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An economic–ecological model to evaluate impacts of nutrient abatement in the Baltic Sea

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ABSTRACT

This paper presents a coupled economic–ecological model that integrates a catchment model with a marine model and incorporates economic data to analyse the long-term economic and ecological consequences of nutrient abatement in the Baltic Sea. The spatially explicit model describes dynamics of soil phosphorus in arable land, developments of nutrient concentrations and phytoplankton biomass in the sea basins, and inter-annual variation in nutrient loads and biophysical processes. The performance of the model is demonstrated by computing the least-cost solution to reach the good environmental state of the sea – as implied by the Baltic Sea Action Plan – within a time span of 40 years. The total cost of achieving this target is 1487 M€ annually. Spatially optimal allocation of load reductions differs from the load reduction targets of the Baltic Sea Action Plan, and focuses more on the control of phosphorus loads.

1. Introduction

The Baltic Sea is a semi-enclosed body of water in Northern Europe. Its limited water exchange with the North Atlantic Ocean makes it one of the few brackish seas in the world, creating conditions for a unique marine ecosystem. This ecosystem, however, currently suffers from several environmental problems, one of the most severe being eutrophication. Human activities have increased the nutrient load flowing into the Baltic to a level that has altered the natural status and functioning of its ecosystem (Österblom et al., 2007). When a marine ecosystem malfunctions, it may fall short of its potential for providing people with services such as recreation and food. This means that by harming an ecosystem, human beings could reduce their own welfare. A balance between the economic activities polluting the marine environment and the benefits of preserving a healthy ecosystem can only be achieved by reducing nutrient emissions to a level that the ecosystem can tolerate.

Integrating scientific and socioeconomic knowledge is needed to increase the efficiency of decision making in management of water resources (Liu et al., 2008; Kelly et al., 2013). Several earlier studies have considered both socio-economic aspects and environmental changes in a single framework in the context of water protection. Janssen (2001) integrates social psychology and biochemical model to study how policies affect behaviour of the polluters. van der Veeren and Lorenz (2002) integrate economic and ecological models to evaluate management options in the Rhine Basin. Massey et al. (2006) introduce a bioeconomic model that links water quality, recreational fishery and the non-market benefits for coastal bays of Maryland. Kragt et al. (2011) introduce an approach to link economic valuation and biophysical modelling of catchment water quality for northeast Tasmania using Bayesian modelling to integrate biophysical and economic components.

In the context of the Baltic Sea, nutrient dynamics have been investigated in several studies using basin models that divide the sea into homogeneous subbasins (see e.g. Wulff and Stigebrandt, 1989; Savchuk and Wulff, 1999, 2007) and three-dimensional biogeochemical models that have high vertical and horizontal resolution and allow heterogeneity on the basin scale (see e.g. Kiirikki et al., 2006; Neumann, 2000; Pitkänen et al., 2007). Some studies combine marine models with catchment model (e.g. Mörth et al., 2007; Wulff et al., 2007) thus allowing the researchers to evaluate the consequences of exogenously given nutrient

Abbreviations: BSAP, Baltic Sea Action Plan; HELCOM, Helsinki Commission.

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abatement measures on the nutrient balance, phytoplankton biomass and other descriptors of eutrophication in the sea.

Marine models and integrated marine and catchment models have enabled researchers to analyse needed load reductions, and the proper balance in reducing nitrogen and phosphorus, the two main nutrients causing eutrophication, to improve the state of the marine ecosystem. For example, Savchuk and Wulff (1999) studied both local and large-scale effects of nutrient reductions on phytoplankton biomass, and concluded that reductions of phosphorus, rather than nitrogen, are more important on a Baltic-wide scale, because they lead to a reduction of phytoplankton without causing cyanobacterial blooms. Effects vary regionally, with nitrogen load reduction becoming the preferred alternative to phosphorus reduction in some sea basins, because nitrogen reductions would convert the area into a nitrogen sink. These conclusions are however based on solely on ecological arguments, and neglect any economic aspects, such as spatial variability in the costs and availability of various nutrient abatement measures. The authors also demonstrated that the state of the marine ecosystem responds slowly to changes in nutrient loads.

Several economic papers have studied the cost-efficient nutrient load abatement to meet the load reduction targets articulated in the international agreements on marine protection: the Ministerial Declaration in 1988 (HELCOM, 1988) and its revision – the Baltic Sea Action Plan (BSAP) (HELCOM, 2007). The cost-efficient combinations of measures to meet the original 50-percent load reduction target have been studied in both deterministic (Gren et al., 1997, 2008; Ollikainen and Honkatukia, 2001) and stochastic setting (Elofsson, 2003). The cost-efficient implementation of the most recent targets, articulated in the BSAP, has been studied by Gren (2008) and Elofsson (2010a,b). A central finding of these papers is that it is worthwhile to focus nutrient abatement efforts on economic sectors, countries and regions, which have the greatest potential for load reductions and have not yet utilized all potential of inexpensive measures. Two recent papers also criticize that the division of obligations in the current agreement is economically inefficient (Gren, 2008; Elofsson, 2010) and unfair (Gren, 2008). On the other hand, all existing economic models are static and they focus on the cost-efficient load reduction, which is only a mean, rather than the goal of marine protection.

