Mussel Cultivation

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MUSSELS ARE BIVALVE SHELLFISH (animals with two shells) and, like many other marine organisms, filtrating animals. They live by pumping in the surrounding water and filtrate off particles, mainly phytoplankton, and are considered keystone species in aquatic ecosystems. As the seawater is in continuous motion, new food particles are continuously brought to the mussels even if they are sessile. In the Baltic Sea, both the blue and zebra mussels can be found. The blue mussel is better adapted to the more saline waters of the Baltic (> 4 PSU) while the zebra mussel is found in fresher water environments (< 1 PSU) as can be found in most of the Baltic Sea inlets, such as the Szczecin, Vistula and Curonian Lagoons, the Gulf of Finland and the Gulf of Riga.

Mussels are characterised by annual reproduction. They produce larvae that remain within the plankton for several weeks and are concentrated by wind and water currents in embayments producing high settling numbers. Mortalities during the free-living larvae and metamorphosis stages are high.

Temperature and salinity are the most important environmental abiotic factors. The spawning period lasts from late spring to early autumn if the temperature is above 12° C.

A contribution towards counteracting eutrophication

Introduction

Globally (blue) mussel farming and harvesting is normally pursued in order to produce food for human consumption. The demand is steadily increasing but the main production areas in Europe have reached a level where they can no longer expand due to shortage of suitable farm areas. Thus there is occasionally even a shortage of mussels on the market.[1] Nevertheless seafood mussels cannot be expected to become a major product in the Baltic Sea, as the low salinity level slows down their growth and leads only to small sized mussels.

Mussel farming may, however, be an interesting option for the Baltic Sea Region as one of the few available operational, simple, flexible and cost-effective methods to counteract the negative effects of eutrophication caused by nutrient leakage from agricultural operations, sewage discharges and other human activities. Around 80% of the nutrients discharged into Baltic coastal waters come from diffuse emissions like run-off from forest – and farm land, atmospheric deposition and rural living and cannot be captured from point sources.

Mussels improve coastal water quality as they "harvest" nutrients through their food intake of suspended particles. Mussel farming can therefore be regarded as an open landscape feeding on land, but in the sea. The potential of mussel farming to improve coastal water quality in marine waters is scientifically well known.[2, 3, 4, 5, 6, 7] Numerous pilot studies have proven that the establishment of mussel farms has dramatic effects on water clarity, increasing light penetration and leading to a significant decline in chlorophyll-*a*.[8, 9, 10]

The mussel biomass, i.e. its meat, can be used as seafood (if coming from marine areas), high protein animal feed, as a fertiliser in agricultural operations or as an energy resource for biogas plants. Considering that the production of nitrogen as a fertiliser is an energy demanding and climate negative process and that phosphate is a limited resource on a global scale, the recycling of nutrients is strategic both from an environmental as well as a socioeconomic point of view.

Nevertheless, in the Baltic Sea, mussel farming for nutrient recycling has not gone beyond the pilot stage yet. The main obstacle so far is the lack of economic incentives, which are necessary since no "income" can be generated from nutrient harvesting. Of course, mussel farming should also not be viewed as the "magic bullet" solution against eutrophication as only a limited number of suitable farm sites exist in the Baltic Sea where mussel farming is actually possible. This is due to environmental or economic perspectives and/or because of other uses are already taking place at suitable sites.

Mussels in the Baltic Sea Region

Baltic Mussel Types

Along the Baltic coasts blue mussels (*Mytilus edulis)* and zebra mussels (*Dreissena polymorpha)* are identified as promising biofilters.[11]

BLUE MUSSELS

The blue mussel, *Mytilus edulis,* have smooth, equally "D" shaped, bluish-black shells that are linked together on one side by a hinge. The inside of the shell is pearly violet or white. The meat inside the shell can be a creamy colour, pink or orange. Projecting out from between the shells on one side is a bundle of tough, brown fibres called byssal threads, more commonly known as the beard. Mussels use these fibres to anchor themselves to stationary objects. A grown up blue mussel may reach a size of 7 to 10 cm.

Blue mussels are very common in the cold waters of the North Atlantic and Pacific oceans, which provide the ideal habitat. A scientific debate is ongoing whether the Baltic blue mussel community is made up by *M. edulis*, a related species *M. trossulus*, or a mixture of both. In the Baltic Sea, the brackish conditions and low salinity hamper the speed of growth and the size of this basically marine organism. It is only in the south western part of the Baltic where the blue mussel may reach a size of 4–6 cm. Compared to e.g. the Swedish West coast the growth in the eastern, central and northern Baltic is about one forth, since it takes roughly the double time for a mussel to reach half the size. On the other hand, the meat content is relatively higher due to the thinner shells of the Baltic mussels. In fact, the blue mussel is the most common organism in the Baltic and the whole population has the capacity to annually filter the total water volume of the Baltic Proper!

Figure 1: Juvenile blue mussels.

ZEBRA MUSSELS

The zebra mussel is also a filter-feeding attached bivalve forming dense colonies on various substrates in freshwater and slightly brackish habitats. According to paleontological and geological data, the zebra mussel *Dreissena polymorpha* (Pallas 1771) existed in the Baltic Sea drainage area during the interglacial time[12] but later became extinct and was re-introduced in the early 1800s.[13] Thus it is not an alien species *sensu strictu*, but rather a postglacial re-immigrant.

In the Baltic Sea, the zebra mussel has a relatively high abundance and distribution range in

Figure 2: Zebra mussels.

shallow coastal lagoons, estuaries, gulfs and inlets,[14] i.e. ecosystems mostly impacted by anthropogenic disturbance and land-based nutrient inputs (Figure 3). There, zebra mussels can be found from the upper littoral down to 3–4 m depth, on hard substrates (boulders, embankments, hydrotechnical constructions) and soft bottoms (sand, silt or mud).[15] An especially large biomass and abundance of zebra mussels can be found in the Curonian Lagoon (south-eastern Baltic Sea).

Existing Mussel Farms in the Baltic Sea

As can be seen in figure 3, only a limited number of mussel farm trials have been carried throughout the Baltic Sea.

BLUE MUSSEL TRIALS

The first known trial of farming blue mussels on ropes in the Baltic was carried out in the 1980s at the Askö Laboratory in Sweden. More recently, during the 2000s, a number of small-scale trials have been carried out in Germany (Kiel), Poland (Puck Bay), Denmark (Great Belt area) and Sweden (South and East coast and in the Åland archipelago). They showed that the basic concept of farming mussels on long-lines in the Baltic Sea works and that a net seemed to be the most practical and cost-effective substrate for mussel farming. As a result, three larger trials were launched in the late 2000s, one in Åland and two on the Swedish East coast.[16] These trials tested nets and pipes for flotation.

ZEBRA MUSSEL TRIALS

There are ongoing experiments with cultivation of zebra mussels in Germany/Poland (Oder Lagoon), in Lithuania (Curonian Lagoon) and in Sweden (Lake Mälaren). However there are still only very few data available on cultivated zebra mussel biomass production and filtration efficiency, so most of the information on these topics is derived only from blue mussel trials.

