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ABSTRACT

This study introduces a prototype model for evaluating policies to abate agricultural nutrients in the Baltic Sea from a Finnish national point of view. The stochastic simulation model integrates nutrient dynamics of nitrogen and phosphorus in the sea basins adjoining the Finnish coast, nutrient loads from land and other sources, benefits from nutrient abatement (in the form of recreation and other ecosystem services) and the costs of agricultural abatement activities. The aim of this study is to present the overall structure of the model and to demonstrate its potential using preliminary parameters. The model is made flexible for further improvements in all of its ecological and economic components. Results of a sensitivity analysis suggest that investments in reducing the nutrient runoff from arable land in Finland would become profitable only if Finland's neighbors in the northern Baltic committed themselves to similar reductions. Environmental investments for improving water quality yield the highest returns for the Bothnian Bay and the Gulf of Finland, and smaller returns for the Bothnian Sea. In the Bothnian Bay, the abatement activities become profitable because the riverine loads from Finland represent a high proportion of the total nutrient loads. In the Gulf of Finland, this proportion is low, but the size of the coastal population benefiting from improved water quality is high.

Key-words: ecosystem services, nutrient abatement, Monte Carlo simulation, recreation, valuation

1 INTRODUCTION

The Baltic Sea suffers from eutrophication caused by elevated nutrient concentrations. These are driven by external nutrient loads and internal nutrient recycling. External nutrient loads are strongly linked to the current economic activities. Agriculture, municipalities, industry, and society as a whole use the Baltic Sea as a rent-free sink of nutrients, deteriorating its water quality. This causes economic losses, as recreational use diminishes, the operational environment of fisheries is impaired, biodiversity is lost, and the non-use value people place on the sea decreases. The situation is an example of a market failure: even though the economic benefits of enhancing water quality outweigh the costs, the markets have failed to provide the correct incentives to polluting firms or nations and the sea remains highly polluted.

Recently, an increasing body of economic research has pinpointed such market failures and suggested corrective measures. Perhaps the most prominent example is the Stern Review (Stern 2007), which analyzes the global economic costs and benefits of CO_2 policies in the long term. Similar analyses combining economic and ecological models have also been conducted for the Baltic Sea area. Studies have estimated least-cost solutions for reaching nutrient abatement targets using a given set of measures (Byström 2000, Brady 2003) or reaching a given overall abatement level by allocation efforts between sectors and countries (Gren 2001, Ollikainen and Honkatukia 2001, Elofsson 2003). Some economic studies have used a dynamic approach for a particular sub-basin (Hart and Brady 2002, Laukkanen and Huhtala 2008). Gren et al. (2000) analyze cost-effective management of coastal nutrient runoff and acknowledge the role of stochastics in pollutant transport. Pitkänen et al. (2007) combine the outcomes from a dynamic 1D model and biogeochemical 3D model with high temporal and spatial resolution. A major effort in Baltic Sea research is the construction of the Mare-Nest decision support system (Baltic Nest Institute 2008, see also Wulff et al. 2001, Savchuk and Wulff 2007). However, none of these studies has truly combined all three essential elements of the tragedy of the Baltic Sea: the stochastic development of water quality and the underlying ecological processes, the relevant economic activities in the sea basin and its watershed area, and the economic benefits to be gained from the improved quality of sea amenities.

We introduce a model which, on one hand, covers the three major elements at the outset and, on the other, is flexible enough to allow for further improvements in both its ecological and economic components. We illustrate the properties of the model by using it to evaluate nutrient abatement policies in Finnish agriculture. In the model, the development of nutrient concentration is described as a stochastic process. The level of nutrient concentration of the next period in a given basin is determined by the concentration of the current period and nutrient inputs and outputs between various sources and sinks (e.g. other basins, air, sediment processes). For the basins surrounding Finland, the riverine nutrient loads are modeled as stochastic inputs. For the Baltic Proper, the model incorporates stochasticity directly into the annual nutrient concentration of the water column. The model is distinctly policy-oriented and currently focuses on agriculture, the principal source of pollution in Finland.

The aim of this paper is to present the structure of the model and to demonstrate its potential with preliminary parameters. The analysis is limited to marine areas along the Finnish coast and to the effects of eutrophication and abatement activities on the country's economy. We also identify the most acute gaps in the model with a view to its further development. For example, the next step future research might take would be to analyze the distributional effects of the damage from eutrophication across some of or all the Baltic Sea countries.

Our model applies cost-benefit analysis (CBA), which has not been used in Finland for evaluating environmental policies as intensively as in many other countries, for example, the UK and the US (Hanley 2001, Turner 2007). The alternative approaches in Finland thus far have been different types of participatory methods and cost-effectiveness analyses. These have not explicitly included the benefits of environmental improvements. The goals of the policy – the environmental quality to be achieved – have been found using the participatory or political processes and the researcher has been left to find the least expensive way to achieve these goals. Our case shows that integrating benefit measures into the analysis augments the participatory approach, as the benefits are derived from the preferences of the public. Our results on the welfare effects of given policies for the Bothnian Sea and the Gulf of Finland, for instance, illustrate the strength and flexibility of the CBA approach.

The rest of the paper is organized as follows. The next section presents the structure of the simulation model and the data used in the modeling exercise. The third section presents the results from different model components and illustrates the steps needed to describe how the deterioration of the Baltic Sea leads to economic costs. The fourth section is devoted to identifying the caveats and most obvious gaps in our present knowledge with a view to developing either the current model further or other models suitable for policy analysis and evaluation.

2 MATERIALS AND METHODS

Our stochastic simulation model combines the ecological processes and economic consequences of eutrophication in the northern Baltic Sea. The model consists of four main components: 1) nutrient stock dynamics in the selected sea basins, 2) nutrient loads from land and other sources, 3) the costs of agricultural nutrient abatement, and 4) the benefits of nutrient abatement to Finnish citizens.

Riverine loads to the sea basins adjoining the Finnish coast, and nutrient concentrations in the Baltic Proper are described as stochastic processes. The benefits and costs of abatement are compared in a cost-benefit analysis. A simplified diagram of the model is presented in Figure 1.

Component 1: Description of nutrient dynamics [FIGURE 1 ABOUT HERE]

The areas of the Baltic Sea adjoining the Finnish coast are divided into three basins (i): the Bothnian Bay (i=1); the Bothnian Sea, including the Swedish and Finnish archipelagoes (i=2); and the Gulf of Finland (i=3). The boundary at which these basins exchange water and nutrients with the Baltic Proper (i=4) forms the southern limit of the area covered by the present model. The nutrient budgets of the basins are described as in Savchuk (2005). The two critical nutrients causing eutrophication are nitrogen (N) and phosphorus (P). The dynamic state variables of the model are $Q_{i,t}^{N}$ and $Q_{i,t}^{P}$, the amounts of total N and P in the water column (in tons). Time is denoted by t=1,…,200 and the time step is one year. The dynamics of the nutrient balances are described by:

$$Q_{i,t+1}^{N} = Q_{i,t}^{N} + \sum_{j=1}^{n_i} L_{i,j,t}^{N} + A_i^{N} + \sum_{k=1}^{4}\left(W_{i,k}^{out} c_{i,t}^{N} - W_{i,k}^{in} c_{k,t}^{N}\right) - D_i - B_i + F_i \qquad [1]$$

$$Q_{i,t+1}^{P} = Q_{i,t}^{P} + \sum_{j=1}^{n_i} L_{i,j,t}^{P} + A_i^{P} + \sum_{k=1}^{4}\left(W_{i,k}^{out} c_{i,t}^{P} - W_{i,k}^{in} c_{k,t}^{P}\right) - B_i + I_i \qquad [2]$$

where L_{it}^{N} and L_{it}^{P} are the annual land loads, and A^{N} and A^{P} the atmospheric deposition of N and P. The land loads are expressed for three basins (i=1,2,3) and n_i countries accounting for the land load in each basin (j=1,…,n_i). Denitrification, burial, and nitrogen fixation by cyanobacteria are denoted by D, B, and F, respectively, and I denotes the internal loading of P from sea bottom sediments.

