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Viewpoint

Mussel farming as a nutrient reduction measure in the Baltic Sea: Consideration of nutrient biogeochemical cycles

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ABSTRACT

Nutrient loads from the land to the sea must be reduced to combat coastal eutrophication. It has been suggested that further mitigation efforts are needed in the brackish Baltic Sea to decrease nutrients, especially in eutrophic coastal areas. Mussel farming is a potential measure to remove nutrients directly from the sea. Mussels consume phytoplankton containing nitrogen (N) and phosphorus (P); when the mussels are harvested these nutrients are removed from the aquatic system. However, sedimentation of organic material in faeces and pseudo-faeces below a mussel farm consumes oxygen and can lead to hypoxic or even anoxic sediments causing an increased sediment release of ammonium and phosphate. Moreover, N losses from denitrification can be reduced due to low oxygen and reduced numbers of bioturbating organisms. To reveal if mussel farming is a cost-effective mitigation measure in the Baltic Sea the potential for enhanced sediment nutrient release must be assessed.

1. Background

The Baltic Sea is considered one of the world's most polluted seas. During recent years cyanobacteria blooms have been frequent and these events have increased the public and political awareness of the vulnerability of this brackish water body. In addition, a large portion of the bottom area (49,000 km^2, i.e. a fifth of the area of the Baltic Proper and the Gulf of Finland), suffers from hypoxic or anoxic conditions (Conley et al., 2009). Hypoxia ($O_2 < 2$ mg l^{-1}) in the bottom water is due to both the increased sedimentation and decomposition of organic matter with eutrophication (Conley et al., 2009) and stratification in bottom waters due to irregular inputs of saline bottom water entering through the Danish Straits.

It is widely recognised that the reduction of nutrients (mainly nitrogen (N) and phosphorus (P)) is necessary to improve the ecological quality in a longer, sustainable perspective. The recent Baltic Sea Action Plan (HELCOM, 2007) has identified country specific targets for nutrient reductions to attain politically agreed upon goals for ecological quality. The countries are currently devising plans to meet the nutrient reduction goals.

Even if nutrient reduction measures on land are implemented today, it might take decades before significant improvements are seen in the open waters of the Baltic Sea (Savchuk and Wulff, 2009). Focus has turned to alternative nutrient reduction measures that can also be implemented within the sea itself. Filter feeders are known to reduce the amount of phytoplankton in the water (Newell, 2004) and natural mussel banks have been shown to increase water clarity at the outlet of the Baltic Sea in the Danish Straits (Haamer and Rodhe, 2000). Mussel farming, today used widely for food production, has been suggested as a measure to mitigate N and P in coastal waters of the Baltic Sea. In this paper we highlight some aspects of mussel farming as a measure to reduce nutrient concentrations in coastal marine ecosystems and assess their capability to remove nutrients.

2. Mussel farming

Mytilus edulis is a native mussel species common to the Baltic Sea where it occupies large areas of hard substrate down to 30 m. *M. edulis* grows in a wide range of salinities, but is significantly smaller in the lower salinity waters of the Baltic Proper (5–8 PSU). Commercial farming of mussels occurs in the higher salinity waters in the Kattegat along the Swedish West Coast and in Danish coastal waters. Commercial farms often use long-line systems or nets suspended from tubes (Smartfarm®) in the water column. Mussel larvae settle on the lines or nets and after 1–2 years of growth they are harvested. The mussels incorporate N and P into their tissue and release the remains as faeces. Particles they do not want to ingest are also handled and released as pseudo-faeces. Both the faeces and pseudo-faeces have high sinking rates and accumulate in sediments under the farm (Newell, 2004).

