Aquacult Int (2016) 24:857–878
DOI 10.1007/s10499-015-9953-0



# The use of shellfish for eutrophication control

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Received: 25 March 2015 / Accepted: 24 September 2015 / Published online: 9 October 2015


**Abstract** Effects of excess loading of nutrients to the marine environment can be mitigated by mussel cultures, basically through nutrient removal from the marine environment when shellfish are harvested. Shellfish farming also provide other goods and services to the marine environment primarily through the impact on water transparency caused by shellfish filtration. There is an increasing awareness of the mitigation potential in mussel culture in relation to eutrophication, but so far practical examples of culture on full scale devoted to mitigation are few. Further, impact of mussel farming on nutrient cycling, e.g. in the sediments below the culture units, has raised concerns. In this review, we clarify concepts in relation to nutrient mitigation and discuss goods and services delivered by mussel mitigation cultures and their impact on an ecosystem scale based primarily on results from studies in heavily eutrofied estuaries. A multi-criteria approach for site selection is presented based on experiences from Danish waters, and economic aspects of mitigation cultures are analysed in relation to use of the produced mitigation mussels. Future perspectives for extractive cultures are discussed in relation to source of excess nutrients.

**Keywords** Mussel culture · Nutrients · Mitigation · Eutrophication · IMTA

## Introduction

Run-off of nutrients from land to sea is of key importance to production of organic material in the sea and especially in the coastal zone, but excess loading of nutrients due to human activities like agriculture and sewage discharge leads to primary and secondary symptoms of

Guest editors: Elena Mente and Aad Smaal/European Aquaculture Development since 1993: The benefits of aquaculture to Europe and the perspectives of European aquaculture production.

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eutrophication, e.g. frequent events of hypoxia or anoxia (Rabalais et al. 2010), reduction in light penetration affecting sea grass and macro-algae distribution causing loss of benthic habitats (Diaz and Rosenberg 2008) and organic enrichment of the seabed. Eutrophication is considered one of the largest threats to the environmental quality of coastal waters. Traditional measures to reduce nutrient loading to the marine environment are land based and are either directed towards point sources like sewage treatment plants or directed towards diffuse emissions mainly from the cultivated land. Measures to reduce diffuse run-off include restrictions in fertilization, catch crops and winter green fields, wetland restoration and wetland reconstruction, afforestation and fallowing of intensively cultivated fields (Hasler et al. 2015). Most of these abatement measures have restricted capacity for further reducing nutrient loads, and the costs of implementing them are increasing at the margin (Hasler et al. 2015).

For decades, it has been recognized that marine suspension feeders possess a significant potential for clearing the water column of particles (Cloern 1982; Fréchette and Bourget 1985; Asmus and Asmus 1991; Møhlenberg 1995; Prins et al. 1996; Norén et al. 1999). By actively pumping water past a filtering apparatus, most of the cultured bivalve species can capture particles >4 µm 100 % efficiently at rates of 6–11 l $h^{-1}$ $g^{-1}$ DW of body parts under optimal conditions (Riisgård 2001). By combining grazing rates with population size, it has been demonstrated that benthic suspension feeders have the potential for controlling phytoplankton concentrations—top-down control—in well-defined coastal basins (e.g. Cloern 1982; Officer et al. 1982; Alpine and Cloern 1992). It has also been shown that this potential control actually does work and can lead to substantial increase in environmental quality of estuaries without reducing load of nutrients (e.g. Petersen et al. 2008). Similar experiences have been obtained from freshwater systems, often in relation to invasion of zebra mussels *Dreissena polymorpha* (e.g. Fahnenstiel et al. 1995a, b; Caraco et al. 2006; Weber et al. 2010; Pires et al. 2010). It is thus obvious to suggest active use of bivalve cultures to mitigate effects of excess run-off of nutrients from land (Officer et al. 1982; Haamer 1996; Newell 2004; Lindahl et al. 2005; Cerco and Noel 2007; Bricker et al. 2014; Gallardi 2014; Kellogg et al. 2014; Petersen et al. 2014). Actual implementation of mussels to remove nutrients from marine waters is sparse, and to our knowledge Lysekil municipality, Sweden was in 2004 the first to use mussels to compensate for discharge of nitrogen from a sewage treatment plant during a 6-year trial period (Lindahl and Kollberg 2009; Lindahl and Söderqvist 2011). In Denmark, mitigation cultures are no longer just a concept, but have recently been accepted by the Danish Nature Agency (Eriksen et al. 2014) as a potential measure for the removal of excess nutrients in Danish coastal waters. Implementation of mitigation bivalve cultures in European countries as well as worldwide is, however, only in its beginning. Consequently, there are several aspects of how to implement mitigation bivalve cultures that need to be discussed before mitigation bivalve cultures change status from “concept” to “real” in Europe and worldwide.

Our main objectives are therefore (1) to clarify the mussel mitigation concept; 2) to review the goods and services provided by bivalve cultures; (3) to address mitigation culture impact on nutrient cycling; and (4) to discuss the potential of mussel mitigation culture in highly eutrophic coastal areas in Europe.

## Mussel mitigation culture

The basic concept of mitigating the effects of excess run-off of nutrients using extractive cultures is to consider excess amounts of nutrients in the coastal waters as a resource to be recycled back to land (Hart 2003; Petersen 2004; Lindqvist 2007; Møhlenberg 2007;

