Nutrient removal capacity and potential ecological consequences of blue mussel farms for nutrient abatement in the Baltic Sea

Nils Hedberg, Nils Kautsky, Linda Kumblad and Sofia A. Wikström

Baltic Sea Centre, Stockholm University
(Nils Kautsky at Department of Ecology, Environment and Plant Science)

Summary

Blue mussel farming has been suggested as a cost effective nutrient mitigation tool in the Baltic Sea, to complement land-based measures. However, the environmental conditions of the Baltic Sea, particularly the low salinity, affect the nutrient uptake efficiency of the blue mussels. Farming of mussels with the primary aim to capture nutrients from the sea has also been questioned due to the risk for unwanted environmental effects. In this report, we discuss potential problems regarding blue mussel farming as a nutrient mitigation measure in the Baltic Sea, based on (1) the effects of low salinity on mussel growth and physiology and (2) potential negative environmental effects.

The low salinity in the Baltic Sea means that the mussels are under high physiological stress and results in a slow growth rate. In addition, blue mussels in the Baltic Sea contain less meat and has a lower nutrient concentration compared to mussels living in higher salinity. Together, this leads to a lower nutrient uptake efficiency in Baltic Sea blue mussel farms. In addition, the longer time to harvest in the Baltic increases risks for practical farming problems due to ice, storms, epiphytes and eider predation affecting the small and weakly attached Baltic mussels. These factors have generally been underestimated, but should probably rather be regarded as normal for the Baltic Sea.

There are few data on harvest yield and nutrient content in blue mussel farms from the Baltic Sea, which makes it difficult to provide a reliable estimate of the nutrient abatement potential of mussel farms. Using available data, we estimate that nitrogen uptake efficiency per farming area and time may be 10 times lower in the Baltic proper than in blue mussel farms from areas with higher salinity. The phosphorus uptake efficiency is approximately five times lower than in higher salinity. This estimation needs to be refined when more data is available. Although it may be possible to reach higher uptake efficiency, it is clear that previously published estimates of mitigation capacity of Baltic Sea blue mussel farms are too high.

Mussel farming is regarded as relatively low-impact aquaculture, but blue mussel farms can have negative effect on the local environment, in particular if they are large or dense. For instance, mussel farms lead to local accumulation of nutrients, which may result in oxygen deficiency on the seabed and unwanted plankton blooms. There is a need for more field

studies and ecosystem modelling before the effects of large-scale farming for nutrient abatement in the Baltic proper can be properly evaluated.

In conclusion, a realistic evaluation of the potential to use blue mussel farming as a nutrient abatement measure in the Baltic Sea needs to account for the low salinity and for the risk for environmental effects of large-scale farming. There is a need for more research supporting that blue mussel farming can provide a cost-efficient nutrient uptake in the Baltic Sea, and research on the environmental effects of mussel farming, before it can be recommended as a measure to reduce eutrophication.

Background

Eutrophication is regarded as one of the main threats to the enclosed Baltic Sea, affecting the underwater ecosystem as well as our opportunities to use and enjoy the sea. Nutrient abatement is therefore recognized to be necessary to achieve a healthy Baltic Sea ecosystem, and to meet the goals set by the EU Water Framework and Marine Strategic Framework Directives, as well as the HELCOM Baltic Sea Action Plan (HELCOM 2013). As a complement, or even alternative, to measures on land to reduce nutrient inputs, blue mussel farming has been suggested as a measure for extraction of N and P from the sea (e.g. Gren et al. 2009, Haamer 1996, Lindahl et al. 2005, Petersen et al. 2014). The idea is that nutrients that are taken up by farmed blue mussels will be removed from the sea and transported to land when the mussels are harvested. Since farmed mussels, in contrast to most farmed fish, do not require addition of feed, the nutrients that are incorporated in the mussel meat and shell can be considered as a net nutrient removal from the ecosystem when harvested.

The first full-scale trial of blue mussel farming as a nutrient abatement method in Sweden was an attempt to extract nutrients from the sea as a cost-effective alternative to improve the local sewage treatment plant in Lysekil, Sweden (Lindahl et al. 2005). Despite that this particular trial failed, a number of trials to farm blue mussel with the primary purpose to extract nutrients from the sea has started since then, mainly in Sweden and Denmark (Gren et al. 2009, Lindahl and Kollberg 2009, Petersen et al. 2014; reviewed by Minnhagen 2017).

Gren et al. (2009) assessed the economic potential for using mussel farming as a nutrient reduction measure in the brackish water Baltic Sea, and concluded that it could be a cost-efficient measure. However, the assessment did not fully consider the slow growth and lower nutrient content of blue mussels at low salinities, nor did it internalize any potential environmental costs. So far, none of the blue mussel farm trials in salinities between 6 and 12 psu in the Baltic Sea have met the expectations set up in Gren et al. (2009). The yields have generally been much lower than expected, which has been explained by low growth, severe ice winters, storms, unexpected technical problems, fouling by epiphytes or eider predation (Minnhagen 2017). Several of the experienced problems are connected with the special environmental conditions in the Baltic Sea, and recent publications conclude that the low salinity in the Baltic proper is a major limitation for blue mussel farming (Maar et al., 2015, Rose et al., 2012, Stadmark and Conley, 2012, 2011).

There have also been critical voices questioning the idea of farming mussels with the primary aim to capture nutrients from the sea. Stadmark and Conley (2011) highlighted the importance of considering the entire biochemical cycles of the nutrients, rather than just focusing on the nutrients that are harvested with the mussels. Farmed mussels excrete both dissolved nutrients at the farm site, and nutrients bound in faeces and pseudo-faeces that can generate anoxic bottoms, which in turn can lead to leakage of ammonium and phosphate from the sediment. Furthermore, depending on the situation, increased sedimentation can either decrease the denitrification (i.e. lower the release of nitrogen to the atmosphere and thus increase the levels of nitrogen in the Baltic Sea), or increase the nutrient sequestration in the sediments (i.e. increasing the mitigation efficiency) depending on local conditions. Stadmark and Conley (2011) also questioned if the planned 800 ha of mussel farms (Gren et al. 2009) would lead to any significant changes in the nutrient levels at the Baltic Sea scale.

The paper by Stadmark and Conley (2011) also started a discussion on the potential negative environmental effects of mussel farming, and on what criteria to evaluate blue mussel farming as a measure against eutrophication. Petersen et al. (2012) were able to show that blue mussel farms in Skivefjord in Denmark generate relatively small effects on the denitrification process, and at the same time improve the water clarity. They also argued that blue mussel farms are easy to move or close, if environmental problems occur, and that few other measures can extract nutrients that have already reached the sea. Along a similar line, Rose et al. (2012) argued that removal of nutrients from the system is always a benefit in terms of eutrophication, as long as the mussel farms are placed at the right sites and the carrying capacity of the system is considered. However, so far, little is known about the carrying capacity for large scale blue mussel farms in the Baltic proper.