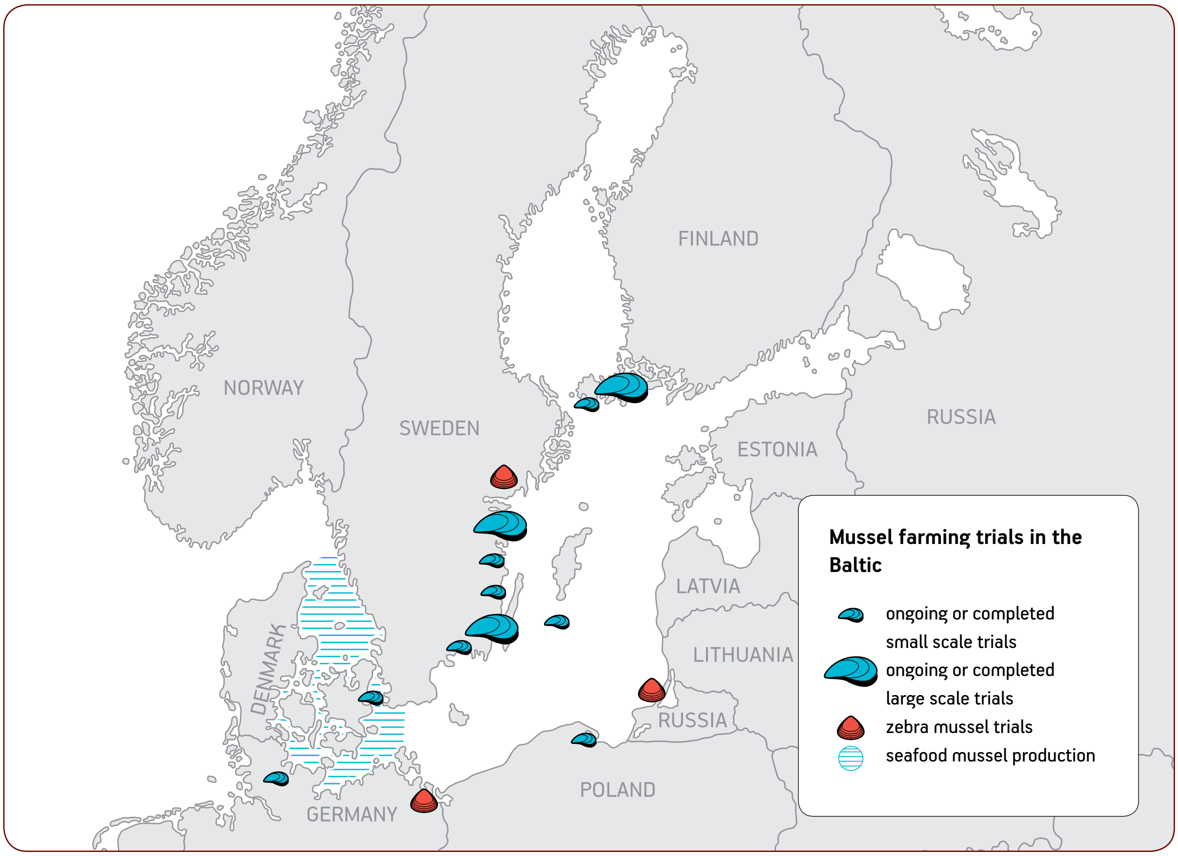
Growth and Biomass of Blue Mussels

In view of the limited amount of farm trials carried out in the Baltic Sea, there is still very limited data on growth and development of Baltic mussel biomass. However, the small-scale trials and experience from the marine areas of the Swedish West coast have provided some information about these parameters for blue mussels.

Many factors affect the growth of a mussel and there can be considerable variation within a limited area. The access of food is determined by the concentration of food in the area as well as the water circulation through the farm (e.g. with which speed food is brought to the mussels). A farming site with large water circulation and high phytoplankton concentration will result in faster growth of the mussels compared to a farm situated in an area with stationary water and containing small amounts of plankton.

Whereas one hectare of mussel farming on the marine Swedish West coast resulted in about 300 tonnes of mussels per hectare, harvested after 1.5 years of growth with about 25 hectares used for phytoplankton production for mussel food,[17] a similar calculation for the brackish Baltic Sea area estimated that maximum 150 tonnes of mussels per hectare could be harvested after 2–3 years of growth and an area of 7.5 hectares used for phytoplankton production. In short: Baltic mussels use

Figure 3: Locations of completed and on-going mussel farming trials in the Baltic Sea.



3 times less food supply area, require a long time to grow and are smaller in size (weight). This is mainly due to the lower salinity level throughout the Baltic Sea. Overall, that is large enough to make nutrient harvesting useful (100–150 tonnes of mussels per hectare) in 2–2.5 years at a good site in the Baltic.

Applications

Mussel use is mainly determined by its size and wet weight. Mussels catch and reuse nutrients and transform these into mussel meat, which in turn can be used as seafood, feed, fertiliser as well as a resource for biogas production.

Although worldwide there is currently no commercial or industrial use for the zebra mussel (*Dreissena polymorpha*) other than in trials for bio-filtration applications, it can be assumed that the same uses associated with blue mussels (with the exception of seafood) will also be possible for zebra mussels.

Lithuanian submariner Case Study

Due to its short and extremely exposed shoreline, the many competitive human activities and the influence of the diluted Curonian Lagoon plume, there are limited possibilities for blue mussel cultivation for remediation purposes along the Lithuanian coastal zone. However, there is an alternative: the zebra mussel *Dreissena polymorpha* in the transitional area of the Lagoon, between the Nemunas river mouth and the Klaipeda strait.

Zebra mussels are known to have been present in the Curonian Lagoon for at least 200 years and they are highly abundant in the central part, from the upper littoral to up to 3 m depths. Their distribution is restricted predominantly by brackish water inflows from the sea, hydrodynamic conditions and availability of suitable substrates for settlement.

The water quality of the highly eutrophied Curonian Lagoon (with a transparency range of 0.3–2.2 m and seasonal chlorophyll a fluctuations of up to 450 µg/l) cannot be sufficiently improved – enough to meet the EU Water Framework Directive requirements – through river basin management alone. Hence, zebra mussel cultivation in the Curonian Lagoon could be a promising additional remediation measure and could serve as a point-source filter reducing nutrient outflow to the Baltic Sea (which amounts to about 43,000 tonnes of nitrogen and 2,100 tonnes of phosphorous annually according to the recent calculations).