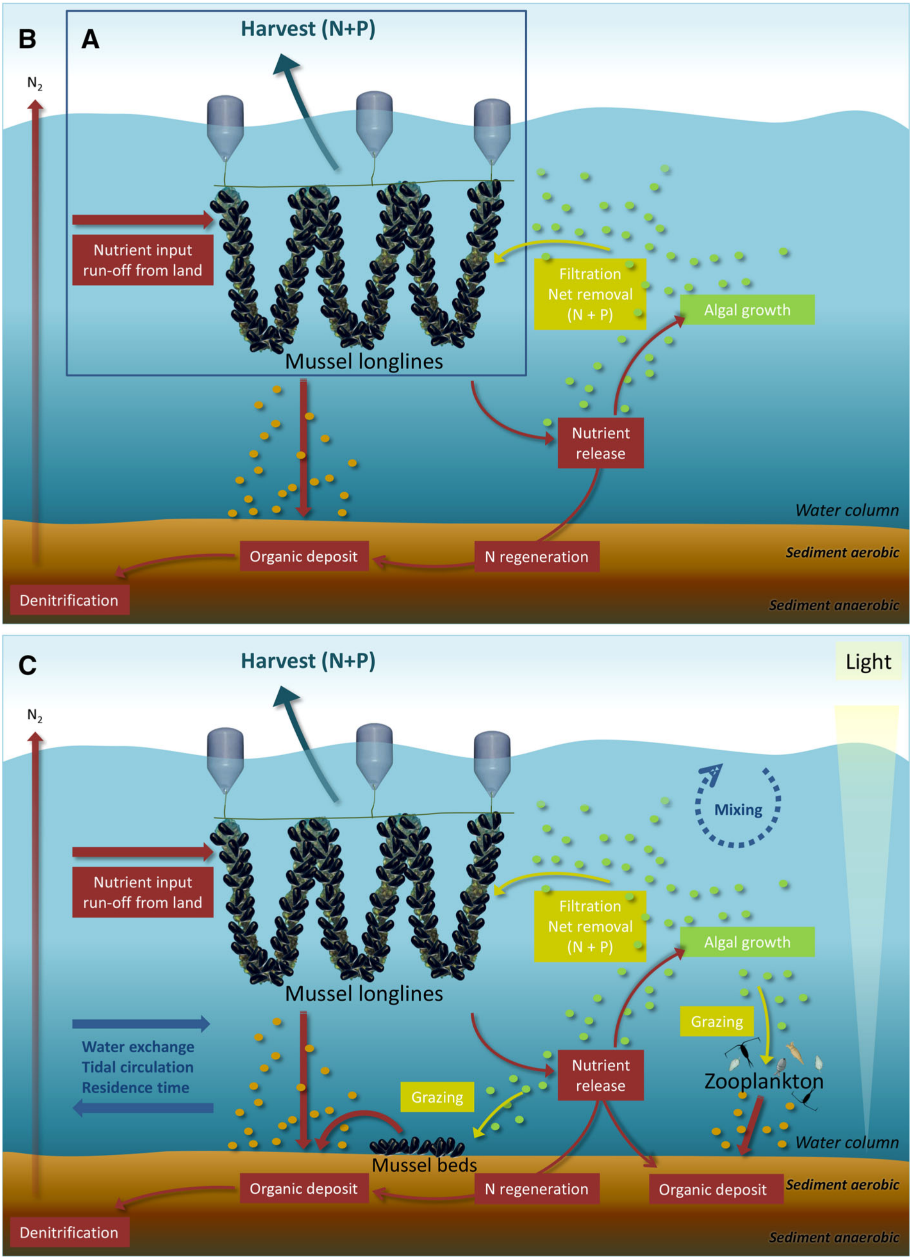


**Fig. 1** **A** Basic principle of mitigation cultures: Harvesting mussels extracts nutrients from the marine environment, **B** nutrient cycling in relation to mitigation culture of mussels; **C** system scale approach to mitigation culture

Lindahl and Kollberg 2009; Weber et al. 2010). Nutrients in the marine environment are being taken up by the mitigation crop (e.g. mussels) and returned to land after harvest of the crop (Fig. 1A). Back on land, the mitigation crop can be used for various purposes, e.g.

food, feed or other (see later). Depending on the purpose, some of the collected nutrients may enter the loop again. Mitigation, bioremediation, bio-extraction, bio-harvesting, agro-aqua recycling or compensation culture thus intends to remove nutrients from the aquatic environment based on a mass balance perspective in the recipient water body, and not as a physical filter removing nutrients from a point source. There is as such no direct link between the nutrient emitter and the mitigation action, e.g. between a specific agricultural farmer and the mussel farmer in the coastal water receiving nutrients from the fields in the catchment area. Mitigation cultures using mussels have also been associated with marine point sources like farming of fed cultivated animals, i.e. fish and shrimps, where mussel production in relation to, e.g. fish farms, has been suggested as integrated multi-trophic aquaculture (IMTA) (Chopin et al. 2001; Troell et al. 2009). Mussels, however, only capture nutrients in particulate form, primarily as phytoplankton, and will only to a limited extent be able to directly use the nutrients emitted from a fish farm. Further, due to hydrodynamic constraints, mussels in IMTA farms will have difficulties filtering major parts of the particulate waste material released from the fish farms (Cranford et al. 2013). Hence, the mitigation of nutrient release from a fish farm in IMTA farms also works on the mass balance principle, and not as a measure to remove exactly the nitrogen (N) and phosphorous (P) molecules released from the fish farm (Cranford et al. 2013). The consequence of this basic understanding of mussel mitigation cultures is that in order to be as area-intensive and cost efficient as possible, mitigation cultures should be operated to realize maximal potential for nutrient extraction, amounts of N and P removed through harvest of the mussels, rather than proximity to the (point) source of the nutrients.

Another implementation of bivalve production as a mitigation tool is the establishing or restoring of bivalve beds, e.g. oyster beds. Aims of bivalve reef creation include habitat formation, but many also relates to the expected goods and services provided by dense beds of benthic suspension feeders, i.e. increased water transparency, temporal burial of nutrients in stable bed structures and enhanced denitrification (Pollack et al. 2013; Kellogg et al. 2014). Several studies have, however, shown that the nutrient removal from restored benthic bivalve reefs might not be as efficient as initially thought (Carmichael et al. 2012 and ref therein), leaving the goods and services provided by this approach to mainly the water clearance potential of the reefs and the habitats they create as well as a variable denitrification component. In stable biogenic (bivalve) reefs, these goods and services will on the other hand be more permanent than in mitigation cultures on long-lines, where harvest of biomass will render the reef creation provided temporary. This will also apply to the water clearance depending on culture practice. If production on a unit is carried out on an annual basis, the gap from harvest in winter or early spring to new settlement in early summer will create a period with no water processing by the specific unit.

