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Zebra Mussel Farming in the Szczecin (Oder) Lagoon: Water-Quality Objectives and Cost-Effectiveness

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ABSTRACT. The Oder (Szczecin) Lagoon in the southern Baltic Sea is a heavily eutrophicated and degraded coastal ecosystem. We applied a systems approach framework to critically evaluate whether existing water-management measures achieve water-quality objectives for the river and lagoon systems. Our simulations reveal that the existing water-quality objectives for the river and the coastal waters are not sufficiently complementary. We suggest new water-quality threshold concentrations, which are in agreement with the European Water Framework Directive, and we calculate acceptable maximum nutrient loads for the Oder River. These calculations suggest that external nutrient-load reductions in the river basin alone seem insufficient to achieve good water quality in the lagoon. A comprehensive eutrophication management approach should also include internal nutrient-retention and nutrient-removal measures in the lagoon. We focus on mussel farming, i.e., that of zebra mussels, *Dreissena polymorpha*, because they are efficient in removing nutrients and improving water transparency in the Oder Lagoon. For this purpose, the ecosystem model ERGOM is extended by a mussel module and an economic model. The economic model describes costs and benefits of mussel cultivation depending on the the farm size. We included additional potential sources of income such as water-quality tax or emission certificates. The simulations show that mussel farming in the lagoon is a suitable supportive measure and, at a load-reduction target of 50% or more, it is a cost-efficient measure for removing nutrients and for implementing the Baltic Sea Action Plan. In the Oder Lagoon, mussel farming could potentially remove nearly 1000 t of N (70 t of P)/year, or about 2% of the present N and P loads, and it would have the additional benefit of improving water transparency.

Key Words: *Baltic Sea Action Plan; coastal ecosystem; cost-benefit analysis; ERGOM; eutrophication; marginal costs; mussel farming; nitrogen; Oder Lagoon; Oder River; phosphorus; Szczecin Lagoon; Water Framework Directive; water management; water quality; zebra mussels (Dreissena polymorpha)*

INTRODUCTION

According to the Baltic Sea Action Plan (HELCOM 2007), eutrophication continues to be a major problem in the Baltic Sea, caused by excessive inputs of phosphorus (P) and nitrogen (N). Over 90% (70%) of P (N) reaches the Baltic Sea via rivers (HELCOM 2005). One of the most important polluters along the Baltic coast is the Oder River with its heavily eutrophied estuary system, which consists of the Oder (Polish: Szczecin) Lagoon and the Pomeranian Bay. Especially during summer, eutrophication effects, such as cyanobacteria blooms or fish kills due to hypoxia, can cause serious economic damage for tourism (Dolch and Schernewski 2003, Wasmund 2002). Because of the size of the Oder estuary system, its pollution level, and its economic and ecological importance, the Oder estuary system has been intensively investigated with respect to nutrient cycles, budgets, and retention capacity (Lampe 1999, Meyer and Lampe 1999, Grelowski et al. 2000, Wielgat and Witek 2004, Pastuszak et al. 2005).

P load reductions are important for the Baltic Sea but have only limited effect on the eutrophic state of the lagoon. During summer the primary production and algae biomass in the Oder Lagoon is limited by N. Model simulations comparing the trophic state of the late 1960s with the situation of the mid 1990s show that riverine N load reductions have positive effects on coastal water quality and algae biomass (Behrendt

et al. 2008, Schernewski et al. 2011). Whether nutrient load reductions and management should focus on N or on P has already been discussed in the Baltic for a long time and argued as controversial (Elmgren and Larsson 2001, Boesch et al. 2006, Conley et al. 2009). For the Oder estuary, both P and N have to be taken into account.

During recent years it became obvious that an improved, but cost-effective, river basin management would have a limited effect on riverine nutrient loads (Behrendt and Dannowski 2005, Schernewski et al. 2008). It might not be sufficient to ensure good water quality in lagoons and coastal waters. A more comprehensive management, which includes nutrient removal measures in coastal waters, is required. In the Oder Lagoon, internal measures to remove nutrients and to improve ecosystem quality could include dredging of sediment and dumping on land, an enlarged reed belt, extended submersed macrophyte areas, algae farms, and enlarged natural mussel beds and mussel cultivation. Mussel cultivation/harvesting is suggested as an efficient way to control nutrient concentrations in coastal waters (Newell 2004, Lindahl et al. 2005) and is assumed to be the most promising measure for the Oder Lagoon (Schories et al. 2006, Stybel et al. 2009).

We applied a systems approach framework according to Hopkins et al. (2011). Our objectives were to critically evaluate existing water-quality objectives for the river and the

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lagoon and to define acceptable nutrient loads. Against this background we analyze the possibilities of zebra mussel (*Dreissena polymorpha*) farming as a measure to combat eutrophication and as an element in a comprehensive eutrophication management concept.

METHODS AND STUDY SITE

Oder/Odra estuary system

The Oder River is 854 km long and has an average discharge of 530 m³/s. Its basin (118 000 km²) is shared between Poland (89%), the Czech Republic (6%), and Germany (5%). The river basin is under strong human influence. Agricultural land covers 70% of the upper river basin and 58% of the middle basin. Several larger cities and many industries are located in the river basin. Total population in the basin is 15.4 million people.

The Oder Lagoon (Fig. 1) is large (669 km^2) but shallow (average depth of 3.7 m). Three outlets link the lagoon with the Pomeranian Bay. The Oder River contributes at least 94% of the lagoon's water budget, and it dominates the nutrient budgets as well. The lagoon's average water exchange time is only 55 days, and a salinity of around 1.5 psu shows that the lagoon is only to a minor degree influenced by the Baltic Sea, which has a salinity of 6 psu (Radźiejewska and Schernewski 2008). Because of the lagoon's low salinity, zebra mussels (*Dreissena polymorpha*) are the only filter-feeding epifaunal bivalves in the lagoon; they form mussel beds with a biomass of about 68,000 t (Piesik et al. 1998, Wozniczka and Wolnomiejski 2008, Radźiejewska et al. 2009). Zebra mussels were introduced into the Oder Lagoon in the nineteenth century (Gruszka 1999), but their prevalence throughout northern Germany even before the last ice age are the reason for considering zebra mussels to be native species (Fenske 2003, Stybel et al. 2009).