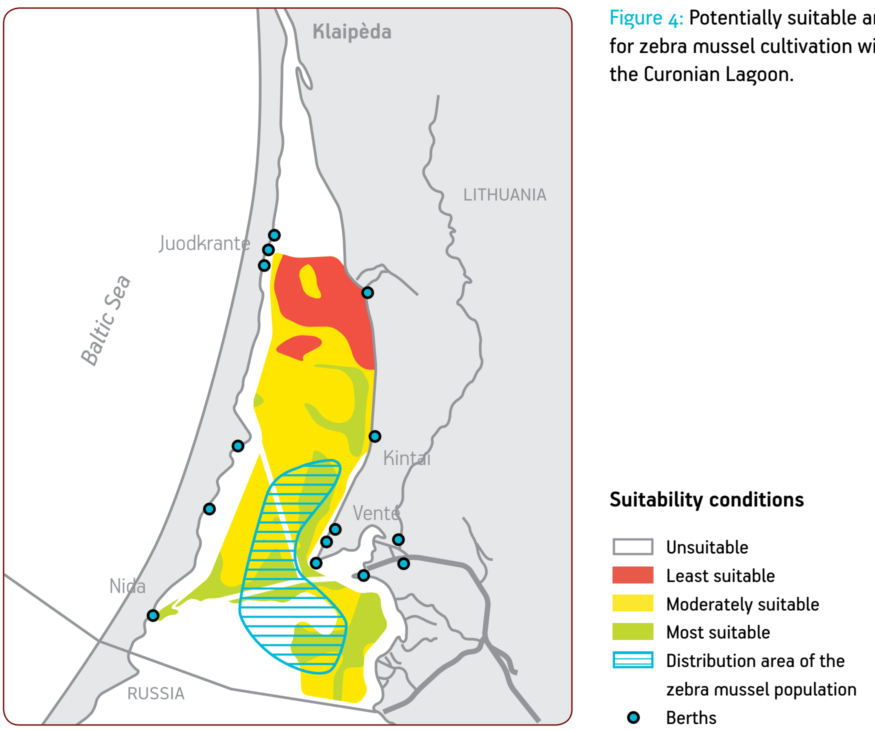


Figure 4: Potentially suitable areas for zebra mussel cultivation within the Curonian Lagoon.

Based on the results of a case study conducted within the SUBMARINER project, the larvae of zebra mussels are available in the central part of the Curonian Lagoon from the late May to late July/early August in relatively high numbers (up to 500 individuals per litre). Therefore it is practical to install farming facilities during this period. Up to 4 kg of mussels per m2 could be harvested after one cultivation season (May–October). The concentration of toxic compounds in zebra mussels is well below the regulatory limits and much lower in young mussels compared to bigger ones. Based on these results and taking into account the specific environmental conditions of the lagoon (shallowness, hydrodynamic regime, pronounced seasonality, ice cover in winter and ice drift in spring), the seasonal zebra mussel farming is suggested as the most appropriate approach for the Curonian Lagoon. The potentially suitable areas for zebra mussel cultivation within the Lagoon are indicated in figure 4.

Zebra mussel farming could also provide a real economic benefit through the utilization of the harvested biomass in feed or fertiliser production. However, still a number of challenges to be overcome related to the lack of aquaculture tradition and experience in Lithuania and the absence of legislative regulatory mechanisms for such an activity. The approach described here for the Curonian Lagoon is also applicable to other Baltic Lagoons (e.g. Szczecin Lagoon), where zebra mussels are present.

Food Products

Most of the global mussel farming is intended to produce mussels for human consumption. The annual world production of mussels today exceeds 1.5 million tonnes, of which half is produced and consumed in Europe. Outside Europe, China, Korea, Taiwan, New Zealand, Chile and Canada are also important producers and exporters of seafood mussels.

Cultured mussels have a number of advantages over wild mussels. They do not touch the ocean bottom and are therefore free of the grit that often spoils the taste of wild mussels harvested from the ocean floor. Since they feed from the nutrient-rich water that surrounds them, they taste sweeter, are plumper, more tender, have thinner shells and yield a higher amount of meat than their wild counterparts.

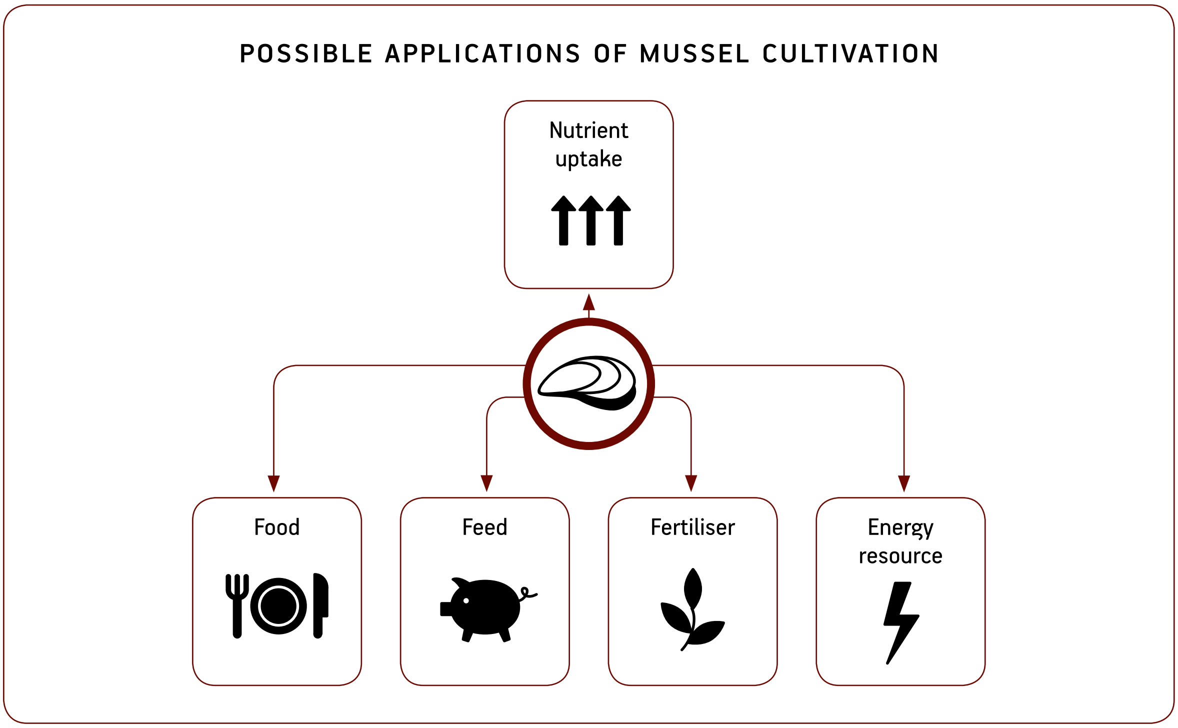
Both wild mussels as well as cultured mussels are available for seafood from the south-western part of the Baltic Sea (with a food mussel farm in operation in the Kiel Bay). With decreasing salinity levels towards the eastern parts of the Baltic Sea, blue mussels become too small to be used for traditional seafood purposes. Thus, this application will not become of major importance within the Baltic Sea Region.

Feedstuff

The blue mussel has a high content of the essential sulphur-rich amino acids methionine, cysteine and lysine, which match the content in fishmeal. They can, when shells are included in the feed, also provide calcium carbonate. At the same time, mussels are an excellent high protein feed for poultry as well as in fish feed and have a fat content of about 8 % (up to 40 % of which are Ω3 long-chain fatty acid molecules).

Measurements have shown that the meat content of Baltic blue mussels is around 22–26 %, which

Figure 5: Applications of mussel cultivation.



is higher than that of Swedish West coast mussels. This is another advantage of their use for feed production. In zebra mussels, meat content is about 16 % of dry weight on average. However, younger mussels (1 year age or less) show a higher percentage (up to 40 % of dry weight).