Mitigation mussel cultures are different from the present mussel farming for human consumption, which is predominantly recognized as a provisioning (Farber et al. 2006; Maltby 2013; Pollack et al. 2013). Where commercial mussel cultures aim for uniform mussel size, high quality and good appearance and are very dependent on the market, mitigation mussels are produced to remove as much nutrients as possible for as low costs as possible, and the resulting product may not be suited for human consumption due to its size, heterogeneity and appearance. Mussel handling costs are also reduced in comparison with mussel production for human consumption, as the culture cycle can be shorter (<1 year) and with no intermediate handling costs, e.g. thinning or socking of the mussels (Petersen et al. 2014).

The mitigation culture concept has scientifically been tested mainly on pilot scale (Lindahl and Kollberg 2009; Weber et al. 2010; Pacific Shellfish Institute 2014) or through modelling for various bivalve species at both system and local scales (Hart 2003; Nunes et al. 2011;

Ferreira et al. 2014; Saurel et al. 2014), but the modelling has mainly been based on experiences from commercial mussel farming. The use of commercial mussel culture units to estimate the nutrient extraction potential of mussel cultivation is, however, problematic as the culture units are not designed to maximize the production biomass irrespective of its quality, thus underestimating the nutrient removal potential of mussel mitigation cultures. Studies of production of mitigation mussels on full-scale mussel nutrient extractive units are therefore lacking in the literature as well as long-term studies examining the nutrient extractive potential during full production cycles are sparse (Lindahl 2011).

To our knowledge, the only experimental validation on full scale of mitigation culture using mussels has so far been performed in the MuMiHus (Mussels–Mitigation and Feed for Husbandry) project in the Skive Fjord, the Limfjorden Denmark (Petersen et al. 2014). A commercial farm of approximately 19 ha comprising 90 long-lines was rented for the purpose. The unit was situated in the highly nutrient-enriched Skive Fjord, Denmark (Maar et al. 2010), which is a partly mixed estuary with stratification occurring on a scale from days to weeks depending on the freshwater input, radiation and wind mixing (Møhlenberg 1999) and further characterized by high chlorophyll *a* concentrations throughout the year and seasonal hypoxia occurring in late summer (Møhlenberg 1999; Maar et al. 2010). Production of mussels took place on approximately 90 km of settling material deployed in May 2010 and with no intermediate handling of the settled mussels prior to harvesting except buoying up during the course of the production period. Trial harvest on a small subsample of the long-lines took place in October 2010 and March 2011 and final harvest took place in May 2011. By then approximately 1100 t of fresh mussels could be harvested corresponding to 16 t of N and 0.7 t of P.

The efficiency of the culture unit corresponds to a removal of 0.6–0.9 t N $ha^{-1}$ $year^{-1}$ and 0.03–0.05 t P $ha^{-1}$ $year^{-1}$, which is a more area-efficient nutrient removal than most land-based abatement measures like the establishing of wetlands or buffer strips around streams and rivers that is estimated to contribute with 0.1 and 0.04 t N $ha^{-1}$ $year^{-1}$, respectively (Andersen et al. 2012). In the Skive Fjord mitigation, mussel farm spatial variations in mussel biomass were examined throughout the year. The results show that no significant differences in mussel biomass were detected between the three different sections (north, middle and south) in the mussel farm (Fig. 2) as well as between edges and the centre of the mussel farm (data not shown). This indicates that the mussels were not suffering from a general food depletion gradient across the farm, which was also confirmed by food depletion measurements conducted on different spatial and temporal scales (Nielsen 2014). Thus, reduced growth of mussels positioned downstream was not observed in the mussel farm in Skive Fjord as observed/modelled in other mussel cultivation units (Heasman et al. 1998; Fuentes et al. 2000; Strohmeier et al. 2005; Aure et al. 2007; Petersen et al. 2008; Strohmeier et al. 2008; Rosland et al. 2011). Modelling further indicated that the density of the mussels in the culture unit at harvest time could be almost doubled without causing reduced growth, which would improve the nutrient removal significantly (Nielsen 2014).

## Additional ecosystem goods and services

Besides nutrient removal, additional goods and services provided by mussel mitigation culture (Table 1) are primarily related to depletion of seston in and around suspended mussel cultures (e.g. Petersen et al. 2008; Cranford et al. 2014; Newell and Richardson

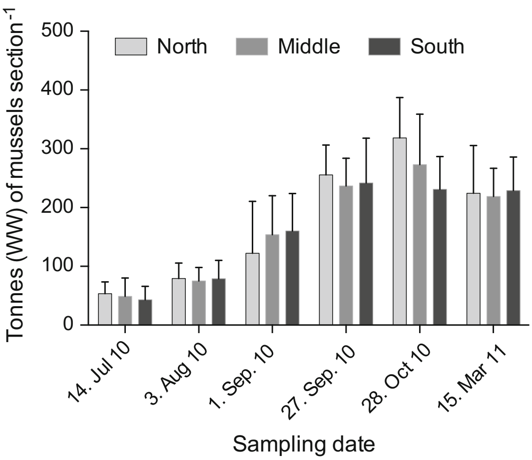


**Fig. 2** Mean ± SD total wet weight of mussel biomass (tonnes) in each of the three sections (*north*, *middle* and *south*) of the mussel culture unit at six different sampling times during the production cycle ($n = 9$ biomass samples of each 1-m culture substrate for each section at each sampling date, except for south at the 15 March 2011, where $n = 5$). Data from Nielsen (2014)

2014). By depleting the water of particles, mussels will enhance light penetration and increase water transparency also outside the specific mussel culture unit (Schröder et al. 2014), thereby providing important goods and services to eutrophic coastal ecosystems. The level of depletion of phytoplankton is highly variable in the different studies depending on measuring techniques and spatial scale but is in the range from 0 to 90 % of upstream seston concentration (e.g. Petersen et al. 2008; Cranford et al. 2014). The variation in magnitude and extension of the phytoplankton depletion is besides measuring techniques applied a result of variations in flux of particles to the mussels and the culture unit configuration including farmed volume, total stock, and stocking density. The flux of particles into the culture will depend not only on particle concentration but also on current velocity, which is affected by the culture unit structures and the mussels themselves by creating turbulence (e.g. Strohmeier et al. 2005; Plew 2011; Stevens and Petersen 2011). The effect of the farm structure on the water column is mainly a modification of the flow pattern, stratification and turbulence in and around the shellfish canopy, but it has been shown that in Danish waters, culture units were not able to mix the water column and disturb stratification (Stevens and Petersen 2011). The actual depletion within and around individual culture units is thus specific for each culture unit and location.

