

ANALYSIS

Managing nutrient fluxes and pollution in the Baltic: an interdisciplinary simulation study

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Abstract

This interdisciplinary paper reports the results of a study into the costs and benefits of eutrophication reduction in the Baltic Sea. A large multidisciplinary team of natural and social scientists estimated nutrient loadings and pathways within the entire Baltic drainage basin, together with the costs of a range of abatement options and strategies. The abatement cost results were compared with clean-up benefits on a basin-wide scale, in order to explore the potential for international agreements among the countries which border the Baltic. Most countries would seem to gain net economic benefits from the simulated 50% nitrogen and phosphorus reduction policy. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

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All countries with a coastline have an interest in the sustainable management of the coastal re-

source systems. The task of sustainable management, i.e. sustainable utilisation of the multiple goods and services provided by coastal resources (processes, functions and their interrelationships), is likely to be made more difficult because of the consequences of global environmental change (GEC). Understanding the interactions between the coastal zone and global changes cannot be achieved by observational studies alone. Modeling of key environmental processes also has an important role to play. In particular, modelling work on the dynamics of carbon (C), nitrogen (N) and phosphorus (P) in the coastal ocean needs to be combined with socio-economic analysis of the drivers of C, N and P fluxes and the human welfare consequences of changes in these fluxes across the coastal zone over time.

A particular characteristic of GEC (encompassing population growth and density increases, urbanisation and the intensification of agriculture, etc.) is that it has led to, among other things, the progressive opening of biogenic nutrient cycles, e.g. much increased mobility of nitrogen and phosphorus. This increased mobility of nutrients has meant increased exchanges between land and surface water and consequent impacts on the ecological functioning of aquatic systems. Other process changes have also added to the cumulative changes experienced in coastal systems.

The major flux of nutrients from land to sea occurs through river transport via the drainage basins network. The network contains various 'filters' such as wetlands which retain or assimilate nutrients during their downstream passage to the sea. The effectiveness and selectivity of these filters depend on the strong biogeochemical coupling existing between carbon, nitrogen, phosphorus and silica circulation. They are also affected by hydrology and land use/cover (Howarth et al., 1996).

This paper reports the overall results of an interdisciplinary study which focused on N and P fluxes on a drainage basins-wide scale in the Baltic Region (Turner et al., 1995). The Baltic Sea region catchment area covers around 1 670 000 km² and contains a population of about 85 million people in 14 countries. A significant proportion of the world's industrial production comes from this

area, but up until around 40 years ago there was little recorded environmental damage in the Baltic Sea. However, since 1960 the environmental condition of the Baltic Sea has increasingly become a cause of public concern and is currently perceived to be in an unacceptably polluted state. Symbolically, eutrophication is a major problem facing policymakers and the public. The aims of the study were decomposed into a number of interrelated intermediate goals including: (1) to provide a comprehensive and rigorous picture of the land use and ecological carrying capacity of the region, and to relate this resource inventory to the patterns of human activity in the region; a 'pressure-state-impacts-response (P-S-I-R) framework (Fig. 1) was adopted to facilitate the analysis; (2) to develop a model looking at different nutrient loading scenarios and their consequences on the ecological state of the Baltic Sea and its sub-systems; (3) to estimate the costs of various strategies designed to reduce the nutrient loading of the Baltic Sea, and the identification of the most cost-effective nutrient abatement options; (4) to estimate the economic valuation of eutrophication damage to the Baltic Sea; (5) to increase our understanding of the institutional issues involved in the management of the Baltic Sea.

The GEC process is a complex flux of factors, the impacts of which can manifest themselves at a number of different spatial and temporal scales. It is, however, possible to identify a group of interrelated socio-economic trends and pressures which both contribute significantly to the Baltic's environmental change impacts, as well as to an increasing degree of environmental risk to the marine ecosystem and the surrounding drainage basins' biophysical and socio-economic systems. This paper therefore seeks to analyse the problems of the Baltic region in terms of a 'pressure-state-impacts-response' (P-S-I-R) framework (Fig. 1).

2. Pressure-state-impact-response framework

Within the Baltic Sea area the northern sub-basins (Bothnian Bay, Bothnian Sea) have a low population concentration, extensive forests, wet-

lands, lakes and a mountainous terrain. The southern sub-basins (Baltic Proper) contain 55 million of the 85 million population and have significant agricultural areas. The Baltic Sea itself has a total surface area of 415 000 km² and because of its semi-enclosed character has a very slow water exchange, the mean residence time for the entire water mass being of the order of 25–30 years (Folke et al., 1991). As we shall see this combination of biophysical and socio-economic characteristics has important implications for the environmental vulnerability of the Baltic Sea and its resource system.

An increasing degree of environmental pressure has been felt in the Baltic region as a result of a range of socio-economic drivers. The outcome has

been that the Baltic Sea and coastal zone resources (including the waste assimilative capacity) have been subject to a range of, often competing, usage demands. In this paper we pay particular attention to nutrient (nitrogen and phosphorus) pollution of the Baltic Sea and its consequences. Evaluating the importance (in human welfare terms) of the various environmental impacts requires that their effects be measured in biophysical and then in monetary terms. This gives us some measure of the state of the Baltic environment and the importance of the environmental degradation that has taken place. In addition, we seek to identify the causes of the problem, priorities for action and cost-effective policy instruments.

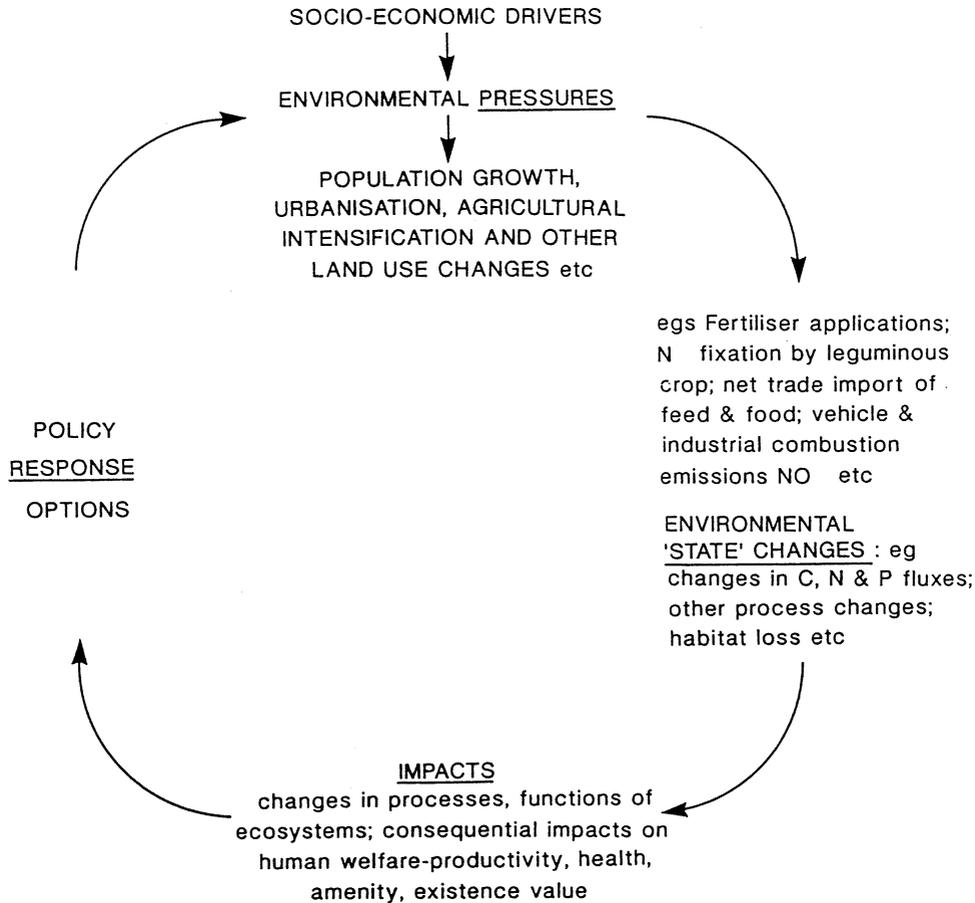


Fig. 1. P-S-I-R cycle, continuous feedback process.

