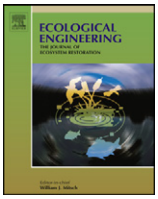
Ecological Engineering xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Values of mussel farming for combating eutrophication: An application to the Baltic Sea

Ing-Marie Gren[a,*], Odd Lindahl[b,1], Martin Lindqvist[a,2]

[a] Department of Economics, Swedish University of Agricultural Sciences, Box 7013, 750 07 Uppsala, Sweden
[b] Royal Swedish Academy of Sciences, Kristineberg 566, 450 34 Fiskebäckskil, Sweden

ARTICLE INFO

Article history:
Received 3 September 2008
Received in revised form 18 December 2008
Accepted 31 December 2008
Available online xxx

Keywords:
Value
Mussel farming
Cost minimisation
Eutrophication
Baltic Sea

ABSTRACT

The purpose of this study is to estimate the value of mussel farming for reducing nutrient contents in the Baltic Sea, which is made in a cost effectiveness framework. The value of mussel farming is then calculated as savings in costs from replacement of more costly nutrient abatement options. In addition to mussel farming, the cost minimisation model includes 20 abatement measures which affect agriculture, industry, transports and households in each of the 24 drainage basins of the Baltic Sea. The results indicate that calculated marginal cleaning costs of nutrients by mussel farming can be considerably lower than other abatement measures, but also relatively high depending on mussel growth, sales options, and formulation of nutrient load targets for the Baltic Sea. The estimated values range between approximately 0.1 and 1.1 billions of Euros per year depending on Baltic Sea nutrient target and net cleaning cost of mussel farming, which correspond to cost savings between 2 and 11 percent. The results also show that the value from contributions to savings of control costs for achieving the Baltic Sea action plan suggested by Helcom ranges between 5 and 60 percent of the market price of live mussel for human consumption.

1. Introduction

The role of bivalve species for regulating pollutant and nutrient concentration in lakes and seas has been recognised since 1950s (e.g. Suzuki, 1957; Seki, 1972; Ryther et al., 1972; Haamer, 1996; Gifford et al., 2005). Damages caused from nutrient enrichment have also been reported for several seas and lakes globally during several decades, such as the Baltic Sea, Black Sea, Mississippi delta, Cheasepeake Bay, and the Mediterranean (see e.g. Turner et al., 1999; Bodungen and Turner, 2001). Eutrophication of coastal waters is causing anoxic bottom conditions and the formation of algal mats in shallow bays (Diaz and Rosenberg, 1995; Cloern, 2001). Huang et al. (1997), Söderqvist (1998), and Markowska and Zylicz (1999) show that people are willing to pay a significant amount of money for reducing damages from nutrient-enriched bays. Although anthropogenic nutrient emissions constitute the main cause of eutrophication, the dispersion of emission sources in large drainage basins may make it prohibitively costly to obtain necessary nutrient load reductions for reaching acceptable ecological status of damaged seas. This is the case for Baltic Sea, where many of the relatively low cost abatement options at point sources are implemented, but further nutrient load reductions are required (Helcom, 2007).

Bioremediation measures, such as mussel farming, may then have cost advantages by their direct impact on eutrophic coastal zones and the multifunctional abatement of several pollutants. Mussel farming is an easy, flexible and realistic measure and can be a cost-effective method to decrease the negative effects of eutrophication in marine waters. At the same time, healthy marine food is produced from a low level of the food chain, and nutrients are recycled from sea to land. This paper points out that mussel farming can be a cost-effective abatement method against eutrophication although the mussels from some basins of the Baltic Sea are too small to be used as seafood. Options for the use of the small Baltic mussels are as organic feedstuff replacing fish meal in feed for e.g. laying hens and chicken poultry (Jönsson, 2006; Waldenstedt and Jönsson, 2006) or as organic fertiliser (Lindahl et al., 2005).

However, in spite of natural science research on the potential of bivalve species as nutrient cleaning options there are few studies valuing the potential of these species as a cleaning measure in polluted waters (Hart, 2003; Lindahl et al., 2005). The purpose of this study is to fill this gap of knowledge by estimating the value of mussel farming for combating eutrophication in the Baltic Sea. This

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[*] Corresponding author. Tel.: +46 18 671753.
E-mail addresses: ing-marie.gren@ekon.slu.se (I.-M. Gren), odd.lindahl@kva.se (O. Lindahl), martin.lindqvist@ekon.slu.se (M. Lindqvist).
[1] Tel.: +46 523 18512.
[2] Tel.: +46 18 67 10 00.

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doi:10.1016/j.ecoleng.2008.12.033

is made by estimating the so-called replacement value of nutrient cleaning by mussel farming in the Baltic Sea, which is calculated by means of a non-linear programming model where costs and impacts of mussel farms are compared with other abatement measures in the entire drainage basin of the Baltic Sea. This is made possible by the relative good access to data made available by the research of this sea during approximately 35 years.

The scant literature on assessment of value of nutrient cleaning by mussel farming usually applies a simple comparison of unit abatement costs with other abatement measures, most often cleaning at sewage treatment plants (Lindahl et al., 2005). This is an appropriate approach when sewage treatment plant is the only alternative cleaning option, which may be the case for nutrient-enriched bays at the local scale. At the Baltic Sea scale, there are a number of additional abatement measures available, such as changes in land use and fertiliser practices in the agricultural sector, and increased cleaning by households and industries not connected to common sewage treatment. The value of mussel farming is then determined by the cost savings obtained by the replacement of abatement measures with higher cleaning costs. To the best of our knowledge, there is no study estimating the value of mussel farms for combating eutrophication in a wider context with respect to alternative abatement measures, spatial scale and different nutrient load targets. A related strand of literature is that on valuation of wetlands as nutrient sinks and forests as carbon sinks, which also applies the replacement cost method (e.g. Gren, 1995, 1999; van Kooten et al., 2004). The literature shows that the value of land as pollutant sink depends on target for environmental policy, costs of all possible abatement measures, precision in target achievement of different measures (Gren, 2008), and time perspective (Hart, 2003). The specific contribution of this paper is the valuation of mussel farms for mitigating eutrophication in the Baltic Sea. Simplifications are made by using a static and deterministic model. The reason for this simplification is the difficulty of finding necessary data, mainly on cleaning capacities of mussel farming and dynamic adjustments of nutrient loads in the Baltic Sea, for stochastic dynamic programming model.

The paper is organised as follows. We first give a simple theoretical basis of the conditions for a positive value of nutrient cleaning by mussel farming and the determinants of the magnitude of the value. Next, calculations of costs and nutrient cleaning of mussel farms are presented. Section 4 gives a brief description of the non-linear programming model used for assessing values of nutrient cleaning by mussel farms at the Baltic Sea drainage basin scale. Section 5 presents the results with respect to value of mussel farms. The paper ends with some concluding remarks.