The outflow of water from i^{th} to k^{th} basin is denoted by $W_{i,k}^{out}$, and the inflow from k^{th} to i^{th} basin by $W_{i,k}^{in}$. The nutrient concentrations c^{N} and c^{P} are expressed in µg/l and are obtained by dividing the quantity of nutrients (in tons) by the water volume (in km^3) in each basin i:

$$c_{i,t} = \frac{Q_{i,t}}{V_i} \qquad [3]$$

It is assumed that the nutrients are well mixed in each basin. For the Baltic Proper, the future developments of nutrient concentrations are predicted by:

$$c_{4,t} = c_{4,1}\left[1 + \alpha\left(1 - e^{-\beta t}\right)\right] + c_{4,t}\,\sigma\, dz \qquad [4]$$

where α and β are parameters describing the future steady-state concentration level and the rate of change, respectively. The parameter σ represents the coefficient of variation and dz is a normally distributed random variable. For other basins, the development of nutrient concentration is determined by equations [1] - [3]. All other nutrient flows except for land loads are assumed to remain constant over time. All the parameter values are presented in Appendix 1.

Component 2: Projecting nutrient land loads

The second component of the model describes the future development of land loads, including nutrient runoff from arable land, forests and point sources. Annual variation in agricultural loads is a special feature of non-point source pollution, and is explicitly taken into account in our model. To project future land loads, information is needed on (1) the probable development of the agricultural sector and other critical sectors by country and region, and (2) the present level of and past fluctuations in land loads. Table 1 shows past and probable future development of the agricultural sector in Finland. The information on past developments has been drawn from the Yearbook of Farm Statistics (1983, 1992/1993, 2000, 2007). The future developments of the agricultural sector are based on the results of the Finnish agricultural sector model DREMFIA (MMM 2008). The predictions on the average land loads after 20 and 50 years (Table 2) are based on the information in Table 1 and the fact that agriculture currently accounts for about 40% of the total land loads in Finland. The predictions for other countries are based on the literature and expert opinions.

In Finland, an increase in the total land area used for farming, increased use of inorganic N fertilization, and an increased rate of clearing arable lands will lead to increased N loads over the next 20 years. The loads are assumed to gradually decrease thereafter. The flow of total P from the Finnish rivers is assumed to decrease due to reduced use of inorganic fertilizers and gradually decreasing P stocks in agricultural land. For the Bothnian Sea, however, the P loads will increase towards 2058 due to intensified poultry and pig farming and increased application of manure fertilization in southwest Finland.

[TABLES 1-3 ABOUT HERE]

In Sweden, nutrient loads are assumed to decrease over time due to adaptation to the current agricultural policies (Kadin 2009). In Estonia, reintroducing arable land to agricultural production is assumed to increase the nutrient loads over the next 50 years. In Russia, plans to increase local animal production in the Leningrad Oblast and the ongoing practice of spreading what is an oversupply of manure on unmanaged fields explain the increasing land loads of both N and P.

Table 3 shows historical data on riverine loads of total N and P flowing into the Baltic Sea for the period 1986-2000. There are large annual fluctuations in the land loads, mainly due to variations in weather conditions. Seasonal distribution and the amount of rainfall in particular are important determinants of nutrient runoff (Turtola and Paajanen 1995). It is assumed that the initial average land loads (in 2008) are the same as the average from the time series. Moreover, the standard deviations of land loads are assumed to remain the same in the future. The land loads for the following 200-year period are predicted by the equation:

$$L = D\gamma + SAZ \ , \qquad [5]$$

where L is a (14 × 200) matrix for annual N and P loads for 7 clusters of rivers for the next 200-year period. The trend for the mean land loads is predicted by $D\gamma$; γ denotes a matrix of land loads interpolated from the values in Table 2 for the first 50 years and it is assumed that the mean loads remain the same thereafter. D is a (14 × 14) diagonal matrix expressing the effects of nutrient abatement on annual mean loads. Without nutrient abatement, D is an identity matrix. With nutrient abatement, the elements of the diagonal are obtained by multiplying the proportion of total land attributable to agriculture, τ_y, by the level of nutrient reduction ϕ_y for each of the seven river clusters and for both N and P (i.e. there are 14 nutrient- and river-specific sources of agricultural land load, denoted by y):

$$D_{y,y} = 1 - \phi_y \tau_y, \quad y = 1,...,14 \qquad [6]$$

In the diffusion part of equation [5], S is a diagonal matrix for the standard deviations of past land loads in the diagonal, Z is a matrix of normally distributed random variables and A is the Cholesky decomposition (matrix square root) of the variance-covariance matrix of the standardized past land loads (see e.g. Fishman 1995, p. 223). The past land loads are spatially correlated and it is assumed that the annual loads covariate in a similar manner also in the future (cf. Elofsson 2003). Historical data on land loads (Table 3) was standardized by subtracting from each observation the average land load and dividing the difference by the standard deviation. Figure 2 illustrates sample projections of land loads and developments of nutrient concentrations. [FIGURE 2 ABOUT HERE]

Component 3: Costs of nutrient abatement

The abatement set consists of reductions in nutrient fertilization, changes in cultivated crops and cultivation methods, reductions in the number of dairy cattle, changes in the cattle diet, and allocation of set-aside land. The abatement costs are derived from a static deterministic non-linear economic watershed model, which provides profit-maximizing solutions for representative dairy and cereal farms (Helin 2009). The abatement cost curve for each farm type is calculated as the difference between unconstrained and constrained optimal profits and for N and P load constraints separately. Thus, we obtain the most cost-efficient abatement path for each nutrient for each farm type. How abatement costs are distributed between the farm types is determined by the curves for each nutrient; the distribution of arable land between the farm types is assumed to be fixed. The economic parameters, such as prices and subsidies, are for the year 2007, and the abatement cost is assumed to be the same for all watersheds of the three basins adjacent to the Finnish coast.

The abatement policies (h) consider reductions of nutrients from the agricultural sector. In addition to the baseline (h=1), where no abatement policy is implemented, we consider policies that obtain cost-efficient nutrient reductions of 30% and 16% for either N (h=2,3) or P (h=4,5). The unit costs of nutrient abatement policies, c_abat_h, are expressed as the average cost reducing 1 kg of either N or P independently of the future developments of the agricultural sector. The unit cost is assumed to remain constant over time. The net present value of the costs of abatement policy, C_h, is approximated by multiplying the unit cost by total nutrient reductions for Finnish rivers and dividing the product by the rate of interest. The equations for policies targeting reductions in N and P are

$$C_h = \frac{c\_abat_h \left[\gamma_{2,1}\left(1-D_{2,2}\right)+\gamma_{3,1}\left(1-D_{3,3}\right)+\gamma_{7,1}\left(1-D_{7,7}\right)\right]}{r},\ h=2,3 \qquad [7]$$

and

$$C_h = \frac{c\_abat_h \left[\gamma_{9,1}\left(1-D_{9,9}\right)+\gamma_{10,1}\left(1-D_{10,10}\right)+\gamma_{14,1}\left(1-D_{14,14}\right)\right]}{r},\ h=4,5\,, \qquad [8]$$

respectively. For the calculation of c_abat_h, the baseline loads and the environmental effects of different abatement measures are derived by meta-modeling the Finnish nutrient process model ICECREAM (Helin et al. 2006, Rekolainen and Posch 1993). The total P load is given as a function of annual runoff, erosion, fertilization and P stock, while N depends more directly on the annual fertilization levels (Uusitalo and Jansson 2002, Uusitalo et al. 2003, Simmelsgaard and Djurhuus 1998). We use the mean weather parameters for the watershed of Kalajoki River in 1996-2007 and assume a mean slope of 1% and mixed soil composition. The nutrient-specific abatement policies and their effects on the non-targeted nutrient are shown in Appendix 1 together with the associated parameter values.

