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Policy guidelines for implementation of mussel cultivation as a mitigation measure for coastal eutrophication in the Western Baltic Sea

By the BONUS OPTIMUS consortium

DTU Aqua Report no. 362-2020

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Edited by Jens Kjerulf Petersen and Daniel Taylor

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Colophon

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DTU Aqua
Report no.: 362-2020

Year: April 2020

Reference: Petersen, JK (ed.), Taylor, D (ed.), Bergström, P, Buer, A-L, Darecki, M, Filippelli, R, Gren, I-M, Hasler, B, Holbach, AM, Nielsen, P, Petersen, LK, Lindegarth, M, Lund, I, Maar, M, Ritzenhofen, L, Sagan, S, Saurel, C, Schernewski, G, Stybel, N & Timmermann, K 2020, Policy guidelines for implementation of mussel cultivation as a mitigation measure for coastal eutrophication in the Western Baltic Sea. DTU Aqua.

Cover photo: © Danish Shellfish Center, DTU Aqua

Published by: Danish Shellfish Centre, National Institute of Aquatic Resources, Øroddevej 80,
7900 Nykøbing Mors, Denmark

ISBN: 978-87-7481-285-2

Preface

In this document, we present a synthesis of updated documented experience in the implementation of mussel cultivation for mitigating effects of eutrophication and parameter estimates to facilitate potential application in coastal water management plans. Included are descriptions of potential for nutrient extraction, ecological effects, and economics of mussel cultivation. The documentation presented is primarily gathered in the BONUS OPTIMUS project as well as in some nationally funded projects on mussel farming or mussel mitigation farming including project participants, while data from other projects is only included to a lesser degree.

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Photo: DTU Aqua

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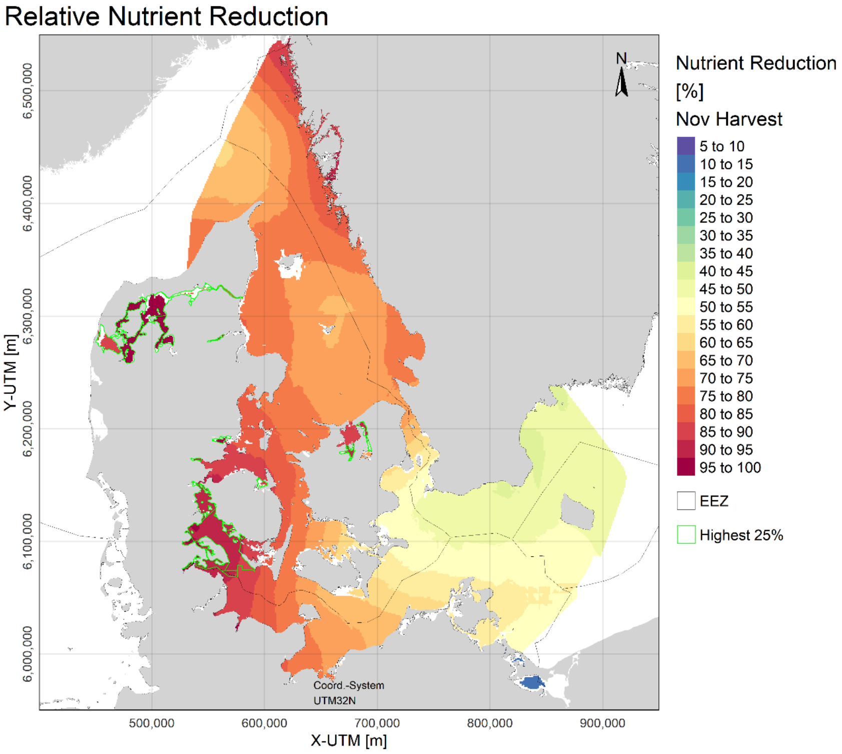
Executive Summary

Bivalve cultivation has been proposed as a means to reduce the effects of eutrophication within coastal waters. The Baltic Sea presents a useful case study in the application of marine mitigation measures due to persistent eutrophic conditions. The BONUS OPTIMUS project (2017-2020), comprehensively evaluated mussel cultivation in the western Baltic Sea area as a marine mitigation tool in terms of optimization of nutrient extraction, economics, social acceptance, and potential ecological impacts. The findings from this project and previous research, are presented here as guidelines to facilitate decision-making and implementation of mussel cultivation for mitigating eutrophication.

For decades, Baltic countries have implemented measures to mitigate nutrient emission to coastal waters with varying degrees of efficacy. Despite many successes, diffuse nutrient emissions are still exceeding reduction targets and internal nutrient loading continue to maintain most Baltic waters in poor ecological condition with persistent eutrophic characteristics; falling short of environmental objectives outlined by the HELCOM Baltic Sea Action Plan to eradicate eutrophication by 2021 and the EU Water Framework Directive to achieve good conditions in all European waters by 2015 (HELCOM, 2018; Kristensen et al., 2018). Once nutrients are introduced into the marine environment, they are largely transported through the environment as organic particles (spring-autumn), and either exported into neighbouring seas or retained within the ecosystem. Retention within the marine environment is problematic, as land-based mitigation measures cannot remove these nutrients. Mussel mitigation farming reduces the effects of eutrophication directly within the marine environment by extracting nutrients through mussel harvest and provision of ecosystem services related to large-scale filtration and immobilization of organic particles.

Mussels feeding on organic matter transform a portion of digested nutrients into mussel tissue, which is proportional to the total amount of nutrients stored in a given mitigation farm and removed from the ecosystem when harvested. As demonstrated in the BONUS OPTIMUS project, nutrient extraction potential can amount to tons of nitrogen per hectare, which is similar or higher in efficiency than most other mitigation instruments. Concentration of phytoplankton (quantified by the pigment chlorophyll-a) are basic metrics of aquatic ecological health as used in e.g. the EU Water Framework Directive and the Baltic Sea Action Plan (HELCOM, 2018; Kristensen et al., 2018). Mussels actively filter phytoplankton, and as demonstrated in the BONUS OPTIMUS project, the intensity of water clarification around a large mitigation mussel farm can be observed from space. The implication of this service is that water clarity increases locally and can enhance ecosystem processes at the sea floor requiring light, such as sea grass colonization. At the ecosystem scale, intensive filtration within the mitigation farm directly leads to reduced particle concentrations across the basin at rates outpacing nutrient load reductions on land.

Economic analysis conducted in the BONUS OPTIMUS project has demonstrated that mussel mitigation farming can be a new cost-effective marine measure compared to land-based measures in the abatement toolbox. The costs of implementation depend on a variety of factors, including environmental conditions, proximity to the coastline, farm infrastructure, and wages, with decreasing costs according to economies of scale. Compared to other abatement measures, costs of nutrient removal are comparable depending on region, but particularly favourable in terms of phosphorus removal. Costs will depend on use of the produced mussels. Only a smaller fraction of the produced mussels will be suited for human consumption. Mussel meat has been shown to constitute an excellent ingredient in feed for poultry, porcine and salmonid husbandry. However, use of the mussels for feed require complete or partial removal of shells and byssus that is of low feed value. This requires further development of efficient methods. Productivity relative to environmental conditions varies across the western Baltic, and is generally greatest in the higher saline, nutrient rich Danish estuaries, as well as the northern Swedish Kattegat coast.



Mitigation potential (%) for a standard mussel farm covering 18.8 ha

Implementation is not without challenges. In physical and technical aspects, the retention of mussel biomass until harvest can be jeopardized by exposure to high energy maritime conditions (winds, waves), ice cover, predating animals such as eider ducks and sea stars, or lack of technical expertise. Self-limiting productivity due to the excessive reduction of organic matter is generally considered a positive outcome but requires strategic and ecological considerations. Like most other uses of coastal waters, multiple competing uses can also inhibit placement of mitigation farms in the most effective places. Spatial modelling and site selection are tools that can facilitate the optimal use of coastal waters, balancing biophysical requirements with other priorities and stakeholder input, of which was investigated in the BONUS OPTIMUS project. Intensive production of mussels, as filter feeders, in a confined space immobilizes a large quantity of organic particles, as previously described. A relatively large fraction of the digested material is deposited to the sea floor, where concern has been raised that local oxygen levels and nutrient processes will be harmed. Research conducted in the BONUS OPTIMUS project demonstrated such impacts are limited to a small area within the farm, are minimal in comparison to the harvest nutrient content, and in turn reduce negative effects at the ecosystem-scale, as sedimentation will be reduced on the basin-scale.