Fig. 1. Oder/Odra River basin and estuary.
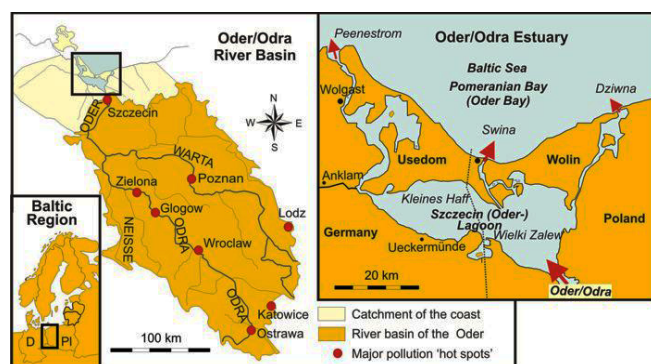
Most of the coastal area is under nature protection. Tourism, agriculture, fishing (3000 t/a in the lagoon), and shipping are important economic activities in the coastal zone. Along the coastline, tourism is the exclusive economic factor and it is likely that altogether more than 10 million tourists visit the estuary region per year (Fig. 2).

Fig. 2. Images of the Oder (Szczecin) Lagoon. Left to right, top: the beach near Ueckermünde on the southwestern coast, and a view over the Polish part of the lagoon and a beach near Wolin. Left to right, bottom: zebra mussel (*Dreissena polymorpha*) accumulation at the shore, and examples of discolouration and foam formation due to heavy blue–green algal blooms in August 2009.

Social system and priority issues

Our systems approach aims to support a sustainable water-quality management and a sustainable regional development. As a consequence, besides economy and ecology, social aspects have to be taken into account and an early mapping and involvement of regional stakeholders is imperative for the success of a comprehensive management scheme. Many development plans and strategies, experts' reports, and scientific papers exist for the Oder estuary region. In a first step, a systematic analysis and evaluation of these documents provided a detailed overview about the major concerns, issues, and challenges in the region. Water-quality and eutrophication management turned out to be major cross-border policy issues because of obvious and severe eutrophication, and because of the pressures arising from implementation of the European Water Framework Directive (WFD) (European Parliament 2000) on both sides of the border. The existing regional Agenda 21 was the basis for the co-operation of, altogether, about 30 stakeholder representatives (ministries, regional authorities, district administrations, NGOs, economic interest groups, research institutes, and companies). The group met twice a year, discussed the policy issue, and took part in the systems approach framework application.

Fig. 3. Conceptual model for the lagoon, showing the ecological part of EROM, the three-dimensional hydrodynamic and ecosystem model, the mussel module, and the components in the economic model. The ecological and economic models are linked via water transparency and mussel crop (yield).
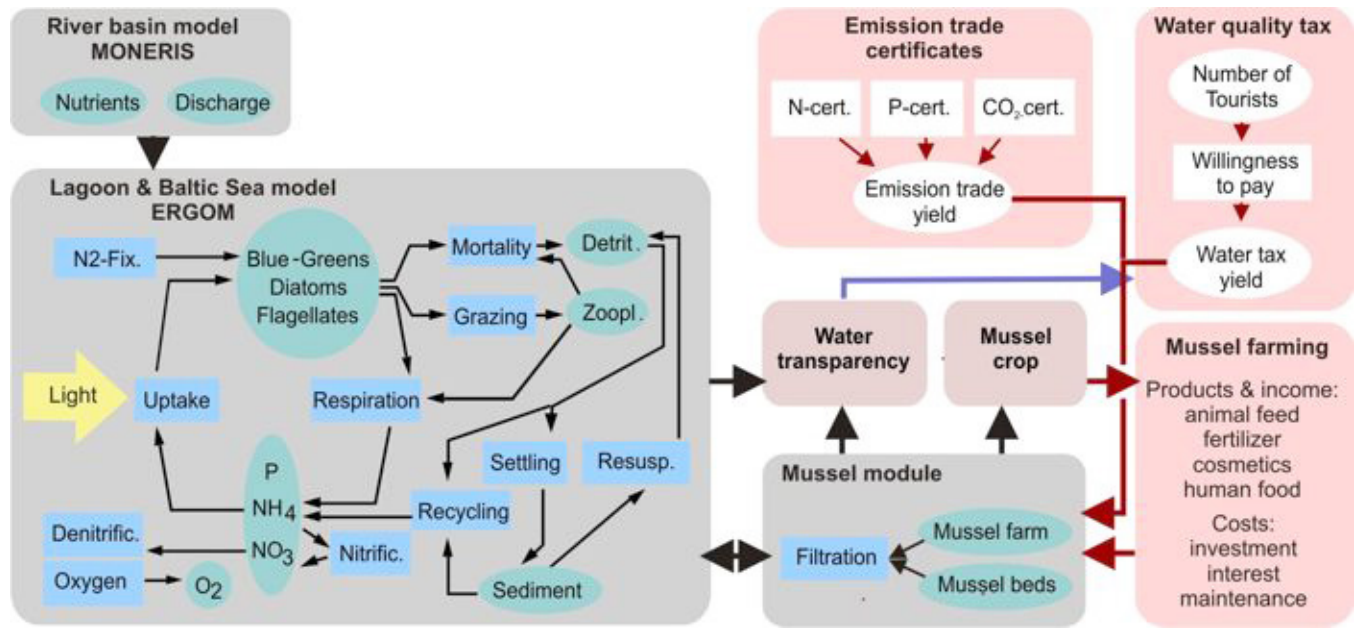
Ecological models

The ecosystem model ERGOM is an integrated biogeochemical model linked to a three-dimensional circulation model covering the entire Baltic Sea. A horizontal resolution of 3 nautical miles is applied in the estuary. However, for simulations of a few years or less the Oder estuary is resolved with 1 nautical mile. The vertical layer thickness in our study area is 2 m. The biogeochemical model consists of nine state variables (Fig. 3). This model is coupled with the circulation model via advection diffusion equations for the state variables. Neumann (2000) and Neumann and Schernewski (2008) provide detailed model descriptions and validations. Weather data are taken from the ERA-40 re-analysis (grid of 50 km and six-hourly data) and ERA-interim. The river basin model MONERIS consists of several submodels, which allow simulations and tracking of nutrients from the emission source through the environment to the river mouth. It is based on a geographical information system that includes various digital maps and extensive statistical information. MONERIS is applied to calculate the nutrient emissions into the Oder River and the nutrient retention in the river, and it provides monthly loads at the river mouth. Behrendt and Dannowski (2005) present details about the model. A comparison between observed and modeled N and P loads for the period 1983 to 2005 at the station Krajnik Dolny is shown in Venohr et al. (2010). We used MONERIS output as an input for ERGOM.