3. Effects on biogeochemical cycles

When mussels are harvested the N and P incorporated into the mussels are removed from the water (Fig. 1). However, before the

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efficiency of nutrient removal from the aquatic ecosystem can be evaluated, the overall impact of a mussel farm on the biogeochemical cycles must be evaluated, which is lacking in most studies regarding nutrient mitigation. Nutrient regeneration within mussel farms is high and the released nutrients support new phytoplankton production (Asmus and Asmus, 1991). The benthic impacts that must be taken into account are the effects on sediment oxygen conditions and on benthic communities and the subsequent changes in nutrient recycling.

Increased sedimentation of organic matter from faeces and pseudo-faeces below a mussel farm potentially can have significant ecosystem effects on the biogeochemical cycles of N and P (Fig. 1). The break down of organic matter increases sediment oxygen consumption (Christensen et al., 2003; Giles et al., 2006; Carlsson et al., 2010). As oxygen is depleted, both the benthic community (Vaquer-Sunyer and Duarte, 2008) and nutrient cycles are affected. If the system becomes anaerobic and hydrogen sulphide is released significant reductions in faunal species abundance occur (Vaquer-Sunyer and Duarte, 2010).

Sediment nutrient release is dependent upon the conditions underneath a mussel farm, such as sediment characteristics, current speed and abundance of bioturbators. Increases in sediment nutrient release with mussel farming are common (Baudinet et al., 1990; Hatcher et al., 1994; Carlsson et al., 2009). Impacts on sediment nutrient cycles are also found in shellfish aquaculture of other species (Yuan et al., 2010) with sediment–water NH_4^+ fluxes more than 10-fold the amount of N harvested in clams (Bartoli et al., 2001) and pore water concentrations of NH_4^+ and PO_4^{3-} underneath an oyster farm higher than in the reference area (Mesnage et al., 2007).

Nitrogen can also be removed through denitrification where nitrate is reduced to N_2 gas and lost from the ecosystem to the atmosphere. Stimulation of denitrification often occurs in the early phase of establishment of a mussel farm (Kaspar et al., 1985) because the enhanced deposition of organic matter provides energy to microbes. However, as organic matter increases in sediments and oxygen consumption exceeds the oxygen supplied, then the lack of oxygen has a significant potential to reduce the overall loss of nitrogen. The dominant nitrate reducing process could then be dissimilatory nitrate reduction to ammonium (DNRA) resulting in an enhanced ammonium production (Gilbert et al., 1997). DNRA does not normally have an important role in estuarine sediment but has appeared to dominate in carbon rich areas with low availability of electron acceptors. Lower rates of denitrification are observed underneath mussel farms as compared to reference areas (Baudinet et al., 1990; Christensen et al., 2003).

Increased sediment release of phosphate has also been observed from the sediment below a mussel farm (Baudinet et al., 1990; Carlsson et al., 2009) and phosphorus regeneration was approximately five times higher than the P harvest below a hard-clam farm (Bartoli et al., 2001). Other studies have only found minor effects on sediment P cycling underneath mussel farms (e.g. Hatcher et al., 1994). Variation in the sediment release of phosphorus is strongly influenced by oxygen concentrations as shown by previous studies (Vahtera et al., 2007), which in turn will be dependent upon the deposition of organic matter in faeces and pseudo-faeces.

Increased sedimentation of organic matter and mussel shells changes both the structure and the nutritional value of the bottom sediment below a mussel farm (Chamberlain et al., 2001; Giles et al., 2006; Dumbauld et al., 2009; Ysebaert et al., 2009). This can have an impact on benthic communities also when sedimentation is not connected to lowered oxygen concentrations. Bioturbators provide an ecosystem service by increasing the area where coupled nitrification–denitrification processes can occur (Fig. 1) and their presence are desired. However, decreases in the abundance of organisms (Carlsson et al., 2009) including bioturbators (Christensen et al., 2003) are often found underneath mussel farms.

