Odd Lindahl and Sven Kollberg
Sven Lovén Research Station
SE-450 34 Fiskebäckskil, Sweden

How mussels can improve coastal water quality

Mussel farming – a way to combat eutrophication

Many coastal areas are affected by eutrophication caused by nutrient leakage from agriculture, rural living, sewage discharges and other human activities. Blue mussels (*Mytilus edulis*) are not only good at harvesting nutrients through their food intake of phytoplankton. They also provide valuable seafood and raw material for feed-stuff and fertilizer. Mussel farming can be used as a management tool to compensate for nutrient discharges in nutrient trading schemes.

Mussels used in "open landscape feeding" in the sea

In the 1990's the idea of farming blue mussels in order to reduce the amount of phytoplankton and thereby the negative effects of the eutrophication was introduced. This was a new concept regarding the increasing nutrient load and plankton amounts in coastal waters as a resource, which should be recycled and reused on land. The blue mussels are, like many other marine organisms, filtrating animals. They live by pumping in the surrounding water and filtrate off particles, mainly phytoplankton. As the sea water is in continuous motion, new food particles are all the time brought to the mussels, even if they are sedentary.

The largest part, around 80 %, of the nutrients which are discharged to the Swedish coastal waters comes from diffuse emissions like run-off from forest- and farm land, atmospheric deposition and rural living. The remaining 20 % comes from point sources like sewage treatment plants and industries. Since the farm land is regarded to be one of the main sources, the researchers considered that the nutrients harvested in the sea should be reused in agricultural operations. They then introduced the expression "agro-aqua

CORRESPONDENCE TO:

Odd Lindahl
Sven Lovén Centrum för Marina Vetenskaper
Kristineberg 566,
450 34 Fiskebäckskil,
SWEDEN
Email: odd.lindahl@kva.se
Tel:+46 523 18512
Fax: +46 523 18502

recycling" (figure 1), where farming and harvesting mussels can be regarded as a recycling engine of the nutrients. As production of nitrogen-compounds for use as fertilizers is an energy demanding and climate negative process and phosphate is a limited resource on a global scale, there is interest from both an environmental and a socio-economical point of view, to try to catch and reuse the excess nutrients. Through the mussels, these nutrients are transformed into mussel meat which in turn can be used as seafood, or as animal feed or fertilizer in agriculture operations.

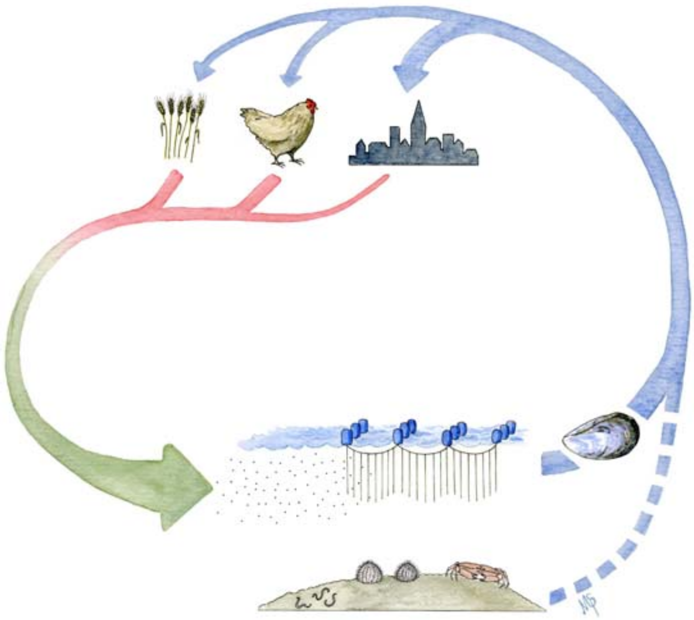

Figure 1*: The principle of the agro-aqua recycling of nutrients. Drawing by Maj Persson.*

Decreasing the discharge of nutrients to the coastal zone as well as their concentrations in the sea is one of the environmental issues with the highest priority as expressed by the Swedish Parliament. Mussel farming has since the 1980's been recognized as a possible measure to improve coastal water quality. From late 1990s and onwards research on how to use mussel farming as a strategic environmental management tool has been ongoing. It has been concluded that trading nutrient discharges most probably is a necessary tool for society in order to use mussel farming to recycle nutrients from sea to land.