A mussel module focusing on *Dreissena polymorpha* has been developed and linked to the ecosystem model ERGOM. The mussels feed on detritus, phytoplankton, and zooplankton. However, in this analysis we use an empirical relationship between zebra mussel biomass and water transparency in the Oder Lagoon, which we derived from data in Wolnomiejski and Wozniczka (2008). Zebra mussels in the amount of 0.1 kg/m³ of lagoon water improve water transparency (Secchi depth) during the summer season by 0.39 m. Water transparency serves as the major link between ecology and economy (Fig. 3).

We assumed floating mussel cultivation systems, which utilize the water body efficiently and are technically well adapted for commercial farming (Lindahl et al. 2005, Walter and De Leeuw 2007). It is assumed that a water depth between 2 and 5 m is suitable for mussel production in the lagoon. This depth layer covers an area of 335 km², which is 50% of the lagoon's total surface area of 669 km². We assumed a mussel cultivation coverage of 20% (134 km²) as an upper practical limit for the Oder Lagoon.

Economic model

The economic model consists of several submodels for calculating the costs and revenues of zebra mussel farming, potential additional sources of income, and the quantity of carbon, N, and P removal.

Costs

The cost calculations distinguish between investment, maintenance, financing, and operational and harvesting costs (e.g., Hoagland et al. 2003). The bases for the parameterization are a concrete offer from Smartfarm AS, and literature about blue mussel (*Mytilus edulis*) farming in the Baltic (e.g., Lindahl et al. 2005, Gren et al. 2009). In the following we assumed that 1 m^2 of a farm is equivalent to 1 m^3. For a 1-ha (10,000-m²) long-line farm, we assumed investment costs (including permission costs) of €1.5 m^{-3}, with a lifetime of 15 years. Together with annual maintenance costs of €0.1 $m^{-3}a^{-1}$ and an interest rate of 5% they form the capital costs. Maintenance costs are investment costs divided by the lifetime. Operational and harvesting costs (including mussel processing) are €0.2/kg. Zebra mussel yields of 0.7 kg $m^{-3}a^{-1}$ are calculated from data in Fenske (2003, 2005). To allow realistic scenario simulations, investment, maintenance, and operational and harvesting costs are decreasing with increasing size and are described by $1/\log_{10}$ functions.

Revenue

Sales: In general, mussels are sold for human consumption or used as animal feed and fertilizer (e.g., Lindahl et al. 2005, Jönsson et al. 2010). In mussel beds of the Oder Lagoon, Zebra mussels grow to a size of 1.2 to 1.4 cm and a weight of 0.5 to 1 g after 2 years (Fenske 2003). Even under favorable conditions, adults hardly reach 4 cm. Due to its small size and biomass, compared to other commercial mussel species, the zebra mussel is hardly suitable for human consumption at a large scale. We assumed that a farm with a size of 1 ha (10,000 m³) can sell 5% of its 7000-kg annual harvest for human consumption at a price of €0.3/kg. For comparison, in Germany, blue mussels have a market price of €0.5/kg to €2.6/kg, depending on the season and region. With increasing farm size, we assumed a decreasing share for human consumption and a decreasing price. In our model at least 90% of the yield is sold as animal feed and fertilizer at a price between €0.023/kg and €0.05/kg. The price increases up to a farm size of 10 ha, but decreases thereafter. We assumed that very small quantities can hardly be sold, and that mussel yields above 1000 t/a have a decreasing price because of increasing transportation costs.

Water-quality tax: Mussels efficiently filter the surrounding water and increase water transparency. Poor water transparency in the lagoon, which is less than 50 cm in summer, hampers tourism. Based on statistical data, about 200,000 overnight stays and 340,000 day tourists are estimated for the lagoon for the entire year. According to an empirical survey, tourists are willing to spend €1/day for an improved water transparency of 1 m (J. Hirschfeld, *personal communication*).

Carbon dioxide certificates: We hypothetically assumed that the amount of CO_2 fixed in harvested mussel shells can be sold,

according to the Kyoto Protocol. In practice, this requires a complex certification process. We assumed Verified Emission Reduction futures (CarbonFix standard), which are sold on the voluntarily market for CO_2 emissions at a price of €12/tonne (adapted from BaumInvest project, see http://www.bauminvest.de/). We assumed 26.4% of CO_2 in fresh mussels and N (P) contents of 1% (0.07%) (Haamer 1996, Gren et al. 2009).

RESULTS

Water-quality objectives and river loads

Fig. 4 shows the long-term course of nutrient loads at the river mouth, and nutrient concentrations in the river and in the lagoon over 40+ years. The MONERIS simulation also covered the 1950s. According to the model and data, the nutrient concentrations in the river increased steadily until the late 1980s, and decreased afterwards (Fig. 4a). According to MONERIS, annual total P emissions increase from nearly 6000 t in the early 1960s, up to over 15,000 t in the mid 1980s, and declined to 9360 t in 2000. In general, the increase of the loads until the late 1980s and the decrease afterwards are reflected in the dissolved inorganic P (DIP) concentrations in observed data as well as in model simulations for the central lagoon. In the lagoon, differences between the model and observed data are visible during summer (Fig. 4b). One reason is that data are single samplings, while the model results are aggregated to monthly values. However, this explanation is not sufficient. In some years, in July and August, hypoxia above the sediment can occur even in this shallow lagoon, and release large amounts of P. Because of the vertical model resolution, the anoxic release is not well reflected in the model simulation and P concentrations are significantly underestimated. However, this anoxic P release does not have implications for lagoon biology, because P is always available in excess during summer, and calcium precipitation removes P from the water column again within days. As a consequence this model shortcoming does not have implications for our analysis.

With respect to N, ERGOM results are well in agreement with observed data. Changes in river loads cause similar changes in dissolved inorganic N (DIN) concentrations in the lagoon (Fig. 4c). In most years, N is depleted (observed concentrations below 1 mmol m^{-3}) in the water column of the central lagoon in late summer and can be regarded as a short and (potentially) limiting element for primary production (Fig. 4d). Between 1977 and 1997, the data and model show excess N during summer in several years.

