Combating eutrophication in coastal areas at risk for oil spills

Hyytiäinen, Kari and Huhtala, Anni

6 April 2011

Combating eutrophication in coastal areas at risk for oil spills

Kari Hyytiäinen and Anni Huhtala

MTT Agrifood Research Finland, Latokartanonkaari 9, FI-00790 Helsinki, Finland

Forthcoming in *Annals of Operations Research,* available online since April 6, 2011

`DOI 10.1007/s10479-011-0879-2`

emails: kari.hyytiainen@mtt.fi

anni.huhtala@vatt.fi

ABSTRACT

In this study we evaluate the profitability of nutrient abatement measures in eutrophied coastal areas exposed to a risk of frequent oil spills. The case studied is the Gulf of Finland, which forms part of the Baltic Sea. We present a dynamic model that integrates land loads of nitrogen and phosphorus, cost of nutrient abatement measures in agriculture, nutrient dynamics in the sea basins adjoining the Finnish coast, exogenous risk of oil spills, and recreational value of the sea, which faces environmental damage of uncertain magnitude and duration. Monte Carlo simulation is applied to evaluate the profitability of nutrient abatement measures carried out unilaterally by Finland or as a joint effort by Estonia, Finland and Russia. We demonstrate that a high exogenous risk of oil damage may render investments in nutrient abatement economically infeasible. On the other hand, several components of the model entail uncertainties owing to the scarcity of data and our limited understanding of the relationship between the ecological processes involved and the values people place on natural resources. For example, the uncertainties related to the curvature of the value function outweigh the uncertainties connected with the oil spills and their potential consequences.

Keywords: nutrient abatement measures, probability, Monte Carlo simulation, recreation, valuation

1 INTRODUCTION

Coastal ecosystems all over the world are exposed to a variety of threats: oil spills, hazardous substances, invasive species, and excess loads of eutrophying nutrients (Brown et al. 2006). Several risks and threats posed by human activities make analysis of marine environmental policy complicated and social management difficult. There is inherent uncertainty related to stochastic generation of polluting discharges, the dynamics of pollution and the ultimate impacts of pollutants on people and ecosystems.[1] The challenges of environmental management are pronounced in coastal and watershed areas shared by several countries.

In this paper, we consider two types of pollution processes affecting water quality: eutrophication and oil spills. We investigate how unilateral or joint actions undertaken by countries to abate nutrients are affected by an exogenous risk of a tanker accident that spoils recreational use of a marine environment. The case study focuses on the Gulf of Finland in the Baltic Sea. The gulf is an area of brackish, shallow water the coastline of which is shared by three countries: Estonia, Finland and Russia. It is among the most heavily eutrophied sub-basins of the Baltic Sea and is increasingly vulnerable to severe oil spills due to intense marine traffic.

To date there has not been a major oil spill in the Baltic Sea, and the potential damage of a spill to ecosystems and societies in the region is not well understood. Previous studies of tanker accidents in other marine areas have valued the ex-post damage of major oil spills: the Amoco Cadiz in France (Grigalunas et al. 1986), the Exxon Valdez in Alaska (Hausman et al. 1995; Carson et al. 2003) and the

---

[1] For a pollution in a stochastic, dynamic setting see, e.g., Plourde and Yeung 1989, Keohane et al. 2007.

Prestige in the coastal zones of Galicia in Spain (Loureiro et al. 2006, 2009). The literature also contains studies investigating the costs of cleaning up marine oil spills (Etkin 2000), the impacts of monitoring on the occurrence of oil spills (Grau and Groves 1997), and the efficiency of spill reductions (Kim 2002). Brown and Savage (1996) use a cost-benefit analysis to study the double hull requirement for oil tankers in US waters, a change prompted by the Oil Pollution Act of 1990 in response to the Exxon Valdez incident. Most of the earlier studies employ data on past incidents. The probabilities of damage and its expected consequences on ecosystems and human beings can be evaluated by simulation models (see e.g. French McCay et al. 2004, van de Wiel and van Dorp 2009), but applications of such models in economic analyses are still rare.

In contrast to the scanty scholarship on oil spills, there is an extensive literature on analyzing the management of eutrophied waters. The Baltic Sea is a typical example of an international water body that has suffered from severe pollution for decades. Several deterministic studies have proposed least-cost or optimal solutions for nutrient abatement measures for the entire Baltic or some of its sub-basins (Byström 2000, Brady 2003, Gren 2001, Ollikainen and Honkatukia 2001, Elofsson 2003, Hart and Brady 2002, Laukkanen and Huhtala 2008). The analyses of Gren et al. (2000), Elofsson (2003), Gren (2008) and Kataria et al. (2010) have incorporated stochastic pollutant transports and agricultural loads, but the management of eutrophication in waters subject to other environmental threats, such as major oil spills, would require additional stochastic elements in the policy analysis. To our knowledge, the impacts of a potential oil spill on the profitability of nutrient abatement measures have not been examined in an economic analysis before.

In this paper, we address this shortcoming by extending a model applied for the evaluation of nutrient abatement measures undertaken in Finnish agriculture to protect the Baltic Sea (Hyytiäinen et al. 2009). We focus on agricultural nutrient abatement, because it is considered as the most important means to reach the water protection targets set for Finland (Helcom 2003). In the model, the development of nutrient concentrations is described as a stochastic process in which the nutrient concentrations of the current period and the nutrient inputs and outputs between various sources and sinks (e.g. between basins, air, and sediment processes) determine the concentrations of the next period. The risks and uncertainties related to oil spills are modelled in three separate terms that capture (1) the annual probability of large-scale damage from an oil spill, (2) variability in the magnitude of the damage as measured by change in recreational value, and (3) expected duration of the damage.

In our analysis, Monte Carlo simulations illustrate the use of the model for evaluation of target levels of nutrient abatement and their ranking in terms of net benefits. Two cases for nutrient abatement are considered: (1) Finland makes a unilateral nutrient abatement decision independently of the decisions of neighbouring countries and (2) Estonia, Finland and Russia, which share the coastline of the Gulf of Finland, jointly reduce their nutrient loads by the same ratio. Since Finland cannot control the exogenous risk of tanker accidents and oil spills, we deliberately limit the analysis to the effects that the costs and benefits of abatement measures cause to the Finnish economy and society. This provides us evidence on incentives for unilateral actions and for international agreements for environmental protection, matters which have been discussed widely in the context of global environmental problems (see, e.g., Hoel 1991). A sensitivity analysis is carried out for different target levels of nutrient abatement, the annual risk of major oil spills, the duration and the magnitude of the expected damage, and the shape of the value function of recreation in response to the changes in water quality in the Gulf of Finland.

The rest of the paper is organised as follows. The next section presents the structure and components of the simulation model as well as the data used in the specification of the model. The two types of water pollution processes – nutrient enrichment and occurrence of oil spills – are described to identify damage that can be valued and expressed in monetary terms and are thus commensurable with the cost of abatement measures. The third section shows how the economic profitability of the unilateral actions of one country or joint actions of several countries to combat eutrophication depend on the likelihood of an oil accident. The net benefits of nutrient abatement decrease and may ultimately prove negative when the probability and impacts of oil spills increase to a sufficiently high level. In the concluding section, we emphasize that improving the management of the coastal areas requires analyses that simultaneously tackle all important environmental threats.

2 SIMULATION MODEL

For the analysis, we need a dynamic model that describes the economic consequences of degradation of the marine environment. The model consists of four components: 1) nutrient stock dynamics in the selected sea basins, 2) stochastic loads of nutrients from land and other sources, 3) the cost of agricultural nutrient abatement measures, 4) the benefits of nutrient abatement to Finnish citizens, including the probability and consequences of major oil spills. The exchange, dynamics and loads of nutrients (components 1-2) are described for all the Baltic Sea basins adjoining the Finnish coast. The costs and benefits of nutrient abatement measures and the probability and the consequences of an oil spill (components 3-4) are described for the Gulf of Finland and the related Finnish watershed areas only. The cost-benefit analysis is conducted from a national point of view in that only the benefits and costs accruing to the Finnish government and the citizens are considered.