Aim of the report

Despite that blue mussel farming for nutrient mitigation in the Baltic proper has not been recommended in the scientific literature since 2009 (Gren et al. 2009, Lindahl and Kollberg 2009), it is still regarded as a viable measure against eutrophication by several actors. Currently a number of blue mussel farms for nutrient abatement are running in the Baltic proper and the Swedish authorities have announced for funding opportunities for new mussel farming enterprises in the Baltic proper.

The aim of this report is to review existing knowledge regarding blue mussel farming in the Baltic proper, when the farms are established with the primary purpose to reduce nutrient levels.

- First, we review the effects that low salinity and the special Baltic Sea ecology has on the physiology and growth performance of blue mussels. Based on available information from blue mussel farms on harvest capacity and mitigation costs, and complementary measurements of nutrient contents, the current estimates of the nutrient mitigation potential are evaluated.

- Secondly, we review the literature on environmental effects of blue mussel farming and discuss the potential negative environmental effects of large-scale blue mussel farming on the Baltic Sea ecosystem.

Effects of low salinity on blue mussels nutrient mitigation potential

The nutrient removal capacity of mussel farms depend on size of the harvest, the time period between harvests and the nutrient content in the mussels at the harvest.. In this chapter, we describe how the low salinity in the Baltic Sea affects the growth and physiology of blue mussels and how that affects the harvests and their nutrient content.

Ecology of the blue mussels in the Baltic proper

There are few marine species in the Baltic proper due to the low salinity. Except for the south western part of the Baltic proper the salinity is below 10 psu, and from here on we will refer to below 10 psu waters when we talk about the Baltic proper. One of the most tolerant marine species is the blue mussel, which can live in salinities down to about 4.5 psu butoptimal salinity for blue mussel growth is around 25psu (Maar et al. 2015). Due to the low salinity the Baltic proper blue mussels are smaller than blue mussels in marine waters, i.e. waters with high salinity (Schlieper 1971, Tedengren and Kautsky 1986). Since they have few predators and competitors for space, they dominate the hard substrate benthic biomass (Jansson and Kautsky 1977, Kautsky 1981a, 1982a, Westerbom 2002, Vuorinen 2002), and play an important role for biodiversity (Norling and Kautsky 2007, Koivisto 2011) nutrient cycling (Kautsky and Wallentinus 1980, Kautsky and Evans 1987) and energy flow (Kautsky 1981b, Kautsky and Kautsky 1995). They also provide a number of ecosystem services (Rönnbäck et al. 2007) in Baltic Sea coastal areas.

Blue mussels in the Baltic proper differ in morphology and physiology from blue mussels in the Atlantic (e.g. in Skagerrak and Kattegat). The low salinity affects growth rate, maximum size, byssus production, shell formation and meat/shell ratio of mussels (Kautsky et al. 1990, Riisgård et al. 2014, Maar et al. 2015). In addition to the effect of salinity, there are also genetic differences between blue mussels in the Atlantic and in the Baltic Sea (cf. *M. edulis trossulus* e.g., Johannesson et al. 1990, Zbawicka et al. 2014, Larsson et al. 2017). The lack of predators in the Baltic Sea also affects shell formation and size of the adductor muscle (Reimer and Harms-Ringdahl 2001).

Blue mussels living in low salinity generally have lower uptake rate of nitrogen and a higher excretion rate of ammonia than blue mussels in high salinity (Livingstone et al. 1979, Tedengren and Kautsky 1987). When the salinity is low, the mussels have to allocate a lot of energy for osmoregulation, which means that they have less energy available for growth compared to mussels in high salinity. For instance, osmoregulation constitutes 74–87 % of the total energy use in blue mussels in the Baltic proper (Maar et al. 2015). The extra osmoregulatory costs are associated with breakdown of endogenous proteins and increased excretion of nitrogen (e.g. Schlieper 1971, Tedengren and Kautsky 1986; 1987; Tedengren et al. 1990; Hawkins and Hilbish, 1992). The "osmotic problems" probably also leads to higher water content observed in mussel meat at low salinities (Maar et al. 2015).

The nitrogen metabolism thus seems to be different for blue mussels at low salinities compared to mussel in more marine areas. This is of special importance to consider when discussing nutrient remediation in the Baltic Sea. Firstly, the difference in nutrient metabolism affects the nutrient content in the mussel harvest and thus the nutrient abatement capacity. Secondly, the excretion of nutrients can affect local ecosystems, as we discuss in the following chapter on environmental effects of blue mussel farming.

The osmoregulatory cost also means that less energy is available for growth, why growth rate, maximum size and the dry weight content of mussel meat are generally lower in Baltic Sea blue mussels (Tedengren and Kautsky 1987, Tedengren et al. 1990, Maar et al. 2015). Several key physiological processes will thus negatively affect the growth performance of Baltic Sea blue mussels. Based on physiological model studies of blue mussel growth, Maar et al. (2015) do not recommend mussel farming for nutrient extraction at salinities below 13 psu.

Mismatch between expected and actual harvest

The slower growth rate can be expected to lead to a lower production in blue mussel farms in the Baltic Sea. Previous expectations on the production potential in Baltic Sea mussel farms have not fully accounted for this. For all blue mussel farming trials in the Baltic Sea, in salinities below 13 psu, there is a major discrepancy between the projected and actual harvest, i.e. between the biomass that was expected to be harvested and the biomass that actually was removed from the sea at harvest (Table 1). All but one of the previous and ongoing farming trials for nutrient mitigation in the Baltic Sea have overestimated their production goals (summarized by Minnhagen 2017). The main reason are various practical farm-related problems such as ice, storms, drifting algae and severe eider predation of the very small mussels, which were not expected. The risk for such problems will increase due to the slow growth rate and longer time needed before harvest, and should thus be regarded as normal for the Baltic Sea.

In the first blue mussel farm in the Baltic Sea (Hagby in Kalmar, Sweden, 7.3 psu), the farming potential was assumed to be "at least 25 % compared to the Swedish West coast" (Lindahl 2008). The same assumption was used in the first calculations of farming potential and economics of blue mussel farming in the Baltic Sea (Gren et al. 2009, Lindahl and Kollberg 2009, Lindahl 2012). The projections by e.g. Lindahl (2012) are still used when describing the Swedish mussel farming potential (Wollak 2018).

A clear indication that the earlier estimates of projected harvests were too optimistic is that the production goal for the mussel farms in the Kalmar strait area of 50-90 ton/ha y (Lindahl 2008, 2012, Gren et al. 2009) recently was adjusted to 25 ton/ha y (Minnhagen pers. com.) (Table 1).