The Baltic Sea is the largest brackish body of water in the world and is a naturally very sensitive area. It depends on short- and long-term variations in climate and has several times in its history transformed from lake to sea, from freshwater to saline water. Vertical variations in salinity cause permanent stratification, hampering the exchange of oxygen in the deeper parts of the sea. In some years as much as 100 000 square kilometres (nearly 25% of the total area) approach 'dead bottom' conditions.

The natural vulnerability of the area has been magnified by the magnitude and extent of socio-economic activities, impacts and interventions that have become commonplace since the 1950s. The economic and the environmental systems are now sufficiently interrelated as to be jointly determined. They are now in a process of coevolution. Because of the sheer scale of economic activity the pollution generated is a pervasive problem across the drainage basin and beyond. Localised solutions, for example at the municipal level, are no longer sufficient; international co-operative agreements and actions are required.

The principal pollution sources for the Baltic Sea are municipalities, industries and agriculture, located both in the coastal zone and also beyond in the drainage basin. A range of pollution pathways can also be identified, including diffuse 'non-point' sources such as airborne emissions and agricultural run-off, and 'point' source pollution from urban areas and industry.

Inadequate or absent municipal sewage treatment in the eastern, southern and south-western sections of the drainage area pose problems which are exacerbated by the synergistic effects of untreated industrial effluent wastestreams passing through the same facilities and into the rivers and the sea. Agricultural practices, including intensive livestock husbandry, are also a major contributor to the high nutrient load and consequent eutrophication problem. Current loads of nitrogen and phosphorous entering the Baltic sea are three times those of the 1950s (Nehring et al., 1990). The resulting excessive biomass growth causes oxygen depletion when it decays and threatens marine life. Eutrophication is now pronounced in the Gulf of Finland, Gulf of Riga and in limited

coastal areas in the eastern, southern and south-western Baltic Sea area. Many toxic algae outbreaks have also occurred.

It is important therefore to know what the principal causes of the resource degradation and pollution problems in the Baltic Sea are. One way of analysing these problems is to identify a set of interrelated 'failures' phenomena which seem to underlie the degradation and quality decline trends. There are two main related 'failures' which can be distinguished—market failure and policy intervention failure—which when combined with scientific and social uncertainties (information failure) can account for the environmental damage process.

3. Market and policy intervention 'failures'

Table 1 presents a typology of market and intervention failures which is relevant to the Baltic context. The most widespread type of market failure is that of pollution externalities. The external costs result from waste generators (municipalities, industry and farms) who over-utilise the waste assimilative capacity of the ambient environment, e.g. rivers and the Baltic Sea, because this environmental function is perceived to be virtually free of charge (absence of market prices). Some waste generators also have had over time close to open access to the marine waste repository.

Government interventions have also been partly responsible for the environmental degradation process in the Baltic. The effectiveness of the regulation of sewage treatment facilities and practices, for example, varies dramatically from country to country around the Baltic. There is a general absence of properly integrated coastal resource management policies and water catchment management and planning. This has resulted in intersectoral policy inconsistencies and resource depletion and degradation, with the loss of wetland ecosystems being an important damage impact.

Although these 'failures' phenomena are or were pervasive across the entire drainage basin, they tend to be focused in greater numbers and

Table 1
Market and policy intervention failures in the Baltic region

<i>Market failures</i>		
1. Pollution externalities		
(a)	Air pollution, outside catchment sources, e.g. North Sea area	Excess levels of nitrogen and ammonia contributing to eutrophication of water bodies
(b)	Water pollution, land-based within catchment sources	Excess nitrogen and phosphorus from sewage and agricultural sources; industrial wastewater and toxic effluent pollution particularly from the pulp-and-paper industry
(c)	Water pollution, coastal and marine sources	Excess nitrogen and phosphorus from coastal sewage outfalls; oil spills and contaminated bilge water from ships
2. Public goods-type problems		
(a)	Ground-water depletion/surface-water supply diminution	Over exploitation on- and off-site of wetlands' water supply
(b)	Congestion costs, on-site	Recreation pressure on beaches, wetlands and other sensitive ecosystem areas
(c)	Fisheries yield reduction	Over exploitation due to badly defined property rights
<i>Intervention failures</i>		
3. Intersectoral policy inconsistency		
(a)	Competing sector output prices	Agricultural price fixing and associated land requirements
(b)	Competing sector input prices	Tax breaks or outmoded tax categories on agricultural land; or tax breaks for non-agricultural land development, including forestry; land conversion subsidies; state farming subsidies (historical)
(c)	Land-use policy	Zoning; regional development policy; direct conversion of wetlands policy; waste disposal policy and regulation (uncontrolled waste disposal dumping)
4. Counterproductive policy		
(a)	Inefficient policy	E.g. policies that lack a long-term structure; wastewater and industrial effluent combined treatment practices; general lack of enforcement of existing policy rules and regulations
(b)	Institutional failure	Non-integrative agencies structure, non-existent agencies; lack of monitoring and survey capacity; lack of information dissemination; lack of public awareness and participation

with greater severity in Poland, Russia, the Baltic Republics and the Slovak and Czech Republics, partly as a result of the historical legacy left by a central planning system based on input intensive, inefficient heavy industry complexes.

In the Nordic countries and the western parts of Germany municipal and industrial pollution loads have been significantly reduced over the last few decades. Nevertheless, the agricultural sector poses problems due to the intensive nature of the farming regimes.

The dire message for Baltic policymakers in the future is clear — if the agricultural sectors in Poland, etc., develop intensive methods similar to those fertiliser/pesticide-dominated regimes commonplace in Denmark and Sweden, the outlook for the reduction of eutrophication pollution is poor.

4. Land use, nutrient loads and damage in the Baltic Sea

The current status of the Baltic Sea is determined by the set of activities present in the entire drainage basin. The load of nutrients to the various sub-drainage basins is determined by several factors such as land use, population density, climate, hydrology, and air transportation of nitrogen oxides and ammonium. A set of geographic information system (GIS) map layers were created and used to generate information on the current landscape characteristics and population distribution patterns in the drainage basin. The map layers included: land cover, drainage basin, administrative units, population distribution, arable lands, pasture lands, wetlands, and the terrestrial net primary production of the Baltic drainage basin. A description of the technical procedures and the primary data sources used to create each layer, as well as an assessment of data quality, is presented in Sweitzer and Langaas (1994), Folke and Langaas (1995), and Sweitzer et al. (1996).

The map layers in this database were combined to generate new results. The maps were used to generate basic statistics on land use and population in the drainage basin, which we briefly report on below. We also present results showing the distribution of land cover and population as a function of distance from the coast, since this information is directly relevant to the eutrophication problem in the Baltic Sea.

It was found that forests dominate the landscape in the drainage basin (48% coverage), followed by arable land (20%), and non-productive open lands (17%). Wetlands cover roughly 8% of the drainage basin and are most prominent in the northern regions. Turning to population, about 85 million people live in the Baltic Sea drainage

basin. Of these, the vast majority (64%) live in the Baltic Proper drainage areas. Of the total drainage basin population 26% (22 065 000 people) live within metropolitan areas (population > 250 000). Of the total population, 54% live in towns or small cities (population between 200 and 250 000), and 29% are inhabitants of rural settlements (population < 200 000).

Using the land cover and population map layers and an adjusted map of the drainage basin we further determined the characteristics of the drainage basin as they relate to distance from the coast. The further away from the coast or from rivers that eutrophying substances are released, the more likely they are to be absorbed through ecosystem processes and prevented from entering the Baltic Sea. High population concentrations, agricultural land, and urbanised land are all important nutrient generation sources. Wetlands, forests and inland water bodies can act as natural filters/sinks for nutrients as well as other pollutants. Given this, it is important to determine the landscape characteristics of the drainage basin as a function of distance from the coastline and rivers.