4. Potential nutrient reductions

The maximum biomass of mussels is determined by the available food, the transport of food by advection, and recruitment success. The amount of mussels that can be harvested in the Baltic Sea and surrounding waters differs greatly (Table 1) and is strongly dependent upon the local salinity, which determines the size of the mussels (Kautsky, 1982). Farms cannot be placed too close to each other, since the mussels need phytoplankton from a larger area than the farm itself (ranging between 7 and 25 ha surface area per ha farm, Lindahl et al., 2005). An area of 800 ha along the Swedish coast of the Baltic Proper has been deemed suitable for mussel farming (Gren et al., 2009).

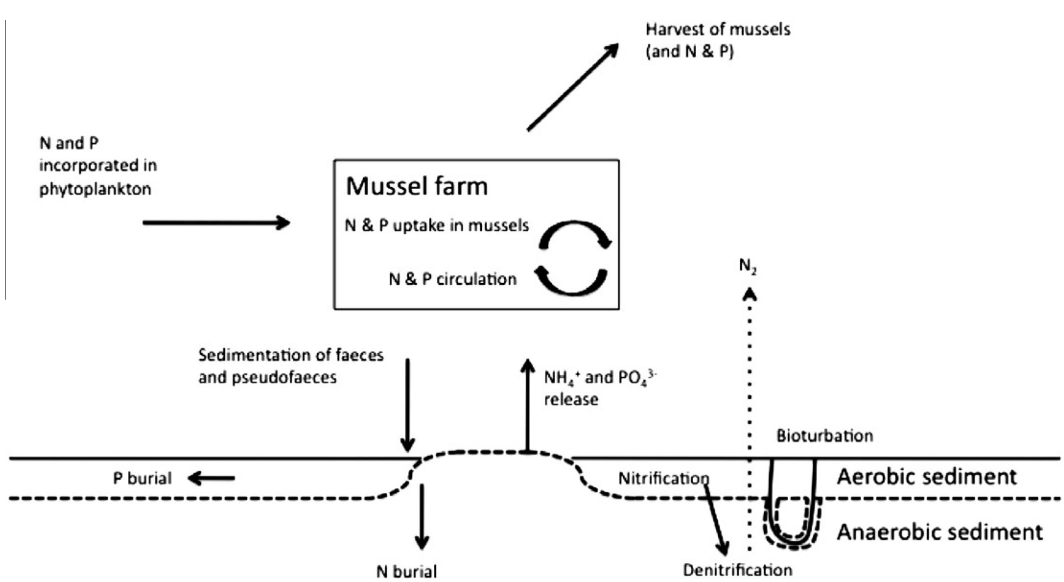

Fig. 1. Potential impacts of a mussel farm on nutrient biogeochemical cycles.

Table 1
Estimated salinity and mussel harvest for different areas.

Area	Salinity (PSU)	Mussel harvest (tonnes ha farm area yr^{-1})
Kattegat	20–30	200–300[a]
Limfjorden	22–32	500–700[b]
Baltic Proper	5–8	40–90[a]

[a] Lindahl and Kollberg (2009).
[b] Jens Kjerulf Petersen, Danish Shellfish Centre, Nykøbing Mors, Denmark, pers. obs. ongoing project.

Table 2
Estimated costs for reduction of nitrogen by different measures.

Measure	Cost
Wetland construction	4–10 € kg^{-1} N[a]
Sewage treatment plant	10–14 € kg^{-1} N[b]
Mussel harvest	21–25 € kg^{-1} N[c]

[a] Weisner and Thiere (2010), cost for 1 kg N reduction means that removal that should have occurred without wetland construction is subtracted from the removal in the wetland.
[b] NV-report 5985 (2009) marginal cost for N-reduction in a sewage treatment plant.
[c] Gren et al. (2009) cost for producing mussels to be used in industry as biogas, animal feed, etc., without reduction by potential income that these enterprises can give.