The basin-scale impact of the mussel clearance of the water column will depend on water residence time of the basin in relation to clearance time defined as time needed for the mussel standing stock to clear the entire water column and primary production time defined as rate of renewal of the phytoplankton biomass (Dame and Prins 1998). Eutrophication control by marine bivalves, i.e. when clearance time exceeds residence time or primary production time, has been demonstrated in various ways. Experimentally, it has been shown that under well-mixed conditions, a mussel standing stock with a potential clearance time of 20–35 % day$^{-1}$ of the entire water volume is enough to control phytoplankton biomass under conditions where primary production is not limited by nutrient concentrations (Cloern 1982; Prins et al. 1995, 1998; Wang and Wang 2011). A similar conclusion can be deduced from modelling studies showing that increasing nutrient loading under conditions with high suspension feeding pressure will only marginally change phytoplankton concentration (Herman and Scholten 1990), implying that given the

**Table 1** Ecosystem services of mussel culture, using functions and services modified from Farber et al. (2006) and Pollack et al. (2013)

| Good and services | Description | Benefits | References |
|---|---|---|---|
| Regulating services—maintenance of essential ecological processes | | | |
| Nutrient uptake | Uptake of particulate organic nutrients | Nutrient removal by harvest of mussel biomass. Temporally immobilisation of nutrients | Stybel et al. (2009), Lindahl (2011), Petersen et al. (2014) |
| Water filtering | Filtering of water by mussels | Reduced seston concentration, increased light penetration | Petersen et al. (2008), Cranford et al. (2014), Nielsen (2014), Schröder et al. (2014) |
| Habitat | Farm structure create habitat in water column | Increased biodiversity, fish and invertebrate habitat | Murray et al. (2007), D'Amours et al. (2008), Wilding and Nickell (2013), Holmer et al. (2014) |
| Provisioning—natural resources and raw material | | | |
| Food | Mussels for human consumption | Commercial and subsistence harvesting | Lindahl (2011), Petersen et al. (2014) |
| Feed stuff | Processed mitigation mussels for feed | Protein source for pigs and poultry | Jönsson and Elwinger (2009), Jönsson et al. (2011), Nørgaard et al. (2015) |
| Raw material | Fertilizer<br>Shells for building | Organic compost<br>Road base, chicken calcium supplement, cosmetics, spat collectors, smoke gas cleaning | Olrog and Christensson (2008), DSC pers. comm. |
| Cultural services—enhancing emotional, psychological, and cognitive well-being | | | |
| Recreation | Mussel unit attract birds and fish<br>Cleaner water | Fishing, birdwatching, snorkelling<br>Bathing | The dissemination centre at the Danish Shellfish Centre[a] |
| Science and education | Use of natural areas for scientific and educational enhancement | Outreach dealing with research about nutrient removal, educational programme, seafood festivals | The dissemination centre at the Danish Shellfish Centre |

[a] DSC dissemination centre is the communication centre from Danish Shellfish Centre, DTU Aqua http://www.skaldyrcenter.dk/ organizing visits of mussel farms, education on biodiversity/mitigation culture/ecology, communication, seafood festival

sufficient capacity, mitigation cultures can act as control for effects of nutrient enrichment like increased phytoplankton biomass if no shift in the phytoplankton community is observed in favour of pico-plankton that is not efficiently filtered by mussels (Riemann et al. 1988; Riisgård 2001). Exceeding production carrying capacity of the mitigation cultures—i.e. reaching a situation where mussel productivity is reduced due to shortage of phytoplankton—is not a major concern in mitigation cultures as it is in commercial mussel production—it can almost be considered an objective, because the aim of the cultures is to remove nutrients and improve water transparency. In any case, heavily nutrient-enriched systems being of interest in this context will require a lot of mitigation cultures in order to reach production carrying capacity. In the inner parts of the Limfjorden, N load is approximately 1600 t N $year^{-1}$, while mean summer concentration of chlorophyll *a* is 11 $\mu g\ L^{-1}$, and reductions of approximately 50 % is required in order to obtain good ecological status (Erichsen et al. 2014).

Few studies have tried to estimate the goods and services provided by mussel mitigation cultures. In the Skive Fjord, the filtration of particles by the mussels resulted in reduced chlorophyll *a* concentrations as well as improved light penetration. The effects were most pronounced within the farm where summer chlorophyll *a* concentrations were reduced by 30 %, and Secchi depth was improved by 16 % relative to a reference situation without line mussels. However, according to model results, the environmental effects of mussel filtration were not only evident on farm scale but also on basin scale (Fig. 3), and the affected area even reached the shoreline potentially increasing the suitable areas for submerged vegetation. A similar conclusion was obtained from an experiment in Kiel Bay showing increased Secchi depth in waters adjacent to a small (0.6 ha) mussel farm (Schröder et al. 2014). The environmental impacts on basin scale are depending on mussel biomass, the number and location of the farm(s) and the water circulation patterns in the estuary. Phytoplankton biomass and abundance—in many member states applied as chlorophyll *a* concentration—as well as light penetration are important indicators for assessing ecological status, e.g. according to the EU Water Framework Directive and since mussel filtration has a positive influence on both indicators, the introduction of mitigation cultures may thus have direct impact on the Water Framework Directive score. Furthermore, model estimations (Nielsen 2014) indicate that the mussel stock within the mitigation farm in Skive Fjord could be doubled without reaching the lower algae concentration threshold of $\sim$0.5 µg chlorophyll *a* $L^{-1}$, where mussels reduce significantly or stop feeding in certain systems (e.g. Riisgård et al. 2003; Saurel et al. 2007). Thus, in such highly nutrient-enriched systems, the mussel filtration potential of the farm could be increased in this highly nutrient-enriched system and thereby improve the environmental conditions on a basin scale by optimization of the farm design.