2.1 Nutrient dynamics

The marine areas adjoining the Finnish coast are divided into three basins: the Bothnian Bay (i=1), the Bothnian Sea, including the Swedish and Finnish archipelago (i=2), and the Gulf of Finland (i=3) (see Figure 1). The exchange of water and nutrients with the Baltic Proper (i=4) is also described. 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 state variables of the model are $Q^N_{i,t}$ and $Q^P_{i,t}$, 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:

$$Q^N_{i,t+1} = Q^N_{i,t} + \sum_{j=1}^{n_i} L^N_{i,j,t} + A^N_i + \sum_{k=1}^{4} \left(W^{out}_{i,k} c^N_{i,t} - W^{in}_{i,k} c^N_{k,t} \right) - D_i - U_i + F_i \qquad [1]$$

$$Q^P_{i,t+1} = Q^P_{i,t} + \sum_{j=1}^{n_i} L^P_{i,j,t} + A^P_i + \sum_{k=1}^{4} \left(W^{out}_{i,k} c^P_{i,t} - W^{in}_{i,k} c^P_{k,t} \right) - U_i + I_i \qquad [2]$$

where $L^N_{i,j,t}$ and $L^P_{i,j,t}$ 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 contributing to the land load in each basin (j=1,…,n_i). Denitrification, burial, and nitrogen fixation by cyanobacteria are denoted by D, U, and F, respectively, and I denotes the internal loading of P from sea bottom sediments.

The outflow of water from the *i*th to *k*th basin is denoted by $W_{i,k}^{out}$, and the inflow from the *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. All nutrient flows other than land loads are assumed to remain constant over time. The parameter values for equations [1]-[3] are described in Table 1.

For the Baltic Proper, the future development of nutrient concentrations is projected 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 speed of change, respectively. The future nutrient concentrations in the Baltic Proper are mainly consequences of the future trends in nutrient loads and abatement in Poland, Germany, Lithuania, Latvia and Southern Sweden. In the sensitivity analysis, a range of parameter values (from -0.1 to 0.7 for α and from 0.01 to 0.07 for β) is applied. The default parameter values are α=0.3 and β=0.04 for both nutrients. The parameter σ represents the coefficient of variation and dz is a normally distributed random variable. The parameter values for σ were selected to accord with past fluctuations (Savchuk 2005) and are 0.05 and 0.135 for N and P, respectively.

2.2 Projecting nutrient land loads

The second model component describes the future development of land loads including nutrient run-off from arable land, forests and point sources. The future land loads can be formulated as a discrete-time continuous-state process:

$$L = G\gamma + S\,H\,Z \ , \qquad [5]$$

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 of the mean land loads is predicted by $G\ \gamma$, where γ denotes a matrix of expected land loads interpolated from the values in Table 2 for the first 50 years and assuming that the mean loads remain the same thereafter. The expected loads are based on results from the partial equilibrium model designed for Finnish agriculture, literature and expert opinions (see Hyytiäinen et al. 2009). G is a (14 × 14) diagonal matrix expressing the effects of nutrient abatement measures on annual mean loads. In the case of nutrient abatement, the elements of the diagonal are obtained by multiplying the initial share of agriculture in total land loads 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):

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

The share of agriculture from initial land loads is 0.359 and 0.443 for N and P, respectively.

In the second part of equation [5], S is a diagonal matrix for standard deviations of past land loads in the diagonal, Z is a matrix of normally distributed random variables and H is the Cholesky decomposition of the variance-covariance matrix of the standardized past land loads (see Table 3 for data on past land loads). The annual loads were standardized with a mean of zero and a standard deviation of one. The land loads were spatially correlated for the period 1986-

2000 and it is assumed that the annual loads will covariate in a similar manner also in the future due to variation in the annual amount and temporal distribution of rainfall (Elofsson 2003).

2.3 Cost of nutrient abatement measures

We consider two alternative targets of agricultural nutrient abatement. The target denoted by the parameter ϕ_y in equation [6] is either 16 or 30 percent. The 30% reduction target was set to comply with nationally agreed policy target for abatement outlined by the Finnish Government (2006). In addition, a 16 % reduction, which is about half of the official target was analyzed. The unit cost of nutrient abatement measures, ρ, was approximated by using a farm-level optimization model calibrated for representative Finnish dairy and cereal farms (Helin et al. 2006, Hyytiäinen et al 2009). The optimized abatement measures included reductions in fertilization, changes in cultivation methods and crops, reductions in the number of dairy cattle, changes in the cattle diet and the share of set-asides out of total farming area. The present value of the cost of abatement measures, *C*, was computed by multiplying the unit cost, ρ, by total nutrient reductions for the Finnish rivers emptying into the Gulf of Finland ($\gamma_{5,1}(1-G_{5,5})$ for nitrogen and $\gamma_{12,1}(1-G_{12,12})$ for phosphorus). Finally, the annual cost is divided by the rate of interest, *r* in order to obtain an estimate of the total cost over an infinite time horizon. The equations for the cost of abatement of *N* and *P* are

$$C = \frac{\rho\ \gamma_{5,1}(1-G_{5,5})}{r} \qquad [7]$$

and

$$C = \frac{\rho\,\gamma_{12,1}(1-G_{12,12})}{r}, [8]$$

respectively. The implicit assumption is that the cost of nutrient abatement measures will remain constant in the future. The unit cost, ρ, for reduction targets in agricultural nutrient loads of 30 and 16 percent are EUR 13.70/kg and EUR 5.70/kg for *N*, and EUR 32.91/kg and EUR 22.04/kg for *P*, respectively. The model also takes into consideration that the optimal nutrient abatement measures aiming at 30 and 16 percent reductions in *N* will lead to a 3.5 percent reduction in *P*. Correspondingly, activities designed primarily to reduce *P* will lead to a 2 percent reduction in the *N* load.

2.4 Recreational value of the Gulf of Finland

In order to estimate the recreational value of the Gulf of Finland, we first need to link the nutrient concentrations in the water to some easily observable measure of water quality. To that end, we apply secchi depth, ς_t, which measures sight depth in m, and adopt a transfer function estimated in Vesterinen et al. (2009)

$$\varsigma_t = \kappa_1 + \kappa_2 \ln\left(c_t^P\right) + \kappa_3 \ln\left(c_t^N\right) + \kappa_4 \frac{c_t^N c_t^P}{1000} \forall\, t, \qquad [9]$$

where the parameter values used are κ_1 =10.771, κ_2=-1.254, κ_3=-0.809, and κ_4=0.007. Vesterinen et al. (2009) also estimated the value of the marine ecosystem for recreation activities using the travel cost method (see Haab and McConnell 2003), and provide value functions for the most common close-to-home water recreation activities, that is, swimming, fishing and boating. At the present level of sight depths, the annual value for Finnish citizens of recreation on the shores of Gulf of Finland was estimated to be MEUR 516. The relationship between the average sight depth (ς) and annual value of water recreation activities (θ_t), expressed in million euros, is modelled as a hyperbolic function which is given by

$$\theta_t = \delta_1 + \frac{\delta_2 \varsigma_t}{\delta_3 + \varsigma_t}, \quad \forall\, t = 1,\ldots,200 \quad [10]$$

The fitted parameter values for the Gulf of Finland are δ_1=118.1, δ_2=485.9 and δ_3=0.448. Hyperbolic function was chosen to accord with the observations ranging between 0.5 m below and 0.5 m above the present average sight depth (Vesterinen et al. 2009), and an assumption that when sight depth is zero, swimming and fishing activities cease completely, while boating remains unaffected.

It should be noted that our benefit function is based on one valuation study only, where observations concentrated on average sight depths. Data from very high or low sight depths were scarce. Due to uncertainties in the specification of the benefit function, we carried out a sensitivity analysis by modifying the shape of the concave benefit function. Figure 2 shows the baseline function, the alternative concave function taking zero value at the origin (δ_1=0, δ_2=821.0, and δ_3=1.225) and another alternative, a linear curve $\theta_t = \delta_2 \varsigma_t$ with δ_2=248.5. When there is no water transparency, that is, the sight depth is zero, the value of the benefit function is zero, since people refrain from all types of recreation, including boating. The linear curve is an extreme case in valuation, as the absolute improvements in sight depth are equally valuable independent of the initial level; in other words, the marginal benefit of sight depth is constant.

Finally, we can describe how oil spills would affect the recreational value of the Gulf of Finland for Finns. Three types of uncertainties may be incorporated in a probabilistic framework by modelling (1) the probability of large-scale oil damage, (2) the variability in the magnitude of the damage as measured by recreational value, and (3) the expected duration of the damage.