Management and control of mitigation farming can take several forms, similar to other abatement measures, such as offsets, direct payment schemes, or credit markets. One advantage of mitigation mussel farming is its lower uncertainty as an abatement measure compared to other measures, since the amount of nutrients removed can easily be measured when the mussels are harvested. While further research is recommended to better refine our understanding of ecosystem services provided by mitigation mussel farms and technological development to suit more environmental conditions with special emphasis the salinity regime of the central Baltic, the results from BONUS OPTIMUS provide the requisite knowledge to sustainably implement mitigation mussel farming. In the following text, we outline the current knowledge of mitigation mussel farming, its potential in the western Baltic, site selection considerations, ecosystem services, management options, and future needs.

1 Introduction

Considerable progress has been made in reducing nutrient loads to combat coastal eutrophication over the past few decades (Boesch, 2019), however, as most of the innocuous measures have been implemented, and due to compiling ecosystem pressures, further mitigation of eutrophication requires multiple concerted measures (Duarte and Krause-Jensen, 2018). The Baltic Sea is a notorious case of the challenges in managing eutrophication, with significant internal nutrient loading, persistent atmospheric deposition, N-fixation in the Baltic proper and low efficacy in further reduction of diffuse nutrients. Additionally, relative to other large estuaries, the Baltic is especially sensitive to compounding effects of climate change (Reusch et al., 2018). Poor ecological conditions in the greater Baltic Sea, where >97% of the region suffers from eutrophication (HELCOM 2018), and in European waters in general, prompted concerted international agreements to reduce nutrient loads, such as the Baltic Sea Action Plan (BSAP) in 2007 (Backer et al., 2010), and the Water Framework Directive (WFD) in 2000 for the EU, requiring all coastal waters to reach Good Ecological Status by 2015-2020s (Borja et al., 2013). For the Baltic Sea, nutrient inputs have decreased since the 1980s but the effects of these measures are generally not yet reflected in the overall status, for example, decreases in chlorophyll-a concentrations; the effects of past and current nutrient inputs still predominate the overall status and therefore most of these water bodies are failing to reach Good Ecological Status (HELCOM, 2018; Kristensen et al., 2018)

As a mitigation tool in the nutrient abatement toolbox, mussel cultivation (*Mytilus edulis, Mytilus trossulus*, and their hybrids) has been proposed as an ecological engineering mechanism to reduce the effects of eutrophication in the greater Baltic area cost effectively (Haamer, 1996; Lindahl et al., 2005; Gren et al., 2009; Petersen et al., 2014). Only recently have large-scale trials been conducted to evaluate the nutrient extraction potential of ‘mitigation mussel cultivation’ (Petersen et al. 2014, Nielsen et al., 2016; Petersen et al., 2019a; Taylor et al., 2019c).

2 Principles and status

2.1 General Concepts

Mussel farming as a mitigation tool is based on a mass balance principle. Nutrients introduced into a coastal water body are assimilated into phytoplankton biomass, which is then consumed by mussels and transformed into somatic tissues. Nutrients are removed from the water body when the mussel biomass is harvested (Petersen et al., 2016, 2019a). In practice, mussels are grown on substrate suspended in the water column, which initially allows settlement of wild mussel spat. Mussels are then maintained on the suspended structure to maximize growth and retention of biomass until harvest. Introduction of hard substrate in the water column provides new habitat for mussel spat, which would otherwise be lost to predation or natural mortality as a minority (<1%) of wild spat are naturally recruited (Barker Jørgensen, 1981; Gosselin and Qian, 1997). This ‘supplementary’ recruitment by adding settling substrate, permits new production and thus independent extraction of nutrients from the water body without the exploitation of wild mussel beds.

Mussel farming for mitigation is situated within the marine environment, the end recipient of nutrient transport from its source, whether that source is point or diffuse. As such, mussel farming is an indiscriminant mechanism of mitigating nutrient enrichment. Fundamentally different than most modes of aquatic food production, such as mussel farming for human consumption, biomass production as a mitigation tool is optimized to yield the greatest total mussel biomass at lowest cost. Efficiency in terms of nitrogen and phosphorus extraction is dependent on local environmental conditions driving growth and accumulation of mussel biomass within the mitigation farm; specifically water depth, phytoplankton concentration, hydrodynamics, temperature, salinity, predation, and recruitment rate of mussel spat (Timmermann et al., 2015, Bruhn et al., 2020). Dependence on wild mussel spat recruitment stipulates this mitigation method is situated in water bodies with relatively abundant wild mussel populations (beds) or in water bodies where larvae is transported from neighbouring water bodies; or an affordable method for hatchery-based seed supply is present.

2.2 Production techniques

Production of mussels for mitigation is adapted from a variety of cultivation techniques established for mussel culture and spat collection. These cultivation techniques are often country or regionally specific due to historical technology transfer and equipment availability. Longline technology and tube-net systems (Figure 1) have been tested at commercial scale for mitigation purposes in western Baltic waters (Nielsen et al., 2016; Taylor et al., 2019c; Hylén et al., 2020). A longline system consists of a series of parallel high-tension spines supporting submerged suspended substrate for mussel settlement, and maintained by with individual buoys. The model setup in Denmark resides in an 18.8 ha space (750 x 250 m) and contains 90 lines of 200m length and shallow substrate, while a Swedish setup is considerably smaller (< 1 ha) but exploits deeper water with longer substrate (Haamer, 1997). The equipment and materials are relatively inexpensive, and buoyancy can be maintained with precision; however, buoyancy maintenance requires greater operational costs. A newer technology consists of 2-3 m x 100m nets suspended from polyethylene tubes (i.e. Smart Farm, Easy Farm systems). Nets are produced with a variety of mesh sizes which dramatically increase substrate surface area available for spat settlement and biomass yield. These require little to no buoyancy intervention but require complicated and expensive harvest machinery. At the present time, in regard to protection against ice coverage, buoyancy control is binary, and thus time consuming, however technological development of controlled submersion is anticipated. Regardless of the technology employed, the production principles of minimal intervention in maintenance and retention of mussel biomass are key to mitigation culture.

Mitigation mussel farming differs from conventional mussel farming (for human consumption) by 1) maximizing total biomass by increasing substrate in the water column, 2) yielding generally smaller mussels, and 3) minimizing intervention steps between spat settlement and harvest. This simultaneously reduces overall cost and increases overall nutrient content of the farm. For further details on technologies, refer to Taylor et al. (2019a, 2019c).

