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Mussel Cultivation to Improve Water Quality in the Szczecin Lagoon

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ABSTRACT

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According to the EU Water Framework Directive, all surface waters should reach a good ecological status by 2015. While it seems realistic to achieve this objective for the river Oder/Odra itself, the water quality of the Szczecin (Oder-) Lagoon cannot be sufficiently improved through river basin management alone. Therefore, supporting internal measures must be considered. The zebra mussel, *Dreissena polymorpha*, a species currently inhabiting the whole lagoon, has a high filtration potential. With filtration rates of 3000-4000 l m^{-2} d^{-1} *Dreissena* could potentially improve water quality, especially water transparency, which is a key factor for beneficial regional tourism development. Cultivation of mussels, combined with systematic harvest could help to reduce the nutrient content in the Szczecin Lagoon. This article presents the results of a literature-based suitability analysis for cultivating *Dreissena polymorpha* in the lagoon. Besides ecological and filtration effects, economic utilization of *Dreissena* is discussed to assess costs and benefits of mussel aquaculture. The results show that selling *Dreissena* is difficult. Therefore, economic benefits of cultivation are limited. Further financing strategies could be a tourism fee for water quality improvement or nutrient emission certificates.

ADITIONAL INDEX WORDS: *Nutrients, Dreissena polymorpha, biomanipulation*

INTRODUCTION

The European Water Framework Directive (WFD) demands a good ecological status in all European surface waters by 2015. Reference conditions for German Baltic coastal and transitional waters, defining a very good water quality status, are still under discussion. The Szczecin Lagoon, a large (687 km^2) but shallow (average depth of 3.8 m) coastal system in the southern Baltic Sea, belongs to oligohaline inner coastal waters with reference concentrations of 10 (0.3-0.5) µmol l^{-1} for total nitrogen (total phosphorous) (BLMP, 2007). A "good" water quality can be defined as up to 50% above the reference value (BROCKMANN *et al*., 2005). But current values are far above values for a good water quality in the Szczecin Lagoon, and a comprehensive management approach for water quality improvement in the river basin as well as in the adjacent coastal area is not available at the moment.

The Szczecin Lagoon is divided into an eastern bay (Wielki Zalew) on the Polish side and the Kleines Haff on the German side. Three outlets link the lagoon with the Baltic Sea. With a length of 854 km, a basin of 120,000 km^2 and an annual average discharge of 17 km^3 (530 m^3 s^{-1}), the Odra (German: Oder) is one of the most important rivers in the Baltic region. The Odra discharge contributes at least 94% to the lagoon's water budget and dominates the nutrient budgets (Wielgat, 2002). These riverine loads control ecosystem processes and keep the lagoon in a polytrophic to hypertrophic state. The water transparency is usually below 50 cm. Heavy blue-green algae blooms are a common feature, especially in the summer (LUNG, 2008).

The WFD considers the interdependence of the river basin, river, coastal waters and the sea and demands a large scale river basin management approach. Recently, SCHERNEWSKI *et al*. (2008) applied linked river basin and coastal water models to analyze the effects of a 35% nitrogen (N) and 60% phosphorous (P) load reduction in the Odra River on water quality in the Szczecin Lagoon. It became obvious that this realistic nitrogen reduction scenario with an annual load of approximately 65,000 t N and 5,000 t P (BEHRENDT *et al*., 2005) is not sufficient to ensure good coastal water quality according to the WFD. With respect to nitrogen and phosphorus, realistic river basin management alone cannot reduce the riverine loads to a sufficient degree.

More comprehensive management is required, which includes nutrient removal measures in the coastal waters. River basin management aiming at reducing nutrient emission and improving nutrient retention remains the basis of nutrient management in the landscape. However, in the Szczecin Lagoon, several supporting internal measures are possible to combat eutrophication, to remove nutrients, and to improve ecosystem quality: a) dredging of sediment and dumping on land, b) enlarged reed belts and extended submersed macrophyte areas, c) algae farms, and finally d) enlarged natural mussel beds and mussel cultivation.

International studies showed that extractive aquaculture in which macroalgae or mussels are grown both for their biomass and the removal of the nutrients from the water body are recognized additions to control nutrient concentrations in coastal waters (EDEBO *et al.,* 2000, LINDAHL *et al*., 2005, NEWELL, 2004). In the Szczecin Lagoon the enlargement of mussel beds and cultivation of mussels seem to be the most promising measure (Schories et al., 2006). To analyze the potential of mussels for water quality improvement according to the WFD the paper considers the following questions: a) What are the major demands and criteria for promising internal nutrient management measures? b) Which mussel species are suitable – for ecological and economic reasons? c) Which cultivation method could be used in the Szczecin Lagoon? d) What are the strengths, weaknesses, opportunities and threats (SWOT) of mussel cultivation?