Table 1. Mussel farms in the Baltic Sea, Kattegat and Skagerrak; farm size (ha), farming cycle (months), total harvest (ton), and projected and actual yields (ton/ha y). Data on reported total harvest, growth time, area occupied (or measured from Google Earth Map) was compiled from both commercial and mitigation farms, and the harvest recalculated to ton wet weight per hectare and year, when not reported. n.d. = no data.

	Salinity	**Location**	**Farm size**	**Farming cycle**	**Total harvest**	**Projected yield**	**Actual yield**	**Source**
	psu		ha	months	ton ww	ton ww/ha y	ton ww/ha y	
Baltic proper	6.5	Kumlinge	0.45	30	14.4	20	12.6	1
Baltic proper	6.5	Hållsviken	n.d.	n.d.	6	50	n.d,	2
Baltic proper	7	St Anna	4	19	15*	4.5	12	3
Baltic proper	7	Byxelkrok	1	n.d,	n.d.	25	n.d,	4
Baltic proper	7.3	Hagby	3.5**	24	n.d	50-90	7-40**	2,4-6
Öresund	12	Malmö	6	21	9***	15-80	0.85	7
Baltic proper	14	Kiel	0.6	21	35	30-50	30	8
Belt Sea	16	Musholm	1	7	14.6	200	25	9
Kattegat	25	Skive fjord	18.8	12	1100		60-90	10
Skagerrak	30	Tjörn	2	12	200		50	11
Skagerrak	30	Tjärnö	0.46	22	160		190	12
Skagerrak	30	Mollösund	13	12-18	1500-2000		75-150	13

*20% of the ropes were harvested (15 ton). Projected substrate densities was 1.2 kg/m rope, but the actual result was 3.2 kg/m.

**This number is based on the present farm in Hagby with 5 smart farm units spread on an area of 3.5 ha (google earth) but could be placed much closer to each other (perhaps 0.6 ha). Each unit carrying ca. 5 tons of mussels (Minnhagen pers. com.).

***Michael Palmgren (pers. com.)

Source: [1]Diaz and Kraufvelin (2013), [2]Lindahl (2012), [3]Mats Emilsson (pers. com.), [4]Minnhagen (pers. com.), [5]Lindahl (2008), [6]Gren et al. (2009), [7]Bucefalos (2015), [8]Schröder et al. (2014), [9]Minnhagen 2017, [10]Petersen et al. 2014, [11]Haamer (1996), [12]Loo and Rosenberg (1983), [13]Vattenbruk på västkusten (2015)

Uncertain and likely overestimated nutrient content in harvested mussels

A reliable estimation of nutrient removal capacity by blue mussel farms requires accurate data on the nutrient content in the harvest. There are, however, few available measurements of the nutrient content in blue mussels from mussel farms in the Baltic proper. Most estimates of nutrient removal capacity (e.g. Gren 2009, Kollberg and Lindahl 2009, Lindahl 2012, BalticEcoMussel 2013) have used values of nutrient contents in mussels from two papers; Lutz (1980) and Petersen and Loo (2004). Both these studies looked at marine blue mussels and include no data on blue mussels from the Baltic proper, despite that studies indicate that the nutrient metabolism differ in the low salinity (Schlieper 1971, Tedengren and Kautsky 1986, 1987, Tedengren et al. 1990).

The harvest nutrient contents that have been used range between 0.85-1.2 % N and 0.06-0.1 % P (Gren et al. 2009, Lindahl 2012, Diaz and Kraufvelin 2013). Several studies have used 1% for N and 0.08 % for P per harvest weight, which likely are overestimations. Our measurements from the Hagby farm (Kalmar sound, 7.3 psu) and recent measurements by Wollak et al. (2018) and Ek Henning and Åslund (2012) indicate that the mussel harvest wet weight N and P content is somewhere around 0.7-0.8 % N and 0.06 % P in mussels farmed in the Baltic Sea (Appendix 1, Table 3). Overestimations of the nutrient content in the harvest may introduce large errors in the estimation of the nutrient removal capacity.

Another uncertainty in the calculations of nutrient uptake from farms is that there is no standardized way to measure the nutrient uptake in the harvests. Mussel producers working in the Baltic proper usually report their harvest in wet weight (ww) including the free water contained between the shells (Minnhagen pers. com.). To accurately calculate the nutrient content of a mussel harvest based on the wet weight, the proportions of meat, shell, byssus and water of the mussels in the harvest must be known or measured, as well as the nutrient content per wet weight of these respective constituents. In particular, it is important to consider the free water contained between the shells, which makes up about a third of the blue mussel wet weight (Haamer 1996, Petersen and Loo 2004) and does not contain any substantial amount of nutrients. In addition, epiphytes need to be accounted for by measuring their proportion of the harvest, and their nutrient content.

There are thus many steps of calculation and conversions involved to estimate the nutrient content in a mussel farm harvest; from lab results presented in e.g. µg N and P per kg dry weight, to harvest weight in tons wet weight (including free water contained between the shells), and with these steps come many possible sources of error. For accurate estimates of the nutrient removal capacity of mussel farms in the Baltic Sea, and possibilities to compare harvests between farms and years, standardized measurements methods and ways of calculations are needed.

Ten times lower nitrogen uptake capacity

The slower growth rate and nitrogen content in blue mussels from the Baltic proper results in a lower nitrogen binding capacity, compared to blue mussels that are farmed in higher salinity. In this section we compare the nutrient abatement capacity, which here is defined as the amount of nutrients removed per surface area and time, between a farm in the Baltic proper (6.5 psu) and in a Danish fjord (25 psu) that use similar farming methods.

One of the largest harvests reported in a blue mussel farm in the Baltic proper was 12 ton ww/ha y after 19 months (St Anna, 6.5 psu, 3.2 kg ww/m rope, Table 1). During just 12 months the farm in Skive fjord (25 psu) produced 5 times more (60 ton ww/ha y, 12.2 kg ww/m rope) (Emilsson pers. com., Nielsen et al. 2016). Per meter substrate and time unit the St Anna harvest was thus only about 16 % of the harvest in Skive fjord. The slower growth rate in the farmed blue mussels in the Baltic proper (ca 0.07 g ww/month; 2 g ww in 30 months) compared with marine blue mussels (ca 0.7 g ww/month; 13 g in 18 months) (Kautsky 1980, Rosenberg and Loo 1983, Kristensen and Lassen 1997), was somewhat compensated by higher densities of mussels on the farming substrate. The type of rope used in St Anna has more surface area (i.e. more space for settling and growth of mussels), than the substrate in Skive fjord. In addition, the St Anna farm also had more mussel ropes per surface area. The difference in production capacity measured in ton wet weight per hectare was thereby 5 times lower instead of 10 times (which is the individual mussel growth difference between these salinities) lower between the two mussel farms.