Since mussels are at the second step of the marine food chain, the use of mussels instead of fish for feed production also is of large ecological importance at a time when many fish stocks are overexploited on local, regional and global scales.

So far one sample of Baltic mussels (Hagby Harbour, Kalmarsund) has been analysed for use as feedstuff. This single result showed that the non-separated meat/shell meal mixture could, without further processing, be used as a high protein feedstuff and calcium source for egg-laying hens. Other feed options currently being tested are the use of mussel meal from fished mussels from the south-eastern part of the Baltic to be used in the aquaculture and breeding experiments of rainbow trout and arctic char, carried out at Rymättylä Aquaculture Station in southern Finland and at Kälarne Research Station in northern Sweden respecteively.[18] In Lithuania, the cast of zebra mussels and their shell deposits are already informally gathered from the shore and used as chicken feed additives by local farmers.

Fertiliser

The nitrogen, phosphorus and potassium levels in mussel biomass make it suitable for use as a fertiliser for grain cultivation.[6] The easily decomposed shells have a liming effect, i.e. they increase pH in acid soil, and a number of micro-nutrients such as selenium, copper and zinc are added to the soil. Discarded mussels used as fertiliser on farmland have given good results and are of special interest for organic farmers who cannot use commercial fertilisers. Studies have shown crop increases from 25 to 50 % compared to land that was not fertilised.[19]

ADDITIONAL POINT

Contaminants in Baltic mussels for use as feedstuff and fertiliser

An analysis carried out with blue mussels farmed from the Kalmarsund area (Sweden)[1] showed that concentrations of possible organic contaminants in the soft tissues and shells were safely below the regulatory limits applicable in Sweden for the use in feed or fertiliser.

According to the Lithuanian EPA monitoring data, in zebra mussel tissue samples from the Curonian Lagoon the concentration of the toxic compounds such as DDT, HCH and heavy metals was also significantly below the maximum allowable concentration.

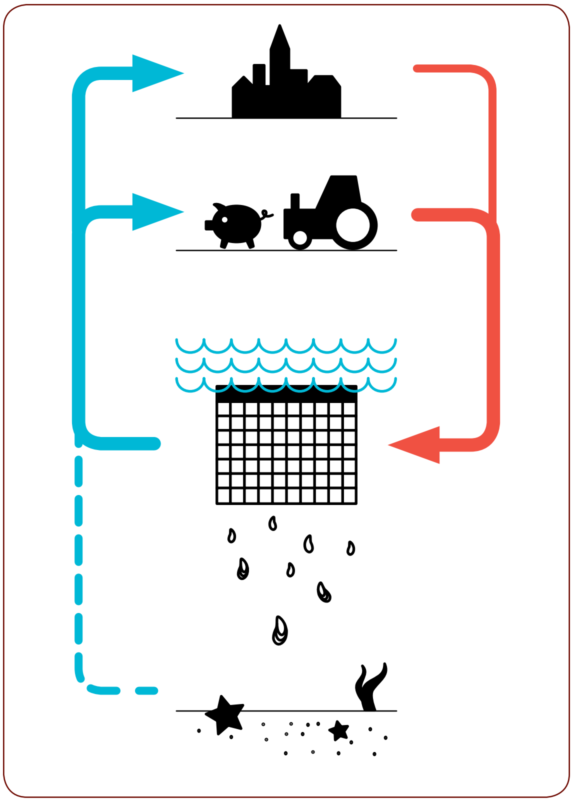
Table 1: Selected elements and substances in farmed and wild blue mussels from the Kalmarsund area on the Swedish Baltic coast, in relation to regulatory limits. Data from Nilsson, 2009[20].

	Farmed	Wild	Feed Limit	Fertilizer Limit
	(mg/kg dry weight)			
Elements				
Arsenic (As)	4.05	7.17	17.05	–
Cadmium (Cd)	0.85	2.53	2.27	2
Cupper(Cu)	7.72	11.60	–	600
Mercury (Hg)	0.05	0.11	0.57	2.5
Lead (Pb)	0.79	1.97	11.36	100
Polychlorinated biphenyls				
Sum PCB(7)	0.0142	0.0066	0.227	0.4
Chlorinated pesticides				
Hexachlorobenzene	<0.001	–	0.011	–
o,p-DDT	<0.001	–	0.057 (DDT)	
Dioxins and furans				
sum WHO-PCB-TEQ	1.12*10–6	–	5.11*10–6	–
Brominated flame retardants				
4-nonylphenol	<0.010	–	–	50
Toxaphene (sum Parlar 26,50,62)	0.000075	–	0.023	–

The mussel biomass had more or less the same effect as the same amount of manure fertiliser. Since the mussels live in saline water and ions of both sodium and chloride have a negative effect on some crops like potatoes, it is important that the water inside the mussels is drained before the remainder is spread on the farmland.

Other obstacles to the increased use of mussels as fertiliser are the bad smell generated during the deterioration of the mussel biomass as well as the fact that agricultural farmers only need the mussel fertiliser during certain periods of the year. However, composting experiments with straw or bark have shown that it is possible to produce a mussel fertiliser that can be stored and that shortens the period of bad odour. The bark compost also has a nice look with its dark bark and shiny shell pieces. Therefore it is anticipated that gardens and greenhouses could be a future market for such compost products.

Figure 6: The concept of "Agro-aqua recycling" was introduced by Haamer et al.[3]



Biogas Production

A study[21] has shown that anaerobic biodegradation is a feasible technique for the solubilisation and methanogenesis of blue mussels and that seeded batch reactors of low salinity (<10 g/l) can be employed to solve the problem of treatment and disposal of mussel wastes.

However, a sustainability evaluation of ecological engineering methods to recover biomass nutrient resources from the Baltic Sea[22] came to the conclusion that Baltic mussels are currently not suitable for biogas production due to a too high energy demand for harvesting, transportation and biogas production, which would result in a too low net energy balance.

Mussels as biofilters – nutrient harvesting

Probably the most important function of mussel farming in the Baltic Sea has to be seen in its ability to improve coastal water quality in marine waters. The idea of farming blue mussels in order to actively reduce the amount of phytoplankton and thereby the negative effects of eutrophication was introduced by Haamer.[23] In his concept, the increasing nutrient and plankton amounts in coastal waters are seen as a resource, which should be recycled to land and reused. In this concept, the farmed mussels should be brought to land in order to maximise the positive effect on the environment, i.e. the amount of harvested and recycled nutrients.

BLUE MUSSELS

Based on the small-scale trials and the experience from marine areas of the Swedish West coast, it is estimated that a nutrient harvest in the ranges given in table 2 should be possible from a given blue mussel farm site.[6]

Table 2: Nutrient harvest potential estimates for farmed blue mussels in the Baltic Sea.[16]

Coastal area	Biomass per longline or pipe (kg/m)	Estimated harvest per ha of farm (tonnes/ha)	Mussel meat content %	Estimated amount N (tonnes/ha)	Estimated amount P (tonnes/ha)
Southern Baltic	35	150	30	1.8	0.12
Northern Baltic	25	100	30	1.2	0.08

PUTTING IT INTO PERSPECTIVE

The Swedish share of the Baltic Sea Action Plan corresponds to an annual reduction of nitrogen of 21,000 tonnes and phosphorous by 290 tonnes, which means that about 14,000 ha of mussel farms should be harvested each year if the whole share should be carried out by mussels. This is of course far from realistic. A rough estimate is that mussels may be able to remove 2–3 % of the Swedish share, which is still substantial in relation to other treatment options. Note that both nitrogen and phosphorous are recycled in parallel by the mussels.