## Nutrient cycling

A major objection against mitigation cultures using mussels is the effects of increased sedimentation under the culture units. Stadmark and Conley (2011) claimed that the increased sedimentation of faeces and pseudofaeces under mussel farms leading to

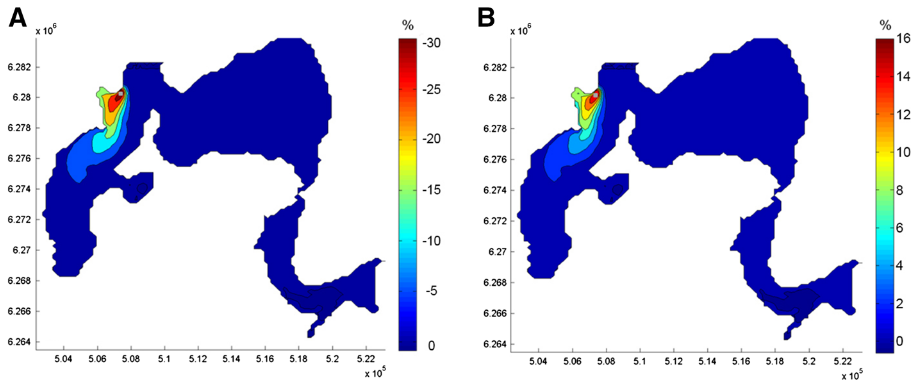


**Fig. 3** Modelled spatial effects of **a** reduced summer chlorophyll *a* concentration and **b** improved summer Secchi depth due to mussel mitigation culture (marked with a *grey square*). Results are shown as the difference (in %) relative to a situation without a mussel farm. The model grid is in UTM coordinates (meters)

increased sediment oxygen consumption and release of ammonia and phosphate together with reduced denitrification potentially could lead to more nutrients being released into the water column from the sediments than being removed through harvest of the mussels. Effects of increased biodeposition below mussel culture units have been reported (e.g. Carlsson et al. 2009), but the arguments presented by Stadmark and Conley (2011) fail to include mass balance considerations and does not take into account that mussel biodeposits are not the main driver for benthic processes in nutrient-enriched waters (Petersen et al. 2012; Rose et al. 2012).

Ingestion of particulate matter by the mitigation mussels will result in mussel tissue, excretion of dissolved nutrients and release of faecal material from the mussels (Fig. 1B). Some of the released faecal material will be consumed by associated fauna on the production lines (Tenore et al. 1985), and the remainder will lead to increased sedimentation of organic material below and in the vicinity of culture units (Dahlbäck and Gunnarsson 1981; Hatcher et al. 1994; Grant et al. 1995; Hartstein and Stevens 2005; Carlsson et al. 2009, 2012). Actual relative increase in biodeposition rate under culture units will depend on physical transport parameters like current velocity and water depth (Chamberlain et al. 2001), production volume (e.g. Carlsson et al. 2009) and season (Cranford and Hill 1999; Carlsson et al. 2009) and level of ordinary sedimentation and resuspension in the specific area (Holmer et al. 2014). Irrespective of the actual increase in biodeposition below culture units, it should be noted that the introduction of mitigation cultures in the water column results in a net reduction in total biodeposition on a basin scale. In the Skive Fjord, mussel filtration and the subsequent production of faecal material resulted in an increased biodeposition below the culture unit, but according to model results, the increased local biodeposition was, however, counterbalanced by a decreased sedimentation outside the unit due to the removal of organic particles from the surrounding waters, and the effects on basin scale were a net reduction in total sedimentation (Timmermann et al. 2015). On longer timescales, the basin-scale reduction in sedimentation may lead to a reduced internal loading of nutrients.

Decomposition of the mussel faecal material can increase the oxygen demand in the sediments and create an anaerobic environment promoting ammonification and sulphate reduction, all classic sediment responses to organic enrichment in nutrient-enriched areas (Cloern 2001). A number of studies have thus documented organic enrichment of sediments, increased oxygen uptake and ammonia release, increased nutrient concentrations, reduced redox potential and increased sulphate reduction rates under mussel culture units (e.g. Dahlbäck and Gunnarsson 1981; Kaspar et al. 1985; Gilbert et al. 1997; Chamberlain et al. 2001; Stenton-Dozey et al. 2001; Christensen et al. 2003; Hartstein and Stevens 2005; Giles and Pilditch 2006; Carlsson et al. 2012). Although increased input of organic material to the sediment initially may enhance denitrification and thus promote natural removal of bioavailable nitrogen, more extreme loading can lead to inhibition of denitrification under culture units (Christensen et al. 2003; Carlsson et al. 2012). The severity of the impact of increased biodeposition has not been consistent among studies ranging from severe impacts on all examined parameters (Nizzoli et al. 2006) to low impacts on only few of the parameters (Hatcher et al. 1994), and some studies could not detect any significant effects (Crawford et al. 2003). The inconsistency is not surprising because benthic effects are influenced by a range of factors such as local hydrodynamics (Chamberlain et al. 2001), benthic macro fauna (Grant et al. 1995) and seasonal variation (Mazouni et al. 1996; Giles and Pilditch 2006; Nizzoli et al. 2011). Of particular interest in relation to mitigation culture is that the nutrient status of the benthic system is important for the additional effect of organic enrichment provided by mussel culture units. If for instance, the sediments in the culture are already organically enriched or the area is frequently subjected to oxygen depletion, the effects under the culture units will be more difficult to predict (Holmer et al. 2014). In any case, water column hypoxia or anoxia can hardly be introduced exclusively under mussel culture units but must be the result of benthic oxygen uptake on a basin scale (Petersen et al. 2012) or imported from other areas.

In the western part of the Limfjorden, it has been shown by studying several culture units that mussel farming will lead to increased sedimentation and sediment fluxes also in highly eutrophic areas and that the sediment oxygen uptake and ammonia flux below the culture units will depend on sedimentation rate (Carlsson et al. 2009). However, below the culture unit used in MuMiHus, the picture was not equally clear. Although increased sedimentation rate was documented, the ammonium fluxes below the culture unit were in two (August, March) out of three seasons into the sediment, and only in May, almost 1 year after deployment, the ammonium flux was out of the sediment and higher below the unit compared to a nearby control (Holmer et al. 2014). The fate of the ammonium in the sediment was most likely nitrification, and as there was no efflux of nitrate, nitrate was probably consumed in denitrification. This is in line with a previous study showing significantly increased denitrification below a mussel farm slightly north of the experimental farm (Fig. 4) compared to a reference area, implying that even in sediments with high organic content, additional increased sedimentation of mussel bio-deposits did not result in stop of denitrification. These results show that effects of biodeposition processes are not straightforward in enriched sediments (Holmer et al. 2014). Further, the smaller mussels of the mitigation cultures compared to cultures of mussels for human consumption can be expected to have higher assimilation efficiencies resulting in less faecal matter production (Holmer et al. 2014).