Component 4: Benefits of nutrient abatement

As eutrophication causes damage to the ecosystem, abatement policies reducing this damage increase human well-being. Assessing the monetary value of the benefits of nutrient abatement in the Baltic marine ecosystem is difficult and, for some elements, impossible. Some of the total benefits, such as improved ecosystem services contributing to human well-being, can, however, be estimated. We use two valuation approaches to describe the benefits (the damage) from decreased (increased) eutrophication: the travel cost method and meta-analysis. The travel cost method captures the value of functioning ecosystem services by the expenditures people make on coastal water-related recreation. Meta-analysis, on the other hand, summarizes the results of previous valuation studies on the Baltic Sea to provide an estimate for marine-related amenities. Using two types of valuation methods provides a broader perspective on the reliability of the estimates and enables comparisons between the approaches, a rare opportunity in a cost-benefit analysis.

As opposed to the travel cost method, which analyzes only use values through recreational demand, the meta-analysis includes the non-use values that people place on having a clean and healthy Baltic Sea. Thus, the meta-analysis will indicate somewhat higher values for changes in eutrophication. The two functions also differ in form (Figure 3), which has a significant effect on the results. The value functions describe the benefits (damage) in monetary terms as eutrophication decreases (increases) from its current level. [FIGURE 3 ABOUT HERE]

To estimate the value functions for the level of eutrophication we need to link the nutrient concentrations in the Baltic Sea to eutrophication and to human activities. Practice has shown that Secchi depth can be used as a reasonable proxy for eutrophication (Michael et al. 2000, Helcom 2007). The advantages of using water clarity as an indicator of eutrophication are its simplicity, both in terms of scientific measurement and the observational capability of the general public. On the other hand, water clarity is affected by factors other than eutrophication, and is therefore does correlate completely with eutrophication. We link water clarity to nutrient concentrations using a transfer function.

The data used to formulate the transfer function are those presented in Vesterinen et al. (2008), but the model used is slightly more advanced. The water quality data are taken from the PIVET (State of Finland's Surface Waters) database maintained by the Finnish Environment Institute. The data are from the summer months of years 1998-2002 and 2004 and contain 16,787 quality measurements at a total of 1,487 points along the Finnish coast. The estimated transfer function to describe Secchi depth (*sch*) in m is

$$sch_{i,h,t} = \eta_i + \kappa_{1,i} \ln\left(c^P_{i,h,t}\right) + \kappa_{2,i} \ln\left(c^N_{i,h,t}\right) + \kappa_{3,i} \frac{c^N_{i,h,t} c^P_{i,h,t}}{1000} + \kappa_{4,i}\, temp + \kappa_{5,i}\, depth,\ i = 1,2,3, \forall h,t, \qquad [9]$$

where η_i and $\kappa_{1,i}, \ldots, \kappa_{5,i}$ are estimated parameter values. The water temperature and depth are denoted by *temp* and *depth*, respectively. Figure 4 provides sample projections of average water clarity. [FIGURE 4 ABOUT HERE]

The results from the travel cost study of Vesterinen et al. (2008) are used to describe the value of recreational swimming, fishing and boating on the Baltic coast of Finland. The study estimates the effect of near-home water clarity on water-related recreation and the value of this recreation in Finland. The reported national aggregate value estimates are converted to basin-level estimates by using the relative proportion of the Finnish adult population living along the coast of each basin. Furthermore, since the data suggest that 29% of water-related recreation occurs in inland waters of coastal municipalities, we have subtracted the corresponding proportion from the number of people participating in coastal recreation. The resulting figure – the number of people affected by eutrophication in the Baltic Sea – is 1.53 million. Drawing a distinction between inland and coastal recreation entails an assumption that recreational behavior is identical among the coastal and the general populations.

The results of the travel cost study indicate that near-home water clarity affects swimming and fishing behavior but not boating. Additionally, the data from the study show that in virtually all coastal trips, water recreation types are enjoyed on separate trips: for example boating and fishing are reported as separate activities. Based on this result, we sum up the estimated values for all water-related recreation types in the value function (Figure 3a).

The value function is formed by fitting a hyperbolic equation to the data on the effects of water effects on coastal recreational demand from Vesterinen et al. (2008). The anchoring points for the equation are observations 0.5 m above and below the present average water transparency in each basin. At zero water transparency, we assume, based on the applied results, that swimming and fishing diminish to zero, while boating activity is unchanged. The hyperbolic functional form thus forces the value function to be concave. The annual value of altered recreation possibilities is

$$val_{i,h,t} = \delta_{1,i} + \frac{\delta_{2,i} sch_{i,h,t}}{\delta_{3,i} + sch_{i,h,t}}, \quad i = 1,2,3, \forall\ h,t = 1,...,200 \qquad [10]$$

where $\delta_{1,i}$, $\delta_{2,i}$, $\delta_{3,i}$ are basin-specific parameters (see Appendix 1).

An alternative approach for describing the effects of eutrophication is to construct the value function based on the results of a meta-regression analysis summarizing the findings of existing valuation studies on the benefits of protecting the Baltic Sea (Ahtiainen 2009). The meta-regression enables prediction of the willingness to pay for specific proportional changes in water quality. Willingness to pay estimates are linked to changes in Secchi depth by assuming Secchi depth is an indicator of overall water quality.

The meta-regression indicates higher willingness to pay to prevent losses in water quality than to make improvements in it, a phenomenon referred to as loss aversion (e.g. Kahneman et al. 1991, Tversky and Kahneman 1991). The value function is thus steeper in the domain where the Secchi depth is inferior to the current status (Figure 3b). Willingness to pay is assumed to be zero for a 0% change, and the fitted equation is anchored to observations for 30% and 50% changes in Secchi depth. In order to increase comparability with the travel cost results, the values are estimated for changes which occur in a sea area and primarily affect recreational activities. The values based on the meta-regression are estimated for both the adult coastal population (2.15 million) and for the total adult population in Finland (4.2 million).

The sigmoidal value function based on the metadata is

$$val_{i,h,t} = \vartheta_{1,i} + \frac{\vartheta_{2,i}}{1+e^{-\left(sch_{iht} - \vartheta_{3i} \middle/ \vartheta_{4i} \right)}}, \quad i = 1,2,3, \forall\, h,t \qquad [11]$$

where $\vartheta_{1,i}, \ldots, \vartheta_{4,i}$ are basin-specific parameters (Appendix 1).