Mussel farming can from en environmental point of view be regarded as open landscape farming on land. In the case of mussels the result is clear water and phytoplankton biomass has been turned into valuable products instead of causing eutrophication.

Trading nutrient discharges

A collaboration project between Norway and Sweden in the beginning of the 2000s became pioneering. The basic concept was to regard commercial mussel farming as a compensating measure against nutrient discharges causing eutrophication. If the right tools were given in order to stimulate and thus increase mussel farming, this could help to decrease coastal marine eutrophication. The idea was a parallel to the global trading that is currently being used for carbon dioxide emissions into the atmosphere, but used on a local or regional scale. Any activity which releases nutrients to the environment should also be charged with the responsibility of and taking care of such emissions. If it is complicated or too expensive for the emitter of nutrients to purify the effluent at the source, emission or discharge quotas can be traded. Compensating the different enterprises, which remove the corresponding amount of nutrients, is a part of the trading scheme. In this case it is the mussel farmer which gets paid for farming and harvesting a certain amount of mussels and then fullfills the ecosystem service. This is done as the released nutrients give rise to a natural production of phytoplankton, which in turn is the main food for mussels. Thus, the nutrients are converted into mussel meat and when the mussels are harvested the nutrients are recycled back to land. The nutrient emitter who buys an emission quota thus combines environmental economy, where funding is used to combat eutrophication, with market economy (figure 2).

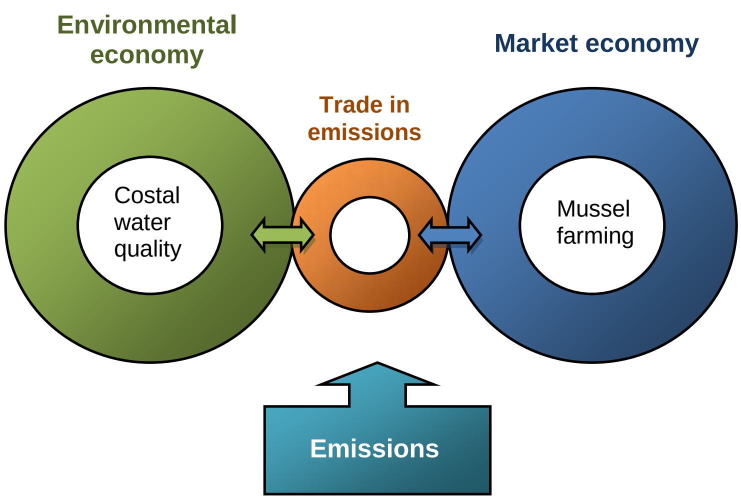

Figure 2: *The surplus of nitrogen/phosphorous can be compensated by mussel farming. The farmers get paid for "taking care" of the surplus. The principle of the compensation farming of mussels for the nitrogen emission from Lysekil sewage treatment plant.*

If the nutrients are discharged from a point source, it is generally easy to measure and calculate the amount of released nutrients. However, when nutrients are released from diffuse sources, the situation is more complex and reduces the possibility of trading discharge quotas. Who is to be blamed and thus who will have to pay for the nutrient emission, if the emission sources cannot be traced? For example, it is possible to quite well estimate the total nutrient emission from the agriculture activity of an area, but it is much more difficult to point out the emission coming from each of the farms within the area. At present there is no statutory demand on the agricultural sector as a whole to do common measures in order to counteract such emissions.

Concerning the nutrient leakage from agricultural operations, a simple way could be to extend the European agricultural environmental aid program to include the coastal zone and aquaculture. However, at present this is not possible since this program is specifically designated only for farm land.

Another option of trading nutrient discharges is from rural living in coastal areas. The cost for single households to connect to municipal sewage plants is in many cases very high, especially along the Swedish Skagerrak coast. Instead, infiltration systems are used, which are simply not very efficient for nitrogen. An option for the nitrogen discharge could be via mussel farming, where the households pay a mussel farmer for the nutrient harvest provided. The nitrogen discharge from a "rural" person is about 3.5 – 4 kg year-1, which means that the harvest of mussels from one long-line could compensate to 100 % for the nitrogen supply from up to 50 persons. Trading of such local solutions would be a task for the coastal communities to organize.