2. Approach for the estimation of values of mussels as nutrient cleaning device

Typical for most eutrophic seas is that excess and unbalanced loads of nitrogen and phosphorus contribute to water quality damages in the sea. Maximum nutrient load targets have been suggested for the Baltic Sea (Helcom, 2007). The value of mussel farming for nutrient abatement is then determined by the abatement targets for both nutrients and cleaning costs of mussel farming and other abatement measures. However, the condition for mussel farming to have any positive value at all is that the marginal cost of cleaning is lower than that of other measures. In order to see this, we derive the value of mussel farming from a cost minimisation principle where total abatement costs, C, are minimised for achieving certain maximum nutrient load targets, P^{L} where L = N, P, on nitrogen, N, and phosphorus, P, which is written as

$$\underset{A^{ih},A^{m}}{Min}\ C=\sum_{i}\sum_{h}C^{ih}(A^{ih})+C^{m}(A^{m})\ \text{subject to}$$

$$\sum_{i}\sum_{h}(D^{hL}-R^{ih}(A^{ih}))-R^{mL}(A^{m})\leq P^{L}\quad \text{for}\ \ L=N,\ P \tag{1}$$

where $C^{ih}(A^{ih})$ is the cost function for abatement measure i in drainage basin h, $C^{m}(A^{m})$ is the cost function for mussel farming in the sea, D^{hL} is the initial load of N and P, respectively, to the sea prior to abatement, $R^{ihL}(A^{ih})$ is the impact of abatement measure i in the drainage basin h on N and P loads to the sea, R^{mL} is abatement of N and P from mussel farming in the sea.

The conditions for a positive value of mussel farming is now obtained from the first-order conditions for a minimum cost solution to (1), which are written as

$$\frac{\partial C^{ih}}{\partial A^{ih}}=\lambda^{N}\frac{\partial R^{ihN}}{\partial A^{ih}}+\lambda^{P}\frac{\partial R^{ihP}}{\partial A^{ih}} \tag{2}$$

$$\frac{\partial C^{m}}{\partial A^{m}}=\lambda^{N}\frac{\partial R^{mN}}{\partial A^{m}}+\lambda^{P}\frac{\partial R^{mP}}{\partial A^{m}} \tag{3}$$

where λ^{N} and λ^{P} are the shadow costs of the nutrient targets, which show the increase in costs from a decrease in each load target by one unit. These shadow costs are usually denoted the marginal costs of the nutrient load targets. The left hand sides of (2) and (3) show the marginal abatement cost at the source, and the right hand sides reflect the value of the impacts on the N and P targets.

In order to get an intuitive understanding of the conditions, we start by assuming that there is a target only on phosphorus, which means that λ^{N} is equal to zero. The first-order conditions (2) and (3) are then written as

$$\frac{\partial C^{ih}/\partial A^{ih}}{\partial R^{ihP}/\partial A^{ih}}=\lambda^{P}=\frac{\partial C^{m}/\partial A^{m}}{\partial R^{mP}/\partial A^{m}} \tag{4}$$

which states that, in a cost-effective solution, the cost of mussel farming for reducing P at the target by one unit is the same as that for all other abatement measures. Mussel farming is then an interesting abatement option only if the marginal cost of mussel farming is lower than that of other abatement measures.

The left-hand side of (4) shows the marginal cost of nutrient abatement of measure i in drainage basin h as $(\partial C^{ih}/\partial A^{ih})/(\partial R^{ihP}/\partial A^{ih})=\lambda^{P}$. The numerator is the abatement cost for an additional cleaning at the source and the denominator is the impact of an additional cleaning at the source on the sea. For example, a decrease in the application of fertilisers by 1 kg P implies a cost from foregone profits of Euro 5, and the impact on the Sea is 0.5 kg. This generates a marginal cost of Euro 10 kg^{-1} P reduction in the sea. The reason for a smaller impact on the sea than the reduction at the source is that not all fertiliser leaches into soil and water and is further transported to the sea. The smaller the impact, the higher is the marginal cost of phosphorus fertiliser reductions. Similarly, the right hand side of (4) reflects the cost of an addition cleaning of 1 unit P in the sea by mussel farming. Since the mussel farm is located in the sea, there is 1:1 correlation between reduction at the source and impact on the sea.

The derived principle for a positive value of mussel farming is illustrated by a simple example on phosphorus reductions in Fig. 1.

The horizontal axis illustrates phosphorus cleaning targets and the vertical axis shows the cleaning cost per unit phosphorus reduction. The MC^{m} and MC^{o} curves reflect the marginal cleaning costs of mussel farming and other abatement measures, respectively. As illustrated in Fig. 1, marginal costs of both types of cleaning measures start at low levels and then increase successively for larger reduction requirements. This is a typical shape of marginal costs

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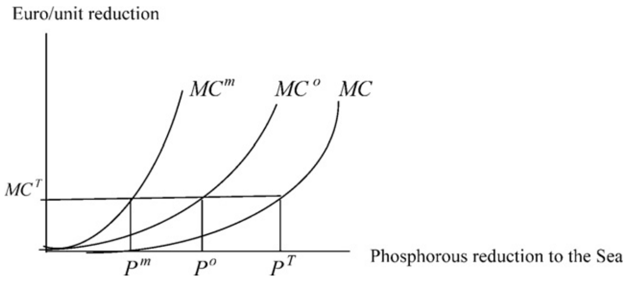

Fig. 1. Illustration of marginal cost of mussel farming, MC^m, for phosphorous reduction in relation to marginal cost of other abatement measure, MC^o at the phosphorous reduction target P^T (MC: marginal cost of mussel farming and other abatement measures, MC^T: marginal cost at target P^T, P^m and P^o: cost-effective allocation of cleaning by mussel farming and other abatement measures where $P^T = P^m + P^o$).

for any abatement measure, where the first units of cleaning are relatively cheap and cost per unit increase at higher cleaning levels.

The marginal cleaning cost of phosphorus by mussel farming, MC^m, is higher than that of other abatement measures, MC^o, at all cleaning levels. Nevertheless, at the overall cleaning target of P^T, cost-effective cleaning is obtained by the combination of mussel farming and abatement by other measures. The cost-effective allocation of abatement, P^m and P^o, is determined by the overall marginal cost, λ^{PT}, at the target P^T. The MC curve shows the marginal cost of cleaning when mussel farming and other abatement measures are included in the cleaning program.

From Fig. 1 we can then see that higher marginal abatement costs of other measures, MC^o, and the lower marginal cleaning cost by mussel farming, MC^m, the more cleaning should be made by mussel farming and vice versa. One reason for the relatively low cost of mussel farming can be its simultaneous abatement of both nitrogen and phosphorus. This is shown in Eq. (5), where we add a nitrogen load target to the phosphorus target. By rewriting (2) and (3), the condition in (4) is extended according to

$$\frac{\partial C^{ih}/\partial A^{ih}}{\partial R^{ihP}/\partial A^{ih}} - \lambda^{N}\frac{\partial R^{ihN}/\partial A^{ih}}{\partial R^{ihP}/\partial A^{ih}} = \lambda^{P} = \frac{\partial C^{m}/\partial A^{m}}{\partial R^{mP}/\partial A^{m}} - \lambda^{N}\frac{\partial R^{mN}/\partial A^{m}}{\partial R^{mP}/\partial A^{m}} \qquad (5)$$

If the abatement measures exhibit joint abatement in both nitrogen and phosphorous loads, such as land use changes in the drainage basins and mussel farming in the marine basins, the cost of a marginal reduction of phosphorus in the sea is reduced. The cost reduction is, in turn, determined by the marginal cost of the nitrogen load target, λ^N, multiplied by the nitrogen reduction obtained per unit of phosphorus reduction. The higher the abatement impact on nitrogen, the lower the marginal cost of the measure for achieving a marginal phosphorus reduction.

Given that $MC^m \leq MC^o$ at any reduction level within the target, the magnitude of the value is determined by the stringency in nutrient load targets, which is illustrated for phosphorus reductions in Fig. 2.