Excretion of dissolved nutrients from the mussels farming will make principally inaccessible particle-bound nutrients available for primary production. Mussels as facilitators of this bottom-up control in coastal areas have mainly been studied in relation to dense benthic mussel beds (Fréchette et al. 1989; Asmus and Asmus 1991; Asmus et al. 1992; Dame 2012 and references therein), showing that direct excretion from the bivalves can account for 17–94 % (Prins and Smaal 1994) of the total ammonium flux from mussel beds resulting in measurable increases in water column concentration of ammonium on larger scale (Haamer and Rohde 2000). For bivalve farming in the water column, increased water concentrations of ammonium and phosphate have been reported from intense culture areas in France (e.g. Mazouni et al. 1998, 2001; Souchu et al. 2001), leading to significant contributions to the ambient pool of dissolved organic and inorganic nutrients (Nizzoli

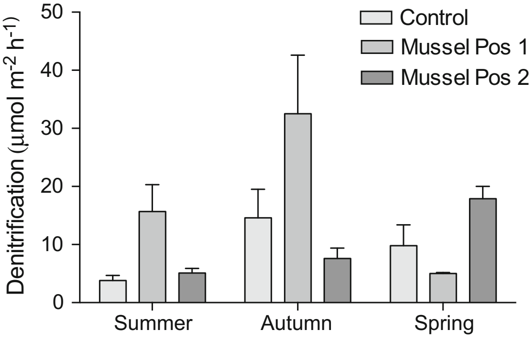


**Fig. 4** Denitrification (µmol $m^{-2}$ $h^{-1}$, $n = 5 \pm$ SD) in an area outside (control) and at two different positions (Pos 1 and 2) underneath a mussel farm in the northern part of Skive Fjord at three different sampling times in 2006–2007 [data from Petersen et al. (2010)]

et al. 2011; Jansen et al. 2011). The nutrients excreted in the water column by mussel long-line cultures are highly variable depending on season, temperature and size of the mussels (Richard et al. 2006; Cranford et al. 2007; Jansen et al. 2011; Nizzoli et al. 2011; Jansen et al. 2012) with 20-fold differences between summer and winter (Jansen et al. 2011). Increased water column nutrient concentrations in mussel culture operating under eutrophic conditions have been more difficult to detect. In the Skive Fjord, a season-dependent response was detected, with highest rates in early summer and similar to rates observed in studies under less eutrophic conditions (Holmer et al. 2014). Water column fluxes contributed more to nutrient regeneration in the MuMiHus culture unit than sediment fluxes, but Holmer et al. (2014) concluded that the impact of the contribution of the released inorganic N from the mussels on primary production in the Skive Fjord was uncertain, as primary production in the Skive fjord is already very high.

In summary, mussel farming may stimulate nutrient regeneration, either by faster mineralization rates in the sediment or through transformation of particle-bound nutrients to dissolved nutrients in the water column. As mitigation culture will be most relevant in heavily nutrient-enriched and hence disturbed systems, focus should be on the nutrient removal capacities through harvest rather than the nutrient immobilization capacities of stable populations of bivalves.

## Site selection

The efficiency of mitigation cultures depends on local environmental conditions making site selection essential for a cost-efficient removal of nutrients. Site selection based on a multi-criteria approach can be used as a tool for identifying the most appropriate mitigation culture sites. The multi-criteria approach include a suite of environmental variables known to affect mussel growth and long-line mussel production as well as variables addressing socio-economic aspects of mitigation cultures (Hossain et al. 2009; Falconer et al. 2013) following "a strategy for the integration of the activity within the wider ecosystem in such a way that it promotes sustainable development, equity, and resilience of interlinked social and ecological systems" (Soto et al. 2008) (Fig. 1C).

Recommendations for a multi-criteria site selection tool for mitigation culture based on the Danish experience are summarized in Table 2. A basic requirement is a minimum water depth of 4–5 m, which allows for 2 m of droppers and at least 1 m buffer zone both below the water surface and above the seabed. The surface buffer zone is required in order to avoid conflict between potential ice cover and the mussels, whereas the bottom buffer zone will prevent predators such as starfish to invade the long-lines and furthermore protect the mussels from sediment induced hypoxia known to occur in eutrophic coastal areas. Another important criterion is the food availability. In many nutrient-enriched Danish waters, food supply is sufficient (>5 μg chlorophyll *a* $L^{-1}$) to sustain maximum mussel growth rates but even at concentrations down to 3 μg chlorophyll *a* $L^{-1}$, mussel production will not be significantly reduced (Clausen and Riisgård 1996) provided proper water exchange rates. Danish waters exhibit a wide range of salinities potentially influencing mussel growth, and dynamic energy budget (DEB) model adapted to low and varying salinities was used to determine a minimum threshold for efficient growth of 13 PSU (Maar et al. 2015). Besides environmental variables directly influencing mussel growth rates, a successful mussel production also depends on spat availability and predation. Natural recruitment of *Mytilus edulis* is preferred in order to minimize transportation costs and avoid introduction of diseases and invasive species (Rosa et al. 2013), and hence, a wild

