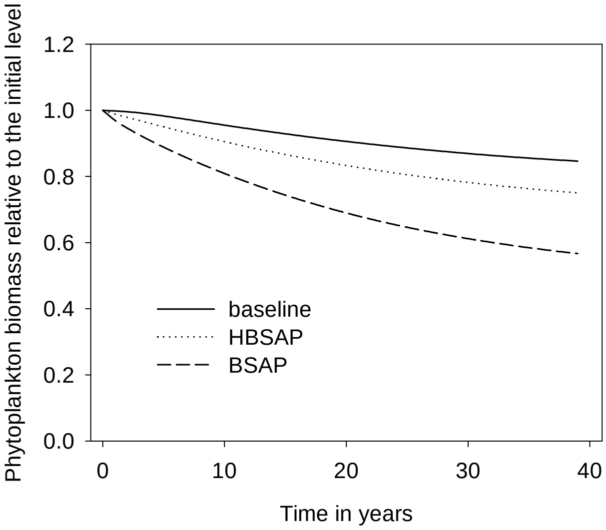
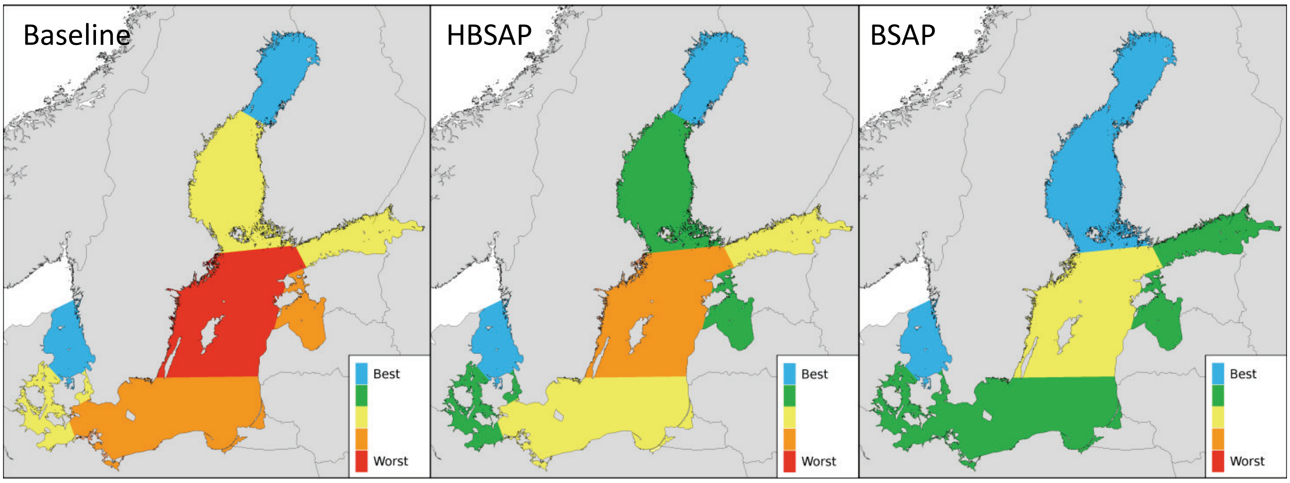
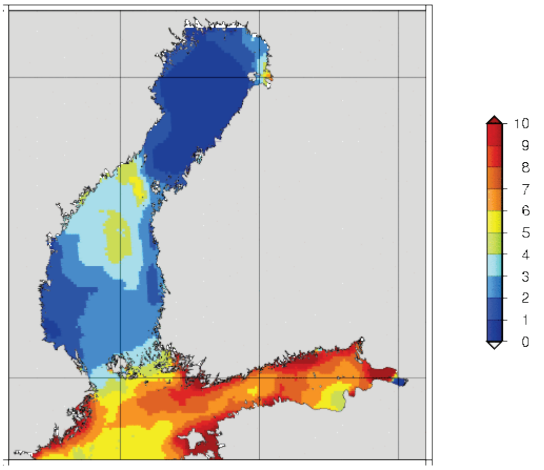


Figure 4. Projections of phytoplankton biomass in the Baltic Sea for the baseline scenario (baseline) and half (HBSAP) and complete (BSAP) fulfilment of the BSAP targets.