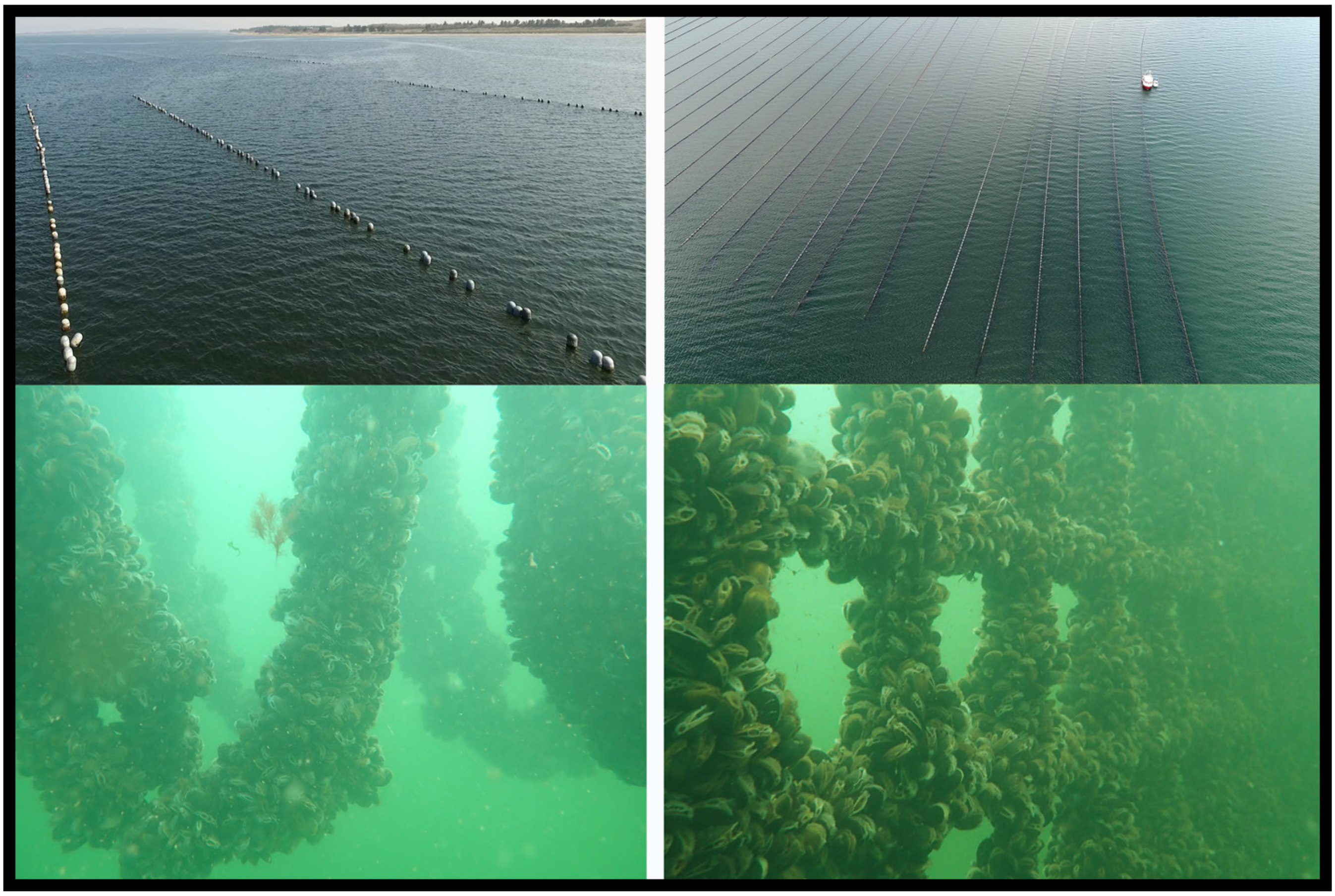


Figure 1. Example mitigation mussel farm setup. Left panel is a standard longline farm from the surface, right panel is a net farm. Example substrates with mussel biomass are shown in lower corresponding panels (Photo: DTU Aqua).

2.3 Production capacity

The production cycle of mussels intended for mitigation depends on mussel growth and optimal harvest conditions, which are again related to local environmental conditions. Production is initialized by spat settlement, which tends to peak between May and late June. Harvest timing aims to maximize biomass yield (nutrient content of the farm) at minimal production costs. Production methods for mitigation purposes have been field tested and optimized in Denmark in full scale farm units (18.8 ha).

The first full scale demonstration of mitigation farming was conducted in 2010 in the eutrophic Skive Fjord, Denmark with a standard longline configuration (see section 2.2.). An estimated 48 t ha^{-1} of mussel biomass was harvestable six months after initial settlement, and up to 59 t ha^{-1} of biomass in the following May (Petersen et al., 2014) and could according to model-estimations be increased to >100 t ha^{-1} in May by increasing substrate density (Nielsen et al. 2016). By increasing substrate density, recent experimentation has increased these estimates up to 96 t ha^{-1} of mussel biomass in a standard commercial farm within 6 months of settlement and little or no gain by delaying harvest until the following spring (Taylor et al., 2019b). Estimations of potential yields from test lines deployed in Danish fjords indicated 64-85 t ha^{-1} can be expected in many Danish coastal waters (Taylor et al., 2019b).

Data from less intensive production, experimental scale longline production, and simulations across the Baltic provide a variety of estimated yields. In the Baltic area, Sweden is the second largest producer of mussels. In western Sweden, configurations and conditions provide maximal yields of 40-47 t ha^{-1} after a 17-20 month production period (Taylor et al., 2019a), while limited production experience and lower salinity in eastern Sweden in the central Baltic demonstrated yields of 20 t ha^{-1} over a 28 month production period (Kotta et al., 2020). Further study along salinity gradients in German waters ranged between 1-51 t ha^{-1} in 6 months, and 0.7-49 t ha^{-1} in 18 months, with higher production proportional to salinity (Buer et al., 2020a). Further reporting from conventional mussel farms in western Sweden exhibit yields between 50-190 t ha^{-1} in 12-18 months (Hedberg et al., 2018).

Adoption of alternatives to conventional longline systems, such as tubes and nets, can dramatically increase areal yields. Initial experimental scale trials in the southern Kattegat estimated up to 130 t ha^{-1} would be possible (Plesner et al., 2015) in under a year, while full-scale monitoring in 2018 at a nearby site estimated yields of 78 t ha^{-1} in 6 months (Hylén et al., 2020). Extensive commercial-scale testing in the Limfjorden demonstrated potential yields of 112-240 t ha^{-1} in a 5-6 month production period, variable by net mesh size and site (Taylor et al., 2019c). A small-scale trial in the northern Baltic proper (Kumlinge) demonstrated 16 t ha^{-1} after 30 months of cultivation (Kotta et al., 2020).

Production potentials are clearly reliant on interacting biophysical factors and cultivation practice. Total substrate surface area is proportional to spat collection and consequently, biomass yield; as such, nets may be more suitable for mitigation purposes. Salinity and food concentrations have direct impacts on mussel growth, where decreasing levels of each tend to extend the production period. Cultivation practice is equally important in defining production potential. Small-scale trials may both overestimate area-specific production capacity as well as underestimate, if cultivation is not carried out by trained and skilled staff. Many small-scale trials, such as those conducted in the central Baltic, have been performed on small test scale without sufficient training in mussel farming as it has not been practiced for commercial purposes in the central Baltic. On the Swedish West coast, mussel farming has not yet been practiced or optimized for mitigation purposes, and areal production capacity from conventional mussel farming cannot be compared directly with optimized mitigation farming results.

2.4 Nitrogen and phosphorus removal

Nutrient extraction is a function of total biomass and proportional content of nitrogen (N) and phosphorous (P), mostly in the soft tissues of the mussel; which is represented by total fresh mussel weight (TFW). Updated nutrient content figures from farmed mussels in Danish coastal waters range from 1.28-1.69% N and 0.07-0.16% P per TFW; including tissue, shell, and byssus. A greater Baltic survey documented 0.67-1.67% N and 0.04-0.19% P per fresh weight mussels with the greatest variability in nutrient content of mussels attributed to position in the water column (suspended vs bottom) and season, with the spring gamete release yielding the lowest contents (Buer et al., 2020b). It is known that tissue weight and biochemical composition can vary due to season, spawning cycle, cultivation mode, and food content (Pieters et al., 1980; Okumuş and Stirling, 1998; Kopp et al., 2005; Pleissner et al., 2012; Fernández et al., 2015; Colombo et al., 2016), as such, nutrient content should be estimated from the total harvested mussel biomass.