At its furthest point, the drainage basin is nearly 650 km away from the Baltic Sea shoreline. Land cover and population of the drainage basin were assessed at 10-km intervals extending away from the coast. It was found that while most of the land use classes are distributed fairly evenly throughout the drainage basin, population—particularly urban population—is heavily concentrated toward the coast. Within a 10-km distance from the Baltic coast, for example, we find 27% of the populated area and 19% of the total drainage basin population—nearly 15 million people. Of these 90% are concentrated in urban areas. Also within this area we find 8% of the total arable land, 5% of the pasture land, 5% of the forests, and 2% of the inland water bodies.

Expanding to a 50-km distance from the coastline, population remains the dominant feature of the landscape. In this zone we find 43% of the total populated area and 31% of the total population (over 26 million people). Of this population, 83% are urban. Additionally, 23% of the total arable land, 17% of the pasture land, 20% of the

forest, and 10% of the inland lakes are found within a 50-km distance from the coast. More detailed results are reported in Sweitzer et al. (1996).

The information on the location of various land uses and population within the drainage basin provides a useful basis for the estimation of nutrient load discharged directly into the Baltic Sea or transported by surface water to which we now turn.

In 1993, the total load of nitrogen and phosphorous to the Baltic Sea amounted to approximately 1022 000 t of N and 39 000 t of P. The largest basin of the Baltic Sea, the Baltic Proper, receives about 85% of the total load of both nitrogen and phosphorous (Table 2).

In principle, there are two major sources of waterborne nutrient loads, arable land and sewage treatment plants. In addition atmospheric transports of nitrogen are also deposited directly on the Baltic Sea. Air transports originate, not only from countries within the drainage basin, but from other external countries.

The agricultural sector, excluding the emissions of ammonium, accounts for one-fifth of the total load of nitrogen. Other water transports of nutrients include flows from sewage treatment plants and air emissions deposited on land within the drainage basin, accounting for nearly 50% of the total load. The direct discharges, mainly sewage treatment plants located at the coast, correspond to approximately 10% of the total load. Poland is the largest discharging country with respect to total nitrogen loading (28.5%), followed by Sweden (10.4%) and Germany (10.2%).

Poland is also the country providing the largest load of phosphorous to the Baltic Sea, approximately 50% of total load. The phosphorous load

from the agricultural sector accounts for about one-third of the total load and the direct discharges, mainly from sewage treatment plants correspond to one-quarter of the total load.

The increased nutrient flux entering the Baltic Sea implies a higher concentration of a given nutrient which in turn may lead to an overabundance of phytoplankton production. As a result of increases in phytoplankton production, oxygen deficits may occur which reduce the spatial extent of regions available for successful cod reproduction. On the other hand, more zooplankton increases the stocks of other fish species (Fig. 2).

Although the impacts of greater nutrient input are well documented, the quantitative relationships between variations in loads of nutrients and concentration are poorly understood. For instance, the eutrophication processes will alter redox conditions and thus the biogeochemical pathways and efficiency of internal sinks of nitrogen and phosphorous through denitrification; phosphorous adsorption will also be altered. The different sub-basins vary in terms of water and nutrient residence times, load received, and internal biogeochemical processes. These differences will significantly alter the N/P ratios in each sub-basin. Fig. 3 illustrates that there are processes in the sea that change the concentrations of nutrients, with specific differences between basins as well as between nutrients species: in the Bothnian Bay, the phosphorus loss (P-sink) is much more efficient than the sink for nitrogen. In the Baltic Proper, it is the opposite—a more efficient N-sink than P-sink. There is a gradient from north to south where the production in the Bothnian Bay is P-limited and the Baltic Proper is N-limited. The N/P ratio of 18 in the Baltic Proper is for total-N and P that includes a lot of refractory organic matter: for the inorganic fractions it is about 4, far below the Redfield ratio (data are not available to show inorganic N/P ratios both in terms of load and concentration).

An empirical budget model of the Baltic Proper has been expanded to cover all three sub-basins. The model consists of the three coupled basins with advective water and nutrient transports between these and with Kattegat (Wulff, 1995). Empirical relationships between load, nutrient

Table 2
Nutrient loads to the Baltic Sea, 1993

	Nitrogen (t)	Phosphorous (t)
Bothnian Bay	60 787	3008
Bothnian Sea	100 699	3063
Baltic Proper	861 268	32 817
Total	1 022 754	38 888

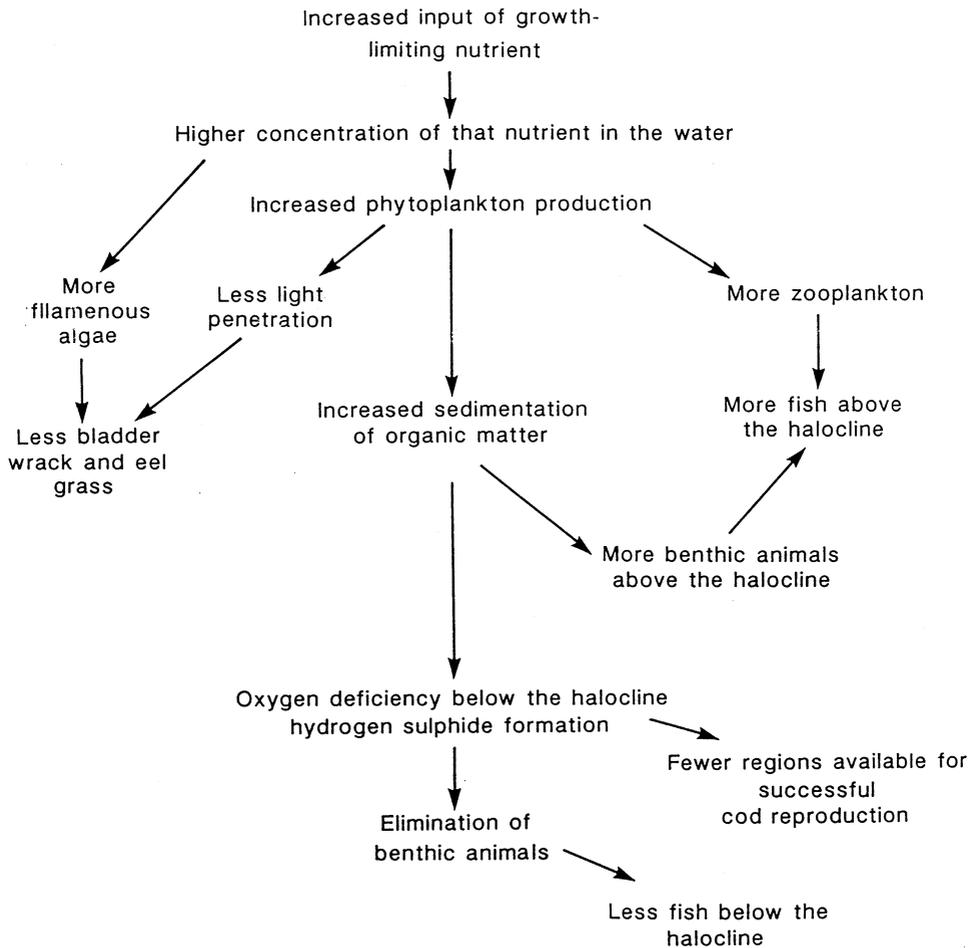


Fig. 2. Eutrophication impacts. Regarding eutrophication problems, the quantitative relationships between variations in loads of nutrients and concentration are poorly understood.

concentrations and advective transports derived from extensive regional data sets over the last few decades have been used to empirically calculate relationships between concentration and internal nutrient sink terms. These models rely on past relationships between inputs of water, nutrients and the observed trends in concentrations in the different basins of the Baltic. Several analyses have been undertaken to collate and verify these data sets.