Fig. 4. Concentrations of phosphorus (top) and nitrogen (bottom) in the river and in the lagoon (Kleines Haff, centre), as well as the riverine loads (at the river mouth,) from 1960 to 2003. Lines indicate model results of MONERIS (river) and ERGOM (lagoon), and dots show data (LUNG, Mecklenburg-Vorpommern, *personal communication*). The colored lines indicate the present German water-quality thresholds according to the European Water Framework Directive (LAWA-AO 2007, *unpublished working paper*).
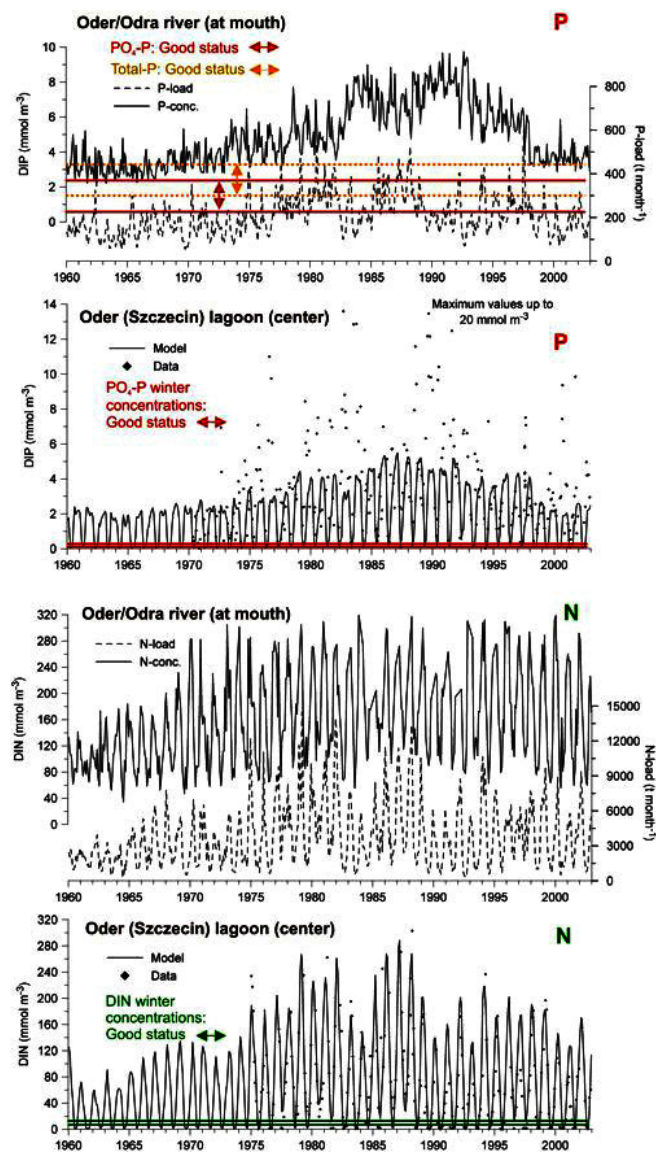
The threshold concentrations for good water-quality status according to the European Water Framework Directive (European Parliament 2000), are indicated for the river and the lagoon (Fig. 4). Between the 1970s and 1990s the P concentrations in the river are far above the upper threshold value (Fig. 4a). Today and in the early 1960s the average annual concentrations exceed the threshold only slightly. For dissolved inorganic N and total N, no river threshold values are defined (Fig. 4c). In the lagoon the threshold values (winter nutrient concentrations) are always far below the observed and modeled winter data. Nutrient concentrations in the river, together with water discharge, determine nutrient loads in the river, and these loads largely determine nutrient concentrations in the lagoon. Therefore, threshold concentrations in the lagoon cannot be defined independently from concentrations in the river. Other direct nutrient sources, such as atmospheric deposition and groundwater intrusion and surface runoff, play only minor roles and are included in the riverine loads. However, it is obvious that, according to LAWA-AO (2007, *unpublished working paper*), the threshold values for the Oder River are not related to the threshold values in the Oder Lagoon. This proves that, according to LAWA-AO, good water quality in the river will not automatically ensure good water quality in the lagoon.

The long-term model simulations with MONERIS and ERGOM allow the definition of consistent water-quality threshold values and this is important for the calculation of annual threshold riverine loads. Tables 1 and 2 compare our suggested values to the existing values. We assumed that the water-quality status in the lagoon and the river was good in the late 1950s. MONERIS provides riverine concentrations for that period for N and P components. Assuming an annual average discharge of 550 m³/s (slightly above the long-term average) we get threshold loads (at the river mouth) for total N and total P. ERGOM simulations allow the estimation of resulting realistic threshold values for good water quality in the lagoon, based on these loads. Our calculated values are on average about five times higher compared to the existing LAWA-AO (2007, *unpublished working paper*) values for the lagoon. The existing officially assumed values are much too low and do not reflect the real conditions and pressures in the lagoon (i.e., high nutrient loads in the Oder River). They cannot be used as water-quality objectives for the implementation of the Water Framework Directive.

Table 1. Existing (LAWA-AO 2007, *unpublished working paper*) and our new, suggested hydrochemical water-quality thresholds and objectives for the Oder (Odra) river.

	Total-P (average) (mg l⁻¹)	PO₄-P (average) (mg l⁻¹)	Total-N (average) (mg l⁻¹)	NH₄-N (average) (mg l⁻¹)	Total-P load (t a⁻¹)	Total-N load (t a⁻¹)
Existing	0.1	0.07		0.3		
Suggested	0.1	0.07	1.5	0.3	1700	25,000

Table 2. Existing (LAWA-AO 2007, *unpublished working paper*) and our model-calculated, realistic hydrochemical water-quality thresholds and objectives for the Oder (Szczecin) Lagoon.

|	Total-P (average) (mg l⁻¹)	PO₄-P (winter) (mg l⁻¹)	Total-N (average) (mg l⁻¹)	DIN (winter) (mg l⁻¹)	NO₃-N (winter) (mg l⁻¹)
Existing	0.016	0.006	0.21	0.15	0.11
Suggested	0.1	0.05	1.2	0.85	0.7

The MONERIS results suggest that a combination of several emissions-reduction measures in the river basin (Behrendt and Dannowski 2005) will reduce the P loads to being close to the critical load for good water-quality status in the river (Fig. 5a). A simple scheme, developed by Vollenweider (1976) for lakes, can give an impression of the consequences of good P concentration in the river on water quality in the lagoon. Vollenweider (1976) related the area's specific P loading to the vulnerability of a system moving towards eutrophication. The vulnerability is defined by average depth and the water retention time of an aquatic system. The shallower the system, the more sensitive it is towards nutrient loads. In case of the Oder Lagoon, its shallowness is compensated by a short water residence time of less than two months. Altogether, the Oder Lagoon is not very vulnerable to P loads, but it receives extremely high loads from a very large river basin. According to the Vollenweider approach, the system is, and possibly always was, eutrophic. The loads resulting from the optimal emission scenario, as well as loads resulting from good water-quality status in the Oder River, would be sufficient to keep the lagoon in an eutrophic state (Fig. 5b). However, it remains uncertain if the Vollenweider approach can be transferred to lagoons.

Lagoon management: mussel cultivation
Our question is whether mussel farming is an ecological and economic feasible additional measure for removing nutrients from, and to increase water transparency in, the Oder Lagoon. In the following, we focus on economic aspects and show the results of several cultivation scenarios for zebra mussels. Fig.