Some estimates have been put forward on the future probabilities of oil spills in the Gulf of Finland. Ylitalo et al. (2008) estimated the probabilities of an accident and an oil spill for selected narrow passages and crossing areas in the Gulf of Finland. On a major route between Helsinki and Tallinn, for example, a cargo oil spill leading to an average release of 3200 tons of crude oil was expected to occur every 126 years. However, the information available so far does not suffice for estimating an aggregate density probability function covering all important routes and crossing areas. Therefore, we assume that the probability of a major tanker accident leading to a major oil spill can be described in a discrete-time model as a Bernoulli process. Major oil spills can be assumed to occur at some average rate and independently of the last event. The probability that at least one major collision leading to a large-scale oil spill occurs in each year is given by $P(\vartheta = 1) = \xi$ and the probability that there is no collision is given by $P(\vartheta = 0) = 1 - \xi$. Alternative parameter values ranging from $\xi = 0$ to $\xi = 0.2$ were studied in a sensitivity analysis to cover a sufficient range of probabilities.

Research information on the magnitude and duration of potential oil damage in the Baltic Sea is scarce due to the lack of major oil spills in the area in the past. Past studies on incidents in other areas have applied travel cost method and data on pre- and post-incident to assess the damage caused to the recreational use value of the sea. According to Grigalunas et al. (1986), the recreational losses to tourism and residents during the year after the Amoco Cadiz incident in France in 1978 were USD 10-80 millions (expressed in 1978 dollars). According to Hausmann et al. (1995), the recreational damage from the Exxon Valdez accident in Alaska in 1989 was USD 5 millions (expressed in 1989 dollars). According to Loureiro et al. (2006), following the Prestige incident in 2002 the direct losses to the tourism industry in Galicia, northeast Spain were MEUR 56 (expressed in 2003 euros) whereas the environmental and recreational damages estimated by the contingent valuation method amounted up to MEUR 574 (Loureiro et al. 2009).

It is important to note that, in addition to recreational losses, a major oil spill may cause large clean-up expenses, income losses to fisheries and other businesses, and sometimes irreversible changes to animal and plant populations. Thus, the economic cost of recreational loss represents only a proportion of the total costs of a spill. The same applies to eutrophication: recreational losses represent only a part of the total economic costs caused by elevated nutrient concentrations. These reservations on valuation are important to bear in mind as we go on to approximate the damage caused by oil spills in monetary terms.

In the worst case, a major oil spill occurring in the middle of the Gulf of Finland would devastate coastal areas such that recreational use becomes impossible, leaving the coast with no recreational value. However, the magnitude of the damage is affected by several factors, among these the amount of oil released to the sea, the location of the oil spill, the season of the year, and the speed and direction of wind. The stochastic impact of an oil spill on recreational value is described here by a cumulative beta function:

$$\psi = \frac{betainc(w, p, q)}{betainc(1, p, q)} \quad , \qquad [11]$$

where *betainc* is an incomplete beta function, *w* is a uniformly distributed random variable taking values in a closed interval [0,1], and *p* and *q* are shape parameters. It is realistic to assume that for extreme realisations of *w* the recreational value is not affected at all (*w*=0) or is completely spoiled (*w*=1) in the year of the accident. However, for intermediate values of *w*, the level of damage depends on the values of the shape parameters. By adjusting the shape parameters it is possible to account for a large variety of probability distributions. In the sensitivity analysis, five alternative combinations for the values of p and q are applied (see Figure 3).

The recreational value of the sea gradually returns to that prevailing before the accident, after the oil has been collected from the water and shorelines. We apply the equation of exponential decay to describe the rate at which the negative effects of an oil spill on recreation diminish over time, with the half-life of the damage denoted by g:

$$\omega = e^{-\frac{\ln(2)}{g}} . \qquad [12]$$

Model simulations (French McCay et al. 2004) and ex-post data on past incidents in other areas (Grigalunas et al. 1986; Loureiro et al. 2006) suggest that the half-life of the damage from a large-scale oil spill in the Gulf of Finland would vary from 1 to 4 years. The default value applied in computations is 3 or 4 years, whereas the sensitivity analysis extends the range to 1-10 years.

The occurrence of oil spills and their negative impacts on recreation are predicted over a 200-year period. In the first year, the proportional reduction in the recreational value of the Gulf of Finland, η_1, is given by $\eta_1 = \psi_1 \vartheta_1$. Later, the reduction in the value is given by:

$$\eta_t = \max\left(\psi_t \vartheta_t, \eta_{t-1}\omega\right) \; t = 2,...,200 . \qquad [13]$$

Thus, the proportional reduction in the recreational value of the sea is a function of potential occurrence of oil damage, ϑ_t, and its magnitude ψ_t during the same year t and the impacts of earlier oil damages, $\eta_{t-1}\omega$. Combining the estimate of the close-to-home recreational value of the sea (θ_t from [10]) and the relative reduction in the value due to past oil spills (η_t from [13]), we have

$$v_t = \theta_t \, \eta_t , \quad \forall \, t = 1,...,200 . \qquad [14]$$

This equation includes the joint effects of oil spill shocks as Bernoulli arrivals and eutrophication as indicated by sight depth.

Finally, the time path of the benefits (*B*) of nutrient abatement measures is obtained by simulating the flow of annual benefits of water recreation with (v_t) and without ($\bar{v}_t$) nutrient abatement measures and discounting the differences. The recreational value of the Gulf of Finland is allowed to vary over the first 200 years. Thereafter the value is assumed to remain constant.

$$B = \sum_{t=1}^{200} \left(v_t - \bar{v}_t\right) e^{-rt} + \frac{v_{200} - \bar{v}_{200}}{r} e^{-200r} \qquad [15]$$

Thus, the benefits are presented as a sum of discounted positive changes in the recreational value of Gulf of Finland that is achieved through active nutrient abatement.

2.5 Computations

The net present value (*NPV*) of investing in water quality is obtained by subtracting the total costs from the total benefits of nutrient abatement, $NPV = B - C$. A 4% real rate of interest is applied in all computations to accord with the average inflation-adjusted interest rates of government debt in Finland. Computation of the results consisted of three steps. First, the time paths for the recreational value of the Gulf of Finland were simulated for a baseline management and four alternative nutrient abatement targets to calculate *NPV*s for a single random sample of land loads [5], the development of nutrient concentrations in the Baltic Proper [4], the occurrence of major oil spills [13], and the magnitude [11] and duration of oil damage [12]. Second, these computations were repeated 500 times, each time drawing a new sample path of riverine loads, concentrations in the Baltic Proper, and the occurrence and consequences of oil spills. Monte Carlo simulation was applied to establish an estimate for the probability distribution and the expected values of *NPVs*. Third, a sensitivity analysis was conducted for the development of average nutrient concentrations in the Baltic Proper [4], curvature of the value function [13] and the annual risk and the magnitude of oil damages.

Two cases for international involvement in nutrient abatement are considered. In the first, only Finland reduces its nutrient loads. In the second, the three countries sharing the shores of the Gulf of Finland – Estonia, Finland and Russia - jointly reduce their loads such that the relative reduction from total land loads is the same in each country. However, only the costs and benefits accruing to the Finnish citizens and society are accounted for in the cost-benefit analysis.

3 RESULTS AND DISCUSSION

3.1 Demonstration of the model performance: model outcomes for a single realization of the random variables

The impact of agricultural nutrient abatement measures on the quality of marine environment can best be described in several steps. These steps involving a chain of causal relationships are demonstrated in Figures 4a-g. First, Figures 4a and b show one possible realization of *N* and *P* loads without nutrient abatement measures (baseline management). The time paths show the cumulative share of the annual aggregate load for each country. The next step is to employ equations [1]-[3] to project the developments of the average *P* concentration (Figure 4c) and N concentration. Thereafter, the development of average sight depth as a function of N and P concentrations can be predicted by employing equation [9] (Figure 4d). Consequently, the value of the close-to-home water recreation activities for Finnish citizens is obtained by using equation [10]. Figure 4e shows the development of this value under the baseline management (solid curve) and a reduction of 30 percent in the agricultural loads of P (dotted curve) when Estonia, Finland and Russia jointly reduce their *P* loads. The benefit from nutrient abatement measures for the Finnish citizens is the difference between these two value curves and is shown, along with constant annual cost in Figure 4f with a zero oil spill risk. Finally, Figure 4g shows the corresponding development of the benefits and costs for one possible realization of oil spills. Two oil spills with varying intensity and duration of damage occur during the 90 years, and temporally reduce the accrual of recreational benefits from nutrient abatement.