The analysis is based on a literature review. It links international experiences in mussel cultivation to regional demands and gives the basis for a further discussion about a comprehensive regional water quality management strategy.

CRITERIA FOR INTERNAL NUTRIENT MANAGEMENT MEASURES

Reductions of nutrient concentrations and phytoplankton biomass are key elements of an internal measure in the lagoon. The following criteria have to be fulfilled:

a) Nutrients (N, P) coming into the lagoon by river should be permanently removed from the lagoon, deposited to the bottom and fixed in the sediment, or recycled from dissolved into a form less available to phytoplankton. The growth of algae would be limited by nutrients (now it is largely limited by light) resulting in a reduction of algae blooms and an improvement of water transparency (KARATAYEV *et al.,* 2002).

b) Anoxia has to be avoided. Measures such as cultivation of mussels can lead to anoxic conditions. That would result in phosphorous release and a decline in water quality due to an overload of nutrients.

c) The measure must be ecologically justifiable. The ecosystem should not be disturbed or negatively changed by introducing invasive alien species for example. The Szczecin Lagoon is an important area for migrating birds and fish spawning. Large areas of the lagoon are FFH and NATURA 2000 sides. The measure has to be in agreement with the requirements of an environmental impact assessment..

d) The measure must be socially acceptable. It is desirable to create jobs in this region with a high unemployment rate (>20%).

e) The measure must follow the regional spatial plan. The lagoon is characterized by different uses such as fishery, shipping, and nature conservation. The measure should not compete with other traditional uses such as gillnet fisheries locating in the shallow areas of the lagoon. Economic losings must be prevented.

f) The measure must be legally feasible. Numerous provisions like the Federal Building Code and laws of the state of Mecklenburg-Western Pomerania, Planning Law, Building Regulations, Environmental Protection Law, Water Law and Waterway Law must be applicable

g) The measure should have an efficient cost-benefit-ratio. Otherwise alternative financing strategies have to be considered to realize internal measures.

WATER QUALITY IMPROVEMENT BY MUSSELS

Worldwide, bivalves have great potential for water quality improvement due to their filtering efficiency. Along the German Baltic coast mussels like blue mussels (*Mytilus edulis)*, zebra mussels *(Dreissena polymorpha)* and Pacific oysters (*Crassostrea gigas)* are identified as promising biofilters (SCHORIES *et al.*, 2006). In the Szczecin Lagoon, sizes and locations of mussel beds seem to vary over the years (ANDRES, 1993). *Anodonta anatina, Unio pictorum, Pisidium spec.* and *Dreissena polymorpha* were detected in 2007 (FENSKE *et al.,* unpubl). The Szczecin Lagoon does not provide a high enough salinity for other bivalve species such as *Mytilus edulis* or *Crassostrea gigas*.

Dreissena polymorpha has the highest densities in the lagoon. In a recent mapping (summer 2007, German territory) density ranged from 864 to 10,444 *Dreissena* mussels m^{-2} (average 3949 inds m^{-2}). In the Polish territory, current densities of 4700 inds m^{-2} are reported (WOZNICZKA and WOLNOMIEJSKI, 2008). *Dreissena* can build up enormous biomass. Densities of >30,000 inds m^{-2} have been found in the Szczecin Lagoon (ANDRES, 1993, HENSEL, 1994), but the population development is not easy to predict. Long-term investigations showed that high population densities can be followed by sudden crashes followed by decades of recovery time (STANCZYKOWSKA and LEWANDOWSKI, 1993, WOZNICZKA and WOLNOMIEJSKI, 2008). The *Dreissena* population in the Szczecin Lagoon seems to have decreased during the last decades. While the precise reasons are not known, probable causes include a lack of appropriate substrate, anoxia, and predators.

Dreissena polymorpha has the potential to spread fast after introduction into a new area, as shown in the unintended large-scale "open-air-experiment" in the 1980s in North America, where it was probably transported as larvae with ballast water. Individuals can reproduce in their second year (MACKIE and SCHLOESSER, 1996). *Dreissena*, unlike large bivalves such as duck mussel, swan mussel or pearl mussel, has pelagic larvae and no parasitic larval stage. They are independent of fish for their reproduction.