The total benefits (B) from improved water quality are obtained by discounting the differences in damage to water quality between "no policy" and "abatement policy" over the first 200 years and assuming that the difference in annual damage remains the same thereafter:

$$B_h = \sum_{i=1}^{200} \left(val_{i,h,t} - val_{i,1,t} \right) e^{-rt} + \frac{val_{i,h,200} - val_{i,1,200}}{r} e^{-200t} \quad h = 2,\ldots,5 \quad [12]$$

Figure 5 provides sample paths for the development of abatement benefits in the Gulf of Finland. [FIGURE 5 ABOUT HERE]

Synthesis of components: Cost-benefit analysis

The net present value is the relevant selection and ranking criterion of environmental projects in cases where there are no other investment outlets competing for the same funds, that is, when the government can borrow any amount of money to finance an environmental project. In such a case, the magnitude of the projects being compared does not matter: the abatement policy yielding the highest expected net present value would be the rational choice for a risk-neutral social planner. However, the state budget may be fixed, with projects in different sectors (e.g. health care, education, public transport) competing for limited funds, whereby the benefit-cost ratio may become an appropriate criterion for ranking alternative projects. The net present value (*NPV*) and benefit-cost ratio (*BC*) of investing in water quality are obtained by

$$NPV_h = B_h - C_h, \quad h = 2,\ldots,5 \qquad [13]$$

$$BC_h = \frac{B_h}{C_h}, \quad h = 2,\ldots,5. \qquad [14]$$

Computation of the results comprises of three steps. First, the time paths of damage are simulated for baseline development and four alternative abatement policies in order to calculate the net present values [13] and benefit-cost ratios [14] for a single random sample of land loads [5] and the development of nutrient concentrations in the Baltic Proper [4]. Second, these computations are repeated 500 times, each time drawing new sample paths of riverine loads and concentrations in the Baltic Proper in order to establish an estimate for the probability distribution and expected values of *NPVs* and *BCs*. Third, a sensitivity analysis is conducted for the valuation method (travel cost [9] or meta-regression [10]), population affected, rate of interest, level of international involvement in nutrient abatement and development of average nutrient concentrations in the Baltic Proper [4]. The rates of interest cover a wide range, including the very low rate (r=0.1%) which was applied in the

Stern Review (Stern 2007). The discount rates used in evaluating public projects in Finland are around 5%, which is the default interest rate (r=0.051) applied in our analysis.

3 RESULTS

[TABLE 4 ABOUT HERE]

The expected net present values and benefit-cost ratios for different abatement policies, rates of interest, valuation approaches, and levels of international involvement are shown in Table 4. The baseline simulations (the first 12 rows in Table 4) assume that only Finland invests in nutrient abatement. The remaining computations assume that the other countries in the northern Baltic Sea (Sweden, Russia, and Estonia) are also committed to nutrient abatement in that they will reduce their nutrient loads in the same proportion as Finland does. However, it should be noted that the benefits and costs are shown for Finland only.

Profitable environmental investments are indicated in bold for both decision criteria in Table 4. None of the alternative policies become economically profitable if Finland makes plans to reduce land loads alone and the benefit estimates are based on coastal population only. Reductions in P load from the Finnish agriculture become rational only if the neighboring countries are committed to similar reductions and if the benefit estimate is based on a large array of ecosystem services such as that included in the meta-regression. A large reduction in P load (30%) is optimal when using the net present value as a ranking criterion and for interest rates of 2.6% or larger. However, an environmental project aiming at a smaller reduction in P load (16%) is likely to be more competitive with other public projects due to its higher BC.

Table 4 also illustrates the effect of the population considered. In addition to the estimates for the adult population living on the coast (2.15 million), meta-regression benefit estimates are derived for the total adult population in Finland (4.2 million). The latter estimates assume that all Finns appreciate the benefits of recreation and ecosystem services of the Baltic Sea in a similar manner irrespective of their place of residence. Where this is the case, national investments in improving water quality clearly become more profitable. A smaller reduction in P load (16%) becomes beneficial for Finland even if its neighbors do not participate in abatement. Also, a larger reduction in P load (30%) becomes relatively more attractive if the neighbors are committed to similar reductions. However, neither a 16% nor 30% reduction in N (not shown) turns out to be economically attractive even when using the highest damage estimate. This reflects the higher costs of N abatement technologies relative to those optimal for abatement of P.

The valuation functions (Figure 3) and time paths of abatement benefits (Figure 5) determine how changes in the rate of interest affect the profitability of an environmental investment. With travel cost data, the expected benefits from abatement tend to increase with time (Figure 5), whereby investments in water quality become more profitable at higher rates. In contrast, with meta-regression data the expected benefits from nutrient abatement are highest over the first decades and gradually decrease thereafter (Figure 5), a trend attributable to the damage function being concave with respect to reductions in water clarity (Figure 3b). As a consequence, the environmental investments in water quality tend to be more profitable at lower rates of interest (Table 4).

The N and P concentrations of the Baltic Proper are important determinants of the nutrient budgets of other basins in the northern Baltic Sea due to the extensive exchange of water. The annual variation and the trends in concentrations of the largest basin reflect the land loads from the Baltic and Central European countries (Poland in particular) and occasional "salt pulses" from the Atlantic Ocean. Table 5 shows how assumptions about the future development of N and P concentrations in the Baltic Proper affect the profitability of environmental projects in Finland. Parameter β represents the speed of change, and parameter α the proportional increase in nutrient concentrations when comparing the present level and the long-run equilibrium. According to the results, investments in reducing the nutrient load from the watersheds of the northern Baltic Sea become economically more attractive, the lower the long-term average nutrient concentration of the Baltic Proper is. Also, the slower the speed at which concentrations increase in the Baltic Proper, the more profitable are the investments in water quality in Finland. [TABLES 5 AND 6 ABOUT HERE]

The results regarding the feasibility of environmental investments on water quality have been shown so far at the national level. In Table 6, the net present values and the benefit-cost ratios are shown by basin when the same abatement policy is applied uniformly in all regions (note also that the unit costs of abatement are assumed to be the same for all regions). Table 6 suggests that the nutrient abatement yields much higher returns for areas adjacent to the Bothnian Bay (BB) and the Gulf of Finland (GoF) than for the coastline of the Bothnian Sea (BS). Reduction of nutrient loads from agriculture is an effective means to improve the quality of the Bothnian Bay because land loads from the Finnish rivers represent a high proportion of the total nutrient inputs. In addition, the exchange of water with the other basins is small. On the other hand, the size of the coastal population (and hence the benefit) is small along the Bothnian Bay. In the Gulf of Finland, land loads from the Finnish rivers represent only a tiny share of total loads, but the relative size of the coastal population is much higher, yielding greater benefits. In the case of the Bothnian Sea, the relative size of the population and the share of nutrient loads from the Finnish rivers are both small and the environmental investment in water quality does not prove profitable. If Finland is the only country investing in nutrient abatement, investments in the Bothnian Bay give the highest return.

However, if the neighboring countries are also committed to abatement, investments in the Gulf of Finland give the most profitable.

There are large differences between the basins in how national and international nutrient abatement efforts may affect the water quality. According to our simulations, it is possible to improve the mean sight depth of the Bothnian Bay by 3-15 cm by investing in reducing Finnish agricultural nutrient runoff. However, joint efforts between Sweden and Finland could improve the water clarity of the Bothnian Bay by up to 30 cm over the baseline development. In the Gulf of Finland, Finnish investments would improve water quality by less than 1 cm. This improvement in water clarity and the consequent benefits would be negligible compared to the weather-induced annual variation in water clarity. However, if neighboring countries, including Russia and Estonia, participated in the abatement, the mean clarity of the Gulf of Finland could be improved by up to 7 cm over the baseline development.

4 DISCUSSION AND CONCLUSIONS

We have presented a stochastic dynamic simulation model capturing the ecological and economic features of eutrophication that are necessary for the evaluation and design of nutrient abatement policies. Non-point source pollution from agriculture is modeled by stochastic nutrient loads, which fluctuate according to weather shocks. Elaboration and utilization of this model feature is particularly important in future work as climate change is likely to increase the variance in land loads and algal growth conditions, and may increase the damage substantially.

The results suggest that national investments in reducing the nutrient runoff from Finnish agricultural lands become profitable only if Finland’s neighbors in the northern Baltic Sea commit themselves to similar reductions. This result is well in line with earlier studies that have investigated optimal allocation of abatement activities between countries. Investments in sewage treatment plants and reductions in other point sources (e.g. Turner et al. 1999) or non-point sources (Elofsson 2003) in the Russian and Polish coastal zones typically turn out to be the most profitable means to improve the overall state of the Baltic Sea.