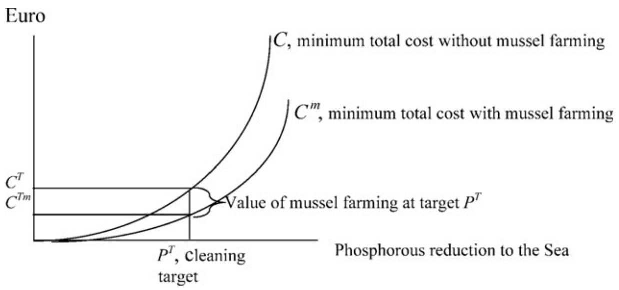

Fig. 2. Illustration of calculation of the value of mussel farming as an abatement measure in a cost effectiveness framework.

The curve C shows the minimum costs for achieving different pollutant cleaning targets when mussel farming is not included as an abatement option in the cleaning program, and C^M illustrates the minimum costs when mussel farming is included. Each point on C and C^M, respectively reflects the allocation of all abatement measures that reaches the target at minimum costs as illustrated for the target P^T in Fig. 1 and shown by Eqs. (1)–(5).

The value of mussel farming at the target phosphorus load target P^T is now determined by the difference in total minimum costs with and without mussel farming, which corresponds to the distance C^T–C^{Tm} in Fig. 2. The value increases from mussel farms' potential cost advantages with respect to its multifunctional cleaning capacity, i.e. simultaneous cleaning of nitrogen and phosphorus, and the direct impact on the sea. Targets exceeding P^T give a larger value of mussel farming and targets below P^T generate lower values. At considerable low targets, mussel farming may not possess any value due to the existence of alternative abatement measures with lower costs, such as modest reductions in fertiliser reductions.

3. Costs and nutrient cleaning by mussel farming

As reported in Section 2, the value of mussel farming is partly determined by two factors: cleaning impacts on the Baltic Sea and on the cost of construction and maintenance of mussel farms. Data retrieval of these two components is presented in this chapter. Unless otherwise stated, all data are found in Lindahl and Kollberg (2009) and in Lindqvist (2008).

3.1. *Mussel farming and nutrient harvest*

Long-line farming is the most common method of mussel farming in Scandinavia. The larvae of the blue mussel settle in early summer on vertical suspenders attached to horizontal long-lines carried up by buoys. The long-lines are typically 200 m long and the suspenders reach close from surface down to about 6 m depth. A varying number of long-lines are collected to a unit which is anchored at both ends. When harvested, 1 kg of live mussels contains 8.5–12 g of nitrogen, 0.6–0.8 g of phosphorous and about 40–50 g of carbon (Lutz, 1980; Haamer, 1996) which will be recycled from the sea back to land. However, the growth of mussels is highly dependent on the content of salinity and varies therefore between different basins of the Baltic Sea.

In the programming model of cost-effective nutrient reductions, the Baltic Sea is divided into seven major basins: Bothnian Bay, Bothnian Sea, Gulf of Finland, Gulf of Riga, Baltic Proper, the Sound, and Kattegat (see Fig. B1 in Appendix B). Experiments with farming of the blue mussel (*Mytilus edulis*) have been made only in one of these basins, the Baltic Proper, and in a basin bordering the Baltic Sea, Skagerack. The salinity content is too low for mussel farming in three basins, the Bothnian Sea, the Bothnian Bay, and the Gulf of Finland, which therefore are excluded as potential basins for blue mussel farming. The study then considers the potential of mussel farming in the Kattegat, the Sound, and Baltic Proper basins. Since there are no data from mussel farming in Kattegat and the Sound, results from experiments in Skagerrak are transferred to these basins.

Along the Skagerrak part of the Swedish west coast the maximum yield per m suspender is about 10 kg of mussels which can be used for human consumption. Recalculated to per hectare of sea surface, the harvest is about 300 ton of mussels in seafood size (5–8 cm) in 12–18 months. These results on mussel growth in Skagerrak can be transferred to potential mussel farming in Kattegat since the biological and environmental conditions for blue mussel farming are as good as along the Skagerrak coast. However,

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there are rather few sheltered sites available. Mussel farming in more or less open waters should be possible by adopting existing technologies for farming at exposed sites, but the experience of such activities in Scandinavia is scarce.

In the Sound and the southwestern part of the Baltic the salinity is lower than compared with Kattegat (10–14 in practical salinity units), which results in slower growth and smaller mussels. There are no data available on growth and yield of long-line mussel farming from these areas, and it is assumed that 1 ha of mussel farming should result in 100–120 ton seafood mussels in 2 years or the same amount of feedstuff mussel biomass in 1 year.

In the central and northern part of the Baltic Proper the salinity varies between 4 and 8 in practical salinity units and the growth and size of the blue mussels are consequently much reduced. Tests of long-line mussel farming started at a small scale in the Kalmarsund and in the Åland archipelago in 2006. In principle the same technique was used as in true marine waters for settling and growth, but Baltic mussels are smaller and attach more loosely which will require some minor technical development for handling and harvest. The mussel biomass per m suspender was in average 953 g ($n = 12$) after 10 months in Kalmarsund and 1293 g ($n = 12$) after 20 months at Åland (Lindahl, unpublished data). The harvest in September 2008 yielded a biomass of about 4 kg per m suspender in Kalmarsund (Thore, pers. com.) and about 2 kg at Åland (Engman, pers. com.). This increase in mussel biomass was in accordance with reported growth of Baltic blue mussels (Kautsky, 1982). Recalculated to a harvest per hectare sea surface this growth will result in a possible harvest of 120 tons in Kalmar Sound) and 60 tons in Åland grown over fully 1 and 2 years, respectively. The mussel biomass can be used as feedstuff or as fertiliser after a risk assessment has been done checking that there are no harmful substances above regulation levels.

Validation of the amounts of nutrients recycled from sea to land when using mussel farming as a nutrient abatement measure is a rather simple and strait forward process. Further, for example, increased visibility in the surface water is a parameter which can be used for validation of the effects of mussel farming on a local scale. However, on a regional or basin scale the contribution from the mussel farming combating the eutrophication will be too small to be measurable as a single measure.

3.2. *Costs of nutrient cleaning by mussel farming*

Appropriate calculation of costs, or more precisely, net cost, includes investment and operational costs of farming for nutrient harvesting minus the value of impacts of all other effects. This requires the quantification and measurements in monetary terms of all positive side effects of mussel farm, such as food provision, metal recycling in the Sea, eventual net contribution to regional and local economic growth, but also negative effects such as costs for control of mussels used as human food or as fodder for laying hens and chicken poultry. Unfortunately, such quantification and valuation of all effects has not been possible to carry out, and the cost estimates therefore rely on partial calculation of cost, which includes investment and operational costs, and the value of mussels as human or animal food resources. Ideally, cost functions are estimated by statistical analysis of data on total costs and production of mussels for a large number of mussel farms. However, costs and mussel harvests are available only for three different experimental mussel farms in the Baltic Sea, which implies that the cost estimation applies the so-called engineering method based on these experiments, see Section 4 for a discussion of different cost estimation methods. These experiment farms apply the so-called long-line technology for mussel cultivation. Unless otherwise stated, all data in this chapter are found in Lindqvist (2008).

Marginal cost calculations are made for the four marine basins discussed in Section 4 due to the differences in mussel growth and use of mussels. In Kattegat and the Sound, harvested mussels can be used for human consumption. This is not possible for mussels in the Baltic Proper except for in the very southwestern part due to the low mussel growth rate and associated small size. It is assumed that these mussels can be used as food for animals, so-called feedstuff mussel. Calculations of constant marginal costs are made with and without the possibility of selling the mussels in two steps. First, estimations of marginal cost for producing mussels are made. Second, these calculations are combined with estimates of content of nitrogen and phosphorus reported in Section 3.1. When net marginal costs are calculated, a third step is added by deducting sales from incomes of the mussels, see Table 1.