ZEBRA MUSSELS

Although the establishment of zebra mussels and subsequent retention of nutrients has likely counteracted the effects of eutrophication in many inland waters, few studies have quantified this. One study[24] recently showed that zebra mussels can greatly reduce algal biomass and negate or mask the increasing effects of nutrient pulses of phosphorus up to 150 mg/l on algal biomass. Several studies have therefore addressed the potential use of zebra mussels in water quality remediation or sewage sludge treatment and some pilots have also been carried out in the Baltic region. However there are still very few data available on the cultivated zebra mussel biomass production and filtration efficiency.

Competence Centres in the Baltic Sea Region

Table 3: Institutions involved in research and development of blue and zebra mussel farming within the Baltic Sea Region.

Institution or corresponding	Country	Mussel related activity	Web address
Askö Laboratory	Sweden	Marine research and education	www.smf.su.se/asko-laboratory
County Board of Östergötland	Sweden	Pilot project on growth of mussels	www.lansstyrelsen.se/ostergotland
East Sweden Energy Agency	Sweden	Project Baltic Eco Mussels	www.energiost.se
County Board of Kalmar	Sweden	Mussel farming for improving water quality	www.lansstyrelsen.se/kalmar
Göteborg Univ,.Dep. of Biol. and Env., Sciences	Sweden	Research and education on mussel farming as an environmental measure	www.bioenv.gu.se
Swedish Rural Economy and Agricultural Soc.	Sweden	Development of mussel meal production	www.hush.se
Novia Univ. of Applied Sciences	Finland	Project Baltic Eco Mussels	www.novia.fi
Husö Biological Station	Finland	Research and education	www.abo.fi/huso
The Åland Government	Åland	Development of mussel farming under Baltic conditions	www.ls.aland.fi
Klaipeda University	Lithuania	Research and development of zebra mussel farming	www.corpi.ku.lt
University of Gdansk	Poland	Development of mussel farming under Baltic conditions	www.ocean.ug.edu.pl
Sea Fisheries Inst. in Gdynia	Poland	Development of mussel farming under Baltic conditions	www.mir.gdynia.pl
University of Szczecin	Poland	Research and development of farming zebra mussels	www.us.szc.pl
Ernst Moritz Arndt University of Greifswald	Germany	Research and development of farming zebra mussels	www.uni-greifswald.de
Leibniz Institute for Baltic Sea Research (IOW)	Germany	Mussel farming research, development and education	www.io-warnemuende.de
Institut für Meereskunde in Kiel	Germany	Mussel farming research, development and education	www.ifm-geomar.de
Coastal Research & Managemant	Germany	Mussel farming research and development	www.crm-online.de
Aarhus University, Dep. of Marine Ecology	Denmark	Research and development of mussel farming as an environmental measure	www.au.dk
Danish Shellfish Centre	Denmark	Research and development of mussel farming as an environmental measure	www.skaldyrcenter.dk

Technology

The Basic Principle

The basic principle of mussel farming is very simple: male and female mussels spawn when the water temperature in spring reaches 10–12 °C and enormous amounts of eggs are released and fertilised resulting in pelagic larvae (open water drifting) called veliger. After roughly a month, normally at around midsummer, the larvae have reached a size of about 0.3–0.4 mm and will settle on a substrate and continue their life in a sedentary mode. In the sea there is most often competition for spaces to settle on and most hard surfaces are covered with algae, barnacles, mussels and other marine organisms.

The mussel farmer offers the mussel larvae a suitable substrate to settle on in the form of a rope, band or net. At a good site many thousands of larvae may settle per meter of rope or band. When growing, the numbers of mussels will be reduced and drop off due to limitations on the available space on the rope or band. At a marine site the number of mussels (40–70 mm in size) can, after 15–18 months at harvest, be about 500 per meter while in the Baltic the number of individuals (15–30 mm in size) after 18–30 months is about is 1,000–1,200.[25]

Cultivation Technologies

Within the last years, several projects have been carried out in the Baltic Sea to analyse and test different mussel cultivation technologies. Small-scale trials have included ropes, curled ropes, bands, net stockings and nets to be tested for settling of the mussel larvae and the following growth of the mussels. Results have shown that the basic concept of farming mussels on long-lines in the Baltic works and also that a net seemed to be the most practical and cost-effective substrate for farming.[25]

Mussel clumps that have settled on nets or lines over several years may break off and live on the sea bottom thus creating additional hard substrate for more mussels to settle. Although the use of submerged horizontal fishing nets has shown quite efficient settlement during field experimental studies, commercial cultivation mussels on horizontal net structures seem to be difficult to maintain and harvest.[26]

Therefore, other methods of cultivating mussels such as vertical line systems and single long tubes carrying vertical net collectors (“Smartfarm”) should be considered. Both systems are used all over the world including the Baltic (e.g. Kiel Fjord) for culturing seed and mussels.

Vertical mussel farm systems utilise the water body efficiently, maintaining high filtering areas and they are technically more adapted for commercial cultivation. This method is also more suitable

ADDITIONAL POINT

Is mussel farming really “farming”?

It could be pointed out that “farming” a mussel is an incorrect expression since you do not have to add any seeds, larvae or spat. Further, you do not add any fertiliser or feed. The blue mussel and its food intake are based on entirely natural resources regardless of whether it is wild or “farmed”. The bands, ropes, nets or other substrate which is offered to the mussels to settle and grown on can be compared with the concept of ranging wild deer by fencing an area for example. Thus, it is therefore suggested that “mussel farming” instead should be called “mussel ranging”.

for husbandry and harvesting using specialized machines. Permanently moored units can reduce labour costs significantly.

In Sweden, long-line farming is the most common method for mussel production. The mussels are mostly grown on vertical suspenders attached to horizontal long-lines (figure 7).

IMPORTANT ASPECT FOR THE BALTIC SEA REGION

Based on the results of three large tests on Åland and on the Swedish East coast[16], it can be recommended to use a mesh size of around 150 mm and a net rope thickness of 10–12 mm. PVC pipes for flotation work well but require special equipment for handling and maintenance. For large scale farming, it is strongly recommended to buy equipment from experienced companies instead of using homemade solutions. However, the existing experience is too limited to be able to provide general one-size-fits-all solutions. It might well be that different parts of the Baltic require different technologies.

Figure 7: Schematic principle of a mussel farm unit using a net for settling of the mussel larvae and growth of the mussels and a pipe for flotation.

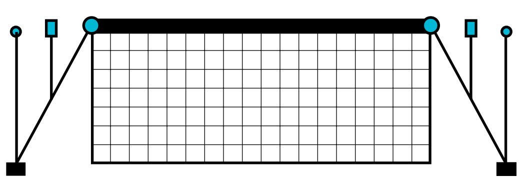


Figure 8: Mussel farming on a net.