Reported N and P areal yields (t ha^{-1}) are variable by production technology, location, and harvest time. Optimized longline configurations in Denmark (Limfjorden) can remove 0.7-1.4 t N ha^{-1} and 0.06-0.09 t P ha^{-1}, while utilizing nets can remove 1.6-3.0 t N ha^{-1} and 0.10-0.17 t P ha^{-1} (Taylor et al., 2019c). In other Danish coastal waters, from Mariager Fjord to Flensborg Fjord, 0.7-1.09 t N ha^{-1} and 0.04-0.06 t P ha^{-1} were estimated for longline configuration. Experimental-scale production at Greifswald Bay, Germany indicated yields of 0.09-0.1 t N ha^{-1} and 0.006-0.007 t P ha^{-1} could be extracted in 12-18 months, where lower salinities were associated with lower growth rates (Taylor et al., 2019a). Kotta et al. (2019) estimated extraction potentials in three Baltic farms of 0.08-0.148 t N ha^{-1} and 0.006-0.011 t P ha^{-1}; however, in neither of these cases had production been optimized and results can be considered preliminary.

Photo: DTU Aqua

3 Site selection, prerequisites and potential

3.1 Spatial model for mitigation potential

Mussel growth is dependent on environmental conditions, particularly temperature, salinity and food concentration, which vary in time and space. To evaluate the potential over the western Baltic, with highly variable conditions, a spatial model was developed to calculate the average potential N and P removal by mussel cultivation for a standard farm (Holbach et al., 2019, 2020). The spatial model is based on an individual mussel growth model, which was calculated from monthly average measured environmental conditions that were interpolated over the entire study area (Figure 2). Under the assumption that mussels for mitigation are harvested in the winter following settlement, the model covers the period from July to November, i.e. less than one year. Provided the strong correlation between mussel density and individual size, the individual growth model can be scaled up to a farm, whereby harvest potential can be estimated. The standard farm defined in the model was setup as a longline configuration with 2 m loop depth, at 30 cm separation between each loop. One farm (750 * 250 m^2 = 18.8 ha) consists of 3 sections containing 30 long lines of 200 m length each. This standard farm is specifically suited for inner Danish waters and is currently the maximum allowable size of a mussel farm in Denmark. To compare model results across regions, the relative nutrient removal in percent was calculated by normalizing with the maximum median value (i.e. the highest potential) corresponding to 100% in Figure 2.

Overall, model calculations demonstrate that salinity above 16 PSU, temperatures ~ 19°C, and chlorophyll-a concentrations of 2-20 $\mu g\ l^{-1}$ are ideal for rapid mussel growth. Growth rates in time are most variable due to seasonal temperature changes. Spatially, growth varies mostly due to local salinity and chlorophyll concentrations. The highest mitigation potential in Danish waters can be found in the estuaries along the Jutland east coast, the Limfjorden, Isefjord, the Swedish west coast, and Kiel Bay, where there are favourable food concentrations and salinity levels are not restrictive to growth (Figure 2). Total production is reduced towards the Baltic Sea due to decreasing salinity and in the more open water areas due to lower chlorophyll-a concentrations. It should be noted that flow velocity and dilution of chlorophyll-a within farms are not included in the model. Positive mussel growth may occur in areas with low chlorophyll-a concentrations combined with high current velocities. Low current velocities, however, results in less water exchange and increases the magnitude of depletion of chlorophyll-a concentration within the farm, which can potentially result in lower growth rates.

The geographical distribution of mitigation potential (0-100%) in the model is assumed to apply to both longline and net configurations, which can be directly scaled to measured values (Taylor et al., 2019c) for N and P removal at harvest. The scaling factor between the model and measured values depends on the technology used and will thus be less for longlines than nets due to the difference in production capacity. For longlines, measurements were conducted with the optimized 2 m depth loop, and 30 cm separation, which can in many cases be considered conservative as longer loops extended in deeper waters should further increase biomass yields. Net configurations were setup with mesh sizes of 17.5 cm and 25 cm, and 3 m depth, which has been tested in the Limfjorden and southern Kattegat (Taylor et al., 2019a).

Larval mussel distribution and spat settlement and later harvest times are not included in the model. Therefore, the model results are only valid if there is sufficient spat settlement on a mitigation farm.

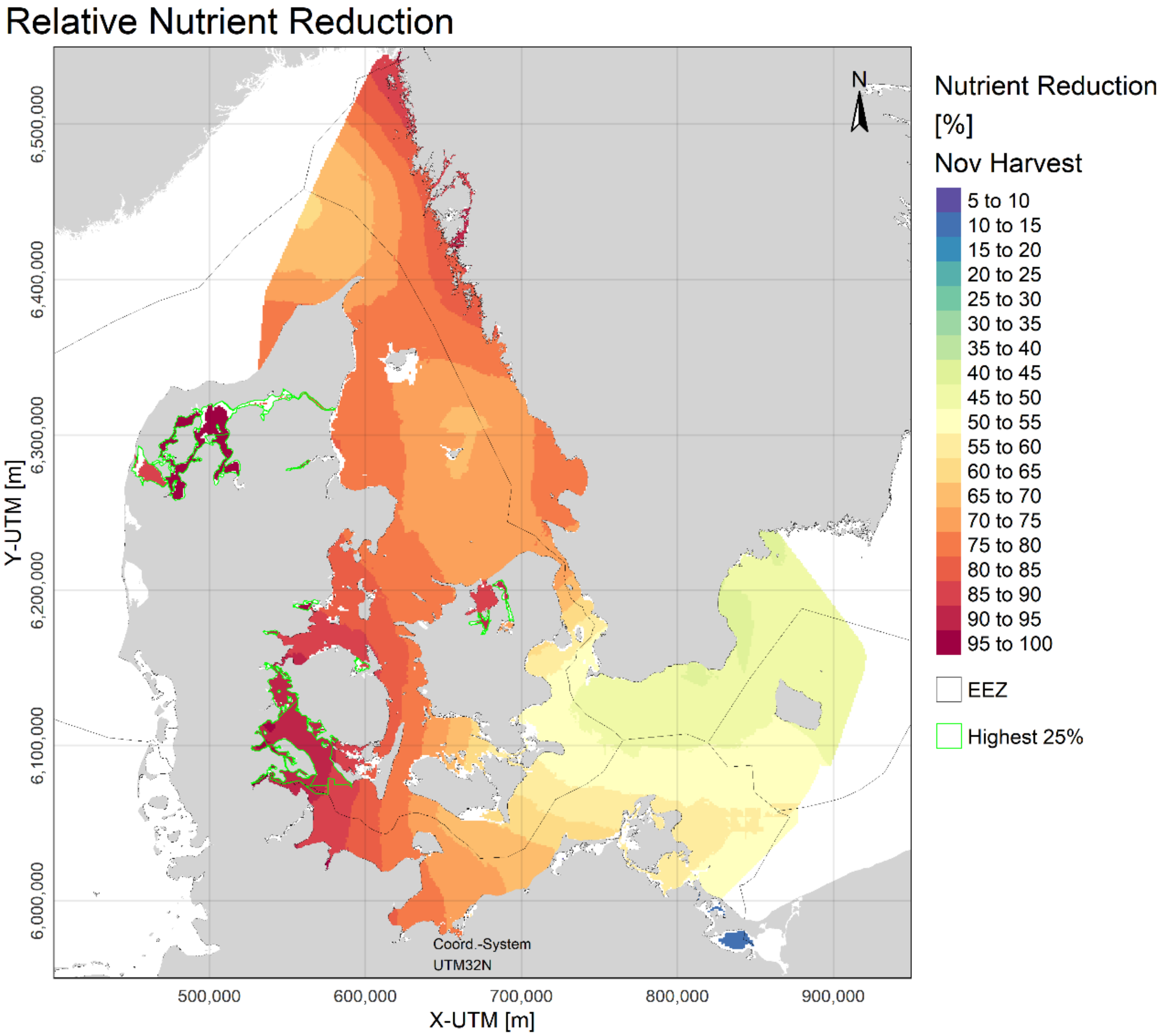


Figure 2. Mitigation potential (%) for a standard mussel farm covering 18.8 ha. The map presents relative areal specific N and P removal at harvest in November. Green lines indicate areas with the 25% highest potential. The map does not include biomass loss processes, food restriction, or other uses of the sea, and can therefore not be used solely for the location of mitigation mussel farms or as a basis for calculating the total remedy potential (From Holbach et al., 2020).