The main part of the production cost of mussel farming consists of labour costs for constructing and maintaining the farm, and to harvest the mussels, see Table A1 in Appendix A. Additional costs consist of capital and administration cost. The relatively low production cost in Southern Baltic Proper is explained by the assumed lower salaries in Poland, Kaliningrad, and Latvia where mussel farming is possible due to the relatively high salinity content. The results in Table 1 show a large variation in estimated marginal cost for both nutrients. The marginal costs of nitrogen cleaning range between Euro 10 kg^{-1} N and Euro 63.5 kg^{-1} N if the harvested mussels cannot be sold, being lowest in Kattegat and highest in Northern Baltic Proper. The corresponding range for phosphorus cleaning is between Euro 150 kg^{-1} P and Euro 900 kg^{-1} P cleaning. The costs are reduced and can be zero if mussel sales for human or animal consumption are possible.

From these calculations of constant marginal costs of nutrient cleaning by mussel farming we can conclude that the potential cost savings are largest in Kattegat when the mussels can be used for human consumption. However, depending on the marginal costs of other abatement measures, mussel farming can be of interest also under conditions of sales as industry mussel and even without the possibility of income from sales. The magnitude of value of mussel farming is then determined, not only by its marginal cost in relation to other abatement measures, but also by its cleaning capacity. This is, in turn, determined by the number of suitable locations of mussel farms with the long-line technology which requires reasonable wind protection, water depths between 6 and 25 m and average current speeds of more than 5 cm s^{-1}. Since no investigation has been made on the availability of such location, it is here simply assumed that mussel farming can be introduced at maximum areas of 200 ha in each of the Kattegat and the Sound and 800 ha equally divided in the Northern and Southern Baltic Proper. This implies contributions of phytoplankton from areas that are 7.5–25 times larger in size (Lindahl and Kollberg, 2009).

4. Brief description of the Baltic Sea cost minimisation model

Similar to costs of mussel farming, costs of abatement measures implemented in the drainage basins are determined by their impacts on the target for the Baltic Sea and on the abatement cost at the location of the measure. Impacts of measures implemented in the catchment depend on nutrient transports in the drainage basins, which, in turn, are determined by emissions from sources, leaching and retention during transports from the source to the coastal waters. Since these transport factors differ among different regions in the drainage basin of the Baltic Sea because of variation in climatic, hydrological, and biological conditions, the entire basin

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Table 1
Marginal cost and net cost of nutrient cleaning by mussel farming.

	Kattegat		The Sound		North Baltic Proper	South Baltic Proper
	Human	Industry	Human	Industry	Industry	Industry
Production cost (Euro kg^{-1})[a,b]	0.28–0.32	0.08–0.10	0.64–0.72	0.16–0.19	0.33–0.54	0.18–0.21
Marginal cost (Euro kg^{-1} N)	23.3–37.7	10–16.5	26.7–42.4	13.3–22.4	27.5–63.5	15–24.7
Marginal cost (Euro kg^{-1} P)	350–533	150–233	400–600	200–317	413–900	225–350
Sales price (Euro kg^{-1})	0.35	0.08	0.35	0.08	0.08	0.08
Net cost (Euro kg)	0	0–0.02	0.29–0.37	0.08–0.11	0.25–0.48	0.1–0.13
Marginal net cost (Euro kg^{-1} N)	0	0–4.3	24–31	6.7–13	21–57	8.3–15
Marginal cost (Euro kg^{-1} P)	0	0–60	363–454	100–183	312–800	125–216

[a] Table A1 in Appendix A.
[b] Lindqvist (2008), tables in Appendix A–D, pp. 45–57, 2.

is divided into 24 drainage basins with nutrient loads into one of the marine basins, see Fig. B1 in Appendix B. Nutrient transports from sources and costs of abatement measures are calculated for each of these drainage basins, which are briefly presented in this chapter. Unless otherwise stated, all data and calculations are found in Gren et al. (2008).

Nutrient loads to the Baltic Sea are, for all emission sources, calculated by means of data on emissions, which are sufficient for sources with direct discharges into the Baltic Sea, such as industry and sewage treatment plants located by the coast and air deposition on the sea. For all other measures data are needed on the transformation of nutrients from the emission source to the coastal waters. This requires data on transports of airborne emissions among drainage basins, leaching and retention for all sources with deposition on land within the drainage basins, and on nutrient retention for upstream sources with discharges into water streams. Nitrogen loads are therefore divided into three main classes: airborne emissions, agricultural loads, and discharges of sewage from households and industry. Phosphorus loads are classified into the same categories with the exclusion of airborne emissions.

Airborne emissions include nitrogen oxides and ammonia which are deposited in the drainage basins and directly on the Baltic Sea. A limitation is made in this study by including nutrient loads which can be affected by measures implemented in the drainage basins of the Baltic Sea. This includes all air deposition on land within the drainage basin, which originates from countries within and outside the drainage basin, which can be affected by land use measures. This is not the case for direct air deposition on the Baltic Sea originating from non-riparian countries, which accounts for approximately 15 percent of calculated load to the Baltic Sea from airborne emissions (Gren et al., 2008). The airborne emission gives rise to deposition directly on the Sea and also indirectly through deposition on land, which is transported by soil and water into the Baltic Sea. Calculation of indirect air deposition and loads from agriculture is made by data on airborne transports of nitrogen and ammonia among countries, deposition on land and on leaching from soil and retention in water transports to the Baltic Sea.

The contribution of nutrient loads to the Baltic Sea from arable land is calculated in the same way as for indirect air deposition. Deposition of nutrients on arable land then includes manure and fertilisers. Discharges of N and P from households are estimated based on data on annual emission per capita in different regions, and on connections of populations to sewage treatment plants with different cleaning capacities. It is assumed that remaining nutrients from households and industry in the drainage basins are discharged into water streams, and the final deposition into the Baltic Sea then depends on nutrient retention. Given all assumptions the calculated total nutrient loads of approximately 830 kton of N and 40 kton of P come close to the estimates obtained in Helcom (2004).

The cost minimisation model includes 12 different measures for nitrogen reduction and 10 abatement measures for phosphorous reductions. Since the agricultural sector accounts for approximately 60 and 50 percent of nitrogen and phosphorous loads, respectively, the majority of the measures affect this sector. Abatement measures reducing airborne emissions and sewage from household and industry are also included, see Table 2 for a list of included abatement measures in addition to mussel cultivation.

For each of these abatement measures, costs are calculated which do not include any side benefits, such as provision of biodiversity by wetlands. Furthermore, abatement measures located in the drainage basins may have a positive impact on water quality, not only in the Baltic Sea, but also in ground and surface waters. However, such data on side benefits are not available for the included abatement measures. This implies an overestimation of abatement costs of measures implemented in the drainage basins. On the other hand, the cost estimates do not account for eventual dispersion of impacts on the rest of the economy from implementation of the measure in a sector, such as eventual increase in prices of inputs of a simultaneous implementation of improved cleaning at sewage treatment plants.

The model applies two methods for estimation of costs of the different abatement measures – partial equilibrium and engineering methods – which differ with respect to consideration of affected sectors' actual behaviour in the market. Partial equilibrium analysis is applied for calculations of costs of reductions in fertilisers, which rests on revealed behaviour on the fertiliser market. Data on prices and purchases of fertiliser can then be used for deriving costs of fertiliser reductions, which correspond to associated losses in profits. Market prices are also used for assessing costs of conversion of arable land into less leaching land uses such as wetlands and buffer strips. However, there is not enough data to evaluate the effect of

Table 2
Abatement measures in the drainage basins of the Baltic Sea.