With filtration rates of 10-25 ml h^{-1} per mussel, *Dreissena* has the potential to significantly affect water quality in the lagoon (FENSKE, 2003). *Dreissena* eliminates suspended matter and increases water transparency. Filtration rates depend on mussel density, population composition (size classes), temperature and salinity. The value of 1083 l m^{-2} d^{-1} is a conservative calculation for the current mussel density at an annual average water temperature of 12 °C, not taking into account the filtration of the juveniles. The actual filtration rate of all mussels taken together (including those on reed stalks and stones near the shore, as well as the juveniles) would probably be higher. With average mussel densities of 15,000 m^{-2} as in the 1990s (FENSKE, 2003), the total filtration rate would amount to 3000-4000 l $m^{-2}d^{-1.}$

Dreissena polymorpha removes particles from the water

Table 1: State of knowledge about zebra mussels (*Dreissena polymorpha)* in the Szczecin Lagoon.

Mussel biomass	68,000 t (8812.65 t in the Kleines Haff (FENSKE, unpubl.), ca. 60,000 in the Wielki Zalew (WOŹNICZKA and WOLNOMIEJSKI, unpubl.))
Abundance of mussels on beds	3949 (864-10,444) mussels per m² (FENSKE, unpubl.)
Abundance of mussels on horizontal nets	Average 6400 mussels m^{-2}, max. 15,800 mussels m^{-2} (FENSKE, 2005)
Mussel size (average after 2 years)	12-14 mm (FENSKE, 2003)
Mussel weight (average after 2 years)	500-1000 mg (FENSKE, 2003)
Filtration rate	1083 l m^{-2} d^{-1}, based on 3949 mussels m^{-2} (FENSKE, unpubl.)
Contamination of pollutants	5.4 As; 1.7 Pb; 0.94 Cd; 0.26 Hg (mg kg^{-1} dry weight) (SORDYL and GERCKEN, 2002)

through filter-feeding, thus reducing phytoplankton and detritus. 70% of the consumed seston reaches the alimentary tract, 30% of the particles are extruded as pseudofaeces (STANCZYKOWSKA, 1984). For planktonic or benthic organisms, nutrients of this kind are less available compared to soluble nutrients in the water. Abundances of phytoplankton species can change resulting in better water quality ((KARATAYEV *et al*., 2002)).

Dreissena polymorpha is by far the most abundant bivalve in the Szczecin Lagoon. However, due to their much larger filtration capacity of 2.75 l h^{-1}, the duck mussel (*Anodonta anatina) (*KRYGER and RIISGARD, 1988), is also a potential biofilter for water quality improvement. Currently, their density in sandy areas is about 1-2 m^{-2} (FENSKE *et al*., unpubl.), thus their total filtration effect is lower than that of *Dreissena*. To increase the *Anodonta* population, they would have to be reared in aquaculture basins up to a size that is less likely to be consumed by predators. As their larvae attach to fish gills, the corresponding fish species would also have to be kept in aquaculture basins.

MUSSEL CULTIVATION

In order to contribute to long-term water quality improvement with fewer algae blooms and higher water transparency, the zebra mussel population and its filter capacity can be increased by enlargement of natural mussel beds as well as by mussel farm systems. The continuous cultivation and harvest of *Dreissena* would reduce the total amount of nutrients in the Szczecin Lagoon. On a wet weight basis, *Dreissena polymorpha* contains approx. 1% nitrogen (LINDAHL *et al*., 2005) that is removed from the ecosystem at harvest (0.85-0.93% P and 11-12.8% N of the mussels' dry weight, STANCZYKOWSKA and LEWANDOWSKI, 1993a). The commercial use of harvested mussels can have great benefits.

Cultivation methods

Within the last years, different projects have been carried out to analyze locations and densities of mussels in the Szczecin Lagoon as well as to investigate the filtration capacity and potential of *Dreissena polymorpha* for water quality improvement. Currently, a cross-border project is in preparation, testing different net substrates for mussel settlement. According to FENSKE (2005), mussel clumps that have settled on nets or lines over several years, may break off and live on the sea bottom thus creating a hard substrate for more mussels to settle. Horizontal fishing nets, fixed in 2.5 m water depth, were settled by up to 15,800 mussels m^{-2}. However, for commercial cultivation, mussels on horizontal net structures seem to be difficult to harvest. Therefore, other supporting measures to cultivate *Dreissena polymorpha* such as vertical line systems (LINDAHL *et al*., 2005) and single longtubes carrying vertical net collectors ("Smartfarm") will be tested in the future. Both systems are used all over the world including German costal waters (Kiel Fjord) for culturing seed and mussels. Vertical mussel farm systems utilize the water body efficiently, can reach high filtration rates and are technically adapted for commercial cultivation. "Smartfarms" are more stable than traditional long lines (WALTER and DE LEEUW, 2007). The concept includes machines for husbandry and harvesting, and permanently moored units can reduce labour costs.