Ice and Ice Drift

The large mussel farming trial in Kalmarsund, Sweden was extensively affected by the heavy drift ice in the winters of 2009–2010 and 2010–2011, with a lot of damage after the first winter and a complete break down during the second winter, although measures had been taken after the first winter in order to improve ice performance.

The experiences learned were used for designing moorings and buoys for another mussel farm trial at Kumlinge in the eastern part of the Åland archipelago. This farm survived well during the hard ice winter of 2010–2011 and is still functioning in 2012, which demonstrates that technical improvements are an important part of successful mussel farming in the Baltic.

Concerning ice and mussel farming in the Baltic, it can be concluded that during winter the lowering of farm units below the surface or a complete subsurface farming is a necessary future development. The farm methodology otherwise used so far was not good enough to survive the harsh ice conditions that may occur in the Baltic now and then.

An interesting observation made during the termination of the large scale farm trial in Hållsviken, south of Stockholm, Sweden was that the anchor lines were completely covered with mussels down to about 15 m in depth. This can serve as an indication that lowering farm units may not necessarily result in reduced settling, slower growth or smaller biomass of mussels.[16] The two leading companies selling mussel farm equipment in Europe, Smartfarm and Kingfisher, are both at present developing equipment to enable lowering of the farm units below the sea surface and the ice.

Thus, assuming that ice conditions can be handled (e.g. through lowering the pipes and nets), the use of nets as substrate for settling and farming seems to work well for mussel farming in the Baltic.

Harvesting Technologies

The net farming technology that was used for the trials on the Swedish East coast requires, as do other similar systems, special equipment for harvesting. In the case of harvesting from nets there is a "farming catamaran" on the market that brushes off the mussels while the nets still hang in their pipes. The mussel biomass is then pumped on board and emptied into large sacks. This is a simple and effective system but requires quite a number of farms to harvest in order to be profitable.

There are also other farming technologies that rely on lifting the nets or farming substrates onto a harvester. As Baltic mussels have rather weak threads for attachment, there is a risk that quite a lot of the biomass may be lost using this technique.

Regardless of the method used, harvesting requires a steady work vessel with a large working deck and a powerful crane and winch of good capacity. Further, capacity to bring the harvest ashore as well as an infrastructure in the form of a dock, loading crane and transportation is necessary. Depending on the further use of the harvested biomass, it may be necessary to have short transportation/handling time in order to keep the mussels fresh and alive.

Environmental Assessment

Environmental Impacts

While their environmental preferences differ, there does not appear to be any significant difference in the environmental impacts from cultivating blue and zebra mussels. Important differences will be found in the environmental impacts as a result of the type of technology used for cultivation (e.g. vertical line systems, single long tubes, other) and the characteristics of the cultivation site (e.g. shallow, protected lagoon versus exposed, coastal site).

WATER QUALITY

In waters adjacent to a mussel cultivation area, bathing water quality is expected to improve as a result of increased water transparency resulting from mussel filter feeding activities. Mitigation against eutrophication is expected to occur as a result of nutrient removal.

There are also unfavourable impacts on benthic communities and on the biogeochemical cycling of nutrients immediately beneath the cultivation site. Increased sedimentation of organic matter from faeces is expected to increase benthic sediment oxygen uptake, which can lead to local oxygen depletion events and ultimately have a negative impact on the mussel production.[27] Increased sedimentation and sediment oxygen uptake can also lead to decreases in abundance and biodiversity of benthic communities as well as a deterioration of food web interactions between phytoplankton and zooplankton communities.[28]

Generally, excessive negative effects can be avoided if the sediment surface stays oxygenised, which also allows for the natural denitrification processes to continue. The denitrification is important as it leads to the transformation of different nitrogen substances, such as ammonium, into biologically inactive nitrogen gas.

In this context it should be mentioned that it is comparatively easy to monitor the effect of the organic sedimentation from a mussel farm on the benthic biogeochemical conditions and ecosystem.

Table 4: Overview of mussel cultivation impacts on environmental objectives and priorities.

Environmental Objective	Environmental Priority	Mussel Cultivation	Comments
Water quality	Bathing quality	●	
	Water transparency	●	
	Eutrophication	●	
	Biogeochemical cycles	■	Beneath the site
Habitat / Species protection	Food web dynamics	■ ?	Phyto-zooplankton interactions
	Biodiversity	■ ◐	Benthic communities & anoxia
	Benthic habitats	■ ◐	Anoxia versus shelter, food supply
	Bird habitats	●	
	Fisheries	●	
	Marine mammals	◧	Depends on location
	Marine noise		
Coastal protection	Coastal morphology	◐	
	Scenery	◧	Depends on setup
Climate protection	CO_2 Emissions reduction		

● strongly supportive
◐ moderately supportive
■ strongly not supportive
◧ moderately not supportive
○ neutral
? gaps in information;
blank not applicable

The most cost-effective and least time-consuming method is probably using a sediment profiling camera and related analysis technique.[29] Even more precise methods[30] are available for measuring the changes in benthic nutrient fluxes caused by the rich bio-sedimentation below a mussel farm and these may also be used in order to judge the overall effects of mussel farming as a remediation tool.

The extent to which these impacts counterbalance the positive effects the mussel farm can have on water transparency and nutrient removal adjacent to the site is still under debate.[28, 31, 32, 33]

HABITATS

Mussel farms may have an increasingly favourable effect on pelagic and surface biodiversity for fish and bird populations since they may act as floating reefs. On the other hand, the location of the mussel farm should take into account any migration routes of marine mammals and their potential to become entangled in a farm site or otherwise disturbed.

COASTAL PROTECTION

Mussel farms may modify local water movement, absorb energy and provide a form of coastal protection for vulnerable coastlines. The visual impact of mussel farm can however be a concern for local communities, in particular if the setting is particularly scenic. This very much depends on how the mussel farm is configured on the surface.

Suitable Sites

Careful site selection is essential in order to achieve sustainable mussel farming. According to existing

Figure 9: Examples of worst (*left*) and best (*right*) case scenarios for a mussel farm's visual impact. In the future, mussel farms will most likely be lowered subsurface, with negligible impact on the scenery. Pictures by Jens Kjerulf Petersen (*left*) and Odd Lindahl (*right*).

knowledge and experience with farming mussels in general and especially in the Baltic Sea, the selection of a farming site for blue mussels should be based on the following criteria:

HYDROGRAPHICAL FACTORS

- Small to moderate water currents
- No or infrequent occurrence of drift ice in winter
- Water depth of 10–30 m
- Salinity should not go below 4 PSU
- Normal bottom water exchange in order to avoid low oxygen benthic conditions

BIOLOGICAL FACTORS

- Good to normal occurrence of mussel larvae during the settling period
- Good to normal occurrence of phytoplankton (mussel food)
- Need to take marine mammal migration routes into account

LEGAL / PRACTICAL FACTORS

- The site must be in accordance with general and local regulations on area use
- Site area should be 1–10 ha
- Protection from heavy seas
- Access to the site during normal weather conditions
- No discharge or other source of harmful contaminants in the close surroundings
- No interference for waterways and only minor interference for recreation activities
- No or minor interference for fisheries
- No or minor to moderate interference for residents and visitors

These criteria need to be adjusted when applied to zebra mussel farming site selection, mainly since zebra mussel cultivations are restricted to enclosed coastal areas (lagoons or inlets). Therefore, they should also consider:

IMPORTANT ASPECT FOR THE BALTIC SEA REGION

Overall, mussel farming as part of an integrated management plan that includes remediation measures addressing nutrient inputs at their source shows promise. What is clear for the prospect of Baltic Sea mussel farming operations is that careful site selection, use of appropriate technology and implementation of appropriate integrated management measures are keys to converging on an environmentally acceptable solution.