In addition to the difference in growth rate, the Baltic proper blue mussels are, as described in the previous section, likely to have higher water content and contain less meat, and thereby also less nutrients compared to marine blue mussels. When applying the nutrient content from measurements in this study (0.7 % N and 0.065 % P, Appendix 1) to the St Anna blue mussel farm, the harvest removed 80 kg N and 8 kg P per hectare and year, compared to the farm in Skive Fjord, which removed 600-900 kg N and 30-40 kg P per hectare and year (Petersen et al. 2014).

Altogether, the lower growth rate and nutrient content of Baltic proper mussels results in a much lower nutrient removal. In the example above, the Baltic proper blue mussel production is 5 times lower and the nitrogen content is only 50 % compared with marine mussels. This results in a 10 times lower nitrogen removal capacity per farming surface area than in marine conditions, while the phosphorus removal capacity is 5 times lower.

There are studies indicating that the production yield might be higher both in Baltic proper and marine waters than in the example above (Minnhagen 2017, Nielsen et al. 2016, Table 1). However, these are one of very few examples, where the farms are using comparable farming substrates and have reported a successful harvest. The total harvest is important. For a mussel farm to have a mitigating impact, the mussels need to be removed from the water. If the farm is ruined by e.g. ice or storms, there is no abatement effect at all.

A need for revised cost estimations of Baltic proper mitigation mussels

Since the harvest yields and nutrient content from Baltic proper blue mussel farms have often been overestimated, the cost for nutrient reduction measure are likely to have been underestimated. Marine mitigation mussel farming costs are better studied and have fewer uncertainties than Baltic proper farming costs (Petersen et al. 2014, Gren et al. 2009). Petersen et al. (2014) estimated that a mussel farm under optimal environmental settings (Skive fjord, 25 psu), that is specifically designed for taking up nutrients as cheaply as possible, can remove nitrogen at a cost of 14.8 €/kg N and phosphorus for 338 €/kg P. This corresponds well with Gren et al. (2009), who estimated the cost for a marine mitigation farm to be 10-16.6 €/ton N and 150-233 €/ton P, and here it is worth mentioning that if you pay for the N reduction you will get a reduction of P included.

For the Baltic proper, Gren et al. (2009) based their cost estimations (21-57 €/ton N and 312-800 €/ton P) on a production yield of 50-70 ton ww/ha y and a mussel harvest N content between 0.85-1.2 %, which seems fit for marine mitigation farms but are too high for Baltic proper conditions. The experience from the different Baltic proper mitigation farms so far indicate that the production potential is 10-30 ton ww/ha y (Minnhagen 2017, Table 1). Thus, each farming unit generates less harvest than previously thought and since the cost of the maintenance remains the same, the production cost per ton mussel is likely higher than in Gren et al. (2009). If the nitrogen content is 0.7 % instead of 1.2 % this will give 58 % less nitrogen for the money, which will affect the cost efficiency. Until more measurements have been performed we propose that it is more accurate to use a moderate harvest N-content like the lower number (0.85%) in the range presented by Gren et al. (2009) or even 0.7 % (this study) rather than 1-1.2 % when estimating costs.

To summarize, better estimates of the farming capacity and cost efficiencies require more measurements from blue mussel farms in the Baltic proper. Basic data, especially of water content, mussel meat content and nutrient content during different parts of the farming cycle are still missing, and measurements and analyses need to be standardized to allow for comparisons and evaluations. It is especially important to standardize how harvest weight is measured. Nutrient content in dried mussels can be measured with high precision, but this needs to be complemented with accurate measurements of the amount of water that is included in the harvest weight.

However, it is clear that the current estimates of the mitigation capacity of blue mussel farms in the Baltic Sea are too high. It is well known that the growth rate and the meat content are lower, although highly variable, in the blue mussels in Baltic Sea (Kautsky 1982ab, Kautsky et al. 1990, Maar et al. 2015, Riisgård et al. 2012, 2014) compared to blue mussels in marine areas. This affects the nutrient content in blue mussel harvests and thus the capacity of a mussel farm to remove nutrients from the water. Besides salinity, the removal capacity will also depend on site-specific conditions, farming technology, and when the harvest is done during the year. For instance, blue mussels harvested in spring, before spawning, will have a much higher nutrient content than mussels harvested later in the year.

Environmental effects of blue mussel farming

§ Several studies have shown that mussel farming has a relatively small environmental impact compared to fish farms and animal production on land (Aubin et al 2017, Folke and Kautsky 1989, Jonell et al. 2013). Still, mussel farming can have negative effects, in particular when the farms are large and dense (e.g. Burkholder and Shumway 2011). Here, we review the literature on environmental effects of blue mussel farming, with focus on studies that are relevant for blue mussel farming in the Baltic proper.

Effects of mussel farming on the N and P dynamics

Blue mussels filter plankton and organic matter from the water and accumulate a part of the nutrients contained in the food in their biomass. When the mussels are harvested, this results in a net removal of nutrients from the ecosystem. However, it is important to acknowledge that the mussels have large effects on nutrient cycling that goes far beyond this nutrient uptake.

Over the entire farming cycle, only about 25 % (5- 45 %) of the nutrients that are contained in the plankton and organic matter consumed by the mussels are removed at harvest (Brigolin et al 2009, Cranford et al. 2007, Folke and Kautsky 1989). The remaining nutrients are deposited as feces and pseudofeces to the seabed below the farm or excreted as dissolved nutrients to the water. A considerable part of the nutrients are released as eggs and sperm during spawning in spring. As we discuss below, this redistribution of nutrients can have large impacts on the local environment.

The net effect on eutrophication and nutrient cycling is thus not limited to the removal of nutrients at harvest, but has large effects on the overall nutrient dynamics (cf. Brigolin et al. 2009, Nizzoli et al. 2011, Stadmark and Conley 2011). The effects on nutrient cycling depends both on how the farm is set up (e.g. density of mussels) and on local environmental conditions (e.g. depth, bottom type, currents). This means that further measurements, calculations and modeling are needed to be able to evaluate the net effect on the nutrient dynamics.