Calculations of investment costs for the installation of a mussel farm in a certain area are difficult to access. Investment costs for mussel cultivation range from 30,000 Euro for a long line system in the Jervis Bay, Australia (including costs for vessels, vehicles and land based infrastructure (9200 Euro) (MARINE POLLUTION RESEARCH PTY LTD, 2006)) to 38,000 Euro per hectare for a "Smartfarm" in the Baltic Sea. The latter includes the establishment of several units based on small meshed mussel collectors. A necessary husbandry and harvesting machine is about 165,000 Euro (calculation by Smart Farm AS).

Commercial use

Worldwide there is currently no commercial or industrial use for *Dreissena* besides biofiltration applications (ELLIOTT *et al*., 2008). General possibilities of mussel industry, especially blue mussels, are used to get an estimation about potential applications and related market values.

Mussel usage is mainly determined by size and wet weight. Based on a marketable production of *Dreissena polymorpha*, the following uses seem possible: human food, animal feed, fertilizer, biogas, and seed mussels for biofiltration. The first three applications are common for blue mussels and require large-scale production. Marketable blue mussels are more than 4.5 cm long, three times larger than average *Dreissena* and therefore are more valuable. Due to a high market penetration and production of blue mussels their market price is comparably small. In 2007, 5900 t of blue mussels were dredged along German coasts (150% more than in 2006). With 1.43 Euro kg^{-1}, the generated proceeds doubled, compared to 2006. Moreover, the import of blue mussels increased by 30% in 2007. 25,700 t were imported from Denmark and the Netherlands (BLE, 2008). Prices for dried mussels or crushed shells, which could be used for the production of fertilizer or animal food (LINDAHL *et al*., 2005), are not available. For rough calculation, the wholesale price of pure sewage is used: approximately 5 Euro per ton.

DISCUSSION

Cultivation of *Dreissena polymorpha* in the Szczecin Lagoon could be as follows: Normally settlement occurs abundantly in June (5-6 weeks after reproduction which starts at a water temperature of 12 °C (FENSKE, 2003)). After 24 months and after reproduction mussels with a size of 14 mm and a weight of 1 g are harvested. A longer growth period would enhance the risk of dropping off and losses by predators or low winter temperatures.

To ensure high settlement of larvae farms should be located in the main water flow direction and not in calm bays. Nets over muddy sediment could help to install mussel beds in areas, which are now devoid of mussels. Since zebra mussels are also produced for human consumption, farm sites should be located away from sewage treatment plant outfalls. Water depths should be as high as possible. Several small farm units should be constructed all over the lagoon (e.g. unit = 280x400 m) to avoid competition for space with other uses such as shipping, fishery and nature conservation. Farm units at different locations can minimize the threat of destruction by unforeseen environmental hazards.

Every two years 6.4 kg m^{-2} zebra mussels could be harvested in the Szczecin Lagoon. This rough calculation is based on an average abundance of 6400 mussels per m^2 on horizontal nets (FENSKE, 2005). The annual production would be much less than the 40 kg m^{-2} annual harvest of blue mussels along the Swedish west coast (LINDAHL *et al*., 2005).

To remove 10% of an annual river load of 65,000 t N the farming area would have to cover 101.5 km^2 based on the mussel content of 1% N. As *Dreissena* would be harvested after 2 years, 203 km^2 would have to be used as cultivation area. Investment costs would range from 609 to 771 million Euros to establish a mussel farm of 203 km^2. An annual harvest of 101.5 km^2 would result in 650,000 t mussels, one hundred times larger than the annual landings of blue mussels on the German coast (BLE, 2008). In a realistic assumption with only 0.1% (650 t) sold for human consumption and the remainder for other products, an income of 4.2 million Euro could be achievable. Only the unrealistic assumption of a 100% food production could result in a total refinancing of the investment costs. As this calculation does not include running costs for manpower and maintenance, the high investment costs cannot be balanced by selling mussels under current market conditions.

Discussing advantages and disadvantages of mussel cultivation in the Szczecin Lagoon the following aspects have to be considered.