A 30 percent reduction in the agricultural *P* load leads to a reduction of about 13 percent in the total Finnish loads to the Gulf of Finland. Since Finland's share of the total land loads to the Gulf of Finland is small (about 10 percent), Finnish efforts with regard to nutrient abatement lead to a negligible improvement in the overall water quality of the Gulf of Finland. However, as shown in Figure 4c, joint abatement efforts lead to a gradual reduction in the average concentration of *P* that evens out to a reduction of about 5-6 percent in concentration after some 10-20 years. This reduction in P concentration is smaller than the reduction in P load, because other nutrient sources – atmospheric deposition and internal loading of *P* from sediments – are assumed to remain constant. Another reason is that there is a large exchange of water and nutrients between the Gulf of Finland and the Baltic Proper basins.

As a result of a reduced *P* concentration, the mean sight depth of the Gulf of Finland is improved only about 6-7 cm compared to the baseline management (see figure 4e). On the other hand, the number of beneficiaries is high, as the adult population living along the Finnish coastline of the Gulf of Finland is about 1.2 million. Thus, even a small improvement in water quality may lead to a significant increase in recreational value. According to Figure 4f, the benefits are lower than the costs during the first 15-20 years, but exceed the costs thereafter (Figure 4f). The NPV from investment is positive (MEUR 5), implying that the environmental investment in water quality is profitable. However, when the exogenous risk and consequences of oil spills are taken into account, the benefits of nutrient abatement are reduced temporarily as shown in Figure 4g. In this case, the NPV is negative (MEUR -1) and the investment in water quality becomes unprofitable for this specific realization of random variables.

3.2 Sensitivity analysis

Monte Carlo simulation and several alternative parameterizations were employed in order to analyze the economic feasibility of nutrient abatement efforts. The results of the sensitivity analysis are shown in Table 4. The expected NPVs are shown for 30 and 16 percent reductions in agricultural loads of *N* (*N30* and *N16*) and *P* (*P30* and *P16*). The results are shown for annual oil spill risks of 0, 4 and 12 percent, three specifications of oil damage magnitude and three alternative durations of oil damage (half-life of effects of 1, 3 and 10 years). Positive expected NPV, printed in bold in Table 4, indicates that the sum of discounted net benefits exceeds the sum of discounted costs and the evaluated investment in nutrient abatement is expected to be profitable.

The results of the cost-benefit analysis in Table 4 reveal that Finnish investments in the water quality of the Gulf of Finland are not profitable if Finland is the only country abating its nutrient loads. The effects of the Finnish reductions on water quality are small. In addition, some of the benefits of the Finnish investments accrue to the citizens of neighboring countries along the gulf, that is, Estonia and Russia. However, if the three countries agree upon joint measures to reduce their *P* loads, the investments in abatement turn out to be profitable at least for Finland (see the first row in Table 4). In contrast, because of the high unit cost, reductions in *N* load are not profitable even if the neighboring countries participate in the abatement.

Table 4 also demonstrates that the expected NPV of nutrient abatement investment is decreased for higher annual risks of oil spills (ξ), heavier effects of oil damage on recreation (parameters p and q), and longer duration of oil damage (g). These effects are logical. However, an important consequence is that, in some cases, the risk of an exogenous oil spill renders nutrient abatement investments unprofitable. For example, the total discounted costs of a 30 percent reduction in agricultural *P* loads are MEUR 66.2. The expected benefits without the risk of an oil spill are MEUR 70.8: that is, the benefits clearly exceed the costs. However, including the risk of an oil spill and its consequences reduces the expected benefits by MEUR 0-23, rendering investment unprofitable.

The effects of an increased risk of oil spills and the concomitant damage on the probability distribution of NPVs are illustrated in Figures 5a-c. Figure 5a shows that even a low risk of an oil spill reduces the expected NPV of investment in nutrient abatement significantly and may render the investment economically infeasible. However, for higher risk levels, the expected NPV is less sensitive to an increase in the probability of a spill. The standard deviation of the NPV increases between 0 and 8 percent, over the range of risk levels but diminishes with higher risk levels, as damage from a given oil spill partially supersedes that of the preceding spill where spills are frequent.

The first box in Figure 5b is an extreme case, in which the oil spill does not affect the recreational value of the Gulf of Finland at all. Other boxes illustrate different specifications of the relationship between an oil spill and its effect on recreational value (see Figure 3). The expected NPV and the lowest 10th percentile decrease steadily with an increasing effect of an oil spill on the recreational value.

However, the 90th percentile is reduced only a little. Increasing the duration of the impact of oil damage on recreation reduces the expected NPV (see Figure 5c). The probability distribution of NPV widens considerably in the case of long-term damage.

3.3 The impact of the Baltic Proper

The profitability of nutrient abatement investments in the watersheds of the Gulf of Finland is conditional on the future development of nutrient balances in the Baltic Proper basin due to the extensive exchange of water and nutrients between the neighboring basins. The contours in Figure 6 show the expected NPVs for combinations of the future steady-state concentration level in the Baltic Proper, α, and the speed of change, β. The future steady state, α, is described as a proportional increase in concentrations of both N and P compared to the present level. The abatement target is a 30 percent reduction in agricultural loads of P (representing 13 percent of total riverine P loads). All three countries on the gulf are assumed to participate in abatement.

Nutrient abatement in the Finnish watershed of the Gulf of Finland becomes more profitable, the more polluted the neighboring Baltic Proper basin becomes. This is a consequence of a concave value function (see Figure 2) and large exchange of water and nutrients between the adjacent basins. First, increased concentrations in the Baltic Proper lead to reduced water quality in the Gulf of Finland. Second, improvements in the water quality at lower sight depths generate higher benefits than the improvements at higher sight depths. Moreover, investments in the water quality of the Gulf of Finland are somewhat more profitable, the faster the water quality of the Baltic Proper degrades. The same result applies with and without the risk of an oil spill.

3.4 Different benefit estimates

Finally, the joint effects of the curvature of the value function and oil spill risk are evaluated. Figures 7a and b show the probability distribution of NPVs for the base value function and two alternative specifications, a concave curve with a smaller radius of curvature and a linear curve (see Figure 2), for zero (ξ=0) and high (ξ=0.12) oil spill risk.

Increasing the slope of the value function in the neighborhood of the reference level (sight depth at present) increases the benefits of improved water quality. As a consequence, employing the alternative specifications for the value function increases markedly the expected NPV of investment in water quality. The probability distributions are also widened with a value function exhibiting a steeper slope, in particular with a high risk of oil spills. However, the variation in the NPVs due to stochastic land loads, as well as the likelihood and consequences of oil damage, is still rather small when compared to the large effect the curvature of the value function has.

If the management of coastal areas is to be improved, it is important to identify and incorporate in a cost-benefit analysis all relevant exogenous risks that might affect the value of the marine resources. On the other hand, there is considerable uncertainty related to the valuation of water bodies, cost and effectiveness of nutrient abatement measures and indicators of water quality. These uncertainties are usually consequences of a scarcity of data and a limited understanding of the relationship between the ecological processes involved and the values people place on natural resources. Many of the model components applied in this study suffer from these limitations. The effects of uncertain components on the robustness and reliability of the estimated NPV distribution of the investment can be crucial when deciding on whether an environmental investment is made or not. For example, our preliminary analysis on the joint effects of value function specifications and the risk of oil spills (Figure 7) suggests that the uncertainties related to the curvature of value function outweigh the uncertainties connected to the oil spills and their consequences.

4 CONCLUSION

This study considers two types of threats that make environmental policies and management of coastal zones challenging. First, eutrophication is characterized as a process driven by stochastic nutrient loads from agriculture fluctuating according to weather conditions. Second, maritime traffic exposes coastal zones to a risk of damaging oil spills. In the literature to date, evaluations of cost-efficient measures to control excessive nutrient loads have not taken into account the impact on management strategies of major oil spills. The present study carries out numerical simulations for the Gulf of Finland, which is exposed to severe nutrient pollution and heavy maritime traffic simultaneously. Oil damage does not affect the level of eutrophication directly but has a potential indirect effect on the profitability of nutrient abatement investments in that it reduces the recreational value of the coastal areas.

An additional challenge is that the coastal and watershed areas of the Gulf of Finland are shared by three countries – Estonia, Finland and Russia. Whether unilateral actions of one country prove to be economically justified depends on the commitment of other countries. Our findings suggest that national investments in reducing the nutrient run-off from Finnish arable lands may become financially feasible only if the neighboring coastal countries commit themselves to reductions too. On the other hand, inclusion of the risk of oil damage in the analysis markedly reduces the expected value of benefits and widens the probability distribution of the NPVs of an environmental investment designed to combat eutrophication.