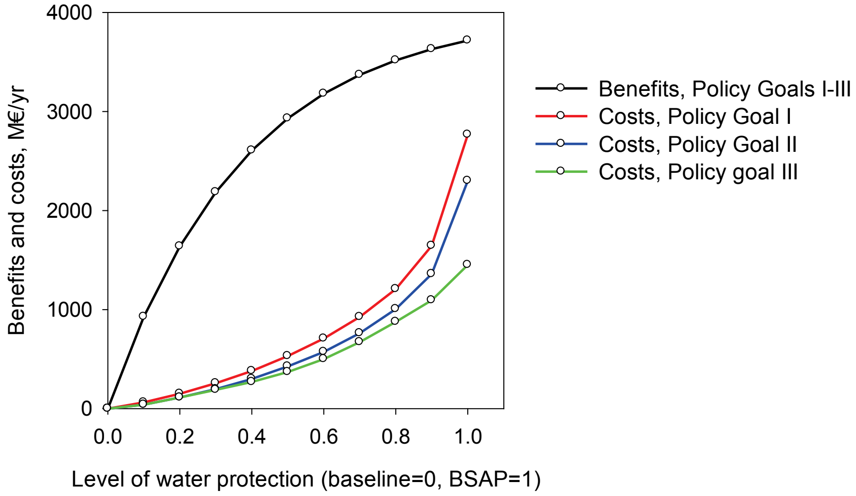


(a) Water quality in the Baltic Sea in 2050 on a five-point scale for three scenarios: baseline development (baseline), and half (HBSAP) and complete (BSAP) fulfilment of the BSAP

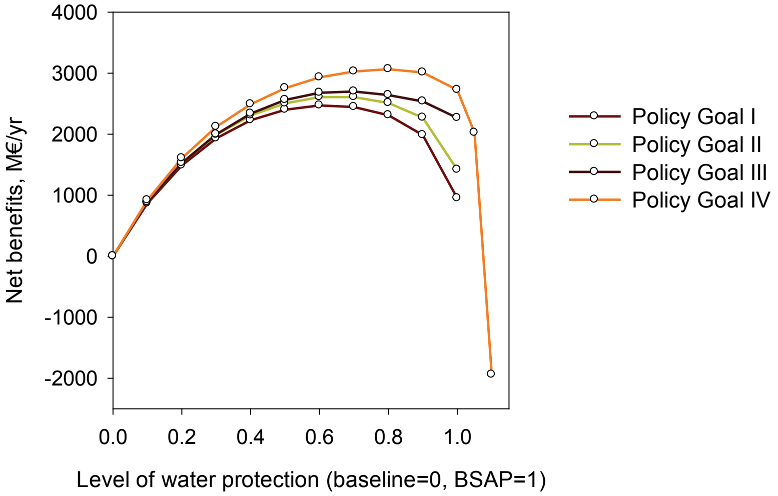


(b) An EIA-SYKE 3D model outcome for the summer months of the year 2001 showing the chlorophyll-a concentration (mg/m3) in surface waters of the northern Baltic Sea, an indicator of phytoplankton biomass.

Figure 5. Graphs of scenarios

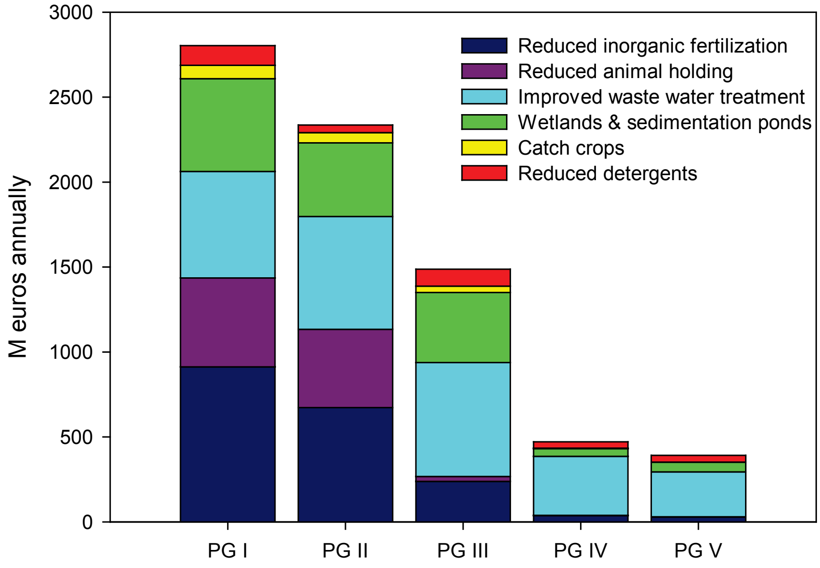


(a) Benefits and costs of meeting BSAP targets



(b) Welfare gains obtained from full or partial implementation of Policy Goals I-IV