An evaluation on the potential of using mussel farming as an environmental tool along the Swedish west coast estimated that at least 50 000 ton of mussels would be possible to farm and harvest annually. If this level is reached, the corresponding amount of nitrogen would be 20 % of the action program set up to 2010 by the county board of Västra Götaland, Sweden in order to decrease the nitrogen amount in the coastal water of eastern Skagerrak.

Lysekil, the first buyer

The first case in Sweden and possibly in the world, trading a nutrient discharge started in the small town of Lysekil, situated on the Swedish west coast. In 2004 this community discovered the possibility to compensate by mussel farming for the annual discharge of 39 ton of nitrogen from its main sewage treatment plant. The community board of Lysekil was permitted by the County Board, as a trial between 2005 and 2011, to continue to emit nitrogen from the sewage plant, presupposed the same amount of nitrogen was “harvested” and brought ashore by 3500 tons of blue mussels (*Mylitus edulis*) annually farmed.

According to an EC-legal assessment (prof. Staffan Westerlund, personal communication.), it was possible to exchange the nitrogen removal in a sewage treatment plant by mussel farming in accordance with the EC sewage directive. However, the community of Lysekil has not become a mussel farmer enterprise. Instead, they have bought this ecosystem service from a mussel farming enterprise, which has the full responsibility to make sure that the nitrogen removal takes place. Since the mussels are produced mainly as seafood for human consumption, farms cannot be located too close to any sewage discharge. A monitoring programme assures that the harvested mussels will not be affected of e.g. pathogenic microbes or by harmful substances which may affect the quality standard for human consumption. The cost of 200 000 USD for the Lysekil community is far below the price for traditional nitrogen removal in the sewage plant. Additionally, a sewage plant has, according to the directive, to remove only 70% of the nitrogen. In this case Lysekil is heading for 100% removal in order to show that the mussels can do a better job compared to nitrogen removal with traditional technique. As an extra bonus about 3 ton of phosphorus is also recycled back to land. The winners with the trial in Lysekil are thus both the community and the environment!

Mussel farming in Sweden

In Sweden farming with long-line systems are mainly used (figure 3). In this a long line is fixed to

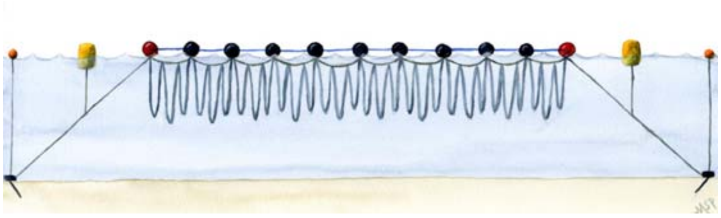

***Figure 3**: A mussel long-line can be regarded as an artificial hard bottom structure which attracts many species including fishes and birds. The lines are usually about 200 m and the hangers go down to depths of about 5 m. Drawing by Maj Persson.*

an anchor system at each end. Barrels or pipes are attached to the lines as floats at certain intervals so the lines are kept near the surface (figures 4 and 5). From the lines 5 cm wide polyethylene bands or net-stockings or rope-ladders are hung at half meter intervals and reaching 5-6 m deep for the mussel larvae to settle on. These hangers are arranged in continuous loops with a small weight at each bottom point (figure 6). The long-lines are generally 200 m long. The system is set up just before the main settling period of the mussel larvae, which usually occurs 1-2 weeks before midsummer (beginning of June). At this time of the

***Figure 4**: Two slightly different types of mussel farms in Trälebergskile north of Lysekil. To the left double long-lines with barrels kept flat in a horizontal position and to the right ten long-lines kept up by blue barrels in an upright position.*

***Figure 5**: Mussel-lines are here carried up by pipes.*

year mussel larvae are normally much abundant and a typical settling density is 5 000 to 10 000 spat per meter hanger. The growth rate is good and the mussels reach an average length of 5-6 cm in 12-18 months. The number of mussels decreases to about 500 per meter hanger at the time for harvest corresponding to about 100 kg per m long-line. At farm sites with good water exchange 20 to 25 single long-lines per hectare farm area may together produce up to 300 ton/hectares in 1 to 1.5 years. Sometimes other settling organisms compete with the mussels. Eider ducks and starfish are predators which at times may cause considerable damage and reduce harvest.