Our results demonstrate how the damage from an oil spill would affect resource allocation in Finland even though Finnish authorities have only limited possibilities to influence maritime traffic in international waters. The exogenous risk of oil spill reduces the profitability of investing in water quality in the Gulf of Finland, and tends to increase the relative profitability of investing in water quality in other coastal areas with less maritime traffic. In contrast to what one might expect, it may be rational for Finland to focus on maintaining the good water quality of the Bothnian Bay and Bothnian Sea rather than improving that of the Gulf of Finland.

In this analysis, Finland can control its own agricultural run-off to a certain extent, but it cannot control the volume of tanker traffic in the Gulf of Finland, which might lead to accidents and oil spills. The risk of oil-spills can be reduced through international collaboration between all countries involved in maritime traffic and by tightening the safety restrictions and requirements on vessels (e.g. double hulls for oil tankers). Comparing the incentives to prevent oil spills and abatement nutrient loads in a cooperative environment opens up an interesting topic for further research. When data become available on the cost of measures preventing the likelihood of oil spills, it will be straightforward to include these measures in our or other corresponding modeling frameworks and to provide valuable policy guidance for the management of coastal zones facing multifaceted threats.

ACKNOWLEDGEMENTS

This study was carried out as part of the PROBAPS project financed by the Finnish Advisory Board of Sectoral Research. We are grateful to the participants of the “EURO summer institute

2009: OR in Agriculture and Forest Management" for constructive comments on the earlier version of this paper.

LITERATURE

Baltic Nest Institute. 2008. Nest, an information environment for decision support system. nest.su.se/nest/. (October 2008).

Brady, M. (2003). The Relative Cost-efficiency of Arable Nitrogen Management in Sweden. *Ecological Economics*, 47(1), 53–70.

Brown, C., Corcoran, E., Herkenrath, P., & Thonell, J. (2006). Marine and coastal ecosystems and human wellbeing. Synthesis. UNEP-WCMC, Cambridge, 65 p.

Brown, R.S., & Savage, I. (1996). The economics of double-hulled tankers. *Maritime Policy and Management*, 23(2), 167–175.

Byström, O. (2000). The Replacement Value of Wetlands in Sweden. *Environmental and Resource Economics*, 16(4), 347–362.

Carson, R.T., Mitchell, R.C., Hanemann, M., Kopp, R.J., Presser, S., & Ruud, P.A. (2003). Contingent Valuation and Lost Passive Use: Damages from the Exxon Valdez Oil Spill. *Environmental and Resource Economics*, 25(3), 257–286.

Elofsson, K. (2003). Cost-effective reductions of stochastic agricultural loads to the Baltic Sea. *Ecological Economics*, 47(1), 13–31.

Etkin, D.S. (2000). Worldwide Analysis of Marine Oil Spill Cleanup Cost Factors. Paper presented at Arctic and Marine Oilspill Program Technical Seminar, June 2000. Available online (March 13, 2009): http://www.environmental-research.com/erc_papers/ERC_paper_2.pdf

French McCay, D., Rowe, J.J., Whittier, N., Sankaranarayanan, S., & Etkin, D.S. (2004). Estimation of potential impact and natural resource damages of oil. *Journal of Hazardous Materials*, 107(1-2), 11–25.

Finnish Government (2006). Vesiensuojelun suuntaviivat (Guidelines for water protection November 26, 2006, in Finnish).

Grau, M.V., & Groves, T. (1997). The Oil Spill Process: The Effect of Coast Guard Monitoring on Oil Spills. *Environmental and Resource Economics*, 10(4), 315–339.

Gren, I.-M. (2001). International Versus National Actions Against Nitrogen Pollution of the Baltic Sea. *Environmental and Resource Economics*, 20(1), 41–59.

Gren, I.-M. (2008). Adaptation and mitigation strategies for controlling stochastic water pollution: An application to the Baltic Sea. *Ecological Economics, 66(2-3), 337–347.*

Gren, I.-M., Destouni, G., & Scharin, H. (2000). Cost effective management of stochastic coastal water pollution. *Environmental Modeling and Assessment*, 5(4), 193–203.

Grigalunas, T.A., Anderson, R.C., Brown, G.M., Congar, R., Meade, N.F., & Sorensen, P.E. (1986). Estimating the cost of oil spills: lessons from the Amoco Cadiz incident. *Marine Resource Economics*, 2, 239–262.

Haab, T.C., & McConnell, K.E. (2003). Valuing Environmental and Natural Resources. The Econometrics of Non-Market Valuation. Edward Elgar, Cheltenham, UK.

Hart, R., & Brady, M. (2002). Nitrogen in the Baltic Sea - Policy Implications of Stock Effects. *Journal of Environmental Management*, 66(1), 91–103.

Hausman, J.A, Leonard, G.K., & McFadden, D. (1995). A utility-consistent, combined discrete choice and count data model Assessing recreational use losses due to natural resource damage. *Journal of Public Economics*, 56(1), 1–30.

Helcom (2003) The review of more specific targets to reach the goal set up in the 1988/1998 Ministerial Declarations regarding nutrients. *Baltic Sea Environment Proceedings*, No. 89, http://www.helcom.fi/stc/files/Publications/Proceedings/bsep89.pdf

Helin, J., Laukkanen, M., & Koikkalainen, K. (2006). Abatement costs for agricultural nitrogen and phosphorus loads: a case study of crop farming in south-western Finland. *Agricultural and Food Science*, 15(4), 351–374.

Hoel, M. (1991). Global environmental problems: The effects of unilateral actions taken by one country. *Journal of Environmental Economics and Management*, 20(1), 55–70.

Hyytiäinen, K., Ahtiainen, H., Heikkilä, J., Helin, J., Huhtala, A., Iho, A., Koikkalainen, K., Miettinen, A., Pouta, E. & Vesterinen, J. (2009). Integrated simulation model to evaluate national policies for agricultural nutrient abatement in the Baltic Sea. *Agricultural and Food Science*, 18(3-4), 440–459.

Kataria, M., Elofsson, K., and Hasler, B. (2010). Distributional Assumptions in Chance-Constrained Programming Models of Stochastic Water Pollution. *Environmental Modeling and Assessment*, 15(4), 273–281.

Keohane, N., Van Roy, B., & Zeckhauser, R. (2007). Managing the quality of a resource with stock and flow controls. *Journal of Public Economics*, 91(3-4), 541–569.

Kim, I. (2002). Ten years after the enactment of the Oil Pollution Act of 1990: a success or a failure. *Marine Policy*, 26(3), 197–207.

Laukkanen, M., & Huhtala, A. (2008). Optimal management of a eutrophied coastal ecosystem: balancing agricultural and municipal abatement measures. *Environmental and Resource Economics*, 39(2), 139–159.

Loureiro, M. L., Ribas, A., Lopez, E. & Ojea, E. (2006). Estimated costs and admissible claims linked to the Prestige oil spill. *Ecological Economics*, 59(1), 48–63.

Loureiro, M.L., Loomis, J.B., & Vázquez, M.X. (2009). Economic valuation of environmental damages due to the Prestige oil spill in Spain, *Environmental and Resource Economics*, 44 (4), 537–553.

Ollikainen, M., & Honkatukia, J. (2001). Towards Efficient Pollution Control in the Baltic Sea: An Anatomy of Current Failure with Suggestions for Change. *Ambio*, 30(4), 245–253.

Plourde, C.G., & Yeung, D. (1989). A model of industrial pollution in a stochastic environment. *Journal of Environmental Economics and Management*, 16(2), 97–105.

Savchuk, O.P. (2005). Resolving the Baltic Sea into seven subbasins: N and P budgets for 1991–1999. *Journal of Marine Systems*, 56(1–2), 1–15.

Ylitalo, J., Hänninen, M., & Kujala, P. (2008). Accident probabilities in selected areas of the Gulf of Finland. Helsinki University of Technology. Faculty of Engineering and Architecture. Department of Applied Mechanics. TKK-AM-6. http://appmech.tkk.fi/fi/julkaisut/TKK-AM-6.pdf

van de Wiel, G., & van Dorp, J.R. (2009). An oil outflow model for tanker collisions and groudings. *Annals of Operations Research*. DOI 10.1007/s10479-009-0674-5

Vesterinen, J., Pouta, E., Huhtala, A., & Neuvonen, M. (2009). Impacts of changes in water quality on recreation behavior and benefits in Finland. *Journal of Environmental Management* 91(4), 984–994.