Figure 6. The costs, benefits and the welfare gains for partial fulfilment of the policy goals (PG). On the horizontal axis 0.0=baseline (no abatement) and 1.0=BSAP (complete fulfilment of BSAP)


(a) Annual cost of reducing nutrient loads by abatement measure

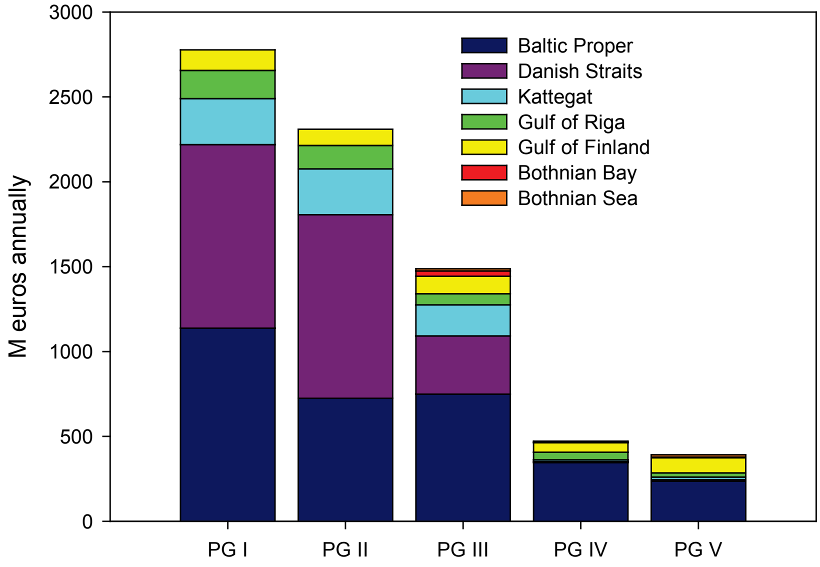

(b) Annual cost of reducing nutrient loads by sea basin

Figure 7. Optimal allocation of efforts for policy goals (PG) I–V across (a) nutrient abatement measures and (b) catchment areas draining into different sub-basins of the Baltic Sea

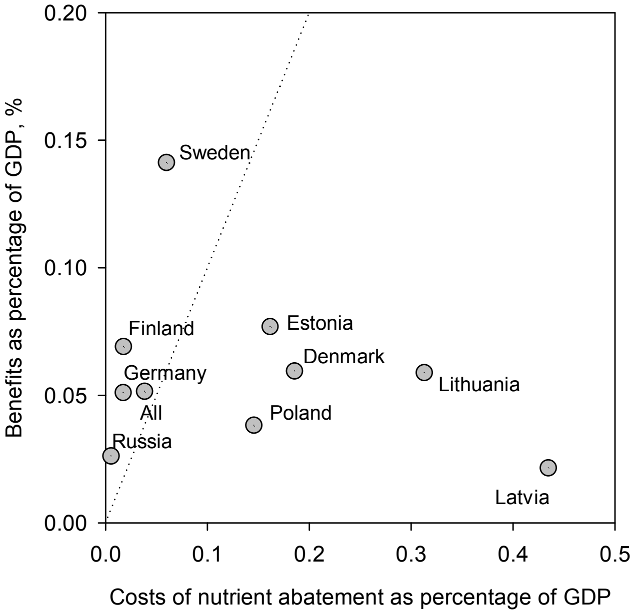


Figure 8. The overall costs and benefits of implementing the Baltic Sea Action Plan, described as a proportion of gross domestic product (GDP). Countries on the left side of the dotted line are net gainers and countries on the right are net losers.