3.2 Other important criteria when siting mitigation mussel farming

In addition to consideration of growth and risk factors, which affect the mitigation potential, other criteria must be accounted for when selecting an appropriate location for a mitigation farm (Petersen et al., 2013; Timmermann et al., 2015, Bruhn et al., 2020). This type of multi-criteria approach is an important aspect of marine spatial planning (Bergström and Lindegarth, 2019).

3.2.1 Physical conditions

Bathymetry determines the lower limits at which mitigation mussel farming can be installed. Net systems, as they are currently kept buoyant at the water surface, can generally be installed in shallower waters than longline systems, but the shallowest operational depths are ~4 m. At greater water depths, i.e. >15-18 m farms require additional equipment for mooring. A safe distance between the growing substrate and the bottom has to be respected and maintained by good technical expertise in order to avoid contact and potential loss by benthic predation or exposure to adverse conditions (anoxia, sulphides).

3.2.2 Competing activities

The coastal zone is utilized for many forms of industrial, commercial, and recreational activities, as well as a large proportion reserved for natural conservation, which may contraindicate the installation of mitigation farms. Areas used for commercial fishing, maritime navigation routes, port entrances, prohibited anchoring areas, submarine infrastructure, military exclusion areas, as well as recreational uses, such as sailing, diving, bathing, recreational fishing, etc. are common designations of conflicting use. Vacation areas are an additional common source of siting conflict due to perceived sea-scape interruption.

3.2.3 Carrying Capacity

As described previously, mussel growth - and relatedly, mitigation potential – is largely determined by food supply. The number and proximity of mitigation farms will need to be assessed on a case-by-case basis for each water body, such that multiple farms are not self-limiting in performance and reducing overall areal efficiency. Estimation of carrying capacity requires detailed model analyses. While in most cases (production) carrying capacity will not be of major concern, as water bodies requiring mitigation mussel farms aim to drastically reduce chlorophyll-a concentrations, at the extreme, major reductions may reduce food availability for other primary consumers in the ecosystem.

Optimal siting of mitigation farms requires weighting of multiple factors, provided by expert input specific to the water body. GIS tools are important to facilitate this process by managers and stakeholders. With GIS tools, it will be possible to set up scenarios to objectively evaluate siting conditions in a transparent manner. While it does not replace thorough assessments, it can supplement this process and serve as a screening instrument.

3.3 Risk of biomass loss

There are several external factors which may cause significant losses of mussels from a mitigation farm. The following factors must be considered before a mitigation farm is established:

3.3.1 Physical conditions

Exposure to strong currents, large or persistent waves, and ice cover can result in the damage of farm structures and loss of mussels from the suspended substrate. In some cases, risk of loss can be reduced by modifying cultivation techniques, such as submerging the farm structure or utilizing more robust materials and configuration. Current cultivation technology for mitigation mussel farming has not been developed enough for siting in very exposed areas, though it is expected that in the near future, controlled submersion and high-energy configurations will be available.

3.3.2 Predation

The primary predators in relation to mussel farming in Baltic waters are sea stars (Asterias rubens) and eider ducks (Somateria mollissima), which can cause catastrophic loss in a short time. Sea stars can settle on spat collectors coincidentally with mussels, or as benthic adults, can climb up farm structures in contact with the sea floor. Typical practices of reducing predation impact is timing of spat collector deployment and maintenance of the suspended substrate off of the sea floor. Eider ducks are a protected migratory waterfowl and consume mussels as a normal dietary constituent. The Baltic coasts are major migratory pathways for this species, particularly in the autumn. It has been observed that flocks passing mussel farms actively feed on the suspended mussel aggregates and can consume and dislodge a large portion of the standing biomass stock. Predation prevention has been focused on protection nets around the suspended biomass, however, the mesh size of these protection nets must be considered as to not entangle ducks (Lindegarth et al., 2019). Protection against predators adds capital and operational costs, so in areas with high eider predation risk, early harvest (September-October) may be optimal.

3.3.3 Technical expertise

Considerable cultivation experience is required to mitigate risks of losing mussel biomass due to problems regarding setup and maintenance of the farm. For example, establishment of the farm contrary to hydrodynamics conditions or improper buoyancy regulation can lead to significant loss of biomass. As such, it is important that mitigation farm operators are knowledgeable and experienced.

3.4 Post-harvest use of mitigation mussels


Photo: Aarhus University

To the extent that mussel farming as a mitigation instrument will be implemented on a larger scale, a significant addition of mussels will become available, but should not be assumed to be marketed to the fresh market to a major extent, as is done with conventional mussel farming. A large proportion of the size distribution of mitigation mussels will be unsuitable for the fresh market. As such, new markets and uses are required. A minor proportion will be able to be processed as cooked mussels and value-added products, but the major proportion will need to be directed towards other uses, such as meals for animal feeds, supplements, or other novel products. As an organic feedstuff, mussel meal has been demonstrated as a suitable ingredient for poultry (Afrose et al., 2016), porcine (Nørgaard et al., 2015), and salmonid feeds (Langeland et al., 2016). One challenge in scaling meal production is separation of the shell from the tissues, which need to be excluded in most meals (porcine, salmonid) and partially for poultry. Processing methods which can result in a finished product comparable in price to fishmeal are currently under investigation and require further research. Economies of scale suggest commercial meal production will be viable provided sufficient volumes. Additionally, high-value products, such as mussel lipids for human nutraceuticals, may play an important role in market utilization of mitigation mussels. Byssus threads have shown to contain a relatively high N content, however, the protein content consists of collagenous, matrix, and cuticle proteins (Hagenau et al., 2009), indicating byssus threads are poorly suited for use in many animal feeds.

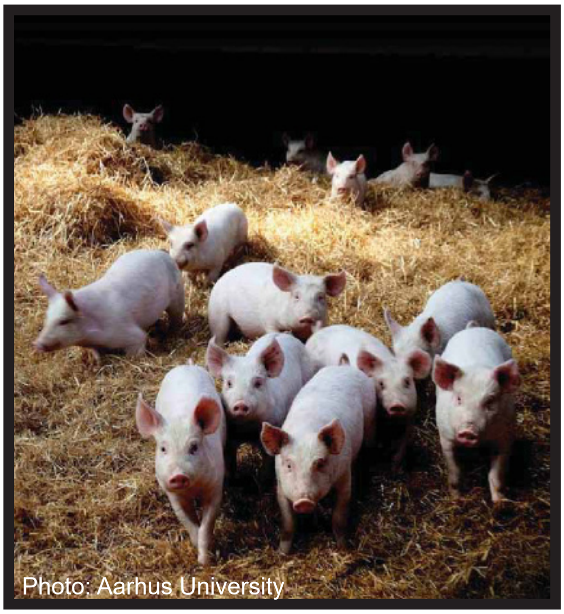


Photo: Aarhus University

Capacity for large scale harvest, transport of fresh materials, and processing will require industrial development of production chains. It is anticipated that mussel meal production will integrate into existing fish meal production chains, provided the relatively limited projected production volumes relative to current northern European fishmeal production[1]. As with all feed ingredients, quality conrol and assessment will be necessary for safety and standardization of product composition and stability.