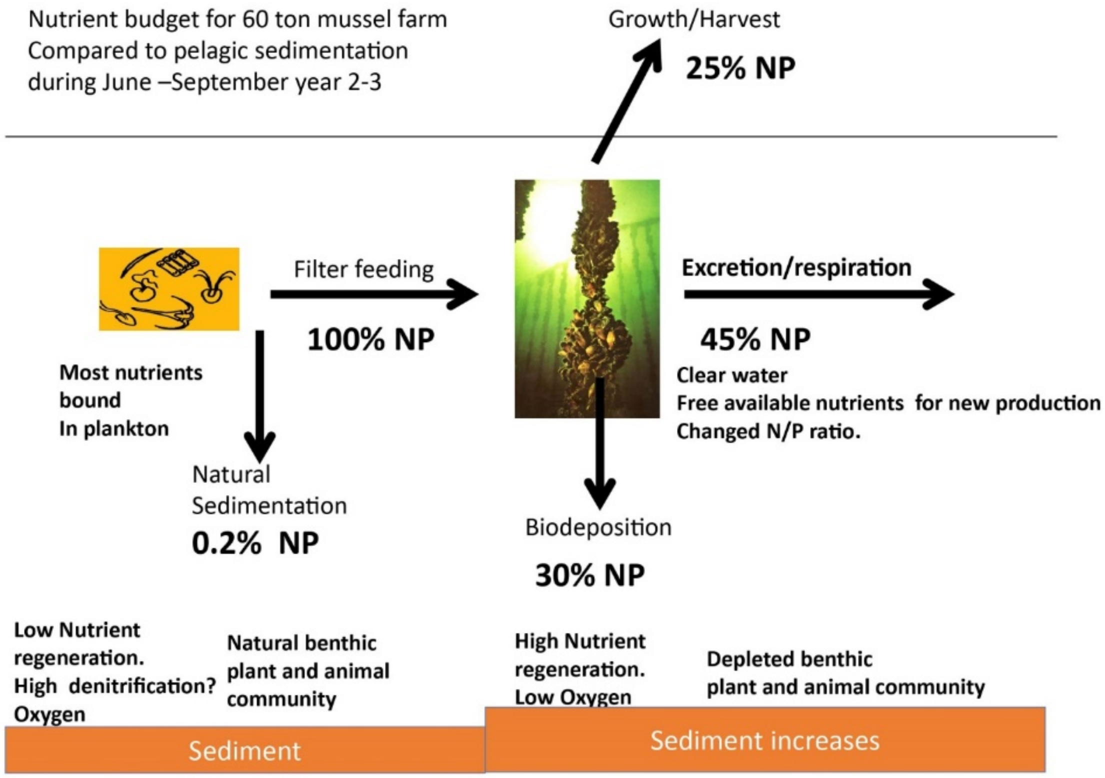

Figure 1. A schematic model of the potential impact of blue mussel farm in the Baltic proper on nitrogen and phosphorous dynamics on the local environment. The percentage roughly indicates the fate of 100 % nutrients (NP) consumed by the mussels along different pathways. Recalculated from Kautsky and Wallentinus 1980, Kautsky and Evans 1987, Folke and Kaustky 1989, natural sedimentation data for sampling point B1 in the Baltic proper retrieved from SMHI Shark data base.

Figure 1 is a schematic illustration of how a mussel farm affects nutrient cycling during summer, when the mussel activity is highest and nutrients are most limiting. Only about 25 % of the nutrients in the plankton and organic matter consumed over a farming cycle is removed at harvest. The rest is relocated and remains in the environment, a large fraction even more bioavailable than earlier. About one third sediments to the bottom as feces and pseudofeces affecting the local sediment environment, and about 45 % is excreted as dissolved nutrients and carried away by currents affecting the pelagic system. Since nitrogen and phosphorus are cycled somewhat differently by the mussels this results in that the N/P ratio in the excretion is changed (cf. Kautsky and Wallentinus 1980, Kautsky and Evans 1987, SMHI Shark database for B1, Prins et al. 1998), which may have implications for which plankton community that is favored by the released nutrients.

Production of faeces and pseudofaeces under a 60 ton blue mussel farm will during the summer period increase sedimentation and organic load to the bottom between 70-150 times under the mussel farm compared to natural sedimentation rate (recalculated from Kautsky and Evans 1987, SMHI Shark database B1). This will affect benthic oxygen conditions and nutrient cycling. The amounts of nutrients recycled from the sediments depends on the amount of organic deposits from the blue mussel farm, but also on biological activity, oxygen conditions, water temperature and depth, which vary locally. Drastic changes or "flips" in the biogeochemistry of the sediment will occur when the sediment shifts from oxic to anoxic conditions, which can occur due to the high sedimentation (Jørgensen 1980). Even if there is a net removal of nutrients from the water body at a blue mussel harvest, the very large sedimentation near mussel farms may smother the existing benthic communities and cause significant changes in the oxygen conditions on the bottoms. This usually leads to highly increased nutrient regeneration rates (Nizzoli et al 2011) and possibly also decreased natural denitrification, which will reduce the abatement effect of mussel farms (Stadmark and Conley 2011).

Effect of mussel farming on water clarity

Increased water clarity is often used as an additional argument for mussel farming as an environmental measure (Petersen et al. 2014, Nielsen et al. 2016). In the western Baltic Sea (14.3 psu), the effect of a blue mussel farm on water clarity in the Kiel fjord was investigated by Schröder et al. (2014). This relatively small farm (harvesting 30 ton ww mussels) improved the Secchi depth by only 30 cm within the farm area and by 5 cm in a 10 km^2 area around the farm.

The mussel filtration impact on water clarity depends on seston particle composition, but also water retention time and the blue mussel biomass (Kach and Ward 2008, Nielsen et al. 2016, Schröder et al. 2014). Thus, increased blue mussel biomass does not always necessarily lead to improved water clarity since the seston composition and water movement are affected by the farming structure itself (Schröder et al. 2014).

Intensification of mussel farming in order to improve water clarity may also lead to food limitation for the mussels in the farm (cf. Rosland et al. 2011) and since food-limited mussels grow less, this may ultimately lead to smaller harvests and less nutrients removed from the ecosystem than expected.

Effects on plankton and benthic communities

During the warm season, when the blue mussel metabolism and filtration are highest, they may have a large impact on the local plankton community and effectively reduce the microplankton and mesozooplankton communities (Prins et al. 1995, 1998, Maar et al. 2008, Petersen et al. 2008). In contrast, they are ineffective in filtering picoplankton (0.2-2 µm), such as some cyanobacteria, although the efficiency increases when plankton aggregate in larger particles (Kach and Ward 2008).

With intensive mussel farming the water mass is largely cleared of plankton and POM by the filtration. The mussels turn the seston into dissolved inorganic and organic nutrients with a shifted N/P ratio, which can stimulate new phytoplankton growth. This will result in increased plankton turnover and a change in species composition, possibly leading to unwanted plankton blooms (Cranford et al. 2007, 2008, Guyondet et al. 2015).

As described above, the deposition of organic matter from feces and pseudofeces can lead to oxygen deficiency on the seabed below mussel farms, negatively affecting benthic communities below the farm (Kautsky 1985, Kautsky and Evans 1989, Stybel et al. 2009, Stadmark and Conley 2011). The risk for oxygen deficiency is largest in deep areas with poor water exchange. On shallow bottoms with good water exchange, moderate mussel farming can instead lead to an increase in diversity of benthic species (e.g. Norling and Kautsky 2007, Diaz and Kraufvelin 2013).