The critical factors affecting the profitability of investment in abatement are the costs of the best nutrient abatement activities, the effectiveness of nutrient abatement on seawater quality, and the proportion of the population benefiting from recreation and ecosystem services. Our results suggest that Finnish investments in agricultural abatement would be most profitable in the case of either the Bothnian Sea, where abatement would have a strong effect despite the small population, or the Gulf of Finland, where abatement would be less effective but the population density is higher. Where the

Bothnian Bay is concerned, the coastal population and the projected effectiveness of abatement activities on water quality are small, making investments in water quality unprofitable.

However, it should be noted that, contrary to the assumption in our basin-oriented model, ecosystem values are not evenly distributed over the entire sea basin. For example, recreational use of the sea is highly concentrated in coastal waters. In this light, even though Finnish investments in improving the overall state of the Bothnian Sea would not be profitable according to our computations, nutrient abatement may be economically justified in critical watersheds and rivers discharging their waters into the recreationally most important marine areas. For example, Pitkänen et al. (2007) illustrate that algae biomass in the Finnish Archipelago could be substantially reduced by reducing the nutrient runoff from Finnish rivers alone.

The abatement cost estimates contain detailed information on the measures available to Finnish agriculture. Although the simulated costs rely on parameters from a single Finnish sub-basin, the framework applied can be spatially extended to any other Finnish watershed or combined with national average parameters. The current parameterization would lead to a reduction in phosphorus through changes in crop cultivation methods on both dairy and cereal farms. Cost-efficient nitrogen reduction turned out to be more expensive than phosphorus reduction. According to the results, nitrogen reductions could mainly be achieved by reducing fertilization. The optimal combination of abatement means and the result that relative reductions in P loads are less expensive than reductions in N loads are in line with corresponding Swedish studies (Brady 2003, Elofsson 2003).

The baseline in the abatement cost calculations includes subsidies for agricultural production with the exception of the environmental subsidy system. Including all the effects of the environmental subsidy system would require even more detailed modeling and introduce a bias in favor of a particular policy into the results on abatement costs. Hence, the abatement costs should be interpreted with care: the baseline optimal solution does not have a one-to-one correspondence with the agricultural practices currently observed in Finland. Furthermore, the abatement cost analysis would benefit from a dynamic element incorporating the phosphorus stock in soil and the future structural trends of agriculture into the abatement cost calculation.

The analysis conducted in this study represents the first attempt to link benefit functions to a dynamic modeling framework for the entire Finnish coastline. We provide two distinct approaches for valuing the changes in Secchi depth and thus provide novel estimates for the monetary effects of eutrophication in the Baltic Sea. Interestingly, the value functions differ in their functional forms and the results are sensitive to the approach chosen.

The valuation of the effects of eutrophication could be further developed to obtain more comprehensive benefit estimates. At this stage, the value functions presented reflect merely part of the total economic value of the Baltic marine ecosystem services. However, the travel cost estimates represent a conservative lower bound to the value of water recreation in Finland, and the meta-data provides an estimate of marine-related use and non-use values. The constructed value functions are less reliable for extreme conditions in the Baltic Sea, which is an issue requiring further study. In addition, the analysis would benefit from more specific descriptions of the causes and effects of eutrophication that take into account temporal and spatial variation. Another challenge is to construct the link between nutrient concentrations and damage, which will require further ecological modeling to become more accurate.

The framework developed in this paper allows a wide variety of possibilities to develop the analysis further. An interesting issue for future research is the spatial and socio-demographic distribution of water conservation costs and benefits. In particular, it is essential to identify the population groups that perceive high water quality as extremely or even immeasurably important. By identifying these groups, we may attempt to find ways to compensate them for their losses.

The focus in this study has been on the agricultural abatement costs. The perspective could be widened to other polluting sources, such as forestry, municipal wastewaters and urban settlements. However, the temporal and spatial boundaries of the analysis present challenges when estimating the policy effects (e.g. Hanley 2001). The incompleteness of an analysis always leaves room for political decision-making in the evaluation of omitted effects. An extensive cost-benefit analysis, such as the one presented in this study, provides organized information on the benefits and costs of an environmental project but cannot be applied as a rule to inform decision-making.

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Appendix 1. Parameter values

Eqs. [1]-[3]: Nutrient balance (source: Baltic Nest Institute 2008)

Basin, i=1…4	Atmospheric deposition *(ton)*		Nitrogen fixation *(ton)*	Burial *(ton)*		Denitrification *(ton)*	Int. loading of P *(ton)*	Initial concentration *(µg/l)*		Water volume *(km³)*	Annual flows of water from basin *i* *(km³)* to:			
	A_i^N	A_i^P	F_i	B_i^N	B_i^P	D_i	I_i	c_{i0}^N	c_{i0}^P	V_i	BB	BS	GoF	BP
1 (BB)	10584	562	0	3964	4086	16987	0	298	6.2	1441	0	290	0	0
2 (BS)	32636	1178	17574	10674	8461	88063	400	262	16	4485	173	0	0	1237
3 (GoF)	15394	445	18073	9911	4118	64421	2800	343	25	1100	0	0	0	554
4 (BP)								272	25		0	1009	435	0

BB=Bothnian Bay, BS=Bothnian Sea, GoF= Gulf of Finland, BP=Baltic Proper

Eq. [4]: Development of nutrient concentrations in the Baltic Proper (sources: Savchuk 2005, expert opinion):

	N	*P*
α	0.3	0.3
β	0.03	0.03
σ	0.05	0.135

Eq. [6]: Shares of agriculture in total land loads (source: Helcom 2005)

basin i	N, τ_y	P, τ_y
1 (BB)	0.417 (y=1,2)	0.382 (y=8,9)
2 (BS)	0.438 (y=3,4)	0.399 (y=10,11)
3 (GoF)	0.359 (y=5,6,7)	0.443 (y=12,13,14)

Eqs. [6] - [8]: Nutrient reductions, ϕ_y , and unit costs, *c_abat*$_h$ (in parentheses), for different abatement policies (*h*) (sources: Helin et al. 2006, Helin 2009)

Abatement Policy	h=2 (N30) $\phi_y, y = 1,...,7$	h=3 (N16) $\phi_y, y = 1,...,7$	h=4 (P30) $\phi_y, y = 8,...,14$	h=5 (P16) $\phi_y, y = 8,...,14$
N	0.30 (13.70 €/Nkg)	0.16 (5.70 €/N Kg)	0.02	0.02
P	0.035	0.035	0.30 (32.91 €/P Kg)	0.16 (22.04 €/P kg)

Eq. [9] Water clarity (parameters derived from the data in Vesterinen et al. 2008):

basin i	η_i	κ_1	κ_2	κ_3	κ_4	κ_5
1 (BB)	8.099	-1.401	-0.506	0.023	0	0.019
2 (BS)	15.602	-1.82	-1.612	0.052	0.032	0.025
3 (GoF)	11.146	-1.254	-0.809	0.007	-0.042	0.031

temp = 20, depth = 15

Eq. [10]: Value function based on recreation possibilities (Vesterinen et al. 2008)

basin i	δ_{1i}	δ_{2i}	δ_{3i}
1 (BB)	-146.4	199.1	1.06
2 (BS)	-182.3	244.1	0.959
3 (GoF)	-397.1	485.9	0.448

Eq. [11]: Value function based on meta-regression and adult coastal population (Ahtiainen 2009)

basin i	ϑ_{1i}	ϑ_{2i}	ϑ_{3i}	ϑ_{4i}
1 (BB)	-42.9	73.4	2.89	0.303
2 (BS)	-53.4	91.4	2.77	0.291
3 (GoF)	-116.6	199.4	2.01	0.211