Photo: DTU Aqua

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[1] https://effop.org/fishmeal-and-fish-oil/production/

4 Potential impacts

4.1 Ecosystem services and impacts

4.1.1 Improved water transparency and reduced chlorophyll-a concentration

Due to the mussel feeding mechanism of filtering suspended matter in the water column, farming mussels can improve water clarity and reduce the chlorophyll-a concentration. This has been demonstrated with in situ data, ecological modelling, and satellite imagery from farms in the Lim-fjorden, southern Kattegat, Sweden, and Germany (Maar et al., 2020a, 2020b; Taylor et al., 2020a, 2020b). Reductions in chlorophyll-a concentrations can be up to 60-85% within the mitigation farm area, on average 14-50% depending on integrated mussel filtration capacity and environmental conditions such as flow velocity, temperature, and chlorophyll-a concentration (Nielsen et al., 2016; Cranford, 2019; Petersen et al., 2019b; Maar et al., 2020; Taylor et al., 2020a, 2020b). Secchi depth (a measure of water transparency), increases on average by 0.8-1.1 m (up to 2-3m) within mussel mitigation farms relative to ambient conditions (Maar et al., 2020; Taylor et al., 2020b). Models demonstrate an improvement in water transparency in an area around mussel mitigation farms of 14 times the area of the farm itself in a study in the eutrophic Skive Fjord with low current velocities (Timmermann et al., 2019) in comparison with less pronounced depletion in areas with higher advection rate and low retention time (Maar et al., 2020; Taylor et al., 2020b). The spatial extent of this effect is greatest for farms with high biomass or with multiple farms in proximity to each other. The model employed in Timmermann et al (2019) showed that in relation to chlorophyll-a and Secchi depth, mussel mitigation farming is more efficient than land-based abatement.

4.1.2 Binding of nutrients

During growth, nutrients are assimilated in mussel tissues, such that they are not available for new primary production. In this way, the mussels contribute to a reduced turnover of nutrients in the basin.

4.1.3 Reduced sedimentation on the basin scale

Related to reduced suspended material in the water column due to filtration, model scenarios from Skive Fjord, Denmark demonstrate that basin scale sedimentation was reduced as a result of particle depletion (Timmermann et al., 2019), which is a natural consequence of the mass balance principle. Although sedimentation increases directly underneath the mitigation farm due to faecal and pseudofaecal production by the mussels, there is a net reduction of sedimentation over the entire basin relative to the absence of the farm. Locally increased nutrient regeneration due to increased local sedimentation rates is therefore offset by reduced basin-scale nutrient regeneration (Petersen et al., 2019a).

4.1.4 Denitrification

Denitrification is an anaerobic bacterial respiration process in which nitrate (NO_3^-) is converted into gaseous free nitrogen (N_2) or nitrous oxide (N_2O). Gaseous N largely is exchanged with the atmosphere and is therefore no longer in the marine environment; this is the most important microbially-mediated process in systemic N reduction. Organic enrichment of sediments often increases the rate of denitrification unless it is inhibited by sulphate reduction or uncoupled from nitrification in anoxic conditions. In mitigation farms, denitrification has been demonstrated to increase rates by 25-260% of conditions outside of farms in the Limfjorden, the Swedish west coast, and southern Kattegat (Carlsson et al., 2012; Petersen et al., 2019a; Hylén et al., 2020). Enhanced denitrification further contributes to systemic N removal in addition to that removed through harvest of the mussels.

4.1.5 Increased local N & P flux, sedimentation and oxygen consumption

Filtration and digestion of phytoplankton biomass by mussels transforms bound N and P in particulate form to mussel biomass. A fraction of digested N and P will be converted back into dissolved compounds in the form of ammonium and phosphate, and into particulate organic faecal and pseudofaecal matter. Faecal production can increase local sedimentation rates underneath the suspended mussels and may result in locally increase nutrient regeneration (Carlsson et al., 2009; Holmer et al., 2015). A benthic impact study in Skive Fjord, Denmark estimated that mussel faecal excretion accounted for 82% of sediment flux and 18% of N emission from a mussel farm (Holmer et al., 2015). Regenerated nutrients are retained within the system and can contribute to regenerated primary production. As these fractions are temporary conversions from one state to another within the system, a net removal of N and P is still realized through harvest of mussel biomass and enhanced denitrification.

In general, locally increased sedimentation and subsequent effects on benthic biogeochemical processes (e.g. nutrient fluxes, oxygen consumption) will be closely coupled to the mussel biomass, but the extent of impact will be influenced by current velocities, water depth, redox conditions, eutrophic conditions, etc. (Carlsson et al., 2009, 2012; Petersen et al., 2019a). A recent study in the southern Kattegat (As Vig) in a mitigation farm configured with nets, it was demonstrated that sedimentation effects are highly localized within the farm; where sedimentation rates were generally increased underneath the farm relative to a reference position, moreover, sedimentation rates were further increased underneath nets relative to between nets (Hylén et al., 2020). During cultivation, sedimentation rates, nutrient flux, and oxygen consumption were observed to be pronounced underneath the farm, while 3-4 months after harvest, only nutrient fluxes were slightly higher in the farm. In Skive Fjord, Denmark benthic impacts of a monitored mitigation farm were limited due to high ambient concentrations of suspended organic matter and nutrients (Holmer et al., 2015). Due to the brief cultivation period of mitigation mussels, sediment accumulation underneath a farm is permitted a brief ‘fallow’ period which facilitates degradation and potentially burial of organic matter before the next cycle’s settlement (Maar et al., 2018).

High sedimentation rates under a mussel farm can lead to organic enrichment to such an extent that sulphide formation and oxygen depletion inhibit the coupled nitrification-denitrification process (Holmer et al., 2015; Petersen et al., 2019a). Subsequently, dissimilative nitrate reduction to ammonium (DNRA) becomes the dominant process (Christensen et al., 2003). If denitrification is inhibited, it is possible that there will be greater ammonium retention within the system. At the same time, phosphate bound to metal compounds in the sediment can be released to the water column by oxygen depletion (Holmer et al., 2003). Thus, the increased N and P release from the sediment has been theoretically proposed to counteract the effect of N and P removal by incorporation into mussel biomass (Stadmark and Conley 2011). However, the magnitude of denitrification accounted for 2% of the total N removal at mussel harvest for a standard farm in the Limfjorden and <1% of the harvest in a mitigation mussel farm in the southern Kattegat (Hylén et al. 2020). This suggests that even if complete inhibition of denitrification will occur, there will still be a significant net N-removal (Petersen et al., 2019a). Most studies on benthic impacts show a general increase in denitrification rates within cultivation units (Nizzoli et al., 2006; Carlsson et al., 2012; Holmer et al., 2015). Exceptions were due to location in areas with limited current velocities, an excess of farms in limited space, and existing ambient poor oxygen conditions (Gilbert et al., 1997; Christensen et al., 2003; Carlsson et al., 2012). It is therefore recommended to position mitigation farms areas with sufficient flow rates (>0.02 m s^{-1}) or to reposition them regularly to avoid the risk of oxygen depletion and increased sulphate formation in the underlying sediments (Petersen et al. 2012).

4.1.6 Nutrient retention

In estuaries and other water bodies with a low residence time, large scale mussel filtration can potentially capture and retain nutrients (either locally or from more open water) through biodeposition, which would otherwise have been transported (advection of plankton) out of the water body (Cranford et al., 2007). In this case, the farm(s) may contribute to an increased retention rate for nutrients and thus locally increase eutrophication near the mussel mitigation farm. Consequently, export of nutrients from the water body will be reduced, which will in turn reduces eutrophication in the adjacent water body.

4.2 Social perception

Coastal residents in proximity to mussel farming, whether they are year-round residents or vacation residents, as well as transient users of the water space, can be affected by farm structures and activities in a variety of ways (Petersen and Stybel, 2019). Visual impacts are a major issue in many regions and depend on physical characteristics such as the number of farms, farm size, materials types, and distance from the coast. Waste, discarded materials, and otherwise lost materials, such as buoys and ropes, that are lost from farms or from associated maritime activity can be washed ashore, littering the coastline. Sailing obstruction to pleasure craft can be problematic in that the perceived sailing space is limited and the farm must be marked sufficiently (bright coloured buoys, reflective materials, lights, etc.) to prevent navigational accidents. Notwithstanding, the degree of ‘social impact’ is determined by public perception of mussel farming as conducting a positive environmental service and/or in accordance with the local community and its values.