Furthermore, mussel cultivation as part of an integrated aquaculture system will have positive impacts by recycling nutrients and effectively treating waste effluent emanating from fish aquaculture (see "Sustainable Fish Aquaculture" Chapter).

- Water currents suitable for effective young settlement and particulate matter uptake, not exceeding 2 m/s
- Much lower water depth (e.g. for the Curonian Lagoon the suitable water depth is considered less than 2 m due to shallowness of the zebra mussel natural habitats).
- Salinity should not exceed 1.5 PSU with no or minimum abrupt salinity fluctuations

It is presently not possible to make a reliable estimate of how many sites and how big the total area that may potentially be available for mussel farming along the Baltic coasts and that meets the criteria given above. For blue mussels the possibility of utilising areas used for wind power generation may be an additional possibility, especially in view of the technical possibility of lowering the mussel nets. This concept should be further explored.

Socioeconomic Aspects

Costing the Nutrient Removal Effect

As a relatively new venture, mussel farming for nutrient removal is still characterised by a lack of available data with respect to production costs, mussel sales options for human or animal consumption or different growth conditions.

So far only one study has been undertaken estimating the value of mussel farms for combating eutrophication[34] by comparing it with costs related to alternative abatement measures such as a) increasing cleaning at sewage plants b) buffer strips c) wetland construction and d) cultivation of catch crops. The "value" of mussel farming as an abatement measure arises then from possible cost savings obtained by replacing other measures that have higher cleaning costs with mussel farming.

The study applied the replacement cost method to four areas in the Baltic Sea with different salinity levels resulting in four different scenarios: mussel farms with and without mussel sales options and with high and low mussel growth rates and meat content (nutrients) in the mussels. The study showed a strong relationship between the marginal cost for nutrient removal and these factors: Costs highly dependent on the mussel growth rate, which in turn is strongly connected to salinity. Connected to this is the ability to market the mussels as high-priced seafood or as less valuable products such as feedstuff or fertiliser.

In the given cases this meant that no marginal cost for nitrogen removal occurred along the Swedish West coast when the mussels were sold as seafood. The estimated marginal cost was about € 23 per kg of nitrogen removed when the mussels were used for feedstuff, whereas it was about € 35 per kg of nitrogen removed when only nutrient removal was valued and the harvested biomass was given no commercial value.

Of course the marginal costs are also affected by the choice of mussel farming technology, though in the given study only long line technology was considered.

Table 5: Estimated marginal costs using mussel farming for nitrogen and phosphorous harvest along the Swedish coasts. Data from Gren et al.[34] (US-$ converted into €.)

	Salinity level	€/kg nitrogen	€/kg phosphorus
Skagerak/Kattegat		0–32	0–323
Öresund Strait		0–36	0–361
Southern Baltic		6–34	61–338
Northern Baltic		13–77	131–769

The same author of the above quoted study is currently involved in further developing cost estimates for mussel farms in the Baltic within the parallel running flagship project "Aquabest". Results are expected to be available in spring 2013.

Cost Factors in Mussel Farming

Table 6 shows the distribution of the various costs elements involved in building up and running a seafood mussel farm with a production capacity of 100 tonnes/year. It is based on cost estimates of a classical farm in western coastal areas of the Baltic Sea. The costs may of course differ quite substantially in other areas further eastwards and offshore mainly due to different technology needs (i.e. lowering nets in order to prevent ice damage).

In the table only a price is indicated if the mussels can be used for human consumption. This is indeed a growing market and high prices may be achieved also in future due to limited farming capacities to meet worldwide demands.

However, with Baltic Sea mussels mainly serving the potential market of feedstuff and fertiliser, it would be interesting to have an indicative price for these products. At the time of writing this compendium such price was not possible to be given. It can, however, be assumed that with growing demands for organic food (and related feedstuff) as well as an enormous market potential for fish meal the price

Table 6: Estimation of costs for a 100 tonnes production unit for food mussels.[35]

Equipment and other items	**Investment costs (€)**	**Depreciation (Years)**	**Annual cost (€)**
Longlines (5000 m)	5,000	5	1,000
Anchors and moorings	5,000	5	1,000
Markings	8,000	5	1,600
Buoyancy	15,000	5	3,000
Socks	2,400	1	2,400
Collectors	500	5	100
Vessel	150,000	5	30,000
Facilities on land			20,000
Machinery	45,000	5	9,000
Staff			125,000
Total costs	**225,900**		**193,100**
Estimation of profit		**€**	
Target price / kg of mussels		2	
Turn over of 100,000 kg		200,000	
Annual profit		7,500	

for such products to be developed from mussels may increase substantially in the future to come. In such case the cost and/or price, which would need to be paid for the nutrient removal, services of mussel farming could either be lowered or the business would simply become more profitable allowing for further (private) investments in development.

PUTTING IT INTO PERSPECTIVE

Despite these large variations mussel farming in all four scenarios was shown to cut costs in meeting stringent environmental targets. Calculated costs savings ranged from € 20–138 million.
Even more – when comparing the marginal cleaning costs of mussel farming with those of 20 alternative abatement measures in 24 different drainage basins of the Baltic Sea, it could be shown that mussel farming has a positive value for a large range of nutrient reductions.[28]

Political Strategies

Since mussel farming in general is a form of aquaculture, all political strategies and regulations related to the issue of sustainable aquaculture in the course of the EU's Common Fishery Policy apply to mussel cultivation as much as to fish aquaculture (see related chapter). It may be added that non-organically produced feed ingredients and thus also the non-organic share in fish meal was supposed to be banned by now through an EU Regulation (EEG 2092/91 and 1294/2005), but was subsequently changed in spring 2008 due to the difficulties of finding organically produced feedstuff containing enough of the amino acid.

The question is to what extent political strategies are in place, which support mussel farming as a compensating measure for nutrient discharges causing eutrophication. So far HELCOM does not list "mussel cultivation" as one of such measures (see also background chapter of this compendium). Nevertheless, the idea is already under discussion on the Åland islands. The Ålandic water act with its so-called "improvement surplus" allows fish farmers to increase their production when implementing compensation measures and the Åland government is further investigating this possibility within the Aquabest project. The need for the promotion and evaluation of mussel cultivation as a tool to reduce nutrients in the Baltic Sea and the Swedish West Coast is also already explicitly mentioned in the most recent Swedish Governmental White Paper 2010 "Measures for a Living Sea", which includes many aspects of the Maritime Policy Bill 2009, where the development of mussel farming on the Swedish East, South and West Coast was already mentioned. Moreover governmental grants for local water management projects improving the marine environment can also be used for such mussel cultivation measures. At present (autumn 2012), the design of a regulatory framework for environmental mussel farming is under development in Sweden, with the aim of being put into force in 2014.