Table 1. Past and predicted developments of the agricultural sector in Finland

Indicator	1950s	1960s	1970s	1980s	1990s	2006/7	2020s	2050s
Subsurface draining (1000 ha/year)	23	34	38	33	8	5	5	5
Clearing of arable land (1000 ha/year)		10	4	7	7	7	12	9
Afforestation of arable land (1000 ha/year)			7	4	10	2	6	5
Total area of agricultural land (1000 ha)	2462	2669	2589	2453	2222	2295	2410	2525
Meadows (1000 ha)		153	146	138	25	34	35	35
Yield of barley (kg/ha)	1650	1980	2570	3150	2700	3500	4000	4500
Fallows and cultivated arable land (1000 ha)		249	290	401	720	230[a]	390	290
Artificial fertilization of N (kg/ha)		69	83	111	84	74	86	74
Artificial fertilization of P (kg/ha)		31	28	30	10	8	5	5
Silage/hay (1000 ha)		1050	943	682	664	654	650	700
Number of cows (1000)	1200	1000	730	490	370	309	230	240
No of estates (1000)		297	229	129	88	69	48	25
Average farm area (ha)	8	10	12	17	26	33	50	100
No of milk estates (1000)	243	210	98	48	24	15	6	2
No of estates on grain cultivation (1000)		80	112	47	41	41	36	15
Lime for soil improvement (kg/ha)	122	150	193	488	376	303	400	450
Use of pesticides (g/ha)				850	500	650	700	700
No of tractors (1000)			234	208	170	175	150	100
No of horses (1000)	300	92	32	42	56	66	82	82
No of pigs (1000)		600	1000	1500	1300	1400	1200	1200

[a] Set-aside fields that are not entitled to agricultural support (about 100,000-150,000 ha) are not included

Table 2. Mean land loads of nutrients now and after 20 and 50 years

	Total P (tons/year)			Total N(ton/year)		
Nutrient source	2008	2028	2058	2008	2028	2058
Rivers from Sweden to Bothnian bay	1 104	950	900	19 273	20 000	19 000
Rivers from Finland to Bothnian bay	1 805	1 600	1 400	29 326	33 000	30 000
Rivers from Finland to Bothnian sea	1 550	1 500	1 800	24 716	35 000	33 000
Rivers from Sweden to Bothnian sea	1 232	900	880	30 278	23 500	23 000
Rivers from Finland to Gulf of Finland	605	600	450	13 091	12 000	11 500
Rivers from Russia to Gulf of Finland	4 174	5 500	7 000	76 733	85 000	90 000
Rivers from Estonia to Gulf of Finland	779	1 000	1 150	18 210	20 000	21 000

Table 3. Statistical data on land loads of total nitrogen and phosphorus (tons/year)

	Nitrogen							Phosphorus						
	Bothnian Bay		Bothnian Sea		Gulf of Finland			Bothnian Bay		Bothnian Sea		Gulf of Finland		
	Sweden	Finland	Finland	Sweden	Finland	Russia	Estonia	Sweden	Finland	Finland	Sweden	Finland	Russia	Estonia
	$y=1$	$y=2$	$y=3$	$y=4$	$y=5$	$y=6$	$y=7$	$y=8$	$y=9$	$y=10$	$y=11$	$y=12$	$y=13$	$y=14$
1986	17610	28865	27463	31297	13229	104135	29414	1106	1672	1668	1255	703	4301	507
1987	18514	28683	20274	33908	14331	109897	31345	1142	2073	1417	1540	658	2824	753
1988	16764	27771	28776	26351	15556	84847	17273	1060	1676	1870	1253	679	5007	984
1989	17106	31830	23656	27147	14931	54565	13730	1416	2185	1402	1264	646	3414	812
1990	15219	19399	29847	27065	15149	69524	19326	822	1250	1675	1134	571	3893	801
1991	17652	29807	24378	25645	13592	77610	18479	990	1830	1496	1183	607	4239	697
1992	19325	38644	28222	29412	15408	82906	19110	1157	2336	1490	1132	664	4282	696
1993	19808	28727	19333	34830	10653	71516	16325	1227	2091	1137	1510	529	4971	614
1994	15212	22428	19188	23382	11261	74242	13692	908	1592	1208	962	606	3976	979
1995	19463	26029	22463	33686	12519	80358	15490	1154	1642	1330	1335	567	4239	843
1996	17644	23488	19937	21539	11566	63932	11556	641	1221	1223	580	582	4073	480
1997	18733	25655	20590	26460	8968	63752	13200	1458	1541	1107	1107	428	4140	647
1998	27049	39461	26790	43643	13296	69860	22260	1232	2210	1479	1206	648	4353	891
1999	21636	26374	24451	27771	12021	75924	18227	924	1551	1599	1380	562	4640	1324
2000	27366	42726	35375	42042	13885	67931	13720	1328	2199	3144	1637	621	4261	662
Aver.	19273	29326	24716	30278	13091	76733	18210	1104	1805	1550	1232	605	4174	779
st.dev.	3632	6504	4676	6359	1920	14646	5722	222	357	490	255	69	545	213

Source: Baltic Nest Institute 2008

Table 4. Cost-benefit analysis for different abatement policies, valuation approaches, rates of interest and international involvement

International involvement	valuation approach	r	Expected NPV, million € N16	P30	P16	Expected B/C-ratio N16	P30	P16
Finland only	Travel cost coastal population	0,1 %	-24365	-12915	-4116	0,04	0,17	0,26
		2,6 %	-942	-503	-162	0,03	0,16	0,24
		5,1 %	-482	-261	-85	0,03	0,14	0,22
	Metadata coastal population	0,1 %	-23799	-9767	-2582	0,06	0,38	0,55
		2,6 %	-882	-275	-44	0,09	0,54	0,79
		5,1 %	-448	-139	-21	0,10	0,54	0,80
	Metadata total population	0,1 %	-22319	-4040	**360**	0,12	0,75	**1,08**
		2,6 %	-795	**29**	**116**	0,18	**1,05**	**1,55**
		5,1 %	-402	**17**	**61**	0,19	**1,06**	**1,56**
Finland, Sweden Russia, Estonia	Travel cost coastal population	0,1 %	-22201	-7648	-1223	0,12	0,51	0,78
		2,6 %	-874	-339	-72	0,10	0,43	0,66
		5,1 %	-452	-189	-46	0,09	0,38	0,58
	Metadata coastal population	0,1 %	-21421	-1796	**1329**	0,15	0,88	**1,23**
		2,6 %	-705	**203**	**203**	0,28	**1,34**	**1,96**
		5,1 %	-345	**124**	**117**	0,31	**1,41**	**2,08**
	Metadata total population	0,1 %	-17643	**11487**	**7974**	0,30	**1,73**	**2,42**
		2,6 %	-450	**963**	**599**	0,54	**2,63**	**3,84**
		5,1 %	-200	**531**	**331**	0,60	**2,76**	**4,08**

Table 5. The effects on the profitability of environmental investment in Finland of assumptions regarding the long-term steady-state nutrient concentrations in the Baltic Proper (α) and the speed of change (β)

		Net present value, million €			benefit-cost ratio		
α	β	N16	P30	P16	N16	P30	P16
-0.1	0.01	-296	**214**	**175**	0.40	**1.70**	**2.60**
-0.1	0.03	-293	**213**	**176**	0.41	**1.70**	**2.61**
-0.1	0.05	-291	**214**	**177**	0.41	**1.70**	**2.62**
0.3	0.01	-317	**184**	**153**	0.36	**1.60**	**2.40**
0.3	0.03	-345	**124**	**117**	0.31	**1.41**	**2.08**
0.3	0.05	-361	**84**	**95**	0.27	**1.27**	**1.85**
0.7	0.01	-344	**123**	**117**	0.31	**1.40**	**2.07**
0.7	0.03	-393	-8	**46**	0.21	0.97	**1.42**
0.7	0.05	-416	-70	**13**	0.16	0.77	**1.12**

Assumptions: Valuation is based on meta-regression data and the coastal adult population. All countries in the upper Baltic sea (Sweden, Finland, Russia and Estonia) participate in abatement.