The basic information on the flow of nutrients from the land to the Baltic Sea and their impact on the sea is required in order that abatement measures designed to improve the conditions in

the Baltic Sea can be selected on the basis of minimum cost. But before we can address the abatement options and their costs question we need to estimate the 'filter'/sink capacities of wetlands in the drainage basins.

The natural wetlands in the drainage basin account for about 8% of the total area. Their nitrogen retention/elimination capacity was estimated to be close to 65 000 t per year when only atmospheric downfall of nitrogen was taken into account. Adding direct emissions per capita in terms of excretory release, in relation to the location of the wetland to human population densities, we estimated the nitrogen retention/

elimination capacity to be about 100 000 t per year (Jansson et al., 1999).

The GIS database was used to assess the spatial relationship between nutrient sources and sinks. Maps were created to show the location of wetlands in relation to population centres in the Baltic drainage basin. The assumption is that wetlands will function more effectively as nutrient traps if they are in close proximity to nutrient sources. A visual assessment of the maps shows that areas with high concentrations of wetlands in the drainage basin are not near the densely populated regions. Areas with moderate or low concentrations of wetlands tend to have low or moderate population densities. These results suggest that development and restoration of wetlands in highly populated and also intensively cultivated areas could be an effective and practicable means to reduce nutrient flows into the Baltic Sea.

Therefore, we estimated the potential nitrogen retention/elimination capacity in a scenario where drained wetlands in the drainage basin would be restored. The capacity of wetlands to retain/eliminate nitrogen in such a scenario was estimated at about 180 000 t per year (Jansson et al., 1999). Additional analyses on the nitrogen filtering capacity will be reported on below in relation to the analyses of cost-efficient nitrogen abatement.

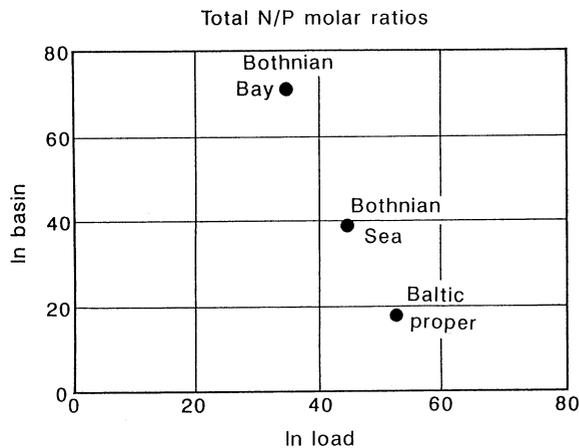


Fig. 3. Variations in N/P ratios.

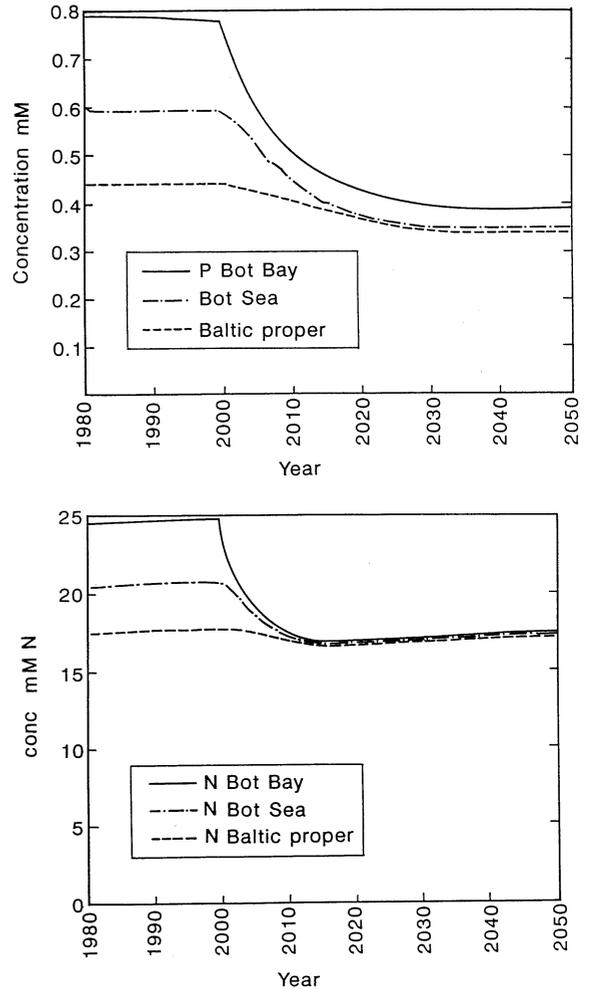


Fig. 4. Reduction from current levels of both N and P load with 50% to Baltic Proper.

5. Nutrient reduction simulations

Two nutrient reduction simulations were carried out.

In the first simulation, both N and P loads are reduced, but only to the Baltic Proper. Since the effect of eutrophication is most clearly seen in the Baltic Proper, this scenario would be the most obvious choice for a future abatement strategy. In this scenario it is assumed that the nutrient reduction occurs instantaneously in year 2000 and the changes in concentrations follow on until a new steady state occurs. As can be seen from Fig. 4

the nitrogen concentrations reach this new steady state within 10 years while it takes about 25 years for phosphorous. This is due to the inherently different behaviour of these nutrients in the Baltic (and in most other marine systems). Denitrification represents an efficient internal nutrient sink for N while P reduction is less efficient in this brackish system. According to the results presented in Fig. 5, the final concentration of P and N are about 50 and 70% of the current levels in the Baltic Proper.

It is difficult to estimate the ecological consequences from the output of this model alone—the results have to be related to empirical knowledge of ‘the state of the Baltic’ with different concentrations of nutrients. The ‘new’ nutrient concentration corresponds roughly to levels found during the 1960s, before the drastic deterioration

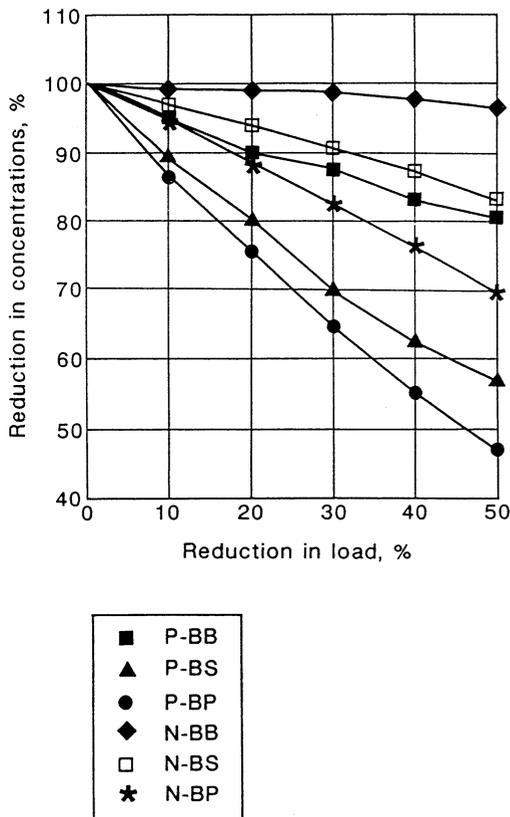


Fig. 5. Reduction from current levels of both nitrogen and phosphorus load but only to the Baltic Proper.