Figure 6*: About one year old mussels, ready for harvest. Every meter band holds about 500 mussels and weighs about 10 kg.*

The approximate cost for long-line set ups is about 50 000 USD per hectar mussel farm, including the cost of labour. The anchor system is heavy and demands a larger vessel or a raft equipped with a crane. The farm is normally placed at depths varying between 8 and 30 m and more or less protected from heavy storms and wave action. Before start it is necessary to apply for a permit and in most cases in Sweden the farm site requires an agreement on a yearly rent by the landowner nearest the farm.

The northern part of the Swedish west coast offers good shelter for mussel farming and is presently the centre of mussel production. The volumes have been low or between 1 000 and 2 000 tons of mussels per year since the beginning of the 1980´s. The reason for this is rather complex but can best be described as shortage of capital, toxin problems, poor cooperation between farmers and almost no marketing efforts. The toxic events were earlier regarded as one of the most hampering factors for an expansion of the mussel farm industry in Sweden. The domestic consumption of fresh mussels is only about 1 000 tons and the rest have to be exported. However, the European yearly consumption of mussels is about 750 000 tons and there is occasionally a shortage.

There are reasons to believe that a production of 50 000 tons of mussels annually on the Swedish west coast is a realistic and possible figure, both from a market standpoint but also looking at the possibilities of the farm area that are needed. A production of this size has been estimated to cover an area of 350 hectars, corresponding to 1 – 2 % of the seawater surface in the Bohuslän archipelago (northen part of the Swedish west coast). As a comparison, this corresponds to 2-3 Swedish average agriculture farms on land. Thus, even if there is a pressure from all kind of activities in the coastal zone, especially recreation, there should be room also for mussel farms.

Bio-sedimentation from long-line mussel farms

In the literature there is much information on the effect of the rich bio-sedimentation of mussel faecal pellets, dropped mussels etc. from a mussel farm. The degradation of the increased supply of organic material will increase the oxygen consumption at the sediment surface. A too rich sedimentation will cause eutrophication effects on the benthic ecosystem below the mussel farm, and cause the development of hydrogen sulphide and in the worst case a dead bottom. A key factor in order to avoid too negative effects is that the sediment surface stays oxygenized, which also allows that the natural denitrification processes continue. The denitrification is important since through this process different nitrogen substances like e.g. ammonium are transformed into biologically inactive nitrogen gas.

In connection with the establishment of about 50 long-lines in the Lysekil area in 2005, the effect on pristine benthic ecosystems and bottom sediments was studied. The result demonstrated that the type of sediment plays a large role as well as the composition of the benthic species community. An important factor was that the long-lines were located at sites having good exchange of the bottom water, which counteracts the risk that anoxic sediment conditions shall develop. At sites, with favourable bottom and water circulation conditions, the natural denitrification may even increase and has been estimated to add up to 25 % of the nitrogen harvested by the mussels.

Mussel harvest with an environmental perspective

When mussels are farmed with an environmental perspective, all of the farmed mussels and other attached biota should be brought to land in order to optimise the positive effect on the environment. By this principle the amount of harvested and recycled nutrients are maximised. However, when the harvest is sorted and treated, a considerable amount, mainly made up of small and crushed mussels, here called the remainder resource, cannot be used as seafood. An increased mussel farming activity will necessarily also mean that the remainder will increase and may in the future make up 10 000 ton or more only along the Swedish west coast. It is essential that this protein and nutrient rich resource is utilized in a sustainable way. Two different products using the resource are presented below. In both cases the interest is directed towards the organic farming industry.

Mussel meal instead of fish meal in feed

Hens and chicken has a great need of sulphur-rich amino acids, especially methionin and cystein, in their feed. The feed-stuff enterprises often use synthetically produced methionin in order to enrich the feed used for e.g. laying hens. It is also common that fish meal is used, since this contains the important amino acids (table 1). However, none of these protein sources are suitable for organic production.

Table 1: Protein and amino acid content in a selection of food sources. The values for mussel meat are taken from Berge and Austreng (1989), other data from Johansen (2007).