**Table 2** Variables used for site selection of mussel mitigation culture in Denmark

| Criteria | Danish thresholds |
|---|---|
| *Physical* | |
| Bathymetry | Minimum 4–5 m |
| Wave action | Coastal areas with a minimum fetch |
| Residence time | Coastal areas with eutrophication symptoms usually have long residence time |
| *Water quality* | |
| Temperature | 0 < temperature < 25 °C, ice coverage do not stop mussel production |
| Salinity | >13 PSU |
| Chlorophyll *a* | >3 $\mu g\ L^{-1}$ all year long for eutrophic areas |
| Dissolved oxygen | Short long-lines above zone of anoxic conditions |
| *Species* | |
| Natural recruitment | Mussel spatfall naturally occurring in the area |
| Predation/fouling | Low level of predation and fouling |
| *Socio-economic* | |
| Marine spatial planning | Conflict of interest with other activities; Social acceptance |
| Harbour/distribution | Logistics and facilities close to the mussel farm for product distribution |
| Use of the raw material | Defined end product food, feed or fertilizer processing close to the farm |

stock of mussels is required to ensure in situ spat production. Mussels grown on long-lines are to some extent protected from epibenthic predators, whereas eider ducks can be a fierce predator for mussel long-lines (Varennes et al. 2013). Although it is possible to protect mussels grown in the water column from eider duck predation, it is associated with additional costs and sites with high presence of eider ducks should be reconsidered. Sites exposed to strong wind and wave action are excluded in order to prevent investment in expensive wave-resistant farm structures. By combining the most important variables for mussel growth and production, it is possible to select sites, which from a biological point of view are suitable for mussel mitigation purposes. Another important aspect in the multi-criteria approach is the possibility to include variables important for marine spatial planning (Douvere 2008) to avoid conflict of interest with other activities (Tiller et al. 2012) as well as to obtain social acceptance from the local population by selecting sites with minimum visual impact of the farms and limited recreational use of the area (Perez et al. 2003; Kumar and Cripps 2012; Falconer et al. 2013).

## Economic aspects of mitigation mussel production

Farming mussels for mitigation purposes is not in its origin developed as a commercial production but as a management tool to reach environmental goals for coastal waters. Costs of the nutrient removal using mitigation cultures are thus important. Cost efficiency of the mitigation culture in the Skive Fjord is compatible with most of the abatement measures in the catchment to the Skive Fjord, especially if it is taken into consideration that many of the land-based measures are already partly in use, and certainly the most cost-efficient measures, and thus have a limited capacity for additional reduction in nutrient load (Hasler et al. 2015). The costs of implementing additional land-based abatement measures are thus increasing at the margin, making mussel mitigation cultures a cost-efficient tool in Danish coastal waters (Petersen et al. 2014). The calculated costs for the nutrient removal in the Skive Fjord did not include any potential income or costs associated with the disposal of the mussels once harvested. Whether the mitigation crop can be considered a potential income or a waste disposal problem, it is important for turning mussel culture into a realistic management tool for improving the coastal environment that there are feasible plans for disposal of the harvested biomass.

The main focus of farming mitigation mussels is to recycle nutrients from sea to land as cost efficient as possible. Any intermediate handling of the mussels, e.g. socking, which will increase costs without increasing biomass, is not a part of mitigation mussel farming, and the resulting mussel crop will thus be heterogeneous. In an additional, subsequent study, it was shown that of the MuMiHus mussels harvested in May 2011, up to 65 % of the harvested mussels could be used by industry for processing to cooked mussel meat (Petersen and Mattesen 2011). The meat clump of the harvested mussels was 1.5–2.0 g wet weight after cooking, which is a suitable size for canning or frozen products (Petersen and Mattesen 2011), but it was estimated that the industry would only be able to process up to 6000 t mitigation mussels annually, which will not be sufficient for mitigation cultures to be more than a marginal mitigation measure. Further, the remaining 35 % of the harvest would still have to be disposed of.

There is a worldwide demand for alternative and more sustainable fish feed in the aquaculture industry as well as for organic feed for organic husbandry (Jönsson and Elwinger 2009; Naylor et al. 2009). Mussel (*Mytilus edulis*) meat is an interesting alternative to fishmeal, as the mussels have a high content of protein (Fig. 5) with an amino acid pattern similar to fishmeal (Berge and Austreng 1989; Jönsson and Elwinger 2009). Thus, mitigation mussels can potentially become an alternative protein source to replace fish and soybean meal as a component in diets for fish (Berge and Austreng 1989; Anagnostidis et al. 2015), pigs (Nørgaard et al. 2015), poultry and egg production (Jönsson and Elwinger 2009; Jönsson et al. 2011). The main problem with mussel meal is that the production costs are too high to compete with fishmeal on a strictly commercial basis (Petersen et al. 2015). A test production of mussel meal using growing techniques as described in the MuMiHus project, processing the mitigation mussels by separation of shell from meat through steam cooking and subsequent processing of the meat to mussel meal resulted in prices 15–50 % higher than current market prices for fish meal, taking the protein content into consideration when calculating the equivalent price (Petersen et al. 2015). However, the major costs with the production of mussel meal were not in the

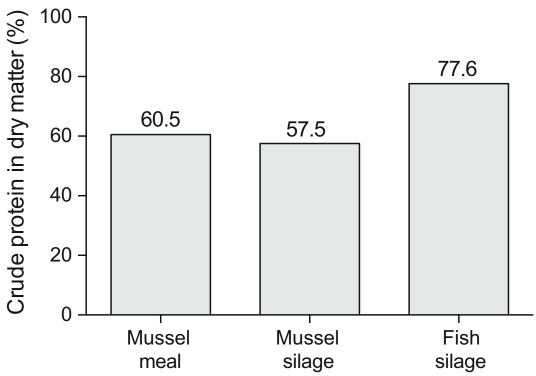


**Fig. 5** Protein content of mussel products from mitigation approximately 10-month-old mussels harvested in March [data from Nørgaard et al. (2015)]

processing but in the production of the mussels, implying that rewarding the mussel producer for the goods and services provided by the mitigation culture, e.g. through a nutrient trading system (e.g. Lindahl et al. 2005), will make mitigation mussel production of mussel meal economically viable and a cheap mitigation measure. Alternatively, as mussel meal may be certified as organic, it will be a suitable protein source in organic husbandry (Lindahl 2011) where there will be a willingness to pay higher prices for protein-rich organic feed components with the right amino acid profile.

An important aspect with regard to mussels as a protein source in feed is the potential risk of contamination with bio-toxins, pathogens such as bacteria and viruses and harmful substances like heavy metals. The majority of bacteria and viruses will be eliminated during processing for feed and will not constitute a problem. Regarding the mussel toxin ocadaic acid, no ill effects on production parameters was reported, when poultry were fed mussels containing ocadaic acid just above the tolerance limit for human consumption (Jönsson and Holm 2010). Occurrence of heavy metal was not a problem for the mitigation mussels produced in the Skive Fjord as the concentrations of the different heavy metals were below threshold for human consumption and feed (Table 3 in Petersen et al. 2014). However, contamination of the mussel meat will be site specific and in any case require local studies as part of the site selection process.