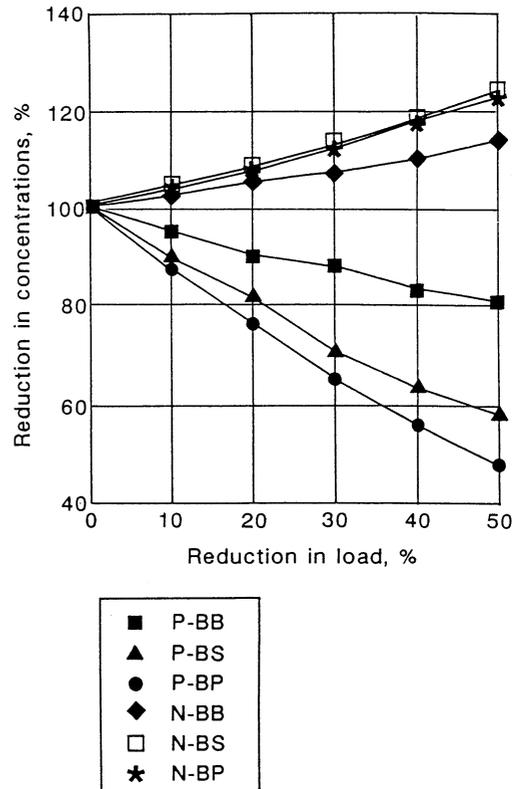


Fig. 6. Reduction of phosphorus loads to Baltic Proper.

of the Baltic environment occurred. We would expect less primary production of organic matter and thus less frequent periods of oxygen deficiency in the deep basins. It is also likely that the decrease in P concentrations will reduce the frequency of cyanobacterial bloom during the late summer. These are now favoured by the high P concentrations (and low N/P ratio) found during summer and cause accumulations of sometimes toxic algal mats on the surface of the Baltic Proper.

In the second simulation, only the P load is reduced to the Baltic Proper. This scenario was included since it is likely that the inputs of P are more easily reduced than those of N, since the sources are mostly municipal and agricultural (Wulff and Niemi, 1992). The model simulations show corresponding reductions of P concentrations on N (50% for the Baltic Proper and 80% for the Bothnian Bay) (Fig. 6). A decrease of

input and concentration of P means that less N will be utilised in the biogeochemical cycles, since these nutrients are utilised in fixed stoichiometric Redfield ratios (16 mol of N for each mol P). Thus, less N will be incorporated into organic matter and subsequently mineralised and denitrified (lost) in this scenario. The Baltic Proper and Bothnian Sea will change from N-limited to P-limited systems in this scenario.

The model simulations presented above illustrate the consequences of nutrient reductions on a basin-wide scale. However, decisions about abatement policies are often made because of concerns at the local or regional level, rather than on the basis of large-scale environmental concerns. The resulting conflicts from a Baltic-wide perspective are discussed by Wulff and Niemi (1992), and are further explored below in a regional study of the Gulf of Riga. A nutrient budget exists that describes nutrient inputs, retention and exports of nitrogen and phosphorous from this highly eutrophicated bay adjacent to the Baltic Proper. This is a region of the Baltic where lack of sewage treatment contributes to very large inputs of P to the sea. A reduction of P inputs of more than 30% would occur if a modern sewage treatment plant was built for the city of Riga. A model was therefore built to explore the consequences of different N and P reduction schemes on the Gulf and the Baltic Sea. One model run is illustrated in Fig. 7. The net exports of nitrogen and phosphorous to the Baltic are shown in relation to different levels of P reduction in the inputs of the Gulf. Naturally, a P reduction in inputs will result in reduced exports of P. However, more nitrogen will be exported to the (N-limited) Baltic Proper.

These model simulations, although based on very simplistic assumptions, empirical relationships and basic physical and biogeochemical properties, show very clearly the basic features and interactions of hydrodynamics and biogeochemistry of nitrogen and phosphorous in the Baltic Sea region. The overall model clearly demonstrates that it is reduction of inputs to the Baltic Proper that is most efficient in reducing concentrations in this basin. A strategy where all inputs are uniformly reduced is not optimal since the situation in the two northern basins is not

critical in terms of eutrophication (only small amounts of nutrients are exported southwards).

The simulations also demonstrate that both nitrogen and phosphorous inputs have to be reduced. This is also emphasised in the regional Gulf of Riga study where it was shown that a P removal might actually increase the net export to the off-shore Baltic Proper. It has also been demonstrated that it will take several decades before the nutrient levels are returned to an acceptable level, particularly for phosphorous.

To understand the institutional implications of this result, consider a problem in which there are two basins, each controlled by a different country acting unilaterally. Basin A is phosphorus-limited (like the Gulf of Riga) while Basin B is nitrogen-limited (like the Baltic Proper). Country A controls discharges into Basin A and has preferences only over the quality of this Basin. Similarly, Country B controls discharges into Basin B and cares only about eutrophication in this Basin. As Basin A is phosphorus-limited, A can enhance its welfare by reducing its phosphorus discharges and improving the state of Basin A. However, the reduction of phosphorus in A will also release

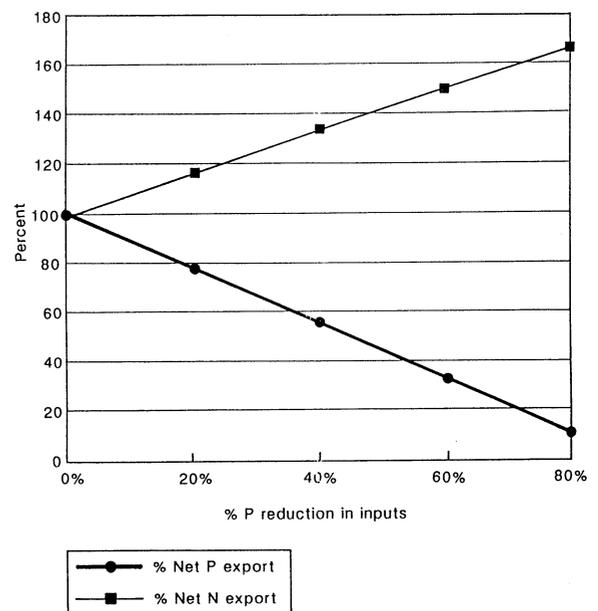


Fig. 7. % Change in nitrogen and phosphorus export from the Gulf of Riga at different levels of reduction in P load.

nitrogen, and this released nitrogen will be exported to Basin B. As B is nitrogen-limited (i.e. phosphorus-rich), eutrophication will increase in Basin B as a consequence of the actions undertaken by A. Similarly, if Country B reduces its nitrogen discharges in Basin B, phosphorus will flow into Basin A, exacerbating A's eutrophication problem.

As abatement of phosphorus by A increases eutrophication in B, Country B's best response is to reduce its nitrogen discharges further. But in doing so eutrophication is made worse in A, and A will therefore respond by reducing its phosphorus discharges even further. The process will continue until neither country can improve its welfare by abating discharges any further. This state defines the equilibrium in unilateral policies. As neither A nor B take into account the effect of their actions on the welfare of the other country, each is driven to abate its own Basin's limiting pollutant too much and the other Basin's limiting pollutant too little. As is typical of all equilibria in unilateral policies, pollution of both Basins is excessive compared with the full co-operative outcome. However, in contrast to every paper so far published in the literature, abatement (of each Basin's limiting pollutant) is also excessive in the equilibrium in unilateral policies. For more detail see Barrett (1995). The policy implication is that full co-operation is the optional strategy, but one in which abatement effort is redistributed rather than merely increased overall. Since marginal costs increase with abatement effort, this means that a small redistribution in abatement will lower total costs as well as total environmental damages.

6. Cost effective abatement strategies

Cost effectiveness is defined as achieving one or several environmental targets at minimum costs. A condition for cost-effectiveness is that the marginal costs of all possible measures are equal. Marginal cost is defined as the increase in costs when, in our case, nutrient load to the Baltic Sea is decreased by 1 kg N or P. As long as the marginal costs are not equal it is always possible

to obtain the same level of nutrient reductions at a lower cost by reducing the load via measures with relatively low costs and increasing the load by the same amount via measures with relatively high costs. Thus, in order to calculate cost-effective nutrient reductions to the Baltic Sea we have to (i) identify all possible measures, (ii) quantify their impact on the Baltic Sea, and (iii) calculate marginal costs for all measures.