Table 1. Load scenarios and costs of nutrient abatement

(a) Present and future nutrient loads to the Baltic Sea

Phosphorus loads, tonnes/year

	Now (2004-2008)	Baseline 2040	Goal I 2040	Goal II 2040	Goal III 2040	Goal IV 2040	Goal V 2040
Russia	5537	5213	3980	3830	3471	3809	3613
EU countries	27182	27957	16921	17480	17004	20990	22558
Denmark	1719	2012	1368	1353	1289	1765	1686
Estonia	1240	1163	1039	891	880	915	922
Finland	3358	3153	3057	3120	2943	2992	2859
Germany	478	323	164	224	260	376	374
Latvia	2994	2853	2120	2143	2172	2310	2619
Lithuania	2111	1925	1135	1194	1204	1373	1729
Poland	11790	13260	4962	5733	5454	8012	9417
Sweden	3492	3268	3076	2822	2802	3247	2952
All countries	32719	33170	20901	21310	20475	24799	26171

Nitrogen loads, tonnes/year

	Now (2004-2008)	Baseline, 2040	Goal I 2040	Goal II 2040	Goal III 2040	Goal IV 2040	Goal V 2040
Russia	87750	86400	82055	83087	85005	86167	85131
EU countries	618960	649080	509127	514774	527886	573273	586434
Denmark	48900	49250	38643	38542	40156	48092	47673
Estonia	33650	33390	28426	24951	27812	28406	28832
Finland	78110	78470	73861	75270	73893	77355	77259
Germany	20080	20090	15224	18221	18895	20041	20036
Latvia	81810	83200	69892	70709	73644	75137	79284
Lithuania	46630	48200	31170	26264	29566	36137	39683
Poland	193590	223280	152952	159208	161588	175763	182763
Sweden	116190	113200	98959	101609	102332	112342	110904
All countries	706710	735480	591182	597861	612891	659440	671565

(b) Marginal costs and upper limits of nutrient abatement

	Marginal abatement cost, €/kg			Max. abat. (tonnes/year)	
	N	*P*	Upper limit	*N*	*P*
Red. of inorg. N fert.	2 - 158		80 % of initial applic.	118684	0
Red. of inorg. P fert.	0	0 - 350	80 % of initial applic.	0	1672
Red. number of cattle	16 - 87	1392 - 167000	50 % of initial stock	32986	472
Red. number of pigs	23 - 106	1392 - 167190	50 % of initial stock	13938	369
Red. number of poultry	22 - 106	1195 - 20920	50 % of initial stock	6402	108
Cultiv. catch crops	4 - 133	433 - 3670	33 % of arable land	17429	199
New wetlands	2 - 332	239 - 3105	5 % of arable land	75521	907
New sediment. ponds		18 - 867	0.04 % of arable land	0	1773
Impr. waste water treatm	2 - 642	10 - 2772	31.9 million people	46926	9772
P-free detergents		22 - 373	100 % of all deterg.	0	3324

Table 2. Determinants of the willingness to pay for full implementation of the Baltic Sea Action Plan (standard errors in parenthesis)

OLS regression, dependent variable is the midpoint of the WTP interval on the payment card in logarithmic form

Variable	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden
Income[1]	0.229***	0.369***	0.238***	0.0832	1.365***	1.190***	0.520***	0.627***	0.375***
	(0.085)	(0.137)	(0.056)	(0.054)	(0.250)	(0.316)	(0.066)	(0.163)	(0.109)
Age[2]	0.0087**	0.0006	0.0001	0.0005	-0.0111**	-0.020***	0.0036	-0.009***	-0.0001
	(0.0043)	(0.0064)	(0.0030)	(0.0031)	(0.0045)	(0.0034)	(0.0032)	(0.0030)	(0.0033)
Female[3]	0.271**	0.179	0.272***	0.192**	-0.0884	0.0585	0.142*	0.133	-0.0796
	(0.128)	(0.170)	(0.087)	(0.091)	(0.148)	(0.108)	(0.074)	(0.106)	(0.112)
High education[4]	0.117	0.0351	0.433***	0.388***	-0.125	0.174	0.567***	0.242**	0.212*
	(0.126)	(0.169)	(0.093)	(0.094)	(0.185)	(0.134)	(0.081)	(0.106)	(0.109)
Distance[5]	-0.812**	0.00167	-0.218***	-0.0154	-0.487***	-0.023	-0.056**		-0.197*
	(0.386)	(0.185)	(0.059)	(0.026)	(0.117)	(0.057)	(0.022)		(0.111)
Russian coast[6]								0.561***	
								(0.111)	
Constant	1.651***	1.815***	2.187***	2.002***	0.342	1.938***	1.118***	-0.316	3.013***
	(0.287)	(0.307)	(0.184)	(0.176)	(0.267)	(0.215)	(0.153)	(0.205)	(0.252)
Number of observations	773	390	1543	1112	621	493	1372	1296	879
R^2	0.026	0.021	0.050	0.028	0.094	0.107	0.114	0.058	0.029
Adjusted R^2	0.019	0.008	0.047	0.024	0.087	0.098	0.111	0.054	0.023
AIC	2959.7	1463.0	5889.4	4003.8	2511.0	1566.7	4673.4	5250.1	3315.4