6 (a to c) shows the dependencies between costs, prices, and sales, and the mussel cultivation area (especially the mussel yield). These figures largely reflect and illustrate the basic assumptions in the model. Fig. 6d summarizes the additional income of mussel farmers from different potential sources. Income from carbon dioxide emission certificates assumes, hypothetically, that the amount of CO_2 fixed in mussel shells can be sold. A mussel farm of 1 ha with an annual total mussel yield of 7000 kg could hypothetically generate an additional income from carbon dioxide emission certificates of €22/year. However, there is an ongoing debate about whether the removal of mussel shells really removes CO_2 from the atmosphere. Because of the bicarbonate buffer system in the sea, calcite removal from the sea lowers the pH in the water by subsequent compensation processes, such as dissolution of sedimentary calcite.

Fig. 5. Nutrient loads at the Oder/Odra river mouth for phosphorus (a) and nitrogen (b). Shown are historic loads, present loads, the loads resulting from the optimal nutrient emission reduction scenario, and background loads (assuming no human activity and no land use in the river basin). Further indicated are threshold loads resulting from water-quality threshold concentrations, according to LAWA-AO (2007, *unpublished working paper*) and BMU 2001 (see Table 1). For the lagoon (c), the critical load concept for phosphorus after Vollenweider (1976) has been adapted. It shows the trophic status in the lagoon that would result from different riverine loads.
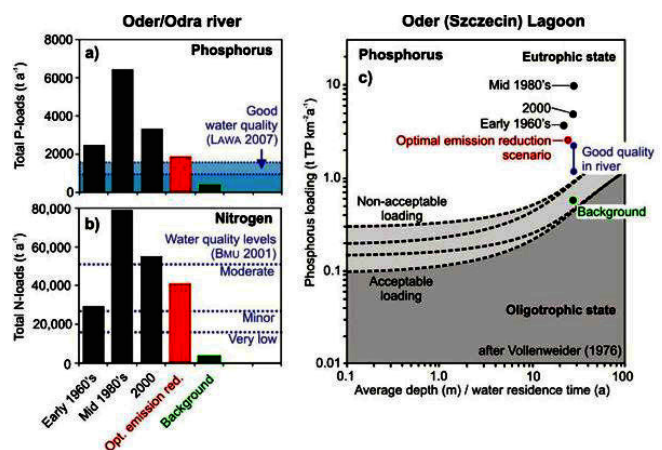
The potential return from a water-quality tax, i.e., resulting from tourists who would pay for an improved water transparency, would be about €19/year for a mussel farm of 1 ha. The relatively low numbers of tourists and the relatively small effect of mussels on water transparency (averaged over the lagoon) are responsible for this relatively small amount. Improved water quality attracts more tourists and increases the total expenditures, and has secondary effects on taxes and