Table captions:

Table 1 Parameter values for the nutrient balance equations. Source: Baltic Nest Institute (2008)

Table 2 Mean riverine loads of nutrients

Table 3 Data on past land loads of N and P

Table 4 Expected NPVs (in MEUR) for investments in nutrient abatement under the risk of oil spills

Figure captions:

Fig. 1 The Baltic Sea drainage area and sea basins. Source: UNEP, Baltic environmental atlas, http://www.grida.no/baltic/

Fig. 2 Three specifications of the recreational value of the Gulf of Finland for Finnish citizens

Fig. 3 Five alternative specifications of the effect of a major oil spill on the recreational use of the coast of the Gulf of Finland

Fig. 4 One realization of nutrient loads, nutrient concentrations, sight depth and the benefits and costs of nutrient abatement with and without the risk of an oil spill. Estonia, Finland and Russia participate jointly in nutrient abatement

Fig. 5 Probability distribution of NPVs as a function of parameters representing the properties of oil damages. The NPVs are computed for a 30 percent target reduction in agricultural load of P. A line within the box marks the median. The boundaries of the box indicate the 25th and 75th percentiles. The error bars above and below the box indicate the 90th and 10th percentiles. The dots indicate the 95th and 5th percentiles. Default parameter values: $\xi=0.04$, $p=1$, $q=1$, $g=4$.

Fig. 6 The effect of the future development of nutrient concentration in the Baltic Proper basin on the profitability of investment in nutrient abatement. The contours represent the expected NPVs for a 30 reduction in agricultural loads of P, when Finland, Russia, and Estonia participate in abatement jointly. Parameters: $p=q=1$, $g=3$

Fig. 7 The impact of the specification of the benefit function on the probability distribution of NPV for a 30 percent reduction in the P load from agriculture. Parameters: $\alpha=0.3$, $\beta=0.04$, $p=q=1$, $g=3$

Table 1 Parameter values for the nutrient balance equations. Source: Baltic Nest Institute (2008)

Basin, i=1…4	Atmospheric deposition *(ton)*		Nitrogen fixation *(ton)*	Burial *(ton)*		Denitrification *(ton)*	Intern. loading of P *(ton)*	Initial concentration *(μg/l)*		Water volume *(km^3)*	Annual flow of water fro basin i *(km^3)* t		
	A_i^N	A_i^P	F_i	U_i^N	U_i^P	D_i	I_i	c_{i0}^N	c_{i0}^P	V_i	BB	BS	GoF
1 (BB)	10584	562	0	3964	4086	16987	0	298	6.2	1441	0	290	0
2 (BS)	32636	1178	17574	10674	8461	88063	400	262	16	4485	173	0	0
3 (GoF)	15394	445	18073	9911	4118	64421	2800	343	25	1100	0	0	0
4 (BP)								272	25		0	1009	43

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

Table 2 Mean riverine loads of nutrients

	Total *P* (tons/year)			Total *N* (tons/year)		
Nutrient source	2008	2028	2058	2008	2028	2058
Swedish rivers to Bothnian Bay	1104	950	900	19273	20000	19000
Finnish rivers to Bothnian Bay	1805	1600	1400	29326	33000	30000
Finnish rivers to Bothnian Sea	1550	1500	1800	24716	35000	33000
Swedish rivers to Bothnian Sea	1232	900	880	30278	23500	23000
Finnish rivers to Gulf of Finland	605	600	450	13091	12000	11500
Russian rivers to Gulf of Finland	4174	5500	7000	76733	85000	90000
Estonian rivers to Gulf of Finland	779	1000	1150	18210	20000	21000

Table 3 Data on past land loads of N and P

	Nitrogen (tons/yr)							Phosphorus (tons/yr)						
	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
mean	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

Table 4 Expected NPVs (in MEUR) for investments in nutrient abatement under the ris

			Finland only				Estonia, Finland, and Russia			
ξ	*p/q*	*g*	*N30*	*N16*	*P30*	*P16*	*N30*	*N16*	*P30*	*P16*
0			-470.8	-101.7	-59.2	-20.0	-420.3	-71.7	**4.6**	**15.4**
0.04	1 / 0.3	1	-471.1	-101.9	-59.5	-20.2	-423.3	-73.4	**1.0**	**13.4**
0.04	1 / 0.3	3	-471.5	-102.2	-60.0	-20.4	-427.3	-75.8	-4.0	**10.6**
0.04	1 / 0.3	10	-471.8	-102.3	-60.3	-20.6	-431.5	-78.3	-9.3	**7.7**
0.04	1 / 1	1	-471.0	-101.8	-59.5	-20.1	-422.3	-72.8	**2.1**	**14.0**
0.04	1 / 1	3	-471.3	-102.0	-59.7	-20.3	-424.9	-74.4	-1.0	**12.3**
0.04	1 / 1	10	-471.5	-102.1	-59.9	-20.4	-428.1	-76.3	-5.1	**10.0**
0.04	0.3 / 1	1	-470.9	-101.8	-59.3	-20.1	-421.3	-72.2	**3.4**	**14.7**
0.04	0.3 / 1	3	-471.0	-101.9	-59.5	-20.1	-422.6	-73.0	**1.8**	**13.8**
0.04	0.3 / 1	10	-471.1	-101.9	-59.6	-20.2	-424.2	-74.0	-0.3	**12.7**
0.12	1 / 0.3	1	-471.6	-102.2	-60.0	-20.5	-428.2	-76.3	-5.1	**10.0**
0.12	1 / 0.3	3	-472.2	-102.6	-60.7	-20.8	-434.3	-80.0	-12.7	**5.8**
0.12	1 / 0.3	10	-472.6	-102.8	-61.0	-21.0	-438.8	-82.7	-18.3	**2.7**
0.12	1 / 1	1	-471.3	-102.1	-59.8	-20.3	-425.5	-74.7	-1.8	**11.8**
0.12	1 / 1	3	-471.8	-102.3	-60.3	-20.6	-430.5	-77.7	-8.0	**8.4**
0.12	1 / 1	10	-472.1	-102.5	-60.5	-20.8	-434.0	-79.8	-12.3	**6.0**
0.12	0.3 / 1	1	-471.0	-101.9	-59.5	-20.2	-423.0	-73.2	**1.3**	**13.6**
0.12	0.3 / 1	3	-471.3	-102.0	-59.7	-20.3	-425.5	-74.7	-1.8	**11.8**
0.12	0.3 / 1	10	-471.5	-102.1	-59.9	-20.4	-427.0	-75.6	-3.6	**10.8**

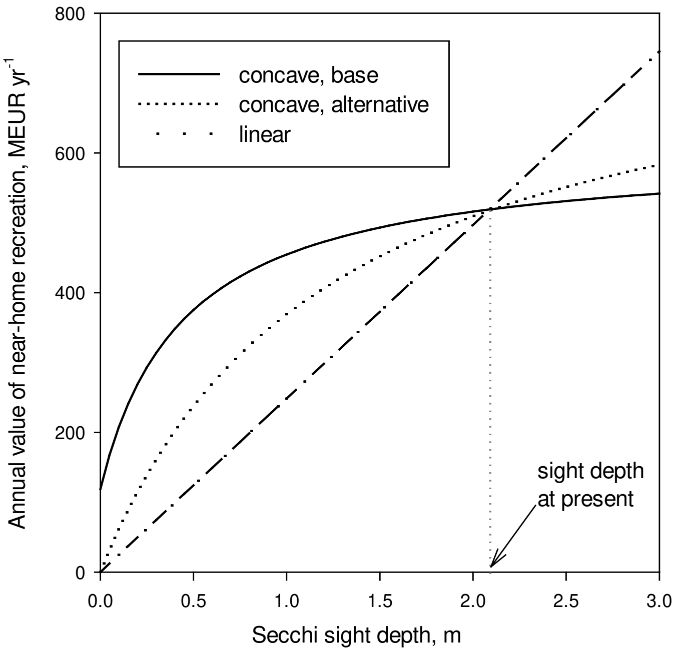

800
600
400
200
0
Annual value of near-home recreation, MEUR yr^{-1}
concave, base
concave, alternative
linear
sight depth
at present
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Secchi sight depth, m

Fig 2.