REGIONAL CASES

Already by 2004 the small town of Lysekil (South West Sweden) managed to interpret the EC sewage directive in such way that the nitrogen removal of a sewage treatment plant could be replaced by mussel farming. The community bought this service from a mussel farming enterprise, which ensured that the nitrogen removal would take place. The cost of € 160.000 for the Lysekil Community was far below the costs related to the construction and running of a traditional nitrogen removal step within the sewage plant. On top current monitoring figures show that the mussel farm achieves almost 100% N-removal as opposed to the 70% actually requested by the EU directive. And even more so – also phosphorous is recycled back to land at no additional cost. However, due to some wrong conditions in the business plan the mussel farming enterprise went bankrupt and the project could not be completed.

Furthermore an interesting coupling, which has – however – not yet been applied for marine uses such as mussel cultivation, is to link rural development programmes to measures affecting eutrophication. Under the existing European agricultural environmental aid programme (EEC 2078/92 and 1257/1999) support has for instance been given for the establishment of wetlands, spring cultivation and catch crops in order to decrease nutrient released from farmland to the environment (see also background chapter). So far, however, this programme has been specifically designated only for farmland and does not include "farm water", i.e. aquaculture operations in the coastal zone.

Legal Aspects

Legal considerations relating to the start of a "mussel farm" in the Baltic Sea may differ substantially according to:

- Where the mussel cultivation is planned (country, region, municipality / coastal zone, territorial zone, EEZ) – and –
- What are the products of the mussel farm (i.e. human consumption vs. feedstuff / fertiliser; environmental service / nutrient removal)

Other aspects to be considered in approval procedures for mussel cultivation are:

- the Council Regulation (EC) No 708/2007 concerning use of alien and locally absent species / often requiring an environmental risk assessment to be carried out
- the Council Directive 2006/88/EC dealing with the control and prevention of diseases in the course of mussel farming

SWOT Analysis

STRENGTHS

- Environmentally friendly and flexible tool for improving eutrophic coastal waters by removing nutrients and improving water transparency, while at thee same time sustainably producing valuable marine protein that can be used in feeds and valuable fertilisers, especially for organic farmers
- Mussel farming is probably relatively cost-effective compared to other measures of combating eutrophication
- Utilises naturally occurring resources and returns discharged nutrients back to land in the form of valuable protein
- Regionally produced mussel meal can replace fish meal, hence contributing to the improvement of fish stocks
- Functioning as a floating reef, a mussel farm can lead to increased local biodiversity and suitable conditions for fish fry sheltering and feeding
- Potential to enhance the local small-scale recreational fishery
- Potential to create new jobs in rural coastal areas
- Areas used for wind and wave energy production may also be used for mussel farms
- May be a useful pedagogic tool for teaching environmental engineering

WEAKNESSES

- The brackish Baltic is not an ideal area for growing blue mussels due to the low salinity, which slows down growth and limits the size of the mussels
- May have negative environmental impacts on benthic bio-chemical processes and fauna below a farm
- Open coasts are too exposed for a mussel farm except if farms are lowered below the surface
- Mussel farming for environmental measures in the Baltic will be dependent on the mussel farmers being compensated for the ecosystem service provided
- Harsh conditions (severe winters and storms) may threaten to physically destroys the farms

OPPORTUNITIES

- Growing European and regional trends to combat eutrophication (e.g. EU Directives, HELCOM)
- Demand from organic farmers and aquaculture enterprises for sustainable feed
- Growing demand for improving coastal water quality
- Growing demand for developing innovative work opportunities for the coastal region population
- There are few other operational measures which can recycle nutrients from the coastal water back to land and also reuse them
- Development of offshore wind energy offering possibilities for combined installations

THREATS

- Mussel farming requires access to suitable farming sites, which may become increasingly difficult to find in coastal areas as spatial conflicts intensify
- Unclear political decision-making regarding how ecosystem service compensation should be performed and who will pay for the remediation
- Resistance of local populations to the new use of "their" coastal waters, regarded as navigational obstacles or ruined views
- Lack of complete consensus within the scientific community on the value of mussel farming as a measure to improve coastal water quality in the Baltic

Knowledge Gaps

There are still a number of knowledge gaps concerning mussel farming in the Baltic Sea, the most critical of which are:

- Assessment of legislation issues related to the implementation of mussel farming for water quality remediation in the different Baltic countries.
- Experience with submerged mussel farming technologies under Baltic conditions as well as technologies – different from the current longline technologies – more suitable for offshore cultivations
- More empirical research needed on growth of mussels, nutrient concentration under different physical environmental conditions
- More experience with harvesting and logistics of large-scale operations of mussel farming for remediation under Baltic conditions
- Possible locations of mussel farms from a large scale perspective
- What is the cumulative ecological impact on the Baltic coastal ecosystem of bio-engineering measures like nutrient recycling through farming and harvesting of mussels?
- What are the consequences for nutrient regeneration and biogeochemical cycling arising from increased sedimentation and sediment oxygen uptake in the less saline, eastern Baltic?
- Depth of knowledge on the economics of environmental mussel farming in the Baltic Sea.

Conclusions

Mussel farming has the potential to be a sustainable means of combating eutrophication provided it is part of an integrated management plan which includes remediation measures addressing nutrient inputs at their source and recycling of nutrients by using mussel harvest for feed production and fertilizer. Furthermore, there is a need to address at a political level, the issue of compensation for ecosystem services.

Given the above, mussel farming may become a new commodity and a commercially promising area for entrepreneurship, creating new businesses and jobs in rural coastal areas.

Beyond environmental remediation, there is a growing interest in using Baltic mussels for feed production and fertiliser. A risk assessment of farmed mussels from the Kalmarsund area in Sweden has clearly demonstrated that the concentrations of toxic elements and organic contaminants in the soft tissue and the shells are safely below the regulatory limits for use in both feed and fertiliser. Production of mussels for these end uses may thus have a substantial potential for growth. Especially the interest in making feeds based on Baltic Sea raw materials is increasing and feed trials with rainbow trout and arctic char are ongoing. Further, feed trials on organic livestock of pig, layers and chicken, where mussel meal of Baltic origin is used as a high quality protein source (replacing fish meal) will be carried out during autumn 2012.

Current technologies such as the use of nets or long-lines as substrate for settling and growth seem to already work well for mussel farming in the Baltic Sea, though future mussel farms in the region will have to be able to manage ice during winter, especially drifting ice.

Recommendations

It should clearly be pointed out that the first option concerning the leakage of nutrients from different kind of human activities shall always be to perform actions as close to the source as possible. However, from numerous of experiments and trials it is clear that nutrient discharge through myriads of point and diffuse sources under foreseeable time will continue to leak and overfeed coastal waters with nutrients. Once the nutrients have reached the coastal water, there are only a few alternatives available in order to collect, harvest and recycle these nutrients. Mussel farming is one such method, which has been shown to have a potential to recycle nutrients from the sea back to land in the Baltic Sea Region, but still