N reduction (12 measures)	P reduction (10 measures)
Selective catalytic reduction (SCR) on power plants	
SCR on ships	
SCR on trucks	
Reductions in cattle, pigs, and poultry	Reductions in cattle, pigs, and poultry
Fertiliser reduction	Fertiliser reduction
Increased cleaning at sewage treatment plants	Increased cleaning at sewage treatment plants
Private sewers	Private sewers
	P free detergents
Catch crops	Catch crops
Energy forestry	Energy forestry
Grassland	Grassland
Creation of wetlands	Creation of wetlands
Changed spreading time of manure	
	Buffer strips

Source: Gren et al. (2008)

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massive land conversion on the market price of arable land, and the engineering method is therefore applied for cost calculations. The engineering method assumes no changes in prices and constant unit abatement costs are then calculated, which result in linear cost curves as compared to the convex cost functions illustrated in Fig. 1 in Section 2. Due to lack of data, the engineering approach is used for calculating costs of, not only land use changes, but also of costs of all other abatement measures except for reductions in fertilisers.

Similar to marginal costs of nutrient harvesting by mussel farm, marginal cost of abatement measures in the drainage basins are calculated by combining estimated costs of cleaning measures with data on impact on the Baltic Sea which occurs by nutrient transports in air, soil and water. Measures affecting airborne emission have the most involved ‘chain of impacts’, where reductions in airborne emissions have direct and indirect impacts on the Sea. The direct impacts consist of the share of emission that would have been deposited on the Sea, and the indirect impacts occur through decreases in dispersal of deposition on land within the entire drainage basin, which, in turn, generates less leaching and final transport to the Baltic Sea. Measures with direct impact on the Sea, such as increased cleaning at sewage treatment plants located by the coast, have the most simple ‘chain of impacts’, where the impact on the Sea corresponds to the reduction at the source. Each abatement measure is also subjected to capacity constraint, such as a maximum cleaning of phosphorus at sewage treatment plant by 90 percent. Additional constraints are the number of households that can be connected to sewage treatment plants. Limitations on fertiliser and livestock reductions and land use changes are imposed in order to avoid drastic structural changes in the agricultural sector. For a detailed presentation of abatement capacities and costs of all measures see Gren et al. (2008).

5. Values of mussel farming under alternative Baltic Sea nutrient load targets

Based on the data on costs and impacts of mussel farming presented in Section 3 and on the nutrient load and cost estimates of other abatement measures reported in Section 4, values of mussel farming as nutrient cleaning device are estimated by taking the difference in minimum total costs for predetermined nutrient targets with and without the inclusion of mussels. Nutrient targets are then defined either as separate nitrogen and phosphorus reductions, or as simultaneous reductions in both nutrients. As shown in Section 2, the necessary condition for mussel farming to have a positive value is that its marginal cost of cleaning in the Baltic Sea is at least equal to that of abatement measures in the drainage basins. We therefore start by deriving marginal cost curves at minimum cost solutions for different level of ambitions for all defined targets without inclusion of mussel farming, and then compare these estimates with marginal costs of mussel farming. Non-linear programming is used for all calculation by the use of GAMS code (Rosenthal, 2008).

The calculated marginal costs without mussel farming for different levels of overall reductions in N and P to the Baltic Sea are presented in Fig. 3. Marginal costs of nitrogen reductions are calculated for reductions up to 60 percent, and for phosphorus reductions to 70 percent.

The calculated marginal cost of nitrogen reductions range between Euro 1.1 kg^{-1} N and Euro 26 kg^{-1} N for reductions between 10 and 50 percent. The marginal costs increase rapidly at higher reduction levels exceeding 40 percent, which is due to the need of implementing high cost measures such as livestock reductions in order to meet the reduction requirement (see Gren et al., 2008). The marginal cost for phosphorus reduction varies between Euro 42.5 kg^{-1} P and 348.4 kg^{-1} P for reductions between 10 and 70 percent. It shows a step wise shape, where the marginal cost is rising significantly at 50 percent reduction, where relatively expensive land use measures are implemented for target achievement (Gren et al., 2008).

When comparing the marginal cost estimates in Fig. 3 with the marginal cost of mussel farming without sales options of mussels in Table 1, it is noticed that mussel farming is a cost-effective option in Kattegat and the Sound for both nutrients at reductions levels exceeding 30 percent. Mussel farming in Southern Baltic Proper has a positive value at nitrogen reductions above 40 percent and phosphorus reductions exceeding 50 percent. However, mussel farming in the Northern Baltic Proper exhibits positive values only for nitrogen reductions exceeding 50 percent.

When mussels can be sold for human consumption, mussel farming in Kattegat has a positive value at all reductions levels. Farming of industry mussels creates positive values in Kattegat at 30 percent nitrogen reduction and 20 percent phosphorus reduction. Positive values also occur for mussel farming in the Sound and Southern Baltic Proper at 40 and 30 percent nitrogen and phosphorus reductions, respectively. Mussel farming in the Northern Baltic Proper now shows a potential, but only at high nutrient reduction levels. It is also interesting to note that mussel farming has positive values in all basins but Northern Baltic Proper under the most unfavourable conditions, without sales options and the lowest mussel growth, at 50 and 60 nitrogen and phosphorus reductions, respectively.

As discussed in the theoretical Section 2, mussel farming shares the multi-pollutant abatement capacity with other abatement measures such as wetland construction. When accounting for this effect, the marginal cost of nitrogen and phosphorus cleaning by mussel farms are reduced. The reduction is determined by the marginal cost of overall reductions of each nutrient, as demonstrated in Fig. 3, and the simultaneous impact on the other nutrient (see Eq. (5) in Section 2). Marginal cost of nitrogen by mussel farming is then calculated as any of the marginal costs from Table 1 minus the simultaneous impact on phosphorus times the marginal cost of phosphorus reduction found in Fig. 3. The impact on phosphorus of a marginal decrease by 1 kg N is approximately 0.07 kg, and the marginal cost of phosphorus reduction range between Euro 42.4 and 348.4 depending on reduction target (see Table A2 in Appendix A). The deduction from the marginal cost of nitrogen reduction by mussel farming from the simultaneous effect on phosphorus then varies between Euro 3 and 24.5. Marginal cost of phosphorus when considering effects on nitrogen is calculated in the same way. However, other abatement measures also exhibit the multi-pollutant abatement capacity, such as wetland and grass land construction, and the merits of mussel farming are determined by its relative effects on both nutrients.

Values of mussel farming are calculated for separate reductions in N and P, and also for simultaneous reductions in both nutrients for low and high cost of mussel farming. When assessing values for

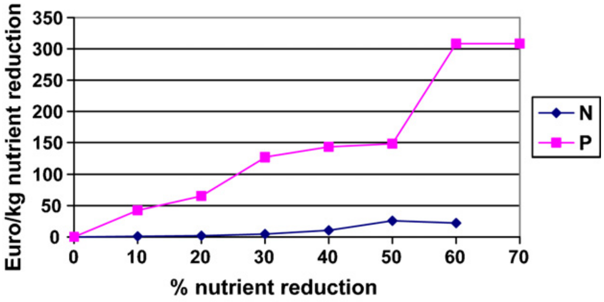

Fig. 3. Marginal costs of nitrogen (N) and phosphorous (P) reductions to the Baltic Sea without mussel farming (source: see Table A1).