The increased water transparency near the farm increases light penetration, favoring benthic vegetation. At the same time, the farming structure itself shade the benthic community under the farm where the water clearance is highest. Furthermore, the increased sedimentation of faeces and pseudofaeces from the farm and ammonia release from sediments may be detrimental to vegetation growing below the farm (Vinther et al. 2008).

Increased water transparency, i.e. lower concentrations of plankton and organic matter in the water, can also affect other filter-feeding organisms, for instance the natural populations of blue mussels. In the Baltic proper, severe food limitation for the natural mussel beds occur in areas with high mussel biomass during summer when temperature and mussel energy demand and respiration are high. Calculations show that in the Askö area (northern Baltic proper) the entire water volume is on average filtered in one month by the natural blue mussel community (Kautsky 1981b). During summer, it will take less than one week, which is close to the doubling rate of phytoplankton (Kautsky 1981b, Kautsky and Evans 1987) and means that the blue mussels may deplete their own food resource. Accordingly, mass mortality of blue mussels have been observed several times in the Askö area, usually during August when the water is warm (>20° C) (H. Kautsky pers. com.) and food intake cannot satisfy the energy demand due to very high metabolism of the mussel population. Such collapses of the natural mussel population have also been observed in other areas, such as in San Francisco Bay (Cloern 1982). Thus, the adding of mussel farms to an area where the natural mussel populations are already at the carrying capacity may severely impact the natural population, since the farmed mussels are situated higher in the water column and have more direct access to pelagic food. Such a decrease of natural mussel populations due to mussel farming can have large impacts on biodiversity and function of the local ecosystem.

The effect of mussel farming on benthic and pelagic communities depends strongly on farming intensity, i.e. the size and density of farms in relation to the size of the water body where the farm is situated. In other parts of the world, large ecosystem changes have been observed in areas with dense mussel farming. For instance, intensive mussel farming can lead to a collapsed zooplankton community cascading into the food chain, increased sedimentation and oxygen depletion (e.g. Guyondet et al. 2015, Burkholder and Shumway 2011, McKindsey et al. 2011). In contrast, few negative effects have been documented from the small-scale farms that have been set up this far in the Baltic Sea. This however shows that up-scaling from small-scale farming should be done with caution, not to get unwanted negative environmental effects.

The effect of mussel farming on benthic habitats will also depend on the specific characteristics of the area and on the type of habitat. Some coastal benthic communities (e.g. soft bottoms) are more adapted to cope with heavy sedimentation while for others, i.e. hard bottom communities, algal and seagrass beds, it could be detrimental. One habitat that may be particularly sensitive is eelgrass (*Zostera marina*) meadows. If projecting for development of mussel farming, mapping of bottom habitats needs to be included in order to assess the potential effects on the local environment.

What is the goal and are mussel farms the solution?

Mussel farms may be used as a management tool to remove nutrients or increase water clarity (Schröder et al. 2014, Petersen et al. 2016, Nielsen et al. 2016). The two different goals; nutrient removal and improved water clarity work at different scales. While the effect of water clarity is primarily limited to the vicinity of the farm (Schröder et al. 2014, Nielsen et al. 2016), the effect of nutrient removal is much more complex and works on larger scales. Much of the effect of the nutrient removal is dependent on origin and fate of the seston filtered by the blue mussels. The actual footprint of the blue mussel farm, i.e. the life support area needed to provide the farm with plankton, is 8-35 times larger than the actual farm area itself (Kautsky and Folke 1989, Lindahl and Kollberg 2009). If farming is performed in coastal areas, archipelago areas and bays, it is likely that more nutrients will sediment and be retained in these areas, compared to areas with no farms where they will remain bound in the plankton (Kautsky and Evans 1989), and can ultimately be transported to the open sea. Although the water may look clearer and nutrients are removed at harvest, this may by definition (Nixon 1995), even lead to locally increased "eutrophication" as the total amounts of nutrients and organic matter will increase, although being relocated to the bottom. For local interests, it is therefore important to consider the risks that come with blue mussel farming at the site level, and acknowledge the fact that the farm can be a net source of free available nutrients to new plankton growth in the bay or estuary were the farm is situated (Brigolin et al. 2009, Holmer et al. 2015).

Coastal areas with mussel farming may thus become a trap for nutrients transported here both from land as well as by currents from the open sea that are deposited to the bottoms by the increased sedimentation. The net effect of coastal mussel farming will then mean less sedimentation to deeper off-shore bottoms, which is positive for the anoxic deep water of the Baltic Sea, but instead result in more loading in coastal areas and bays with potential large impacts on biodiversity and the local oxygen situation. From a management perspective, it is therefore important to decide the primary environmental target for the blue mussel farming.

Depending on the goal and scale of blue mussel farming, very different considerations need to be made, which will have different implications for the environment.

1. If the goal is to improve the water clarity and nutrient status in a restricted water body like a bay, this may be feasible but depend on site characteristics; mainly salinity, water exchange and local ecosystem properties. As discussed, improvement of water clarity will be rather limited due to non-linear relationships between size of the farm and effect. Counter to expectation, the total amount of nutrients and organic matter in a bay may even increase due to sedimentation locally. In summary, careful environmental mapping and modelling need to be made before blue mussel farms are started in restricted water bodies.

2. If the goal is solely to remove nutrients from the water, e.g. to compensate for the nutrient release from a fish farm, this is possible as long as the salinity and water exchange are sufficient for the blue mussels. However, knowledge about the abatement efficiency, costs and environmental effects are still lacking. It is also important to consider that even though the blue mussel farms can compensate for the nutrient release by e.g. fish farms, the mussel farm will enhance the negative effects on benthic communities and oxygen levels at the site.

3. Finally, if the goal is to meet Regional or National Water Action Plans, or even the HELCOM Baltic Sea Action Plan, the technical and environmental challenges may quickly become enormous. The scale of farming needed to get any abatement effect will be massive and may affect the entire nutrient balance of the Baltic Sea, including coast-offshore nutrient exchange, oxygen situation, benthic and pelagic communities, plankton composition, food webs, fish populations etc. Experience is lacking from such large-scale farming and extrapolations from existing knowledge are not possible. More modelling and experimental research, e.g. on effects of mussel grazing and changed N/P ratios on the plankton community are needed before such large-scale projects are started.

It is also important that the targeted effect and the scale of the project are matching; otherwise it can lead to unwanted results. For example, if the goal of the farming project is to reduce the eutrophication in the Baltic Sea, and the scale of the farming has little measurable effects on the Baltic Sea nutrient levels but only results in locally anoxic bottom sediments, this will probably be perceived as very negative by the local community where the farm is situated.