Table 6. Cost-benefit analysis of abatement investments by basin

International	valuation		Expected NPV, million €			benefit-cost ratio		
involvement	approach	Basin	N16	P30	P16	N16	P30	P16
Finland only	Travel cost	BB	-212	-101	-30	0.03	0.24	0.36
		BS	-188	-112	-38	0.03	0.06	0.10
		GoF	-82	-48	-16	0.03	0.08	0.13
Finland only	Metadata	BB	-194	-5	**19**	0.11	0.95	**1.37**
		BS	-178	-95	-29	0.08	0.20	0.31
		GoF	-75	-37	-10	0.10	0.29	0.46
Finland, Sweden Russia, Estonia	Travel cost	BB	-208	-81	-20	0.05	0.39	0.59
		BS	-184	-107	-36	0.05	0.10	0.17
		GoF	-59	-1	**10**	0.29	0.98	**1.52**
Finland, Sweden Russia, Estonia	Metadata	BB	-179	**80**	**62**	0.18	**1.59**	**2.28**
		BS	-165	-79	-20	0.15	0.34	0.53
		GoF	**0**	**127**	**77**	0.99	**3.41**	**5.10**

Assumptions: Valuation is based on the coastal population only.

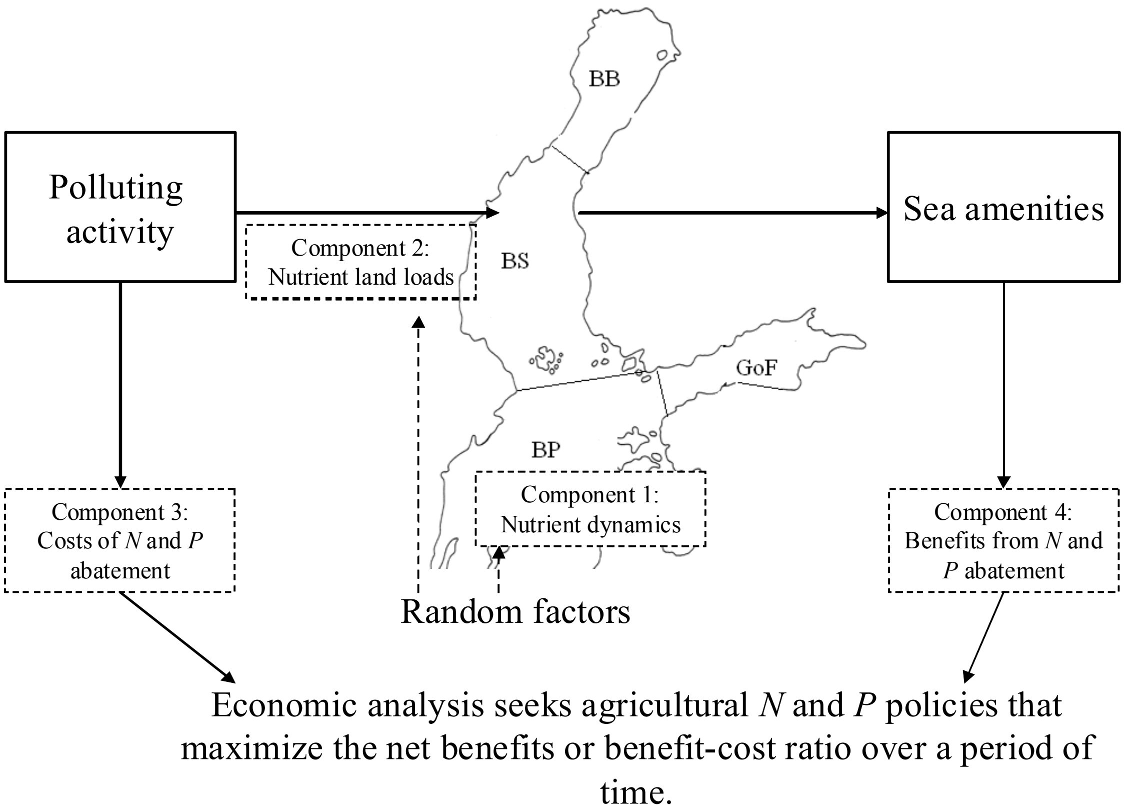

FIG. 1. Framework for the application of economic methods to management of eutrophication.

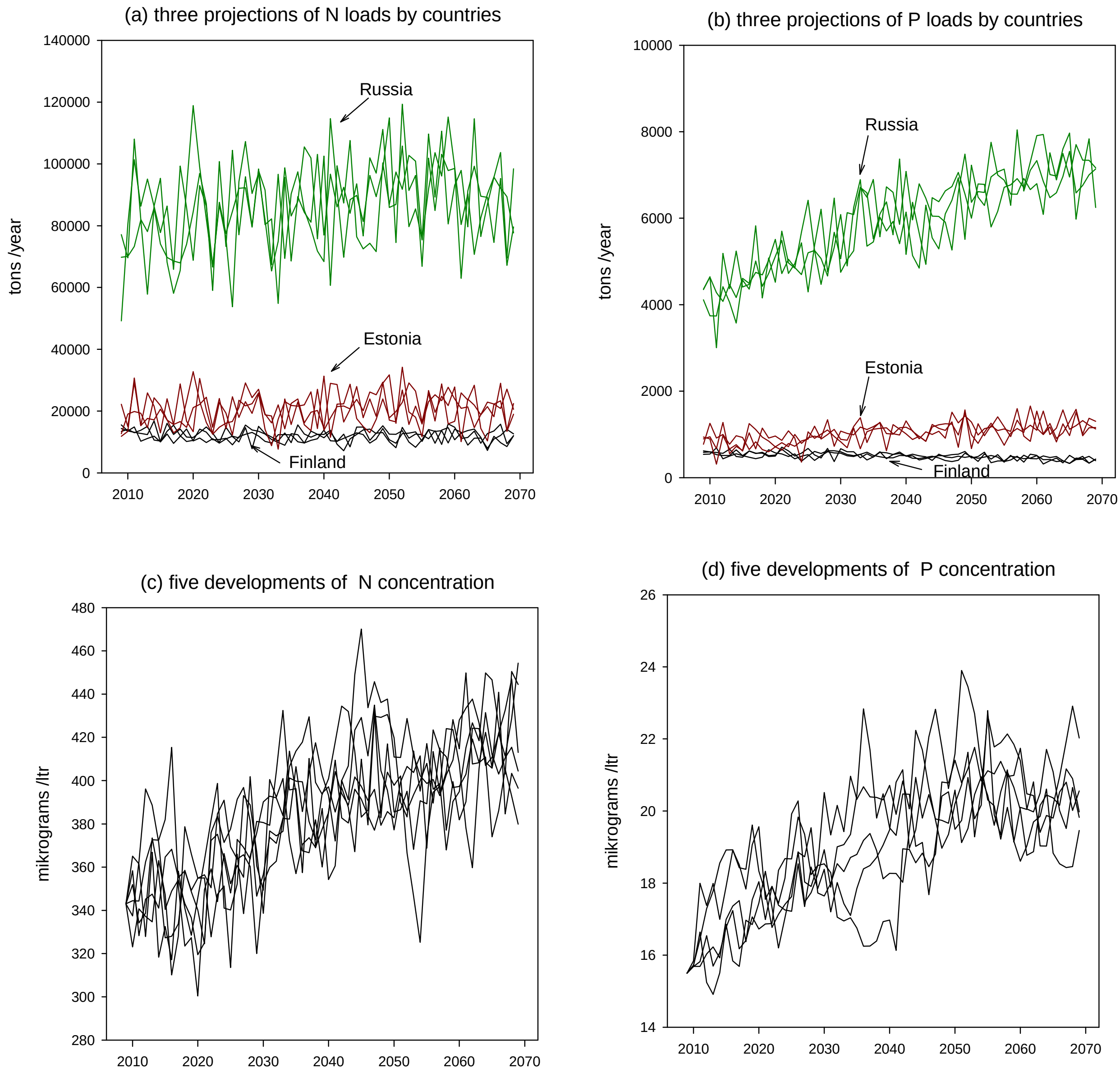

Figure 2. Baseline projections of land loads and developments of nutrient concentrations over the next 60 years in the Gulf of Finland.