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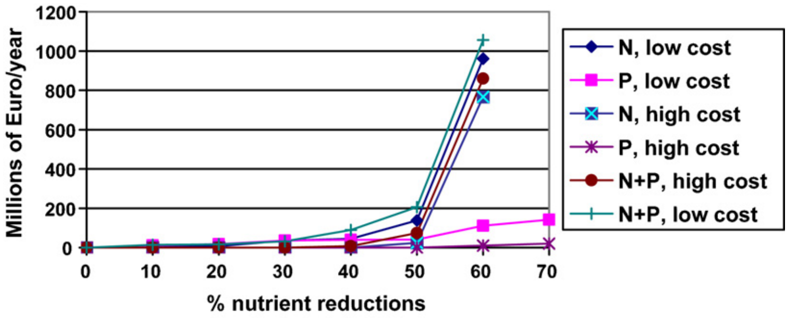

Fig. 4. Value of mussel farming for nitrogen and phosphorous reductions to the Baltic Sea at low and high marginal nutrient abatement cost by mussel farming. Source: calculations based on Tables A1 and A2 in Appendix A.

Table 3
Annual value of mussel farming under the Helcom BSAP for different scenarios of mussel production cost, in millions of Euro and Euro kg^{-1} live mussel.

	No sale for human or animal food		With sale for human or animal food	
	Low cost[a]	High cost[b]	Low cost[a]	High cost[b]
Mill Euro	69.8	20.2	138.3	116.0
Euro kg^{-1} live mussel	0.11	0.02	0.21	0.12

[a] High mussel growth and content of nutrient.
[b] Low mussel growth and content of nutrient.

simultaneous reductions it is assumed that the reduction target is the same for both nutrients as measured by reductions in percent from initial load levels. The low cost is attributable to favourable growth conditions and to the relatively high content of nutrients in a live mussel, and vice versa for the high cost case. In total, values are estimated for six different scenarios, see Fig. 4.

As shown in Fig. 4, the values of mussel farming are highest for simultaneous nutrient reductions in the low cost scenario and can then amount to approximately 1.1 billions of Euro for the largest nutrient reduction requirement. The introduction of mussel farming then reduces total costs by 12 percent. Corresponding value in the high cost case is only 30 percent lower, and amounts to 0.8 billions of Euro. The main reason for these values is the significant role of mussels for nitrogen reductions, where abatement measures in the drainage basin are relatively expensive.

However, the large nitrogen reduction scenarios are in excess of the nutrient reduction targets suggested in the Baltic Sea Action Plan (BSAP) by Helcom, where the overall nitrogen reduction amounts to 25 percent (Helcom, 2007). The suggested phosphorus reductions are in the same order of magnitude, 66 percent, as in the maximum reduction scenario in this study. Total estimated cost of simultaneous achievements of both these targets without mussel farming amounts to approximately 3 150 millions of Euro. When inserting mussel farming under different assumptions of production costs as reported in Table 1, the calculated values of mussel farming for the achievement of the Helcom BSAP are as presented in Table 3.

The results in Table 3 indicate that mussel farming contributes to cost savings for reaching the Helcom BSAP under all four scenarios. Cost savings, or values, from mussel farming range between 20 millions of Euro and 138 millions of Euro. It is interesting to note that the corresponding value per kg live mussel exceeds the payment for animal fodder in all scenarios except for the high cost case when mussels cannot be sold.

However, the estimated values are sensitive, not only for assumed production cost and growth conditions of mussels, but also for assumed cleaning capacity. Whereas marginal cleaning cost determines if mussel farming has any positive value at all, assumed abatement capacity influences the magnitude of the value of mussel farming. For example, if the abatement capacity is doubled, the value of mussel farming under the Helcom BSAP and low cost scenario increases by 110 percent.

6. Conclusions and discussion

The purpose of this study has been to assess the value of mussel farming for nutrient cleaning in the eutrophied Baltic Sea. The theoretical chapter showed that a positive value occurs when the marginal cleaning cost of mussel farm is lower than or equal to the marginal cost of other abatement measures. Mussels then have a comparative advantage by the multi-pollutant abatement capacity. Since mussel farming is a relatively recent innovative technology for cleaning, there is a lack of data with respect to production cost, mussel sales options for human or animal consumption, and growth under different conditions. The study therefore calculated marginal cleaning cost of mussel farms with and without mussel sales options, high and low mussel growth rates and contents of nutrient in mussels. The calculated constant marginal cost then varied between Euro 0 kg^{-1} nutrient cleaning and Euro 63.5 and 900 kg^{-1} for nitrogen and phosphorus cleaning, respectively. The low marginal cleaning cost occurred for the Kattegat and the Sound marine basins, whereas the largest costs were found in the Northern Baltic Proper basin.

When comparing the marginal cleaning costs by mussel farming with those of other abatement measures, 20 measures in 24 different drainage basins of the Baltic Sea, it was found that mussel farming has a positive value for a large range of nutrient reductions. The estimated values, calculated as the difference in minimum costs for given nutrient reduction targets with and without the inclusion of mussel farming as a cleaning option, show a large variation, between 0.1 and 1.1 billions of Euro per year. An evaluation of mussel farming as a cleaning device under the Helcom Baltic Sea Action Plan revealed that the inclusion of mussel farming could decrease total abatement cost by approximately 5 percent. This corresponds to a value of Euro 0.22 kg^{-1} live mussel. However, under unfavourable cost and growth conditions, this value could be reduced to Euro 0.02 kg^{-1} live mussel. The results are also sensitive to assumptions of mussel farming capacity in the Baltic Sea.

The large range of results with respect to the value of mussel points to the need of more empirical research on growth

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of mussels, content of nutrient under different salinity and current conditions, and also on possible locations of mussel farms in a large scale perspective. Furthermore, the results indicate that the options of selling mussels are crucial for the marginal cleaning cost of nutrient by mussel farming, which therefore needs further exploration in particular with respect to content of toxins and pathogenic microbes in mussels. However, marginal cleaning costs are also affected by choice of mussel farming technology, where only the long-line technology is assumed in this paper. This is a suitable technology for mussel farms in relatively wind protected coastal zones, but may not be appropriate for open coastal zones prevailing in the Baltic Proper (see e.g. Prioli, 2004 for an evaluation of mussel farming technologies in Italy).

Another phenomenon not included in this paper is the possible increase in nutrient regeneration in the Baltic Sea from mussels' filtration. There is no doubt that mussel farming will affect biogeochemistry and the benthic ecosystem below the long-lines through the rich bio-sedimentation of mussel faecal pellets, dropped mussels and other detritus (e.g. Newell, 2004; Hatcher et al., 1994; Grant et al., 1995; Mirtho et al., 2000). The negative effects are known to be restricted to be near the farm and have to be judged in relation to the overall positive effects of using mussels to improve coastal ecosystem quality. The degradation of the increased supply of organic material will increase the oxygen consumption at the sediment surface. A too rich sedimentation will cause negative eutrophication effects on the benthic ecosystem below the mussel farm and cause the development of hydrogen sulphide and a dead bottom in the worst case. The size of the affected area as well as the degree of influence will depend on the amount of sedimentation in relation to the local conditions like depth, bottom topography and water exchange. The natural benthic fauna under a farm may be negatively influenced through a reduction of individuals, biomass and species diversity. Best management practice will help to avoid too negative effects and keep the sediment surface oxygenized, which also allows that the natural denitrification processes continues. The denitrification is important since through this process different nitrogen substances like, e.g. ammonium are transformed into biologically inactive nitrogen gas (Newell, 2004). The focus of this paper was to demonstrate the potential in relation to the cost effectiveness of mussel farming as an environmental measure in the Baltic. Future investigations will have to find out if the eventual negative effects on the Baltic ecosystem can be kept local and be acceptable.