The environmental impact of a certain reduction of nutrient load at the source is, *ceteris paribus*, determined by the location of the source. If the source is located some distance away from the coastal waters of the Baltic Sea, only a fraction of any reduction at the source is finally felt at the coast. The share of the source reduction that reaches the coast depends on the retention of the nutrient that may occur at various points between the source and the coast. This implies that, for a given marginal cost at the source, the marginal cost of coastal load reduction is higher than for remote sources with low impact on the coast. In order to calculate impacts of source-related measures we require information on source location as well as on transportation of nitrogen and phosphorus. No water and soil transport models exist for the drainage basin and so we use very simplified retention numbers.

The abatement measures can be divided into three different classes:

1. reductions in the deposition of nutrients on Baltic Sea and on land within the drainage basin,
2. changed land uses reducing leaching of nutrients, and
3. creation of nutrient sinks which reduce the transports of nutrients to the Baltic Sea.

The first class of measures includes improvement in sewage treatment plants, reductions in air borne emissions from traffic and stationary combustion sources, and reductions in the agricultural application of fertilisers and manure on land. Reductions in air emissions are obtained by the installation of catalysts in cars and ships, reductions in the use of motor fuel and other petroleum products, and the installation of cleaning technologies in stationary combustion sources. Reductions in agricultural deposition of nutrients are

Table 3
Marginal costs of different measures reducing the nitrogen load to the coast, SEK/kg N reduction

Region	Agriculture	Sewage treatment plants	Atmospheric deposits	Wetlands
Sweden	20–242	24–72	135–9500	23
Finland	57–220	24–60	874–6187	66
Germany	20–122	24–60	210–3576	27
Denmark	23–200	24–60	544–3576	12
Poland	12–101	7–35	523–3412	10
Latvia	59–196	7–35	183–1195	20
Lithuania	72–208	7–35	254–1723	15
Estonia	55–192	7–35	153–1999	36
St Petersburg	43–236	7–35	353–1884	51
Kaliningrad	28–210	7–35	273–1593	43
Belgium			742–4184	
France			1507–9045	
Netherlands			562–7184	
Norway			475–3460	
UK			785–4855	

obtained by a reduction in the use of fertilisers and reductions in livestock. Another measure included is a change in spreading time of manure from autumn to spring. Decreases in leaching from arable land are obtained by increasing the area covered by catch crops, energy forests, and ley grass. Nutrient sinks are created by constructing wetlands downstream in the drainage basin close to the coastal water.

In principle, the cost of an abatement measure includes the cost at the emission source and the cost impacts on other sectors of the economy. In the following analysis we only include the abatement costs at the source, which are calculated by means of engineering methods and econometric techniques (see Gren et al., 1995, for details about the cost estimation work). The calculated marginal costs at the source for different abatement measures aimed at reducing nitrogen load in different regions (Table 3) indicate that increased nitrogen cleaning capacity at sewage treatment plants is a low cost measure in all countries. Further low cost measures include, in the agricultural sector, the reduction in use of nitrogen fertilisers and cultivation of cash crops. Another low cost option is the construction of wetlands, whereas measures reducing air emissions are relatively expensive in all countries.

The marginal cost of phosphorous reductions tends to be much higher than those for nitrogen (Table 4). Nevertheless, measures involving improvements in sewage treatment plants represent relatively low cost reduction options. Restoration of wetlands is relatively expensive. It can be seen that phosphorus reduction in Swedish wetlands is more than ten times more expensive than Finland, for example. This is because the cheaper Swedish measures with respect to wetlands have already been extensively deployed, whereas they have not in the other countries.

Table 4
Marginal costs of phosphorous reductions, SEK/kg P reduction

Region	Agriculture	Sewage treatment plants	Wetlands
Sweden	155–6604	41–52	18232
Finland	225–6080	41–52	1748
Denmark	144–2610	41–68	1202
Germany	188–2964	41–68	899
Poland	114–2033	20–100	611
Estonia	282–5622	20–100	6090
Latvia	234–5662	20–100	1234
Lithuania	186–6696	20–100	964
St Petersburg	230–4314	20–100	823
Kaliningrad	338–4290	20–100	545

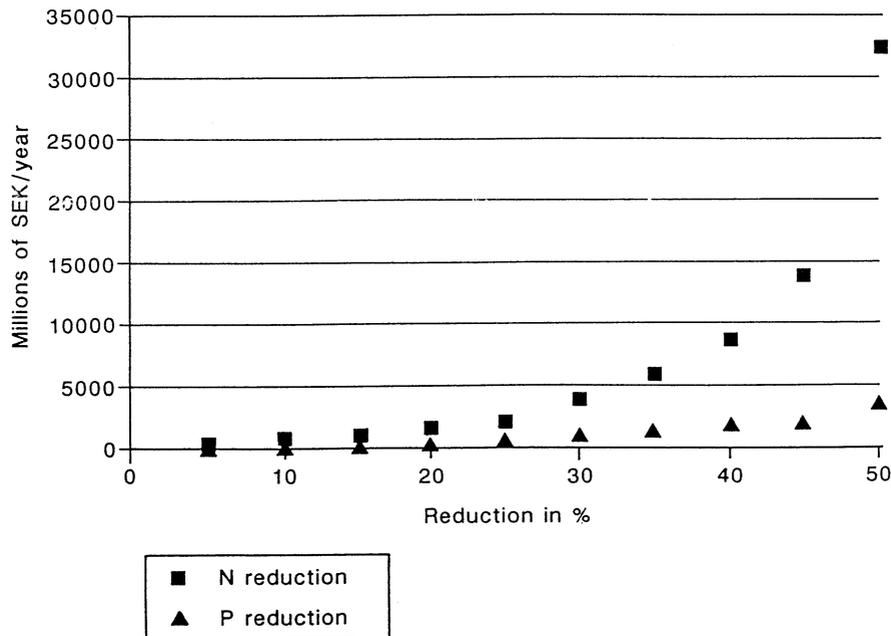


Fig. 8. Cost effective N and P reductions.

6.1. Minimum costs of nutrient reductions

Because it is reductions in nutrient loads to the Baltic Proper which have the main impact on the ratio N/P, we estimate minimum costs for load reductions to this basin only. The minimum costs for various reductions in either N or P are shown in Fig. 8.

We can see from the figure that the costs of reducing the load of nitrogen are much higher than the costs of corresponding decreases in phosphorous loads.

Several of the measures, such as livestock reductions, change of manure spreading time and wetlands restoration, imply reductions in both nitrogen and phosphorous. When one of these measures is implemented with the aim of reducing the load of one nutrient, reductions are obtained in the other nutrient load 'free of charge'. These joint impacts on several nutrients imply that abatement measures are relatively less costly if simultaneous reductions in N and P are undertaken. Total costs for various reduction levels are then lower for simultaneous decisions on N and P

than for separate decisions, especially for abatement levels in excess of 40% reductions (see Gren (1995) for more details). Note that P is more 'mobile' than N and therefore requires more abatement effort, thus P can be the 'keystone' pollutant, i.e. if P is managed then so is N but not usually the other way around.

In order to achieve a 50% reduction in nitrogen loading the most cost effective mix of measures would be one in which agriculture, wetlands and sewage treatment plant-related measures account for 35, 28, and 31%, respectively, of the total nitrogen reduction. Measures involving air emissions account for 6%. The single most important country source in a cost effective reduction strategy is Poland, which accounts for 40% of the total reduction (corresponding to about 2/3 of the Polish load of nitrogen). We also note that Poland, Russia and the Baltic states account for 72% of the total nitrogen reduction. The nitrogen reduction contribution of Swedish and Finnish regions amounts to only 8 and 7%, respectively.