Fig. 6. Results of the economic zebra mussel model relative to the mussel yield or the mussel cultivation area: a) the costs functions, b) the market prices of two products, and c) the potential sales income for mussel farmers. Additionally, different potential sources of income are indicated in comparison to the income from sales (d). Finally, the balance between total costs and total income is shown (e).
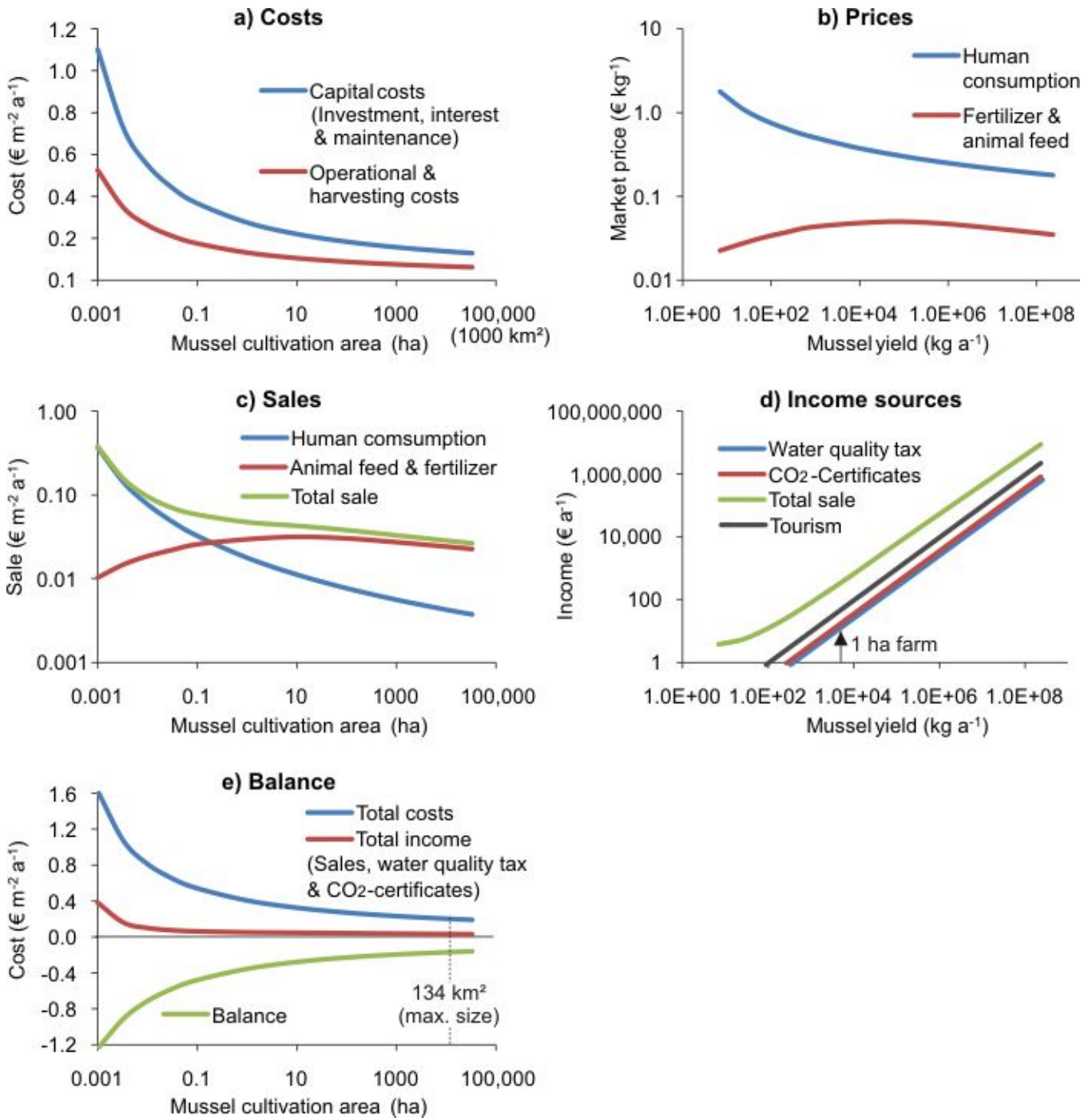
Fig. 7. Zebra mussel cultivation scenarios in the Oder (Szczecin) lagoon: a) impacts of increased fertilizer/animal feed market prices on the profitability of mussel cultivation in the lagoon, b) effects of additional income from nitrogen emission certificates (financial compensation/subsidy for removing nitrogen from surface waters) on profitability, c) financial compensation (subsidy) required to run profitable zebra mussel farms relative to the mussel cultivation area, d) N-removal costs of a 1000-ha (10-km²) zebra mussel farm compared to average marginal N and P reduction coasts in the Baltic region relative to the target nutrient reduction level (after Gren et al. 2008).
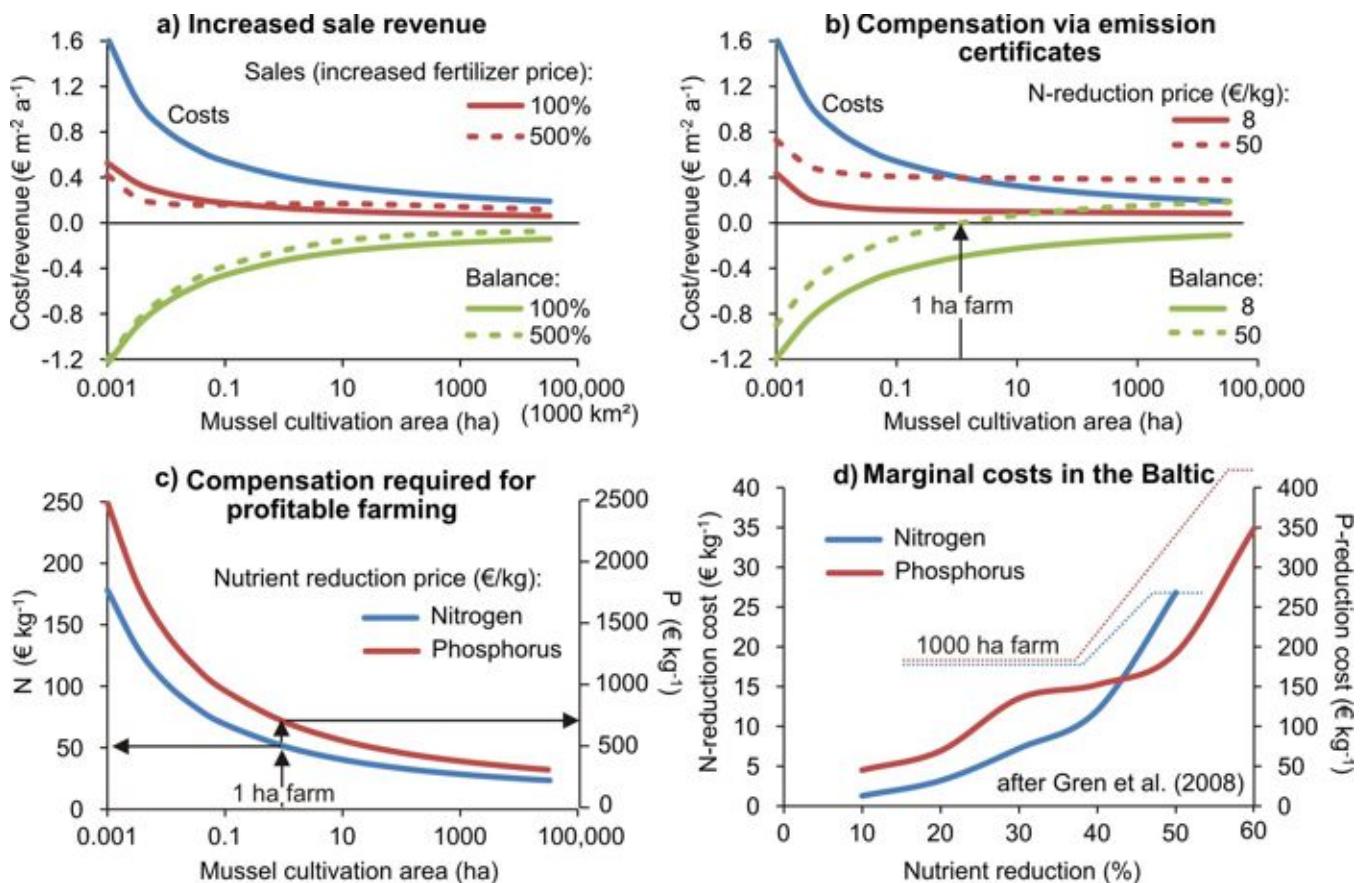
jobs. However, regional income generated by more tourists has only a minor benefit for mussel farmers and cannot be considered an additional direct source of income. Altogether, carbon dioxide emission certificates and a local water-quality tax would generate little income for mussel farmers.

The sales of mussels for human consumption, as animal feed, and as fertilizer are by far the most important potential sources of income. A mussel farm of 1 ha could, according to the model, generate an annual income of €420. However, this is not sufficient to cover the total costs of mussel farming, even if all sources of additional income are taken into account (Fig. 6e). But, by increasing the mussel cultivation area, the difference between total costs and total income decreases; the losses become smaller and mussel farming becomes relatively more attractive. However, even at the assumed maximum mussel cultivation area of 134 km², the annual loss would be

€0.25 m⁻² a⁻¹, or a total of €34 million/year. The conclusion is that, under the given assumptions, mussel farming in the Oder Lagoon cannot be profitable.

Fig. 7a shows the financial aspects of mussel farming if the market prices for fertilizer and animal feed are hypothetically assumed to increase by 100 and 500%. The result is significantly higher sales revenues, while the costs remain similar. However, even if the higher market price for fertilizer and animal feed is five times higher (€0.25/kg), the balance for mussel farming is negative. Assuming a maximum mussel cultivation area of 134 km², the annual losses would be reduced to €0.13 m⁻² a⁻¹. Even strongly increased sale revenues will not result in economic, profitable farming.