	Mussel-meat	Mussel-meal	Fish meal	Rape cake	Peas	Soya cake	Wheat
Protein, g/kg dry material	645	764	670	237	265	520	120
Metionin g/100 g protein	1,8	2,5	2,8	2,0	1,0	1,4	1,6
Metionin + cystin g/100 g protein	2,6	4,2	3,7	4,5	2,4	2,9	3,9
Lysin g/100 g protein	6,0	7,7	7,4	5,6	7,1	6,2	2,8

After 2003 and according to the Swedish KRAV and IFOAM (International Federation of Agricultural Movements), no more than 15 % of none-organic components in the feed are allowed, if the egg or poultry production should be regarded as organic. The non-organic share in which fish meal constitutes a considerable part should according to the original plan decrease to 10 % in 2008, 5 % in 2010 and 0 % in 2012. In 2012 organic laying hens should thus only feed on organically approved feed-stuff components. Since synthetically produced metionin was not allowed and it was difficult to find organically produced animal feed containing enough of the essential amino acids, the regulation was changed in spring 2008 allowing for fish meal to be used further on. However, there is nowadays a growing resistance to use fish meal in feed and the research to find useful replacing products is therefore as important as earlier.

***Figure 7**: Hens who could choose between cooked mussel meat (to the left) and ordinary feed preferred the mussel meat.*

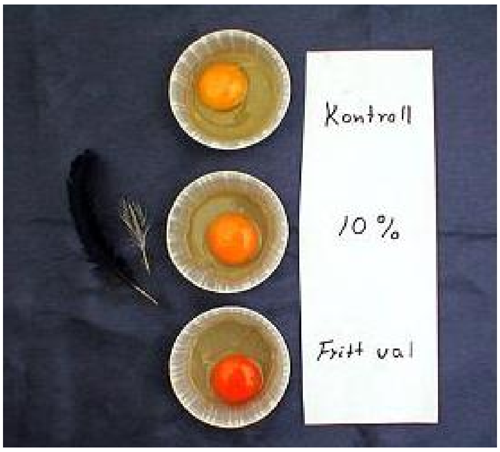

***Figure 8**: Egg yolks become more yellow in colour when the hens are fed with mussel meat. Furthest down on the page, the hens have had free supply to mussel meat. The colour of the yolk became red-orange. The eggs did not taste of mussel.*

Here, research focused on the replacement of fish meal for meal produced from dried mussel meat, to be used as a high protein source, is reported. Since mussels are at the second step of the marine food-chain, the use of mussels instead of fish for meal production has a large ecological advantage. Further, mussel meat contains all the important and essential sulphur-rich amino acids, which are required by poultry.

The first pilot experiment with 64 hens showed, that the hens strongly preferred steamed mussel meat before the ordinary standard feed for laying hens, which also was served (figure 7). The yolks became strongly coloured (figure 8) and no bad taste was perceived in the eggs. These eggs were actually much appreciated for cooking, baking, making mayonnaise or just eaten. Also the meat of the hens was tasty. However, steamed mussel meat is difficult to handle as a feed-stuff and the next step was to dry and grind it into mussel meal.

The Department of Animal Nutrition and Behavior at the Swedish Agricultural University continued the experiment at a much larger scale on about 1000 laying hens and over a full production cycle. The results demonstrated that feed using mussel meal as a high protein source resulted in an as high production of eggs, and with the same quality as when fish meal was used. The only obvious differences were that hens fed with mussel meal got stronger colour of the yolk, but also that the plumage was denser. The latter results, which were unexpected, were important because that meant that the hens would freeze less, which in turn involved less feed intake.

The market for organic eggs has increased considerably during recent years. Presupposed mussel meal will be produced at a large scale, at a higher but reasonable cost compared to fish meal, a market will be easy to find. It should be pointed out that about only 5 % of the meal has to be used in the poultry feed, which means that a higher price not necessarily will become a large obstacle. Swedish organic egg producers already ask for feed containing mussel meal.

Processing mussel meat to mussel meal

A fresh live blue mussel roughly consist of three equal parts; shell, meat and water. In order to separate the meat from the shell the mussels are steamed during a couple of minutes and thereafter spread on a shacking grid, where the coagulated meat comes loose from the shell. Then is it simple to separate meat and shell by using a density bath where the meat floats and the shell sinks. The meat is dried at about 85 - 90 °C and grinded. Starting with 1000 kg of raw mussels there will be about 250 kg meat, which in turn will be 50 kg meal. There will also be 350 kg shell, which will have a value for liming.