For phosphorous load reductions wetland measures can only play a minor role in coastal waters,

and in fact it is only in Germany that such measures form part of a cost-effective abatement package. Instead, measures relating to sewage treatment plants are of major importance, accounting for 66% of the total reduction. This is a reflection of the relatively large load of phosphorous from households and industries and the availability of low cost abatement options. Again the single most important country source in a cost effective reduction strategy is Poland, which accounts for 67% of the total reduction. The Baltic states, Poland and Russia together account for approximately 90% of the total phosphorus reduction.

It is important to emphasise that the cost estimates are based on several assumptions of a biological, physical and economic character. The biological assumptions refer to retention of nutrients, the leaching impact of agricultural measures and the nitrogen removal capacity of wetlands. The physical assumptions concern the feasibility limits of different measures such as nutrient cleaning capacity of sewage treatment plants and area of land available for alternative land uses. The economic assumptions relate to the estimation of the costs of the various measures. According to the results of sensitivity analysis, both the costs of nitrogen and phosphorous reduction seem to be sensitive to assumptions of a biological character. Changes in the physical assumption about land available for agricultural measures often have a significant impact of the total costs. It should be noted, however, that the sensitivity analysis was carried out only for an overall reduction of 50% in the load of both nutrients. At other overall reduction levels, the costs may be sensitive to other types of assumptions.

7. Benefits valuation

The process of measuring the economic value of eutrophication damage in the Baltic involves three basic stages. Firstly, discharges of nutrients into the Baltic lead to eutrophication as outlined earlier and this leads to reductions in the various measures of environmental quality. Second, these changes in environmental quality lead to changes

in the stream of services (use and non-use values) provided by the Baltic region. Third, the change in the stream of services will affect individuals' well-being and the economic proxy for well-being, money income, such that willingness to pay for the stream of services will change.

A concerted attempt was made to estimate the economic benefits of environmental improvements in the Baltic. A total of 14 empirical valuation studies in three countries—Poland, Sweden, and Lithuania—were carried out to look at benefit estimation issues. These included the total economic value of reducing the effects of eutrophication, as well as sub-components of this total value such as beach recreation benefits, existence and option values of preserving species and their habitats, and the benefits from preserving and restoring wetlands. Of the applied studies that have been done in the different countries, some of them have focused on similar valuation issues, thus enabling a comparative evaluation of the studies to be carried out between the differing economic, cultural and political systems. We also have considered the question of total basin-wide benefit estimates and benefits transfer. Whilst the studies outlined here provide a large amount of information about the value of the Baltic's resources, there are still gaps in our knowledge of total basin-wide benefit estimates. Nevertheless, the estimates that are available indicate the significant value of the limited number of resource types considered.

The full results of all the studies are presented in Georgiou et al. (1995). Here we present the results of two of the studies carried out in Poland and Sweden which looked at the use and non-use value of reducing eutrophication to a sustainable level. These two studies were used to estimate basin-wide benefits.

The first study was a contingent valuation study focusing on Baltic Sea use and non-use values in Sweden. This study was designed as a mail questionnaire survey. The questionnaire was sent to about 600 randomly selected adult Swedes. The response rate turned out to be about 60%, which is quite similar to other contingent valuation method (CVM) mail questionnaire surveys that have been undertaken in Sweden.

The eight-page questionnaire is presented in detail in Söderqvist (1995). It contained, *inter alia*, summary information on the causes and effects of eutrophication of the Baltic Sea. In the valuation scenario, the respondents were asked to assume that an action plan against eutrophication had been suggested, and that this action plan would imply that the eutrophication in 20 years would decrease to a level that the Baltic Sea can sustain. The types of action that this plan would involve were briefly described. It was also explained that the way to finance the actions would be to introduce an extra environmental tax in all countries around the Baltic Sea.

The respondents then met the following question: “If there were a referendum in Sweden about whether to launch the action plan or not, would you vote for or against the action plan if your environmental tax would amount to SEK X per year during 20 years?”. Seven different amounts of money, X, were randomly used for the question. The answers to the question give an estimate of mean annual Willingness To Pay (WTP) of about 5900 SEK per person (or 3300 SEK if we assume non-respondents to the survey have a zero willingness to pay).

It is likely that the respondents considered use values as well as non-use values when they answered the WTP question. This means that the WTP reflects perceived total benefits. However, note that there may be important differences between perceived benefits and real benefits. One reason for this is that the information communicated to the respondents about the eutrophication and its effects was far from complete. Moreover, the results from this CVM study may be influenced by embedding phenomena, *i.e.* that the respondents have also considered their WTP for other environmental improvements, and not only for a reduction of eutrophication. Embedding is a recognised problem in CVM studies. Note also that it is not easy to relate the outcome in the valuation scenario—a reduction of the eutrophication to a level that the Baltic Sea can sustain—to a specific reduction of the nutrient load (though such an outcome is probably consistent with the 50% nutrient reduction target adopted by the Helsinki Commission). A time horizon of 20

years is reasonable in the sense that even if considerable action is taken today, it takes many years until any results will be evident. The description of the outcome as a ‘sustainable’ level reflects the fact emphasised by ecologists that actions against eutrophication will probably result in neither the complete disappearance of eutrophication, nor a return to the same ecological situation that characterised the Baltic Sea some decades ago, but rather to some new equilibrium.

The second study was almost identical to the first, except that it was carried out in Poland, thus providing a direct international comparison to be made between the benefit estimates found in both countries. Again a mail questionnaire was used and 600 questionnaires were sent out to a random sample of Polish adults. The response rate was just above 50% which was considered reasonable for this context and location. It was found that the level of support for the environmental tax was 54.9%. Mean annual willingness to pay per person for the action plan was 840 SEK (or 426 SEK if we assume non-respondents to the survey have a zero willingness to pay).

In order to calculate basin-wide benefit estimates we need to add up the values for the different activities carried out, taking care not to double count, and using the relevant correct populations. Since there are benefit estimates available for the same valuation scenario in only two of the 14 countries that are included in the Baltic drainage basin, any aggregation to the whole basin has to rely on strong assumptions. The aggregate benefit estimates to be presented below should thus not be taken too literally. However, they may give useful information regarding the order of magnitude of basin-wide benefit estimates.

Table 5 shows estimates of aggregate benefits for the total economic value of a Baltic Sea nutrient reduction strategy. Data from the Polish and Swedish mail surveys are used since they are both concerned with total economic value (use + non-use value), and they contain the same valuation scenario. Given an adjustment for the difference in GDP per capita levels between the countries, the Polish mean WTP estimate of 840 SEK (426 SEK) will be regarded as representative

for the transition economies around the Baltic Sea, i.e. Estonia, Latvia, Lithuania, Poland, Russia; and the Swedish mean WTP estimate of 5900 SEK (3300 SEK) is taken as representative of the market economies of Finland, Germany, Norway and Sweden (Table 5). The possible WTP of the population in the other countries included in the Baltic drainage basin (Belarus, Czech Republic, Norway, Slovakia and Ukraine) will be ignored in this analysis.

In order to calculate national WTP estimates, the estimate per person was multiplied by the (adult) population in the Baltic drainage basin part of each country. According to Table 5, the basin-wide estimate for total economic value is SEK 69 310 million per year (SEK 37 892 million per year). This is a highly uncertain figure, but it indicates that the benefits from a Baltic Sea clean-up of eutrophication may be considerable.

Table 6 brings together both the costs of pollution abatement and related economic benefit estimates in a cost-benefit analysis framework. It is clear that there are considerable net benefits available to a number of Baltic countries, sufficient for them to pay their own clean-up costs and subsidise the Baltic republics' abatement programme, while still gaining increased economic welfare benefits. While the economic benefit calculations are not precise point estimates, they are indicative of the range or order of magnitude of clean-up benefits in the Baltic.

Poland faces the largest cost burden because of its relatively high pollution loading contribution and the modest levels of effluent treatment that it currently has in place.