To be able to run a mussel farm profitably in the Oder Lagoon, a subsidy or financial compensation is necessary. Fig. 7b shows results of a scenario where mussel farmers receive €8/

kg of N and €50/kg of N for removing N from the Oder Lagoon. The first value adapts the Lysekil example in Sweden in Lindahl and Kollberg (2009). The costs are kept constant and the compensation for removing N is added to the income from sales. At €8/kg of removed N, the balance is still negative. At €50/kg of removed N, a farm of 1 ha or more becomes profitable. The maximum mussel cultivation area of 134 km² would result in a profit of €0.18 $m^{-2}a^{-1}$. These calculations show that significant additional income from nutrient emission certificates is necessary to run mussel cultivation profitably in the Oder Lagoon. This is only shown for N, but the approach can be transferred to P as well.

The compensation necessary for profitable farming relative to the cultivation area is shown for N and P in Fig. 7c. A small farm of 1 ha would require compensations of €51/kg of N or €733/kg of P, while the maximum mussel cultivation area (134 km²) would require compensations of €24/kg of N or €350/kg of P. A combination of N and P compensation prices into a joint nutrient removal compensation would cause a significantly reduced compensation price. These prices can be regarded as marginal nutrient removal costs, and are comparable to the data in literature. Gren et al. (2008) calculated total marginal costs for N and P for the Baltic region relative to the nutrient reduction target level. Marginal costs increase with increasing load reductions because more and more expensive measures have to be implemented to reach the target reduction. Mussel farming in the Oder Lagoon would only be cost-effective on a Baltic scale if a N reduction target above 50% is assumed and if the cultivation area exceeds 1000 ha.

Fig. 8 summarizes the results and compares the costs for using a mussel farm to remove 1 kg of nutrients to those of single external measures in the river basin. The data for external measures have been calculated by Gren et al. (2008) and refer to the Oder River basin. The comparison shows that, in the river basin, much more cost-effective measures for reducing nutrient loads exist. However, to reach the target for N loads in the Oder River, it would be necessary to reduce the load to 25,000 t/year, from the current load of about 55,000 t/year. At a load reduction level of 50% and more, marginal costs of river basin measures would be in the same order of magnitude as the marginal costs for mussel farming. In this situation mussel cultivation would become a cost-efficient measure and has the additional benefit of improving water transparency. However, 134 km^2 of mussel farms (20% of the total lagoon area) could remove 938 t of N/a.

DISCUSSION

Mussel cultivation: an option for the Oder Lagoon?
Lindahl et al. (2005) give an overview about the strengths, weaknesses, opportunities, and threats of blue mussel cultivation in Sweden, and Stybel et al. (2009) specify these

aspects for zebra mussel cultivation in the Oder Lagoon. Therefore, here we focus on the economic aspects only.

Due to the special situation in the lagoon (i.e., shallowness, and a lack of experience in zebra mussel farming) our calculated capital costs of €4150/a for a 1-ha farm are comparatively high. A translation of assumptions in Gren et al. (2009) for a 1-ha farm in the south Baltic proper results in capital costs of €5800/a. However, the Gren et al. assumed a long-line system suspended from the surface down to about 6 m, and therefore a much higher volume of production. Our operational and harvesting costs (including mussel processing) of €0.2/kg cause additional annual costs of €1400 $m^{-3}a^{-1}$ and are very close to the data in Gren et al. (2009). Our zebra mussel yields of 0.7 kg $m^{-3}a^{-1}$ are calculated from data in Fenske (2003, 2005) and are nearly 50% lower compared to data for blue mussel cultivation in the south Baltic proper (Gren et al. 2009). The low supply of food for mussels in the lagoon due to low flow velocities is not compensated by a higher primary production in the lagoon. However, our mussel production and cost calculations are conservative and they are, by far, not balanced by sales.

Zebra mussels are too small to become important for human consumption. Therefore the market price for animal feed as well as fertilizer is most important for the sales revenue. In our scenario we hypothetically assumed average price increases of 100% and 500%. Recent results by Jönsson et al. (2010) indicate that mussels may be a high-quality protein source and may replace fishmeal in organic diets for laying hens. Fish aquaculture production depends upon the supply and use of external off-farm nutrient inputs in the form of compound aquaculture feeds. At present, the production of aquafeeds is highly dependent on capture fisheries for sourcing essential dietary lipids and high-quality marine animal proteins (Mente et al. 2006). It is very likely that zebra mussels could serve very well as aquafeed. These examples show that there are potential new and profitable markets for zebra mussels that could increase return from mussel sales. Further, it is very likely that the ongoing increase of market prices for high quality protein feed will go on. However, even rising prices for fertilizer and protein-rich animal feed will hardly be able to balance the enormous cultivation costs. Possible additional sources of income for mussel farming, such as CO_2 emission certificates or a water-quality tax paid by tourists, would have only marginal consequences for the profitability of mussel farming and thus can be disregarded. The major challenges for the future are to reduce the costs and to increase the yield of mussel farming in the Oder Lagoon.

Usually, water quality is viewed from an ecologic, ecosystem health perspective and in terms of the legal demands resulting from the Water Framework Directive. Tourism is the most important economic factor and is the major source of income around the lagoon. For local people, the demands of tourists

Fig. 8. Costs of measures to reduce 1 kg of nitrogen (a) and 1 kg of phosphorus (b) (after Gren et al. 2008) in the Oder/Odra river basin. Some measures focus on emission prevention and others focus on nutrient retention. In comparison, the nutrient-removal costs for a small 0.1-ha (1000-m²) and a large 1000-ha (10-km²) zebra mussel farm are shown.
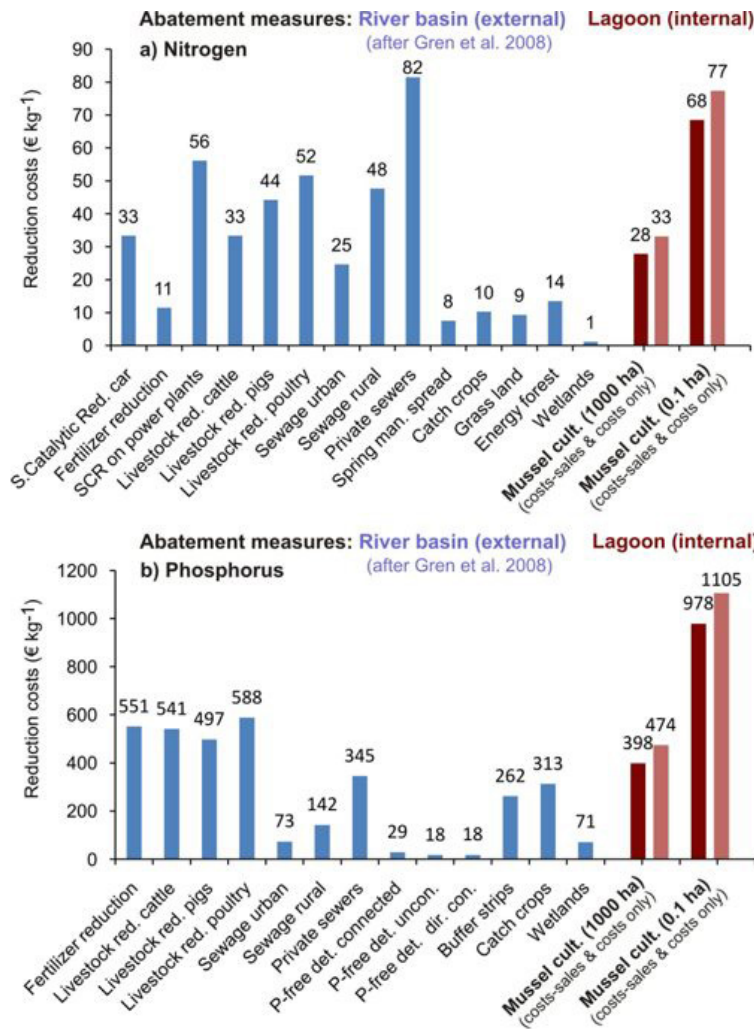
towards water quality and their satisfaction are very important, and tourists largely perceive water quality in terms of good water transparency (Dolch and Schernewski 2003). Elmgren and Larsson (2001), Wulff et al. (2001), and Savchuk et al. (2006) show that water transparency is a suitable indicator for the state of eutrophication in Baltic coastal waters. It is a core parameter of our systems approach because it establishes links between ecological, economic, and social aspects.