The fact that mussel farming can create social impacts is also related to the perception of the undisturbed seascape as a substantial good, similar to the concept of undisturbed nature. The experience of social impacts can be exacerbated if the region has negative experience with other forms of sea use, specifically fish aquaculture that can be related to environmental risks such as pollution with nutrients and antibiotics. It is apparent that perception and awareness of local coastal users depend on the level of knowledge and experience with mussel farming and its ecosystem services (Petersen and Stybel, 2019).

Photo: DTU Aqua

5 Economics

The main economic questions are: i) does mussel mitigation farming contribute to cost-effective achievements of nutrient reduction targets and ii) how it shall be implemented when there are no markets for nutrient removal. In order to answer the first question, information is needed on costs for nutrient removal by mussel farming and other relevant abatement measures in agriculture and/or at sewage treatment plants. For all types of abatement measures, the cost includes investment and operational costs which are usually measured in cost per year with assumptions of discount rate and technical life length of the abatement measure.

5.1 Costs of mussel farming on the Baltic scale

Several studies have calculated costs of mussel farming and Gren and Tirkaso (2020) show in a global meta regression analysis of 23 studies estimating costs of mussel farming (with several different purposes of mussel farming) that the cost per unit biomass depends on the wage rate, discount rate, scale of harvesting, salinity level at the site and if the mussels are used for human consumption or for nutrient removal. It was shown that there exist economies of scale, i.e. that the cost per unit biomass decreases for larger mussel farms as measured by harvested biomass. While unit cost at low production levels, approximately 50 t biomass yr^{-1} amounts in average to 0.6 € kg^{-1}, the unit cost at production levels exceeding 150 t approaches 0.1 € kg^{-1}. It was also shown that the salinity level affects the cost, 1% increase in the salinity level reduces cost by 0.3% because of the higher productivity.

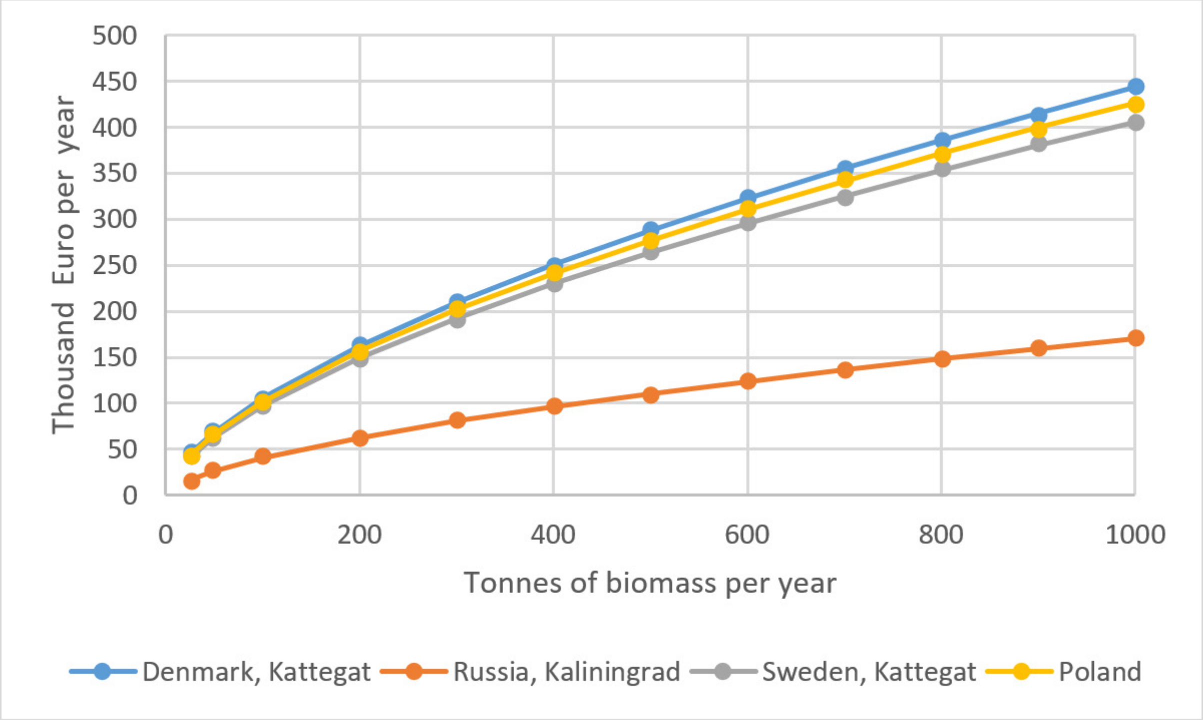

Figure 3: Costs of mussel farming of different sizes per farm and locations Source: Gren and Tirkaso (2020)

However, in the Baltic Sea coastal regions with relatively high salinity levels also face high wages and the cost of mussel cultivation depends on both these counter acting factors (Figure 3). The cost is lower at each level of biomass harvesting for mussel farming in the coastal region of Kaliningrad because of the low wage level, which corresponds to 1/6 of that in Denmark. The calculated cost is therefore highest in Denmark despite the higher salinity level.

5.2 Comparison of Baltic scale nutrient abatement costs

Whether mussel farming is of interest in a cost-effective solution for reaching nutrient abatement targets depends on its cost in relation to other abatement measures. Only a few of the studies estimating costs for mussel farming as a nutrient removal tool compare the cost with other abatement measures. The most common approach is to compare with one abatement measure such as costs of increasing cleaning at sewage treatment plants (e.g. Lindahl et al. 2005). However, in practice there exist a suite of alternative measures, in particular in agriculture, and costs of mussel mitigation farming should therefore be compared with the costs of all possible measures. This is made by e.g. Gren (2019) where marginal removal cost of nitrogen and phosphorus are compared with corresponding costs for a number of measures including agriculture for reaching the nutrient targets set by the BSAP (HELCOM, 2013). The results then show that marginal abatement cost for nitrogen by other measures is in general lower than the marginal cost of nitrogen removal by mussel mitigation farming, but the opposite is the case for phosphorus. Because of the high reduction requirements on phosphorus loads to the Baltic Proper, the introduction of mussel farming as a nutrient removal option could reduce the overall abatement costs of reaching the BSAP target by 10% or approximately €400 million.

5.3 Regional scale economics

On a local or regional scale of the individual countries in the Baltic, economics of mitigation farming can be calculated in relation to implementation of the WFD. In Denmark, the costs of mussel mitigation farming have been calculated as budget and welfare-economic costs. The prices that are included in a budgetary financial statement are calculated in factor prices that the companies (here the mussel mitigation farmers) actually have to pay. The factor prices (prices without VAT and excise duties, etc.) are adjusted by a net tax factor to express the welfare economic prices, which express the market prices. These prices are used in connection with socio-economic impact assessments (Ministry of Finance, 2019), and for comparing cost-effectiveness between instruments (e.g. between mussel mitigation farming and land-based abatement measures).

The budgetary and welfare economic calculations have been carried out without including use of the mussels, as there is as yet no certain knowledge of the marketing of the mussels. The assumptions regarding productivity and N uptake in the different water catchments were based on the same assumptions as used in the calculations of N removal. The operational cost of mussel farming as a tool is calculated for the study area (Figure 2). An interval of € 0.17-1.2 kg^{-1} mussels (wet weight) (€ 0.22-1.5 kg^{-1} in welfare economic prices) has been calculated for long-line production, and € 0.08-0.75 kg^{-1} mussels (€ 0.1-0.9 kg^{-1} in welfare economic prices) for production with nets.