In the end, it is also important to consider how the harvested mussels are used. Life cycle analysis of commercial mussel farms shows that compared with other protein production; mussel farms have a rather small environmental impact. However, if the primary aim is to improve the environment and the mussels are not used as food or feed, it is important to weigh the gains against negative impacts discussed above, as well as acidification and generation of greenhouse gases (Aubin et al. 2017, Iribarren et al. 2010, Lourguioui et al 2017). How the cost of these environmental side effects should be internalized is rarely discussed but important to consider if to create a fair market in comparing various environmental measures.

Discussion and Conclusions

The original estimates of farming potential, abatement effect and economics of using mussels for nutrient mitigation in the Baltic proper (e.g. Gren et al. 2009) are still largely used when new mitigation initiatives are justified. We show that these estimates overestimate farming yield and nutrient abatement potential and underestimate environmental costs for a number of reasons. The following main factors need to be taken into account to obtain more realistic estimates:

- Potential yields in the Baltic proper are much lower than expected and practical farming problems e.g. storms, ice, eider predation and epiphytes are severe. Most of these problems are “normal” for the Baltic proper and may not be so easily solved.

- Mussels from the Baltic proper need a longer growth period before harvest due to slow growth. This increases risks for farming problems.

- The special physiology and ecology of Baltic mussels must be taken into account, as this influence the abatement efficiency.

- Water content is higher and meat and nutrient contents are lower in mussel harvests from the Baltic proper, which affect abatement efficiency and cost.

- Environmental effects of large-scale farming need to be evaluated and environmental costs need to be internalized and included in the economic calculations.

The total environmental impact of blue mussel farming activities on large ecosystems is hard to predict, but especially important when mussel farming is launched primarily as an environmental measure. We emphasis that a large majority of the nutrients from plankton that are filtered by the mussels in a mussel farm are not accumulated and removed at harvest, but recirculated locally in the water. The effect of large scale changes in plankton communities and nutrient dynamics are crucial to assess before it is possible to evaluate blue mussel farms for nutrient mitigation both from an environmental and economic perspective.

In conclusion, there is no doubt that the harvesting of farmed blue mussels will remove nutrients from a water body, just as fishing or any other harvesting of biomass. However, in the Baltic proper, the low salinity restricts production and it is technically more challenging to farm mussels. This lowers efficiency and increases costs. Current economic estimates have not fully considered this. Furthermore, the potential negative environmental effects of large-scale-farming have not been internalized in the economic calculations.

Acknowledgements

We thank Jan Andersson for providing us with knowledge and experience and blue mussels from his farm. We also thank a number of other experts that has provided helpful discussions and input; Susanna Minnhagen (Kalmar kommun), Izabela Alias (Länsstyrelsen i Kalmar), Susanna Andersson (Linné University), Hans Johansson (Long Island Divers), Mats Emilsson (Sankt Anna), Lena Tasse (Region Östergötland) and Michael Palmgren (SeaU). The study was financed by the Baltic Eye project.

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Personal comments

Emilsson, M. (Januari 2018) Sankt Anna musselodling.

Lindehoff, E. (Mars 2018) LNU. ALGOLAND.

Minnhagen, (May 2018) Kalmar kommun and Baltic Blue Growth.

Palmgren, M. (November 2017) SeaU, Marint kunskapscenter

APPENDIX 1.

Measurements of blue mussels from the trial farm in Hagby, Kalmar

To get complementary data on nutrient content in farmed blue mussels from the Baltic proper, we collected samples from the trial blue mussel farm in Hagby hamn in Kalmar, Sweden (7.29 psu, positions: y 56.565998° x 16.237507°) in November 2017. The mussel farm had been running since summer 2015 and the oldest blue mussels were about 2.5 years. There were three dominating size/age classes; ~5 mm probably mainly newly settled in summer 2017, ~15 mm probably mainly settled in the summer 2016 and ~25 mm from summer 2015 (Table 2).

Twenty blue mussels (25-32 mm) were sampled and immediately transported in a cold box, without any added water, to the Linné University (Kalmar) for analysis of wet weight (including water, meat and shell), shell length and height, wet weight of the mussel meat, wet weight of the shell, and dry weight of the mussel meat and shell (72 h at 68°C). The harvested mussels where generally free from epiphytes and occasional barnacles where removed before analysis. The dried mussel meat and dried shells where homogenized to a fine powder using a stone mortar. The nitrogen content was analyzed using an organic element analyzer (Flash 2000, Thermo Fisher Scientific, Waltham, MA, USA) and the phosphorus content was analyzed spectrophotometrically (SFA, ALPKEM O. I. Analytical Flow Solution IV). The results are presented in Table 2, and are further discussed in the next section.

Table 2. Length (mm), wet and dry weight (mg), nitrogen and phosphorous content (mg) per blue mussel (n=20, ca 2.5 years old) sampled from Hagby blue mussel farm, Kalmar (7.3 psu) in November 2017. Mean ± std. Percentage of the total mussel wet weight within brackets.

	Length	**Height**	**Wet weight**	**Dry weight**	**Nitrogen content**	**Phosphorous content**
	mm	mm	mg/mussel	mg/mussel	mg/mussel	mg/mussel
Shell	28.3 ± 2.58	11.6 ± 1.57	558.9 ± 152.4. (30.5 %)	531.2 ± 140 (29 %)	3.6 ± 1.1 (0.5%)	0.1 ± 0.0 (0.007 %)
Meat	-	-	565.2 ± 144 (31%)	86.6 ± 20 (5 %)	8.6 ± 2.2 (0.2%)	1.0 ± 0.3 (0.057 %)
Byssus	-	-	12.1 ± 8.7 (0.6 %)	4.5 ± 2.9 (0.2 %)	0.5 ± 0.3 (0.0%)	0.0 (0.0%)
Water	-	-	765.9 ± 420.2 (38 %)	-	-	-
Total	-	-	**1898.5 ± 645.3**	**621.9 ± 156.8**	**12.9 ± 3.1 (0.71%)**	**1.1 ± 0.3. (0.065%)**

Water contained between the shells – 30-40 % of a harvest

The free water contained between the shells make up between 30 % (USA, Lutz 1980) and 38 % (Kalmar Sound, this study) of the harvest weight, but contribute little to the nutrient content. Danish commercial producers report a water content of 33 % (Petersen and Loo 2004), which has also been suggested as a "rule of thumb" (Bucefalos 2015). Since the free water contributes to approximately one third of a blue mussel harvest in terms of weight, it is one of the most important parameters to measure and account for in an adequate way in order to be able to accurately calculate how much nutrients that are removed at harvest. The content of free water likely varies with season, which also needs to be studied.

Higher water content in meat of Baltic proper mussels compared to marine blue mussels

The mussel meat contains most of the nutrients in a blue mussel harvest (Haamer 1996, Petersen 2014, this study Table 2). Due to the low salinity, the Baltic Sea blue mussels generally have higher water content in the meat, and thus a lower dry weight to wet weight ratio of the meat, compared to marine blue mussels (Maar et al. 2015, Kautsky et al. 1990). How much lower this ratio is, is not well studied.