The costs in Table 6 refer to the allocation of nitrogen reductions that minimises total costs. We note that the reductions, measured in percentages of original loads, vary between 39% (Germany)

Table 5
Basin-wide benefit estimates

Country	GDP per capita at PPP ^a (US\$)	Annual WTP per person ^b (SEK)	National WTP, year 1 ^c (MSEK)	National WTP, present value ^d (MSEK)	National WTP, present value per year (MSEK)
<i>Transition economies</i>					
Estonia	3823	700 (355) ^e	790 (401)	8369 (4248)	418 (212)
Latvia	3058	569 (284)	1100 (549)	11653 (5816)	583 (291)
Lithuania	3632	665 (337)	1743 (883)	18465 (9355)	923 (468)
Poland	4588	840 (426)	21958 (11136)	232623 (117974)	11631 (5899)
Russia	4970	909 (461)	6585 (3340)	69761 (35384)	3488 (1769)
<i>Market economies</i>					
Denmark	19306	6770 (3790)	23365 (13080)	247529 (138570)	12376 (6929)
Finland	15483	5430 (3040)	20387 (11414)	215980 (120920)	10799 (6046)
Germany	18541	6500 (3640)	15800 (8848)	167385 (93736)	8369 (4687)
Sweden	16821	5900 (3300)	39122 (21882)	414458 (231818)	20723 (11591)
Total			130850 (71533)	1386223 (757821)	69310 (37892)

^a PPP = purchasing power parity.

^b For the transition economies, the Polish mean WTP estimate of SEK 840 (SEK 426) was multiplied by the ratio between each country's GDP per capita (at purchasing power parity) and Poland's GDP per capita at PPP. For the market economies, the Swedish mean WTP estimate of SEK 5900 (SEK 3300) and Sweden's GDP per capita at PPP were used correspondingly. Source of GDP data: OECD.

^c The annual mean WTP estimates per person multiplied by the (adult) population in the Baltic drainage basin part of the country.

^d Time horizon: 20 years (specified in the CVM studies). Discount rate: 7% (this rate was also used in the estimation of nutrient reduction costs).

^e Figures in brackets are for benefit figures which assume zero WTP of non-respondents.

Table 6

Costs and benefits from reducing the nutrient load to the Baltic Sea by 50%, millions of SEK/year^a

Country	Reduction in %	Costs	Benefits	Net benefits
Sweden	42	5300	20 723 (11 591)	15 423 (6291)
Finland	52	2838	10 799 (6046)	7961 (3208)
Denmark	51	2962	12 376 (6929)	9414 (3967)
Germany	39	4010	8369 (4687)	4359 (677)
Poland	63	9600	11 631 (5899)	1761 (–3701)
Russia	44	586	3488 (1769)	2902 (1183)
Estonia	55	1529	418 (212)	–1111 (–1317)
Latvia	56	1799	583 (291)	–1216 (–1508)
Lithuania	55	2446	923 (468)	–1523 (–1978)
Total	50	31 070	69 310 (37 892)	38 240 (6822)

^a Figures in brackets are for benefit figures which assume zero WTP of non-respondents.

and 63% (Poland). If the abatement cost strategy was based not on a cost-effectiveness criterion linked to an overall ambient quality target, but on some ‘political’ solution based, for example, on uniform national load reductions, then aggregate costs would be increased significantly (Table 7). This cost increase is due to the expensive measures that have to be implemented in Germany and Sweden. However, several countries with reduction levels exceeding 50% in Table 6 will gain from a country restriction as compared to a restriction of the total load of nitrogen.

The costs presented in Table 6 may also be overestimated because they do not include other environmental improvements associated with these nutrient reductions such as improved ground water quality and less acidification related to nitrogen oxides emissions. It is well known that several of the measures implying land use changes also yield other ecological services. For example, wetlands provide food, biodiversity and flood water buffering, and energy forestry on arable land provides fuel and may act as a carbon sink. If all these other positive aspects were included, some measures might imply internal net benefits instead of net costs.

The simulation results derived from our modelling of nutrient transports in the Baltic Sea provide a proxy for the missing dose-response scientific data. The model simulates the impacts of nutrient reduction on the concentration ratios of N and P but does not provide any detailed infor-

mation on the impacts on the biological conditions and production of ecological services. The available model does, however, predict that a 50% reduction in the loads of nitrogen and phosphorous to the Baltic Sea may correspond to the levels found during 1960s, i.e. before the major deterioration in the Baltic environment occurred. This scenario is likely to be consistent with the one used in the CVM studies. Therefore, a crucial assumption when comparing costs and benefits is that a 50% reduction in the loads of nitrogen and phosphorous imply that we reach ecological conditions which resemble those of the Baltic Sea prior to 1960s. Another important assumption

Table 7

Cost change of a move from a 50% reduction in total load to 50% reduction in the load of each country, in percent^a

Region	Nitrogen reduction	Phosphorous reduction
Sweden	–57.8	361.8
Finland	–51.9	718.1
Denmark	–48.8	29.1
Germany	543.6	32.1
Poland	–80.4	–57.9
Latvia	18.6	195.0
Lithuania	–17.5	289.2
Estonia	–13.4	277.1
St. Petersburg	981.8	–80.0
Kaliningrad	779.4	–81.6

^a A negative sign implies cost savings when country restrictions are imposed as compared to reduction by 50% in the total load of nutrient.

concerns the nutrient filtering capacity of different Baltic Sea coasts, which is likely to vary a lot. There is, however, no appropriate data on the coasts' filtering capacity. Therefore, no distinction has been made between different coastlines. Given all these qualifying assumptions, estimated costs and benefits of an overall reduction in the nutrient loads by 50% for different countries are as presented in Table 7. Note that Belarus, Czech Republic, Norway, Slovakia and Ukraine are excluded, since these countries were excluded from the cost estimation work.

8. Policy implications

There is considerable merit in the adoption of a basin-wide approach to pollution abatement policy in the Baltic and therefore in the implementation of an integrated coastal zone management strategy. It is clear that the ambient quality of the Baltic Sea is controlled by the coevolution of both biophysical and socio-economic systems throughout the macro-scale drainage basin.

Despite the pioneering nature (i.e. in the 'transition' economies) of some of the economic benefits research, there seems to be little doubt that a cost-effective pollution abatement strategy roughly equivalent to the 50% nutrients' reduction target adopted by the Helsinki Commission would generate significant positive net economic benefits (benefits minus costs). The research into the monetary valuation of environmental benefits also indicated that the public's and experts' perception of environmental quality and quality decline are not necessarily synonymous.

A policy of uniform pollution reduction targets is neither environmentally nor economically optimal. Rather, what is required is a differentiated approach with abatement measures being concentrated on nutrient loads entering the Baltic Proper from surrounding southern sub-drainage basins. The northern sub-drainage basins possess quite effective nutrient traps and contribute a much smaller proportionate impact on the Baltic's environmental quality state. The countries within whose national jurisdiction these southern sub-basins lie are also the biggest

net economic gainers from the abatement strategy.

Although there are a range of feasible individual N-reduction and P-reduction measures available, our research indicates that the simultaneous reduction of both N and P loadings into the Baltic is more environmentally effective as well as cost effective. The increased deployment of N-reduction and P-reduction measures within existing sewage effluent treatment works, combined with coastal wetland creation/restoration schemes and changes in agricultural practice, would seem to be a particularly cost-effective option set.

The marginal costs of nutrient reduction measures increase sharply towards the full works treatment end of the spectrum. This finding suggests that the greatest environmental and economic net benefits are to be gained by an abatement policy that is targeted on areas which lack treatment works of an acceptable standard, rather than on making further improvements to treatment facilities that already provide a relatively high standard of effluent treatment. This finding, combined with our findings relating to the importance of the spatial location of nutrient loading, suggests that nutrient reduction measures in the Polish and Russian coastal zone areas would be disproportionately effective. The financing of such measures remains problematic if only 'local' sources of finance are to be deployed. Non-commercial funding from the European Commission and other international agencies, together with bilateral agreements, could play a vital role in the enabling process for an effective and economic Baltic clean-up programme.

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