The ultimate aim of nutrient abatement is to improve the state of the sea and to alleviate the symptoms of eutrophication, such as increased water turbidity, benthic oxygen depletion and harmful algal blooms. In order to analyse the full long-term effects of abatement measures on eutrophication, one needs a dynamic model that combines the essential features of catchment and marine models. Dynamic setting was applied by Laukkanen and Huhtala (2008) and Laukkanen et al. (2009) who analysed optimal allocation of abatement efforts between waste water treatment capacity and agriculture. Their model was calibrated to the coastal waters of the Gulf of Finland, which represents only a small part of the Baltic Sea.

Only few studies have examined the entire causal chain from the use of abatement measures in the catchment to nutrient concentration or phytoplankton reduction in the sea. In the previous literature, the dynamics of marine nutrients have been investigated using either direct transport coefficients between the subbasins of the Baltic (Gren, 2001) or more subtle input–output analysis that takes into account the long-term interactions between subbasins (Gren and Wulff, 2004; Ahlvik and Pavlova, 2013). In a recent study, Gren et al. (2013) calculate the cost-efficient spatial and dynamic allocation of nutrient load reduction for the Baltic Sea, where the nutrient stock targets of the BSAP were met such that the total cost was minimized. However, none of these approaches includes positive and negative feedbacks on load reductions caused by

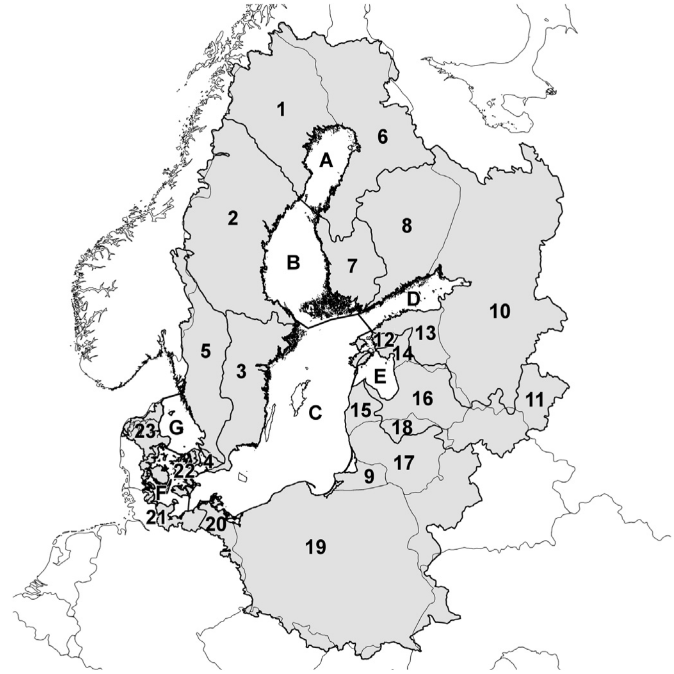

Fig. 1. Division of the sea (subbasins A–G) and the catchment area (subcatchments 1–23) as applied in this study. Source: Larsen (2008).

interdependencies between nutrients, such as benthic release of phosphorus or decreased denitrification, which might significantly affect the development of nutrient concentrations (Vahtera et al., 2007). This oversimplification of the biochemical processes might lead to biased result.

The objective of this study is to introduce a coupled economic–ecological model for evaluating the costs and long-term effects of nutrient abatement measures on nutrient and phytoplankton biomasses in the Baltic Sea. The coupled model combines a catchment model with a marine model and incorporates economic data on the effectiveness and costs of a variety of agricultural measures and improvements in the capacity of waste water treatment. It takes into account the interdependencies between nitrogen and phosphorus in the sea as well as the positive and negative feedbacks of nutrient load reductions on the state of the sea. Owing to these properties, the model can be used to identify the cost-efficient solutions to nutrient abatement at the level of Baltic Sea catchment. Further extending previous models, it takes into account the dynamic effect of the phosphorus stocks in agricultural soils, which cause lags in some phosphorus-related measures and makes them unsuitable for quick phosphorus load reductions.

The coupled component model has been designed to meet two goals: to produce credible large-scale and long-term projections of the effects that different abatement measures will have on marine ecosystem; and to be simple enough to be used in optimization, allowing us to seek the economically justified ways to reduce phytoplankton biomass in the Baltic Sea. The model is demonstrated by solving for the cost-efficient set of nutrient abatement measures to reach the good environmental status of the Baltic within a time span of 40 years.

2. Marine model

In this study we employ a coupled component model that combines a marine model with a catchment model. The marine model employs the system dynamics approach, which is well