Mussel meal has turned out to be as good as or even better then fish meal when used as a high protein source in feed, depending on its content of fat, protein and the amino acids metionin and cystein. It is technically a rather straight forward process to produce mussel meal. Further, the nutritional content of the mussel meal is more than good enough. The remaining problem is the price on the market since mussel meal will be more expensive to produce compared to fish meal.

The use of the mussel remainder as fertilizer

The proportion between nitrogen, phosphorus and potassium in the mussel remainder makes it suitable to use as a fertilizer for cultivating grain. The easily decomposed shells have a liming effect and micro-nutrients like e.g. selenium are added to the soil. Since the mussels live in saline water and ions of both sodium and chloride have a negative effect on e.g. growing potatoes, it is important that the water inside the mussels is drained before the reminder is spread on the farmland.

Figure 9. *Composting mussel waste with straw. The compost was almost free of smell after just a day and ready to use after three months.*

Figure 10. *Composting mussel waste with bark. The brownblackish ready product with iridescence pieces of shells is very decorative and can be used for covering and as fertiliser for flower beds and flowerpots.*

Another obstacle with the mussel remainder is that there is a very bad smell during the deterioration and also that the agricultural farmers need fertilizers only during certain times of the year, while the mussel industry produces the remainder more or less continuously. To overcome these problems composting experiments have been carried out in order to produce a "fertilizer of the sea", which can be stored and used when the farmer needs it and lacking the bad smell of decomposing organic material. The mussel remainder has been composted with straw (figure 9) or bark (figure 10), and the result was positive with only a short period of bad smell and a composted product which both can be stored and quality assured.

The discarded mussels as fertilizer on farmland have given good results and are of special interest for organic farmers who cannot use commercial fertilizers. The crop has increased with between 25 and 50 % compared to land which was not fertilized and had more or less the same effect as manure. The bark compost looks nice with its dark bark and shiny shell pieces. Therefore gardens and green-houses could also be a future market.

Risk assessment of toxic and harmful substances in mussels

A literature search was carried out on the content of harmful substances in mussels sampled by monitoring programmes from along the Swedish west coast. The concentrations found were compared with the Swedish limits used for food and feed-stuff and for fertilizers on farmland. Moreover, a comparison with the Norwegian classification limits on the environmental state, which has been set up by Statens Forurensningstillsyn (SFT) in order to asses the condition of marine areas, was also made. This study included a group of heavy metals, arsenic and some different organic substances with and without halogens. The technique analysing organic substances has improved considerably and therefore only data from recent years were included.

In short, the concentrations of heavy metals were in general well below recommended limits, except for cadmium, which eventually can create a risk when mussel remainder are used as fertilizer on farmland. The existing limits about 10 tons of mussel fertilizer per hectare of farmland that can be used, should be compared with grain farming experiments, which showed that the optimal use of mussel fertilizer was in the range 5 to10 ton hectares.

One substance which was not approved according the Norwegian environmental classification was Tributyltin, which is used to prevent fouling in bottom paint of ships. However, for this substance there are no limits set for food or feed. Concerning PCB and dioxin, the values in mussels were far below the limits, when older and analytically unsafe values were discarded. The only remaining substance in the blue mussel which may exceed the limits was Toxaphen, and this calls for continued attention. Finally, remains from medicaments entering coastal waters through sewage have lately been given attention as a potential problem. However, there are so far neither any data on occurrence and concentrations of harmful medicaments available nor any limits.

Conclusion

Mussel farming is a simple, flexible, cost-effective and straight-forward concept for improving coastal water quality at many coastal sites. Mussel farming can be regarded as open landscape feeding, but in the sea. At the same time it is a sustainable production of valuable seafood and provides coastal jobs. Since mussels are early in the food chain and long-line mussel farms are like artificial floating reefs, the ecological threats are small and can be handled. The use of mussel farming in order to the combat effects of eutrophication, has a large potential in tempered areas, and may become a new commodity on a global scale.

Useful link

More information, references, reports, brochures about environmental mussels can be found on the link (in Swedish):

http://www.miljomusslor.loven.gu.se/