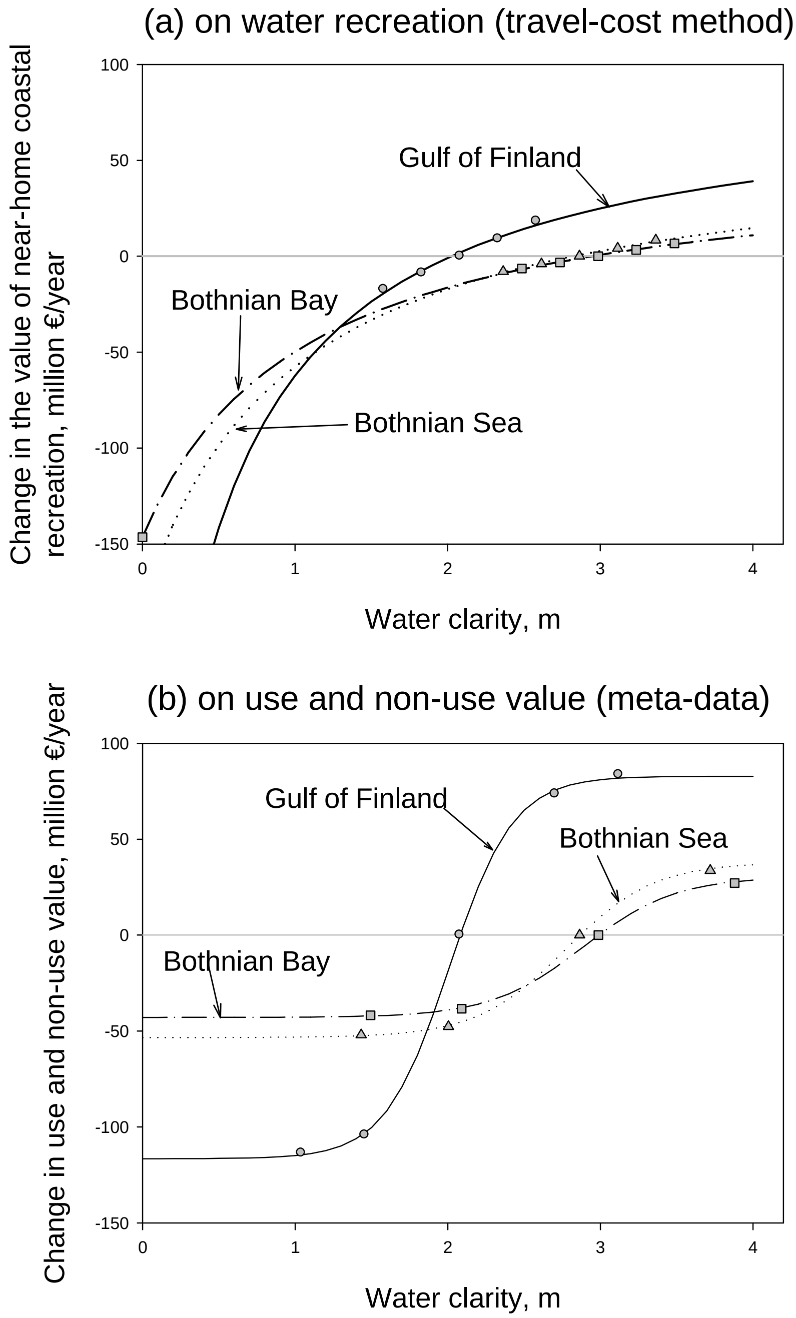

Figure 3. The effect of altered water clarity

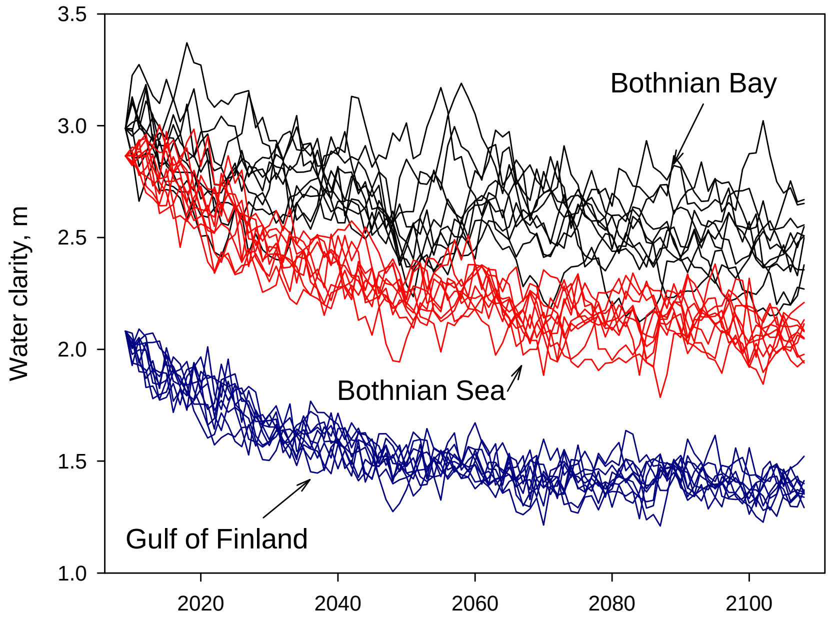

Figure 4. Ten baseline projections for average water clarity in the three basins.

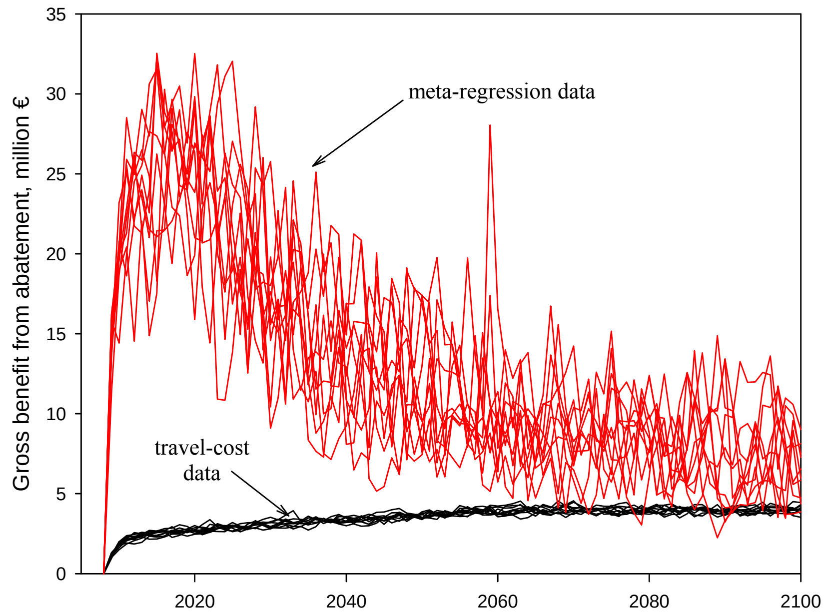

Figure 5. Ten sample paths for abatement benefits in the Gulf of Finland for a 30% reduction in *P* loads. Assumption: All countries in the upper Baltic Sea reduce nutrient loads in the same proportion.

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