Lindahl (2012) found that the wet weight of the mussel meat in mussels farmed at 7.3 psu in Hagby (Kalmar) constituted 30 % of the total wet weight, which is similar to our measurements (31 %), from the same mussel farm in November 2017 (Table 3). The dry weight of the meat varied between 3.7-5.9 % (average 5 %) of the total wet weight of a mussel, and the meat dry weight to wet weight ratio was 0.15 ± 0.2 (Table 3). This is lower compared blue mussels farmed in marine areas that contain 6-10 % dry weight meat and have a meat dry weight to wet weight ratio of about 0.20 ± 0.5 (Petersen and Loo 2004 and references therein, Maar et al. 2015). Furthermore, blue mussel dry meat content (and the nutrient content of the dry meat) varies a lot during the year, mainly due to the spawning cycle (Kautsky 1982b, Lindehof pers. com., Smaal and Vonck 1997, Jansen 2012). During spawning they may lose more than 30 % of their meat dry weight (Kautsky 1982b). The meat content (and nutrient content) in a blue mussel harvest can thus vary substantially with season.

Nutrient concentrations in mussel dry meat is similar or higher compared to marine mussels

The nutrient concentrations in the dry mussel meat in our study was 9.85 % N and 1.14 % P, respectively. This is higher than the estimates from marine environments presented by Petersen et al. (2014) (6.5 % N and 0.7 % P, average of 3 different sampling occasions over the year) and by Smaal and Vonck (1997) (yearly average 8.5 % N and 0.61% P), but lower/similar to Jansen et al. (2012) (yearly average ~ 13% N and ~ 1% P).

Nutrient content in shell and byssus threads

The shell is contributing with a substantial part to the total nitrogen content of a blue mussel. In our study 29.5 % of the nitrogen and 11.6 % of the phosphorous of the analyzed mussels was bound in the shell, which is in the upper range of the nutrient content in blue mussels from marine environments, 25-30 % N and 3-18 % P (Lutz 1980, Petersen and Loo 2004, Petersen et al. 2014).

The mussel byssus has been shown to contribute with a significant part of the total harvest nutrient content in Skive fjord, Denmark (Petersen et al. 2014). The nutrient content in the byssus was not measured in this study, but it is known that the mussels in the Baltic proper produce less byssus than blue mussels from marine environments (Kautsky 1981). For our NP content estimates (Table 2), we assumed that the byssus had the same nutrient concentrations as in marine waters, i.e. 11 % N and 0.08 % P (Petersen et al. 2014).

Mussels with barnacles and other epiphytes were excluded in our study as the amount and types of epiphytes vary very much with age of the mussel, season and site. However, the nutrient content of byssus and epiphytes are important to measure in an actual harvest, since e.g. barnacles sometimes can make up a substantial part of the total harvest weight.

Nutrient content in blue mussels is different in different salinities

The measured/calculated/estimated nutrient content in blue mussels from farms located in areas with different salinities seems to differ quite a lot (Table 3). The blue mussels from Hagby trial farm (7.3 psu) contained on average 0.71 % N and 0.06 5% P per wet weight whole mussel, including shell and free water contained between the shells. This is likely similar to the nutrient content in the trial mussels farmed in Östergötland, but cannot be confirmed since the water content was not reported in that study (Table 3). If assuming a third of the wet weight is water (containing no nutrients), a third is meat (as reported 1.25 % N and 0.12 % P) and a third is the shell (as reported 0.9 % N and 0.07 P), the total N and P concentrations per total mussel wet weight would be 0.72 % N ((0+1.25+0.9)/3) and 0.063 % P ((0+0.12+0.07)/3) respectively (Ek Henning and Åslund 2012). Compared to Skive fjord in Denmark (26 psu), the N content in the Hagby trial farm was less than half, whereas the P content was almost the same as in our measurements. This is explained by considerable higher P content in the shells and meat (on dry weight basis) in the Hagby mussels compared with Skive Fjord. If the mussel meat had been analyzed in the spring before the spawning, the meat content would likely be about 1/3 higher (Kautsky 1982b), which would have led to higher nutrient content of about 0.85 % N and 0.08 % P (Lindehof pers. com.). If the mussels instead had been analyzed after spawning during the summer, the meat content could instead be 1/3 lower, generating N- and P contents of 0.5 % and 0.04%, respectively (Kautsky 1982b, Lindehof pers. com.). Although we have too few blue mussel samples to generalize nutrient content in blue mussels for mussel farms in the Baltic Sea, the data clearly indicate that the estimates of nutrient removal capacity presented by e.g. Gren et al. (2009) are overestimated, especially for nitrogen (0.85 -1.2% N).

Table 3. Compilation of studies with reported N and P content in shell and meat in mussels from different salinities. Since there is no standard procedure to report N and P content, the information was reported in different units in the different studies, but have recalculated to allow for comparisons. The most important variable from a mitigation farm perpective is the total N and P content. Estimated (marked **e**) tot N and P, based on 1/3 part of water contained between the shells.

Location	Salinity (psu)	shell content (%)	meat content (%)	ww meat N content (%)	dw meat N content (%)	shell dw N content (%)	ww meat P content (%)	dw meat P content (%)	P shell (%)	tot N content (%)	tot P content (%)	Source
Östergötland	7	n.d.	n.d.	1.25	n.d.	0.90	0.12	n.d.	0.07	e 0.7	e 0.06	1
Kalmar HagbyFarm	7.3	28	31.2	1.54	9.85	0.68	0.18	1.14	0.03	0.71	0.06	2
Kalmar Öland bridge	7.3	n.d.	n.d	n.d.	n.d.	n.d	n.d.	n.d.	n.d	0.081	0.06	3
Malmö *	12	n.d.	n.d.	0.86	n.d.	0.56	0.039	n.d.	0.022	e 0.5	e 0.02	4
Öresund Bridge	12	n.d.	n.d.	1.10	n.d.	0.56	0.08	n.d.	0.022	e 0.6	e 0.03	5
Skive Fjord	26	n.d.	n.d.	n.d.	6.5	0.97	n.d.	0.71	0.0043%	1.45	0.06	6
Main (USA)	30	30	40	2	10.64	1.13	0.15	0.80	0.05	1.19	0.07	7

*The project reported to have problems with the preparations and analysis of the nutrient content from the farmed mussels

Source: 1Ek Henning and Åslunde (2012), 2This study, 3Wollak et al. 2018, 4Bucefalos (2015a), 5Bucefalos (2015b) 6Petersen et al. (2014), 7Haamer (1996) with data from Lutz (1980).

References

See the reference list in the main report (page 18-24).