However, the realisation of the potential values of mussel farming as a cleaning device and technological development of mussel farming is dependent, not only on research, but also on policies for combating eutrophication in the Baltic Sea. In general, economic instruments create the incentives for making the best use of scarce cleaning resources and for stimulating technological development (see e.g. Baumol and Oates, 1988). One option is then to extend current EU support systems directed towards reduced nitrogen and phosphorus, which now includes land use changes, such as wetland construction and cultivation of catch crops (EEC 2078/92 and 1257/1999). Another opportunity is to introduce a system with trading of nutrient reduction requirements between sectors. It has been suggested that mussel farming could be a compensation measure for agricultural emissions in a trade bidding system (Lindahl and Kollberg, 2009). Since the agricultural sector is likely to make use of this option only when nutrient reductions by mussel farming are less costly than other abatement measures, the same overall nutrient target is achieved at a lower cost. Such a nutrient trading system is currently tested at the local scale in the West coast of Sweden where a sewage treatment plant is allowed to trade nitrogen cleaning with a mussel farm (Lindahl and Kollberg, 2009). The usefulness of the mussel farming concept in combination with nutrient emission trading may have significance also at an international environmental scale. Although there is lack of experiences of large scale nutrient trading systems, there is now a large literature on experiences in practice from such systems for other pollutants, such as carbon dioxides and sulphur dioxides which can be useful for exploiting the potential of mussel farming in the Baltic Sea (e.g. Tietenberg, 2003).

Appendix A. Appendix A

See Tables A1–A4.

Table A1
Production costs of a mussel farm of 0.5 ha under different assumptions of production capacities under a 2-year period.

	Kattegat		The Sound		North Baltic Proper	South Baltic Proper
	Human	Industry	Human	Industry	Industry	Industry
Production (ton)	120–150	200–250	50–60	100–120	50–90	60–100
Labour						
Operational[a]	16,900	6,772	16,900	8,700	16,400	5,160
Harvesting[b]	14,500	7,295	11,110	6,110	3,150	3,200
Sales	−15,480	−8,980	−13,300	−7,300	−5,400	−5,300
Capital cost[c]	5,800	2,200	5,800	2,900	5,800	5,800
Others[d]	2,640	615	2,640	820	1,640	1,640
Total costs	38,643–41,808	16,860–18,545	36,450–38,640	18,510–19,700	26,990–29,240	12,600–17,900
Cost/kg	0.28–0.32	0.08–0.10	0.64–0.72	0.16–0.19	0.33–0.54	0.18–0.21

[a] Number of labour hours needed for farm construction and maintenance multiplied with salary of Euro 18.5 h^{-1} (Kattegat, the Sound and Northern Baltic Proper) or Euro 5 h^{-1} (for southern Baltic Proper).

[b] Number of labour hours for harvesting and sales of mussels multiplied with salary/h, Source: Lindqvist (2008), tables in Appendix A–D pp. 47–59.

[c] Interest rate of 5%.

[d] Toxin and bacterial control, application for mussel farming permission, and fuel.

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Table A2
Total and marginal cost for separate and simultaneous reductions in N and P to the Baltic Sea without mussel farming as an abatement option. Total cost, TC, in Mill Euro per year and marginal cost, MC, in Euro kg^{-1} nutrient reduction.

% reduction	N reduction		P reduction		N and P reduction TC
	TC	MC	TC	MC	
10	54	1.1	99	42.5	121
20	160	1.9	260	65.2	337
30	453	4.6	570	126.9	721
40	1052	10.5	1072	143.3	1568
50	2297	26.0	1594	148.1	3218
60	7937	221.9	2404	308.5	9310
70			3658	348.4	

Table A3
Minimum cost for alternative nutrient reduction targets at different marginal cleaning costs of mussel farming with no mussel sales, millions of Euro per year.

% reduction	High growth and nutrient content			Low growth and nutrient content		
	N	P	N + P	N	P	N + P
10	54	99	1 21	54	99	121
20	160	260	337	160	260	337
30	453	570	721	453	570	721
40	1052	1072	1538	1052	1072	1561
50	2225	1594	3059	2274	1594	3143
60	7049	2354	8328	7171	2393	8450
70		3588			3683	

Table A4
Minimum cost for alternative reduction targets at different marginal cleaning costs of mussel farming with mussel sales, millions of Euro per year.

% reduction	High growth and nutrient content			Low growth and nutrient content		
	N	P	N + P	N	P	N + P
10	50	87	107	52	89	109
20	153	242	320	155	245	323
30	417	535	689	420	537	691
40	1008	1032	1478	1014	1034	1494
50	2160	1553	3012	2181	1555	3049
60	6976	2292	8254	7062	2321	8341
70		3516			3563	

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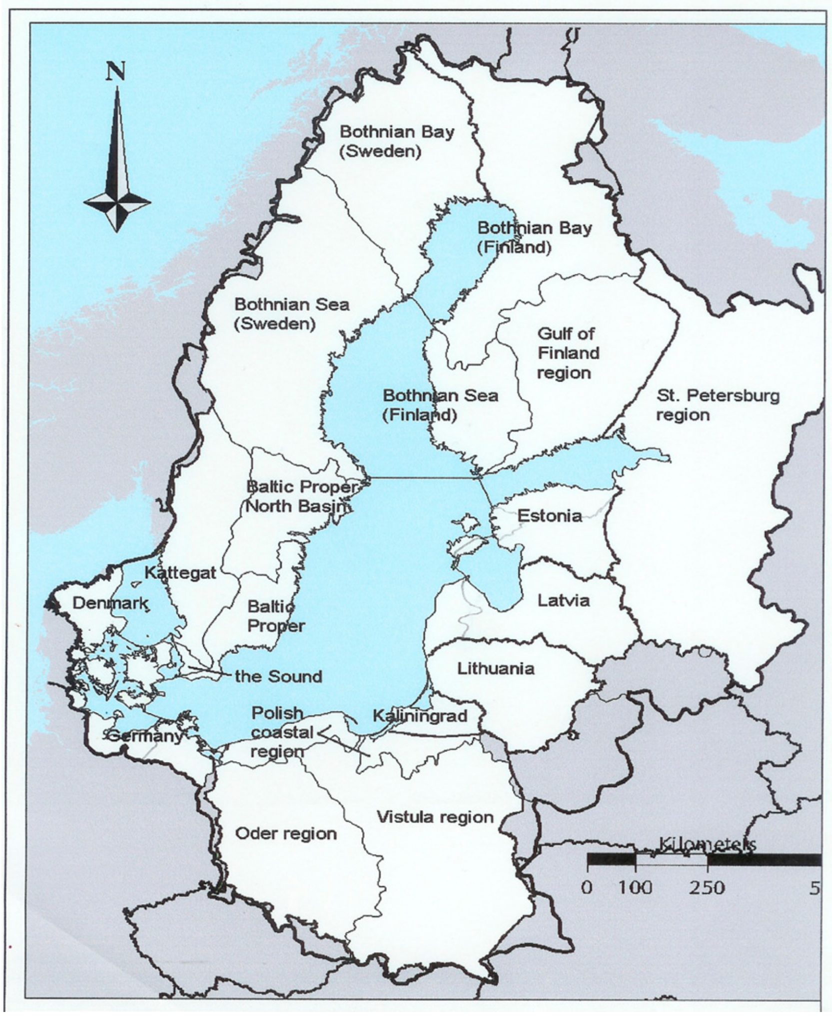

Fig. B1. Drainage basins of the Baltic Sea (originally from Elofsson, 2003) (drainage basins in Denmark (2), Germany (2), Latvia (2), and Estonia (3) are not provided with names, but are delineated only by fine lines).