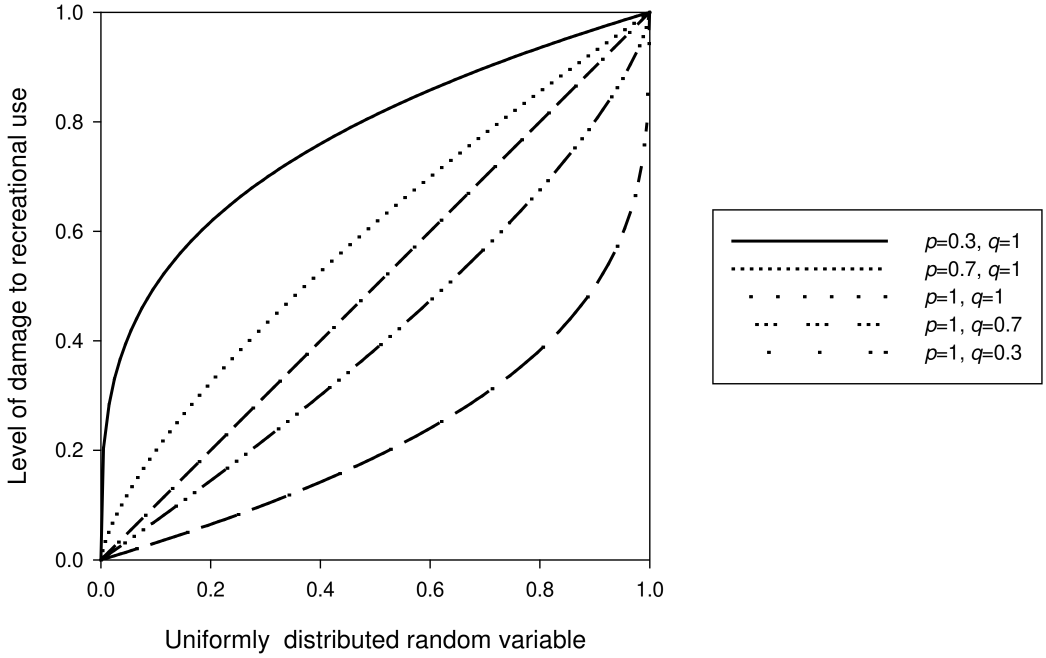
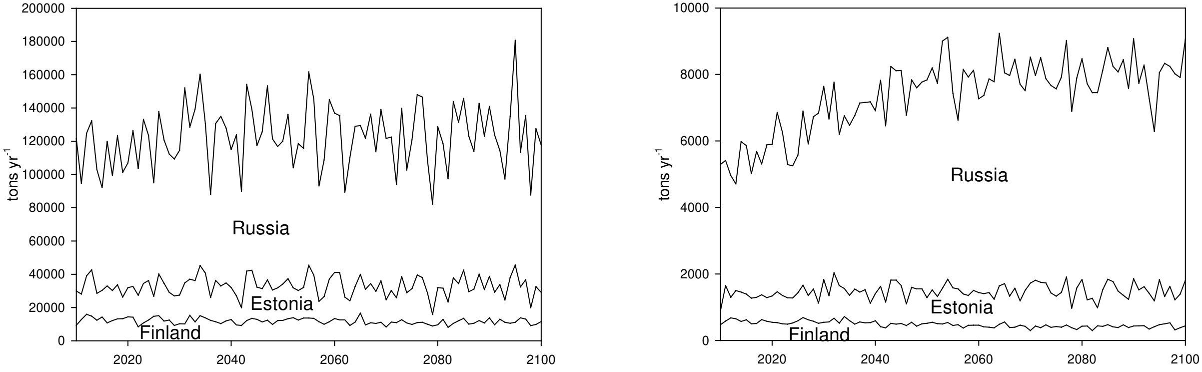
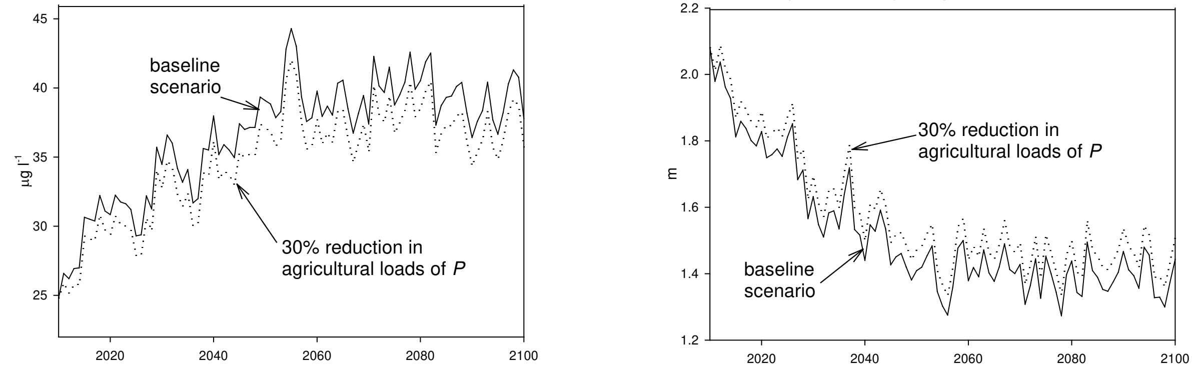

1.0
0.8
0.6
0.4
0.2
0.0
Level of damage to recreational use
0.0
0.2
0.4
0.6
0.8
1.0
Uniformly distributed random variable
p=0.3, q=1
p=0.7, q=1
p=1, q=1
p=1, q=0.7
p=1, q=0.3

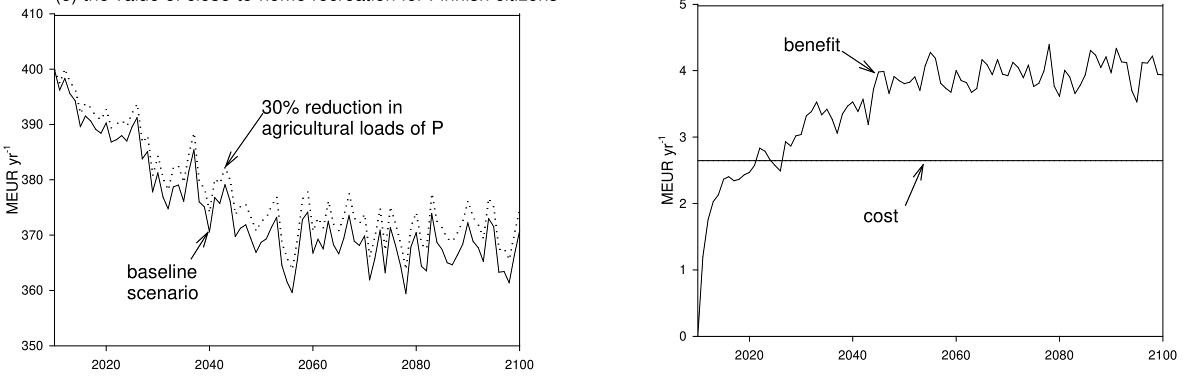
Fig 3


(a) Land load of *N* to the Gulf of Finland

(b) Land load of *P* to the Gulf of Finland


(c) Concentration of *P* in GoF

(d) Average secchi sight depth in the Gulf of Finland


(e) the value of close-to-home recreation for Finnish citizens

(f) benefits and costs from 30% reduction in agricultural loads of *P*

(g) benefits and costs from 30% reduction in *P* for sample scenario of oil spills and consequences