Costs per kg of N are also calculated for the study area (Figure 2), based on Filippelli et al. (2019). The cost of the farms is not differentiated between catchments, assuming that the same type of farms can be established in all estuaries and coastal areas. The cost per hectare of longline farm is calculated at € 13,165 ha^{-1} yr^{-1} and for a farm with nets at € 14,870 ha^{-1} yr^{-1}. It is assumed that production costs do not vary significantly with the volume of production. The calculations for longlines indicate that the cost is on average € 16 kg^{-1} N in the most productive areas when measured data is used and processing of the mussels is not considered for feed or other use. Welfare-economic prices have been used for the calculation. For other areas, the reduction costs are calculated to be between € 18-67 kg^{-1} N. For mussels produced on nets, reduction costs have been calculated between € 8-38 kg^{-1} N for the study area in welfare economic prices. The cost was also calculated in terms of cost per kg P removed by longline (€ 225-1,123 kg^{-1} P) and net production (€ 141-765 kg^{-1} P) of mussels and calculated in welfare economic prices and for the study area.

In general, the reduction costs for N uptake in mussel mitigation production will be lowest in coastal eutrophic waters, where the growth of blue mussels is greatest (Figure 1) and the operating cost is lowest. It is estimated that mussel mitigation farming will have greater reduction costs in the open sea areas, as mussel growth will be reduced due to generally lower food availability and low or fluctuating salinity in e.g. the western Baltic Sea and Belt Sea (Maar et al. 2015, Riisgaard et al. 2012). The cost of operating and harvesting offshore farms is also expected to be higher, but no data are available at this time to quantify these differences in costs. On the other hand, a greater depth of water in the open water areas will allow the greater use of the water column, i.e. greater area production, if technology allows.

Photo: DTU Aqua

6 Challenges in relation to control and administration

Given that mussel mitigation farming can contribute to a cost-effective achievement of nutrient targets, the question remains on how the cost savings should be materialized. The lack of markets for nutrient removal sales necessitates the introduction of policies promoting mussel mitigation farming. In principle, nutrient removal by mussel mitigation farming could be compensated by taxpayers as subsidies or introduced as an option in existing policy schemes for nutrient abatement. The latter can be made by allowing for mussel mitigation farming as an offset mechanism for firms in compliance with a regulation where they can reduce part of their nutrient abatement requirement by paying for nutrient removal by mussel farms. The firm will not pay more than the own cost of abatement and the mussel farmers requires (at least) compensation for the costs. Depending on the resulting prices, both buyers (firm in compliance) and sellers (mussel farmers) of nutrient removal by mussel mitigation farming can make net gains.

However, one problem to address is the differences in such an offset system is the differences in the uncertainty in nutrient abatement between mussel mitigation farming and other abatement measures. Biomass growth, and thereby, nutrient removal by mussel mitigation farming is affected by natural variation. Impact on the coastal zone by upstream abatement by agriculture or sewage treatment plants is uncertain because of weather conditions affecting the transformation of nutrients from the source to the coastal zone. If certainty in reaching the nutrient target is important for decision makers, these differences need to be accounted. Gren and Hasler (2020) suggested an exchange system where, ceteris paribus, relative high uncertainty reduces the value of the abatement and vice versa. This means that the payments for nutrient removal by mussel mitigation farming is reduced (increased) if it is more (less) uncertain than for abatement by other measures. The results in Gren and Hasler (2020) indicated that nutrient abatement by mussel mitigation farming was less uncertain than other abatement measures in most coastal regions. Calculations with such exchange rates were made for mussel mitigation farming as an offset for sectors in compliance under the BSAP targets. It was shown that the profits of mussel mitigation farming from selling nutrient removal differ considerably between different countries.

Control of mussel farming as a mitigation instrument will depend on the model employed. If private operators are used within a nutrient credit market regime, it will be required to demarcate the effective water body related to the source of emission as well as the scale of productivity expected for the mussel mitigation farm. Consequently, it will also be necessary to verify if the targeted nutrient removal is being carried out. Location and extent can be controlled by the issuance of permits. Control of the harvest quantities (nutrient removal) can be achieved by a combination of weighing the bulk harvest quantity and sampling for nutrient quantity of the proportion of tissues, shells, and byssus (Petersen et al., 2016). Since there are no specific requirements for the specific use of mitigation mussels, current documentation of nutrient removal is the total wet weight of harvested material given that all of the harvested material stays on land.

7 Knowledge gaps

7.1 Biodiversity

The effects of mussel farming on biodiversity have not been thoroughly studied. Farming of mussels can affect biodiversity locally through their filtration, affecting plankton community composition and food availability for other organisms. Farms can also function as artificial reefs and habitat for other species; e.g. epifauna, epiflora, fish (Maar et al., 2008; Callier et al., 2018). In the longer term, biodeposition of faecal matter and loss of dead mussels/shells can accumulate underneath the farm, influencing benthic habitat and communities. As a source of food, mussels detached from nets or ropes can attract potential predators, such as lobsters (Sardenne et al., 2019).

7.2 Carrying capacity of the system

Further study is required to determine generally how many mitigation farms can operate in a given water body without food restriction, which will reduce the effectiveness as a mitigation tool. Large scale food restriction can similarly impact natural wild populations of filter feeders, which could influence the other members of the food chain. In the long term, when the ecological status of the water body improves due to fewer nutrients and phytoplankton biomass, the system's carrying capacity will be lower and the tool will become less effective. This can be investigated directly by observation of farm production or through 3D ecological models, which are often costly and not available for the studied water body.

7.3 Climate effects

There is a paucity of research and documentation on mussel farming impacts on the climate. As described above, biodeposition under farms may locally enhance denitrification and thus the potential release of nitrous oxide (N_2O) from the sediment, whereas some of the carbon is presumably buried in the sediment. On the basin scale, however, reduced emission of nitrous oxide and carbon burial, due to lower net sedimentation rates, will likely be observed. Carbon is bound in the mussel shell, but whether it can contribute to carbon sequestration will depend on the fate of the shells (e.g. loss to the seabed, landfill, incineration). In a recent review on the role of mussels in the CO_2 cycle, it was concluded that harvested mussel shells can be considered a net CO_2 sink (Filgueira et al., 2019). The contribution is limited on the scale of a single farm, but it was estimated that the CO2 extraction at the annual production of mussel species worldwide equals 6.3x105 t of CO_2 (Filgueira et al., 2019). However, application of the shells will determine the degree of deposition; if the shells deposited in building material, for example, the shells will act as a permanent CO_2 burial. There will be a consumption of fuel in connection with maintenance and harvesting of the farms as well as in the processing of the mussels for feed. The harvested mussels, on the other hand, will be a protein source with a very low CO_2 imprint compared to land-based protein sources (Hilborn et al., 2018; Parodi et al., 2018).

7.4 Technological optimization

It is not expected that further technological development for longline systems in shallow estuaries, such as in Denmark, will significantly increase N removal. Net systems are a somewhat newer technology, although there are a few large-scale commercial operations that have been established within the past few years in shallow estuaries. There may be further technological development for these systems, such that they can be submerged at a controlled depth, and thus have a longer production period or be configured optimally in relation to higher energy conditions. These modifications are unlikely to significantly alter N removal but can ensure that potential production of up to 3,500 t per farm can be achieved with an associated cost reduction. Improvements in maintenance and harvesting can be carried out by both technological development and management strategies which will primarily affect costs. With regard to the processing of the mussels produced, further technological development will be needed to reduce the price of the processed products. This is anticipated to be possible within a short period of time.

7.5 Incentives for mussel farming

Without any markets for sales of nutrient removal by mussel mitigation farming, eventual social net gains will not be materialized. As all firms, mussel mitigation farmers need net benefits in order to live and survive. This calls for analysis and comparisons of effects of governmental intervention with respect to different payment systems for mussel mitigation farming. Such studies are lacking which limits an effective implementation of mussel mitigation farming as a nutrient removal mechanism in practice, not only for the Baltic Sea, but for other regions as well. On the other hand, there are experiences in the USA from different systems where point sources in compliance with regulations (mainly sewage treatment plants) can purchase nutrient abatement credits from non-point sources (mainly agriculture) and recently, shellfish producers (Stephenson and Shabman, 2017; Ferreira and Bricker, 2019; Bricker et al., 2020). Analysis of these experiences could be useful for evaluations of offset system for mussel farming in the Baltic Sea and other seas.

Photo: DTU Aqua

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