Strengths: i) *Dreissena polymorpha* can be considered as native species (*Dreissena* was prevalent throughout Northern Germany even before the last ice age). It could be used for cultivation in an environmentally friendly way. An increase in population density in the lagoon would imply no substantial risks, because the natural abundance was once much larger than it is today. ii) *Dreissena* improves the ecosystem quality. Mussel beds and deposited shells provide substrate for settlement of sessile organisms and increase habitat complexity (KARATAYEV *et al*., 2002). iii) According to FENSKE (2005), it can be assumed that the cultivation on the German side of the lagoon would be in line with the environmental law and the water law analysis. iv) Suspended mussel cultures would not be as limited by low spatfall as bottom cultures (SMAAL, 2002).

Weaknesses: i) The commercial use of *Dreissena polymorpha* is uncertain, because of the small harvest size. The concentration of heavy metals in mussels, especially arsenic, cadmium, and mercury (SORDYL and GERCKEN, 2002) could prevent mussel use for animal husbandry. A reduction of pollution load is absolutely necessary. ii) Waterfowl, fish and crustaceans are known to feed on *Dreissena polymorpha.* The Szczecin Lagoon is an important wintering bird area in the Baltic Sea region. In shallow areas of Lake Constance (Southern Germany) wintering water birds decreased *Dreissena's* biomass by >90% (WERNER *et al*., 2005). In other areas, the calculated biomass reduction is only 10 % (VAN NES *et al.,* 2008). iii) At the German Baltic coast, especially in the eastern part there is no tradition and almost no experiences in mussel cultivation that could be used for installation, harvest and marketing measures.

Opportunities: i) The enlargement of natural mussel beds and the establishment of mussel farms improve water quality, especially water transparency. Because light penetrates deeper into the water, macrophytes can grow better and settle in new places (MACISAAC, 1996). Moreover, macrophytes and mussels can have mutual beneficial effects which enhance production output in polyculture systems as seen in China (YELLOW SEA FISHERIES RESEARCH INSTITUTE, 1998). Mussel cultivation in the Szczecin Lagoon could be linked to cultivating macrophytes to reach a better nutrient abatement level. ii) According to changes in plaktonic (phytoplankton) and benthic (mussels) biomass food web interactions can be altered. The abundance of benthic feeding fish can be enhanced (KARATAYEV *et al*., 2002, Reeders and Bij de Vaate, 1990), a related fishery could be expanded. iii) Water transparency is a key factor in tourists' quality perception of a beach destination (KESSLER, 2008). An improvement of water transparency could thus result in a higher number of tourists and overnight stays in the summer season. iv) Mussel cultivation may also enhance regional economic power by providing new regional jobs in harvesting and processing of mussels. v) The new approach of nutrient removal could serve as a best practice project of interest to representatives of science, tourism and the economy.

Threats: i) Mussel cultivation also has negative environmental effects. Organic material (mussels, faeces, pseudofaeces, and other detritus) deposited below the farm will influence biogeochemistry and the benthic ecosystem. Intense microbial activity can lead to local over-enrichment of the sediments and anoxic surface sediment (NEWELL, 2004). ii) Beside positive effects on tourism through increased transparency, people may be bothered by *Dreissena* shells if many are washed ashore. Regular beach cleaning might be necessary.

Conclusion: Following the defined criteria for internal water quality improvement, the cultivation of *Dreissena polymorpha* is a suitable method of reducing nutrient concentration in the Szczecin Lagoon. The current lack of a commercial value of *Dreissena* is a big disadvantage of the approach. To finance high investment costs, other financing strategies must be developed. One option is to involve local tourism. A survey in summer 2008 showed that many tourists are willing to pay a fee for water quality improvements. A further option could be to rededicate subsidies to internal water quality measures in the future instead of the current practice of spending the money on agriculture in the river basin today. A third option is the trading of nutrient quotas described by LINDAHL *et al.* (2005). Based on the nitrogen removal service of mussel farms as a benefit to society, mussel producers are supported e.g. by paying them per kilogram of nitrogen removed from the sea. Emission quotas are then traded and bought by the emitter.

The article gives a preliminary overview about possibilities and limits of mussel cultivation as an internal measure for water quality improvement. Some of the described uncertainties like the cultivation method, suitable locations and overall filtration rates will be considered in a future project starting in 2009. Regarding the economic effects, future investigations should include regional marketing for *Dreissena* and methods to process mussels for fertilizer and animal food. Financing strategies such as nutrient trading systems or a tourism fee will be analysed regarding the regional applicability within the projects SPICOSA and IKZM-Oder. The development of a non-dimensional mussel model combining ecological, economic and social aspects in the lagoon is in progress.

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