Appendix B. Appendix B

See Fig. B1.

References

Baumol, W., Oates, W., 1988. The Theory of Environmental Policy: Externalities, Public Outlay and the Quality of Life, 2nd edition. Prentice-Hall, Englewood Cliffs, NJ.

Bodungen, B.V., Turner, K., 2001. Science and Integrated Coastal Management. Dahlem Workshop Report. Dahlem University Press, Berlin.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210, 223–253.

Diaz, R.J., Rosenberg, R., 1995. Marine benthic hypoxia. A review of its ecological effects and the behavioral responses of benthic macrofauna. Oceanogr. Mar. Biol., Ann. Rev., 245–303.

Elofsson, K., 2003. Cost effective control of stochastic agricultural loads to the Baltic Sea. Ecol. Econ. 47 (1), 1–11.

Engman, T. Seglinge Forell, AX – 22820 Kumlinge, Åland personal comment.

Gifford, S., Dunstan, H., O'Connor, W., Macfarlane, G.R., 2005. Quantification of in situ nutrient and heavy metal remediation by a small pearl oyster (*Pinctada imbricata*) farm at Port Stephens, Australia. Mar. Pollut. Bull. 50, 417–422.

Grant, J., Hatcher, A., Scott, D.B., Pocklington, P., Schafer, C.T., Winters, G.V., 1995. A multidisciplinary approach to evaluating impacts of shellfish aquaculture on benthic communities. Estuaries 18, 124–144.

Gren, I.-M., 1995. Value of investing in wetlands for nitrogen abatement. Eur. Rev. Agric. Econ. 22, 157–172.

Gren, I.-M., 1999. Value of land as pollutant sink. Ecol. Econ. 30, 419–431.

Gren, I.-M., Lindqvist, M., Jonzon, Y., 2008. Costs of nutrient reductions to the Baltci Sea—technical report. Working paper 2008:1. Department of Economics, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Gren, I.-M., 2008. Adaptation and mitigation strategies for controlling stochastic water pollution: an application to the Baltic Sea. Ecol. Econ. 66, 337–347.

Haamer, J., 1996. Improving water quality in a eutrophied Fjord system with mussel farming. Ambio 25, 356–362.

Hart, R., 2003. Dynamic pollution control. Ecol. Econ. 47, 79–93.

Hatcher, A., Grant, J., Schofield, B., 1994. Effects of suspended mussel culture (*Mytilus* spp.) on sedimentation, benthic respiration and sediment nutrient dynamics in a coastal bay. Mar. Ecol. Prog. Ser. 115, 219–235.

Helcom, 2004. The Fourth Baltic Sea Pollution Load Compilaon (PLC-4). Helsinki Commission, Helsinki, Finland.

Helcom, 2007. An Approach to Set Country-wise Nutrient Reduction Allocations to Reach Good Marine Environment of the Baltic Sea. Helcom BSAP Eutro Expo/2007. Helsinki Commission, Helsinki, Finland.

Huang, J.H., Haab, T.C., Whitehead, J.C., 1997. Willingness to pay for quality improvements: should revealed and stated preferences data be combined? J. Environ. Econ. Manage. 34 (3), 240–255.

Jönsson, L., 2006. Can mussel meal replace fish meal in feeds for organic poultry? In: Proceedings of the 12th European Poultry Conference, Verona, p. 349.

Kautsky, N., 1982. Growth and size structure in a Baltic *Mytilus edulis* population. Mar. Biol. 68, 117–133.

van Kooten, C., Eagle, A., Manley, J., Smolak, T., 2004. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environ. Sci. Policy 7, 239–251.

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.-O., Olrog, L., Rehnstam-Holm, A.-S., Svensson, J., Svensson, S., Syversen, U., 2005. Improving marine water quality by mussel farming—a profitable solution for Swedish society. Ambio, 131–138.

Lindahl, O., Kollberg, S., 2009. Can the EU agri-environmental aid program be extended into the coastal zone to combat eutrophication? Hydrobiologica, forthcoming volume.

Please cite this article in press as: Gren, I.-M., et al., Values of mussel farming for combating eutrophication: An application to the Baltic Sea. Ecol. Eng. (2009), doi:10.1016/j.ecoleng.2008.12.033

Lindqvist, M., 2008. Value of Mussels for Nutrient Cleaning in the Baltic Sea. Manuscript. Department of Economics, Swedish University of Agricultural Sciences, Uppsala (in Swedish).

Lutz, R.A. (Ed.), 1980. Mussel Culture and Harvest: a North American Perspective. Elsevier Scientific Publishing Company, Amsterdam.

Markowska, A., Zylicz, T., 1999. Costing an international public good. Ecol. Econ. 30 (2), 301–316.

Mirtho, S., La Rosa, T., Danavaro, R., Mazzola, A., 2000. Microbial and meiofaunal response to intensive mussel-farm biodeposition in coastal sediments of the western Mediterranean. Mar. Pollut. Bull. 40, 244–252.

Newell, R.I.E., 2004. Ecosystem influences of natural and cultivated populations of suspension feeding bivalve mollusks: a review. J. Shellfish Res. 23, 51–61.

Prioli, G., 2004. Shellfish farming: technologies and production. Vet. Res. Commun. 28, 51–56.

Rosenthal, R., 2008. GAMS—A User's Guide. GAMS Development Corporation, Washington, DC, USA.

Ryther, J.H., Dunstan, W.M., Tenore, K.R., Huguenin, J.E., 1972. Controlled eutrophication: increased food production from the sea by recycling human wastes. Biol. Sci. 22, 144–152.

Seki, M., 1972. Studies on environmental factors for the growth of the pearl oyster, *Pinctada fucata*, and the quality of its pearl under the culture condition. Bull. Mie Prefectural Fish. Exp. Stations, 32–143 (in Japanese with English summary).

Suzuki, K., 1957. Biochemical studies on the pearl oyster (*Pinctada martensi*) and its growing environments. Bull. Natl. Pearl Res. Lab. 2, 57–62 (in Japanese with English summary).

Söderqvist, T., 1998. Why give up money for the Baltic Sea? Motives for peoples willingness (or reluctance) to pay. Environ. Resour. Econ. 12 (2), 141–153.

Tietenberg, T., 2003. The tradeable-permits approach to protecting the commons. Lessons for climate change. Oxford Rev. Econ. Policy 19 (3), 400–419.

Thore, A., Miljökontoret, Mönsterås Kommun, Box 54, 383 22 Mönsterås, Sweden, personal comment.

Turner, K., Georgiou, S., Gren, I.-M., Wulff, F., Barett, S., Söderqvist, T., Bateman, I.J., Folke, C., Langaas, S., Zylicz, T., Mäler, K.-G., Markowska, M., 1999. Managing nutrient fluxes and pollution in the Baltic: an interdisciplinary simulation study. Ecol. Econ. 30, 333–352.

Waldenstedt, L., Jönsson, L., 2006. Mussel meal as a high quality protein source for broiler chickens. In: Verona, Proceedings of the 12th European Poultry Conference, pp. 349–350.

Please cite this article in press as: Gren, I.-M., et al., Values of mussel farming for combating eutrophication: An application to the Baltic Sea. Ecol. Eng. (2009), doi:10.1016/j.ecoleng.2008.12.033