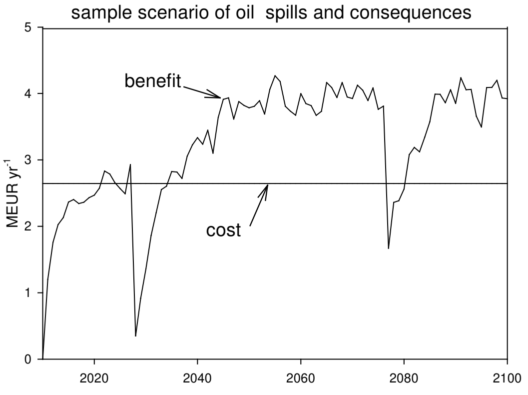
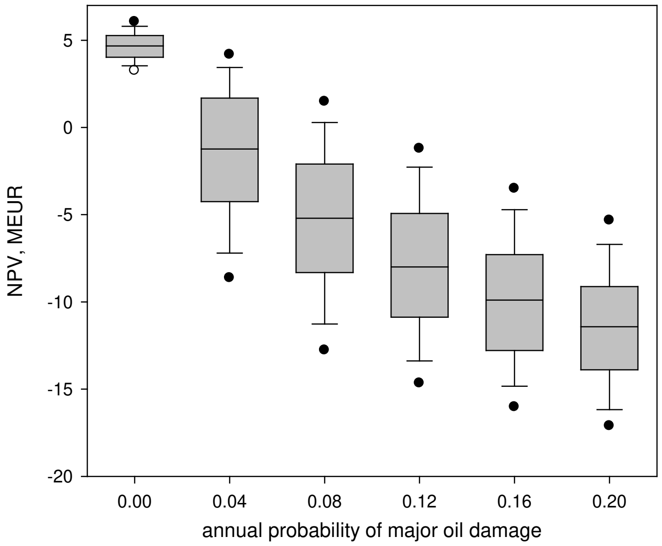
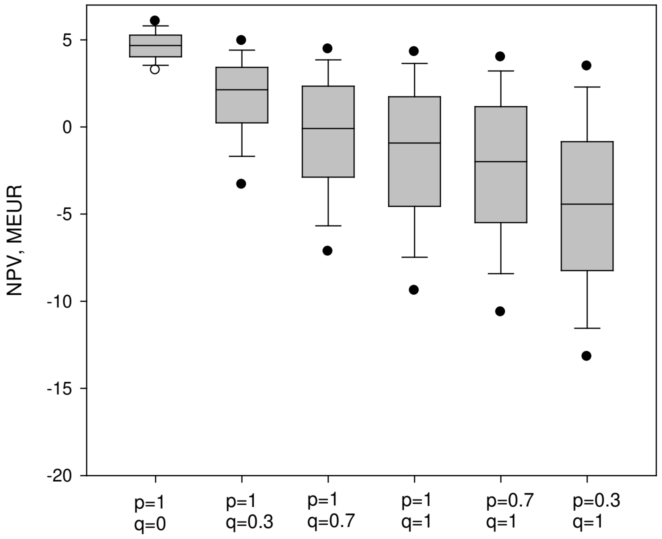


Fig 4

(a) probability of oil spill



(b) magnitude of damage



(c) duration of oil damage

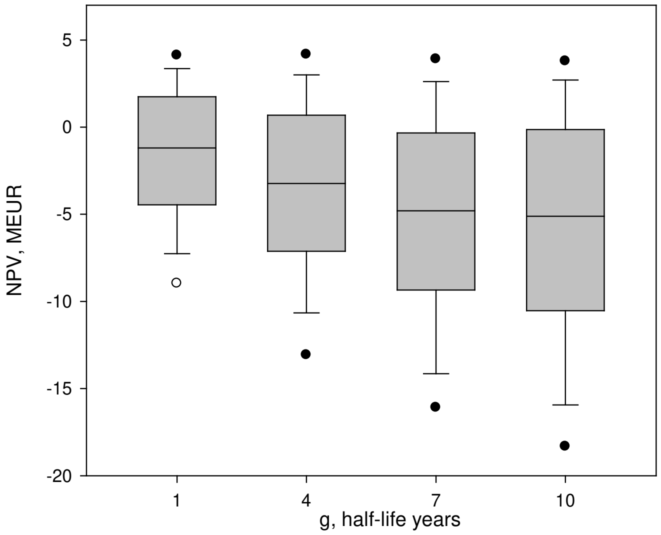


Fig 5

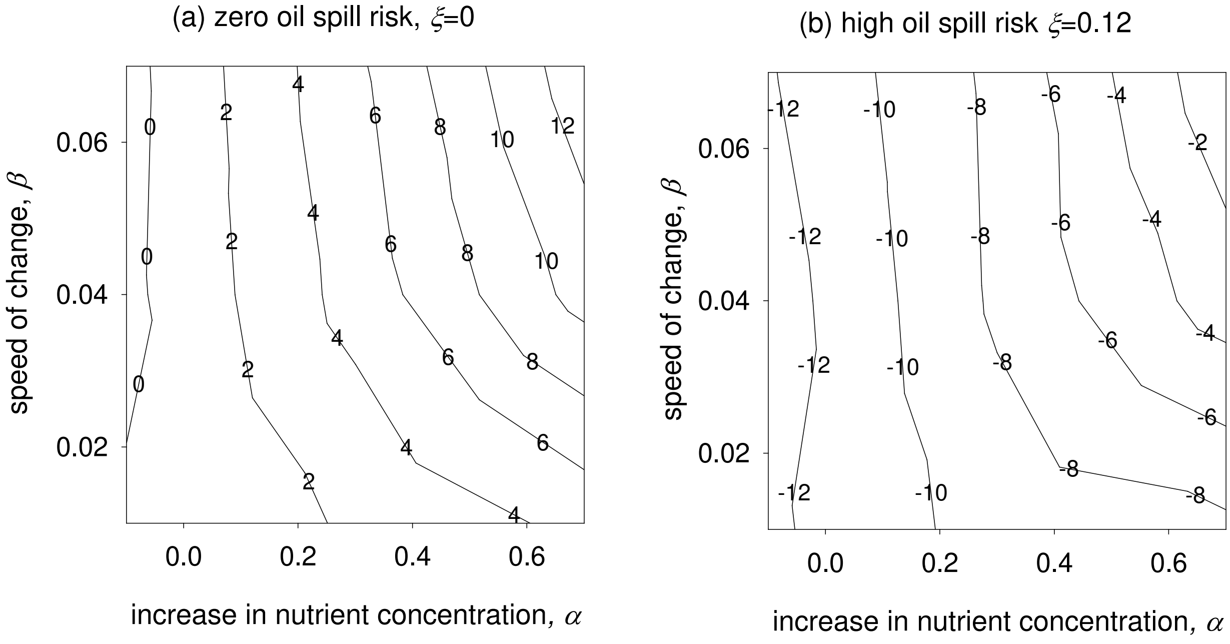

(a) zero oil spill risk, ξ=0
(b) high oil spill risk ξ=0.12
speed of change, β
increase in nutrient concentration, α
0.02
0.04
0.06
0.0
0.2
0.4
0.6
0
2
4
6
8
10
12
-12
-10
-8
-6
-4
-2

Fig 6.

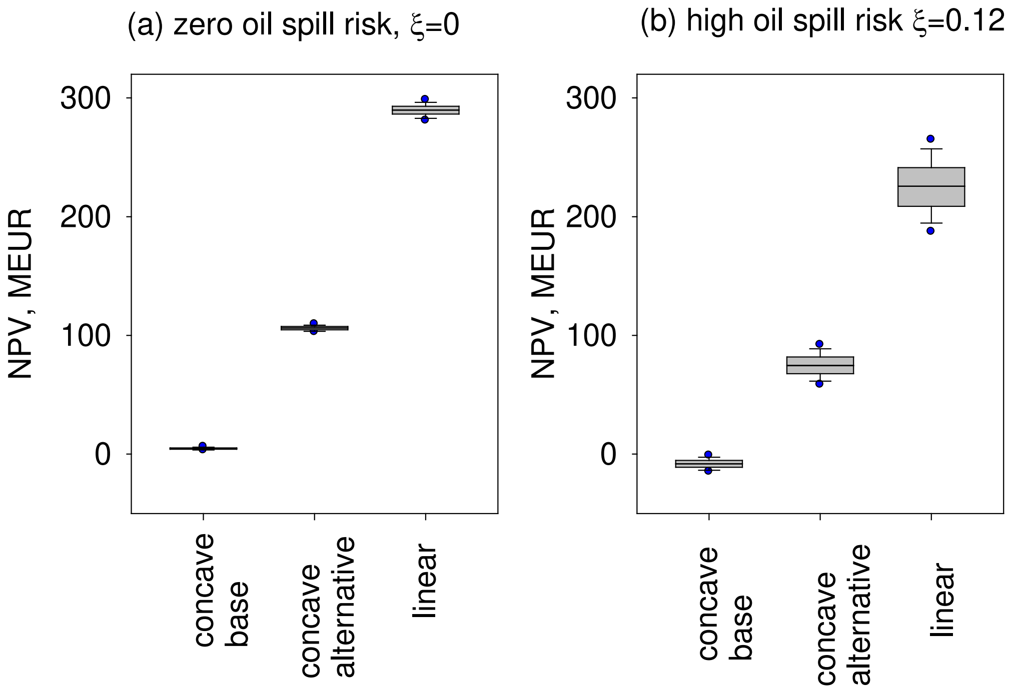

(a) zero oil spill risk, ξ=0
(b) high oil spill risk ξ=0.12
NPV, MEUR
300
200
100
0
concave base
concave alternative
linear

Fig 7.