The potential amount of nutrients that can be removed when harvesting mussels also depends upon the average N- and P-content, which has been estimated to be ca. 1% N and 0.06% P per wet weight mussel (Petersen and Loo, 2004). The potential mussel harvest in the Baltic Proper is in the range of 40–90 tonnes per ha mussel farm per year (Lindahl and Kollberg, 2009), which corresponds to a total potential reduction of 320–720 tonnes of N and 19–43 tonnes of P per year. According to the Baltic Sea Action Plan (HELCOM, 2007) the suggested reductions of the annual inputs of N and P to the Baltic Proper and the Gulf of Finland should be 100,000 tonnes N and 14,500 tonnes of P. If 800 ha of mussel farms are established in the Baltic Proper, then N and P reductions will be 0.3–0.7% and 0.1–0.3%, respectively, of the suggested reductions.

5. Nutrient reduction costs

The costs directly associated with mussel farming are construction costs, labour costs (operational and harvesting), and capital costs. The costs for nutrient reduction measures also depend on the amount of N and P removed during the harvesting of mussels. However, other aspects of nutrient biogeochemical cycles must be considered, not only nutrient removal. We may overestimate nutrient reduction if the deposition of faeces and pseudo-faeces increases the release of N and P from the sediment into the water column or denitrification decreases (Fig. 1). In addition, we may underestimate nutrient reduction if enhanced denitrification occurs or if sediment burial of N and P occurs, which is rarely accounted for. Estimation of the cost for removal of N or P assumes no changes in nutrient biogeochemical cycles in the sediments (Gren et al., 2009) and the studies on enhanced nutrient release described above suggest there is probably an overestimation of the nutrient reduction capacity if only harvesting of mussels is considered.

The production cost of mussels has been estimated to be 21–25 €/kg N in the Baltic Proper (industry mussels) and 33–38 €/kg N (mussels for human consumption) in Kattegat (Gren et al., 2009). If the mussels are large enough for human consumption and not poisoned by harmful substances, and there are market connections, then there are possibilities to sell the mussels on the open market. The income from this enterprise can reduce the cost for amelioration. The options for industry mussels considered in the Baltic Sea to date include selling the mussels as food for chickens or fish, or as a substrate for biogas production (Lindahl and Kollberg, 2009). Another option to make it economically feasible is to develop a system for nutrient trading, where polluters pay mussel farmers to reduce the nutrient concentration in the water. Currently, none of these options are operational.

Compared to other potential measures mussel farming is a relatively expensive measure (Table 2). These calculations show that N-reduction in mussel farms (industry mussels) are 2–5 times more expensive per kg N than N-reduction in sewage treatment plants and wetlands.

6. Conclusions

When filter-feeding organisms are abundant in the environment they have the potential to increase the clarity of water by removing phytoplankton and suspended sediments (Newell, 2004) and mussel farming has been suggested as a mitigation tool to improve water clarity. However, nitrogen and phosphorus excreted by bivalves during digestion and nutrients regenerated from bio-deposits can be used to support further phytoplankton production downstream counteracting the positive effects of phytoplankton removal. The amount of N and P harvested must be compared with modification of biogeochemical cycles, especially the potentially enhanced release of nutrients from the sediment or decrease in denitrification. These adverse effects of mussel farming on nutrient release (Fig. 1) connected to the increased sedimentation of organic material are often confined to a relatively small area underneath the mussel farm. Mitigation by mussels for nutrient removal could be used if enhanced nutrient release from sediments is not a significant factor. For example, if mussel farms are located in areas with greater water depths and the current speed is sufficient, bio-deposits are spread over a larger area without posing the risk of enhanced sediment nutrient release. However, under such circumstances in areas with sufficient water turnover, local impact of the measure is often lost.

In the Baltic Sea we do not support mussel farming as a cost-effective measure of nutrient reduction, mainly due to the potential for enhanced nutrient regeneration and increased nutrient fluxes underneath the farms reducing the effectiveness of nutrient removal by the mussels. The primary focus for nutrient mitigation should be on nutrient reductions from land-based sources before nutrients enter into the coastal zone.

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