Alternative use of the mitigation mussels could be as e.g. fertilizer (Olrog and Christensson 2008; Lindahl 2011) or biogas, but the less the unique qualities of the mussel meat is utilized, the lower the prize for the mussels can be expected and the more the costs of the mitigation culture will have to be paid by the nutrient emitters.

## Mitigation culture: future perspectives

The use of mitigation measures in the recipient water body rather than eliminating or reducing emissions at the source of the pollution raises political considerations. In the case of well-defined point sources like sewage treatment plants, where affordable technological solutions for nutrient removal are in place, mitigation in the recipient water body based on mass balance principles cannot be considered a reasonable measure, as the nutrients can be removed at the source. In the case of diffuse sources of nutrient run-off from land to the coastal area or atmospheric deposition, abatement or mitigation is not likewise straightforward. Any form of cultivation of the land will result in some level of excess loss of nutrients from land to the coastal environment, and removing all the excess nutrients at the source is either technological impossible or not cost efficient (Hasler et al. 2015). Most land-based abatement measures like catch crops and wetland reconstruction reflects this dilemma, as they neither can be considered as direct intercepting filters of emitted nutrients. Mitigation in the marine environment is furthest from the source of the land-based nutrient emissions and will not abate or mitigate effects of excess nutrients used in agriculture on groundwater reservoirs or freshwater systems. However, extractive cultures are the only documented measure for dealing with internal loading from sediments, which in some areas can be a major part of the total nutrient loading (Christensen et al. 1994). Further, extractive cultures in the marine environment will recycle vital nutrients inevitable lost from land back to land. In this context, it is worthwhile noticing that P is becoming a limited resource and that extraction of N is energy demanding. In relation to, e.g. the EU Water Framework Directive, it is worth noticing that it is the environmental goals in the marine environment set by the directive rather than the source of the problem(s) that the efforts are measured upon. Hence, measures mitigating internal loading might become necessary to reach set water quality goals. In the special case of IMTA, it is important for the future use of mussel mitigation cultures in relation to open sea fish farming that authorities recognize that it is impossible to filter nutrients off at fish farm point sources and that mitigation cultures also in this context operates on the mass balance principle. If pre-conditions for expanding off-land fish farming are mitigation of associated nutrient emissions using extractive cultures, these will not necessarily be most efficient in the near proximity of the fish cages.

In Europe, mitigation using bivalve cultures has mainly been a topic in the Baltic region. In the SUBMARINER network (http://www.submariner-network.eu/index.php) for sustainable use of marine resources, mussel production is seen as a contribution towards counteracting eutrophication, and up to 13 trial sites have been reported in operation for the last decade cultivating both *Mytilus edulis* and *Dreissena polymorpha* (Lindahl et al. 2012). The results from these trials are sparse with preliminary results indicating that mussels in the Baltic due to the low salinity require much longer time to attain harvestable size (2–2.5 year) compared with mussels on the Swedish west coast (1–1.5 year) or the Limfjorden, Denmark (<1 year), but mussel mitigating cultures can still be useful (Lindahl et al. 2012). Stybel et al. (2009) concluded from a feasibility study of using *Dreissena polymorpha* for mitigation purposes in the Oder Lagoon, that the low economic benefits from culturing the mussels would require alternative financing strategies in order to install mitigation cultures in the lagoon. For the heavily nutrient-enriched Baltic Sea, recovery of nutrients through extractive cultures is an obvious supplementary mitigation measure, but the low salinity of the Baltic proper makes the mitigation less effective and thus puts more emphasis on generating income from the mitigation mussel crop in order to make it a cost-efficient tool (Stadmark and Conley 2011; Rose et al. 2012).

From a worldwide perspective, nutrient enrichment of coastal waters is a problem occurring in almost all parts of the world (Diaz et al. 2011), and extractive cultures using e.g. mussels could be an alternative tool in mitigating the effect of the excess load of nutrients. In a European perspective, excess nutrient loading is a problem all along the European coastline and encompassing all European seas from the Baltic to the Black Sea. In the Netherlands, France, UK, Spain, Italy and Greece, local expertise in mussel production is available from commercial farming of mussels for human consumption, and build-up of expertise will not be required to the same extent as in the Baltic proper, where no experience with mussel production were available. It is, however, mainly in North Europe and specifically in the Baltic region that mitigation cultures are discussed. In the USA, mitigation of nutrient enrichment of coastal waters using bivalves has had focus on oyster reef restoration, which by definition is an ecological restoration (Palmer and Filoso 2009; Beck et al. 2011). Oyster reef can mitigate effects of nutrient enrichment and restore ecosystem good and services (i.e. habitat restoration, food supply for predators and denitrification, Newell et al. 2005; Kellogg et al. 2014 and references therein) but do not remove nutrients from the sea back to land. On the other hand, oyster aquaculture for food consumption is efficient to remove nutrients back to land (Higgins et al. 2011). In Canada, there is extensive experience with mussel farming, and in many areas, e.g. Prince Edward Island, the extensive mussel farming can be related to nutrient run-off from land (Meeuwig 1999; Cranford et al. 2007). In Asia, there is practical experience with IMTA or polyculture (Neori et al. 2004) although these cultures have not been installed for mitigation purposes from run-off at first but in order to use excess nutrients for food production purposes (Nunes et al. 2003). A starting point for the use of extractive cultures, like mussel farming, for mitigating effects of excess nutrient load to coastal waters could be to recognize that productive mussel farming on the one side relies on a nutrient-rich environment and on the other side that mussel farming in itself provides some goods and services to the ecosystem. Bivalves grown for provisioning can thus also be considered as a mitigation tool. Whether the goods and services provided by this shall be rewarded will depend on local conditions like the environmental status on the water body, water body environmental goals and possibilities for abatement measures in the catchment. In a next step, strategies to develop mussel cultures with the sole purpose of mitigating effects of nutrient enrichment can then be developed, e.g. for coastal areas where mussel farming for provision has not been developed or where the commercial farming does not contribute sufficient to meet environmental goals.

**Acknowledgments** The authors acknowledge support from the Danish Council for Strategic Research for the Mussels–Mitigation and Feed for Husbandry (MuMiHus) project, Grant Agreement No. 09-066983 and all our colleagues participating in the project.

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