The avoidance of nutrient emissions and measures to increase the retention of nutrients in the river basin have the highest priority in eutrophication management. However, even the combination of all of the most important emissions-reduction measures in the river basin (Behrendt and Dannowski 2005) will still cause a riverine N load of about 40,000 t of N/a. The

critical loads defining the upper threshold are 25,000 t of N/a. This load is very close to the threshold that separates minor and moderate pollution, as defined by the Ministry for the Environment (BMU 2001) in the German report about surface water quality. A reduction of 15,000 t of N/a beyond the optimal scenario loads will be very expensive and all reduction measures considered so far for the river basin will not be sufficient to reach this target load (Behrendt and Dannowski 2005).

Nutrient retention measures in the river basin, as well as internal management measures, such as mussel farming, are hardly profitable and require additional funding. Who shall cover the costs for these measures? The European Water Framework Directive (European Parliament 2000) and the

Baltic Sea Action Plan (HELCOM 2007) can be regarded as major driving forces for water-quality protection. Its implementation asks for a cost-effective nutrient management and requires new funding schemes. Lindahl et al. (2005) compared the costs of external N removal measures with blue mussel farms using the example of the Gullmar Fjord in Sweden. Blue mussel farming turned out to be a cost-effective method, but still required subsidies. One solution to fund nutrient removal is a nutrient-emission trading system. Polluters pay for the emission of nutrients and the money is used to fund cost-efficient internal or external removal measures. Other alternatives would be a nutrient removal tax on fertilizer, or the redirection of agricultural subsidies (Lindahl and Kollberg 2009).

Mussel cultivation is an option for reducing nutrient loads and for improving water quality, but in the Oder estuary it can only support and not replace measures in the river basin. The costs for removing 1 kg of N (phosphorus) from the lagoon varies, depending on mussel farm size and assumptions, from €28 to €68/kg of N (€398 to €978/kg of P). Today, several measures in the river basin have much lower marginal costs for removing 1 kg of N and are more cost-efficient. The implementation of the Baltic Sea Action Plan requires a load reduction of 62,400 t of N/year in Poland (HELCOM 2007), and the achievement of good water-quality status in the Oder River requires the load to be reduced to 25,000 t/year of N (1700 t of P) from the current load of about 55,000 t/year. Mussel farming in the Oder Lagoon could potentially remove nearly 1000 t/year of N (70 t of P), or about 2% of the present N and P loads. At a load-reduction target of 50% or more, mussel cultivation would become a cost-efficient measure, compared to measures in the river basin, and has the additional benefit of improving water transparency. However, it is not a profitable business and requires subsidies.

CONCLUSION

The systems approach framework is a suitable tool for structuring a work process, and it helps to integrate ecological and economic aspects on a large scale. The method allows for simultaneous evaluation of measures to combat external (river basin) and internal (lagoon) eutrophication with respect to ecological objectives and economic cost-efficiency in one of the largest Baltic river systems, the Oder.
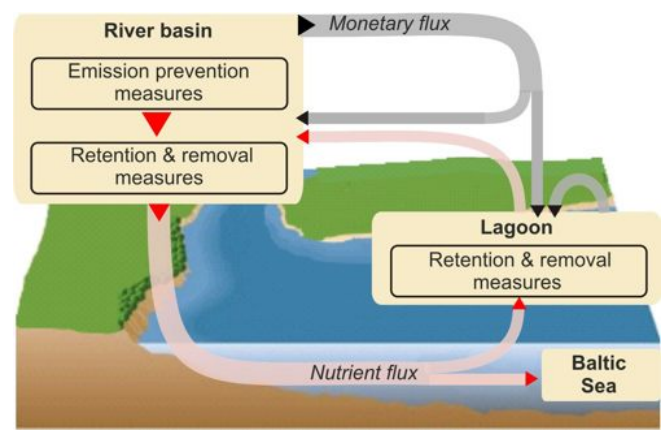
To make mussel farming a realistic option, a new, large-scale management system is necessary. It has to allow the re-allocation of money between river basin (polluter) and coastal waters (victim and purification system) and, in the Oder case, has to allow a money transfer between Germany and Poland. A comprehensive, large-scale approach for managing nutrients between land and sea has to link external and internal management measures and has to follow guiding principles.

Firstly, the application of nutrients on terrestrial systems and their loss to the surface waters have to be minimized. Secondly,

nutrient cycles have to be established and/or strengthened. In practice it means that the application of fertilizer and agricultural land use have to be optimized, to reduce the loss. New and improved measures in the river basin have to be established to increase nutrient retention.

Finally, measures in coastal waters have to be considered as an option. With mussel harvesting, nutrients are removed back to the land and end up as fertilizer in agriculture. Thus the cycle is closed; and, if correctly implemented, mussel farming may help mitigate negative impacts of eutrophication in the Baltic Sea (Fig. 9).

Fig. 9. Sketch showing the flux of nutrients and money in a management approach to reduce eutrophication, taking into account the river basin as well as internal lagoon measures.

Responses to this article can be read online at:
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