Variables are significant at the *** 1%, ** 5% and * 10% level

[1] Income = respondent's mean monthly net income in thousands of PPP corrected 2011 euros

[2] Age = age of respondent, in years

[3] Female = 1 if respondent is female, 0 if male

[4] High education = 1 if the respondents has a university level or has other higher education, 0 otherwise

[5] Distance = distance between the respondent's place of residence and the Baltic Sea, in hundreds of kilometres

[6] Russian coast = 1 if the respondent lives in the coastal region of Russia (Kaliningrad, Leningrad, St. Petersburg), 0 otherwise (only Russia)

Table 3. Policy goals

Description	Problem
Policy Goal I: Meeting country-wise and sub-basin specific load reduction targets of the BSAP cost-effectively	solving [6] with respect to [1]-[3] and [7]
Policy Goal II: Meeting sub-basin specific load reduction targets of the BSAP cost-effectively	solving [6] with respect to [1], [3] and [7]
Policy Goal III: Meeting the state target of the BSAP	solving [6] with respect to [1], [4]-[5] and [7]
Policy Goal IV: A socially optimal solution for the Baltic Sea	solving [9] with respect to [1] and [8]
Policy Goal V: A socially optimal solution guaranteeing positive net benefits for each littoral country	solving [9] with respect to [1], [8] and [10]

Table 4. The costs and benefits of meeting policy goals I–V

(a) Meeting BSAP targets

		Policy goal I Country & basin targets			Policy goal II Basin target			Policy goal III State target		
	Benefits M€/yr1)	Costs M€/yr	Net ben. M€/yr	B/C	Costs M€/yr	Net ben. M€/yr	B/C	Costs M€/yr	Net ben. M€/yr	B/C
Russia	416	113	303	3.7	105	311	4	106	310	3.9
EU countries	3301	2692	609	1.2	2231	1070	1.5	1383	1918	2.4
Denmark	178	620	-442	0.3	630	-452	0.3	267	-89	0.7
Estonia	18	36	-18	0.5	78	-60	0.2	36	-18	0.5
Finland	192	49	143	3.9	23	169	8.4	52	140	3.7
Germany	1882	651	1231	2.9	480	1402	3.9	99	1783	19.0
Latvia 1)	6	123	-117	0.1	85	-79	0.1	55	-49	0.1
Lithuania 1)	14	134	-120	0.1	101	-87	0.1	83	-69	0.2
Poland	185	753	-568	0.2	544	-359	0.3	580	-395	0.3
Sweden	826	326	500	2.5	290	536	2.8	211	615	3.9
All countries	3716	2805	911	1.3	2336	1380	1.6	1489	2227	2.5

1) Note that in Latvia and Lithuania the country-specific reduction target in the BSAP is not fully reached

2) The aggregate benefit estimates are based on the following adult population sizes (in millions): Denmark: 3.6, Estonia: 1.0, Finland: 3.6, Germany: 68.3, Latvia: 1.7, Lithuania: 2.5, Poland: 24.6, Western Russia (Central, Southern, North-Western and Volga Federal Districts): 81.5 and Sweden: 7.6, totalling 194.7 million.

(b) The costs and benefits for the socially optimal solutions

	Policy goal IV: socially optimal solution				Policy goal V: constrained solution			
	Benefits M€/yr	Costs M€/yr	Net ben. M€/yr	B/C	Benefits M€/yr	Costs M€/yr	Net ben. M€/yr	B/C
Russia	400	64	336	6.3	386	96	290	4.0
EU countries	3102	403	2699	7.7	2930	288	2642	10.2
Denmark	175	4	171	43.8	174	6	168	29.0
Estonia	17	18	-1	0.9	16	16	0	1.0
Finland	182	10	172	18.2	173	22	151	7.9
Germany	1737	3	1734	579.0	1619	3	1616	539.7
Latvia	6	29	-23	0.2	6	6	0	1.0
Lithuania	13	39	-26	0.3	13	13	0	1.0
Poland	178	284	-106	0.6	170	170	0	1.0
Sweden	793	17	776	46.6	760	51	709	14.9
All countries	3502	467	3035	7.5	3316	384	2932	8.6

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