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Published

2022

Journal Title

Ecological Economics

Version

Version of Record (VoR)

DOI

10.1016/j.ecolecon.2022.107549

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Ecological Economics 200 (2022) 107549

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

ANALYSIS

Water quality trading markets – Integrating land and marine based measures under a smart market approach

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ARTICLE INFO

Keywords:
Water quality trading
Non-point pollution
Mussel farming
Farmer participation

ABSTRACT

Implementation of effective policy instruments to reduce emissions from non-point agricultural sources has been challenging. Mussel farming has the potential to mitigate diffuse nitrogen losses from agricultural production, and a Water Quality Trading Market (WQTM) between agricultural and mussel farmers could potentially be an efficient mechanism. We simulate a hypothetical WQTM in a catchment in northern Denmark using a relatively new approach referred to as a smart market for water quality. Building on previous work, we integrate mussel farmers as nitrogen permit sellers in a WQTM involving agricultural farmers and analyze the effect of the market on the cost of meeting water quality improvement targets. In addition, we set-up scenarios with decreasing levels of participation by agricultural farmers (−10%, −20% and − 30%). The results show a clear benefit from allowing trading between agricultural and mussel farmers, reducing the total costs by as much as 11.9%. Lower participation results in reductions in the benefits from trade. However, allowing mussel-based mitigation to supply N permits at modest cost can potentially partially circumvent the well-documented challenge that agricultural farmers are reluctant to act as N permit suppliers in WQTMs. The study illustrates the economic and environmental potential of integrating land- and marine-based farmers in a joint policy scheme to reduce nitrogen emissions to coastal and marine areas.

1. Introduction

Non-point nutrient pollution remains one of the most challenging environmental problems. In Europe, diffuse pollution is the main environmental hazard for 38% of surface water bodies.[1] Agriculture is the major source of diffuse water pollution, and excess nutrients (nitrogen in particular) causes eutrophication, with negative impacts on aquatic biodiversity and fish stocks (Zal et al., 2018).

The Water Framework Directive (WFD), a European initiative for improving water quality (European Commission EC, 2000), sets targets for the ecological status[2] of European water bodies. Mitigation of eutrophication is likely to be one of the most important elements in achieving this target, and reductions of nutrient concentrations in water bodies are therefore required. In that context, and in line with the Directive's obligations, it is desirable to find the most cost-efficient combination of environmental measures to achieve such reductions.

Designing agri-environmental policy schemes to reduce diffuse pollution cost-efficiently is a daunting task. It entails coordinating hundreds or thousands of farmers to achieve a common goal whilst also dealing with complexities that are characteristic of the diffuse pollution problem (Shortle and Horan, 2001). Emissions from agricultural non-point sources leave farm fields diffusely and are difficult to measure with accuracy, making it harder to enforce reductions (Horan and Shortle, 2011). An understanding of the spatial distribution of emissions is essential, as the actual environmental damage is dependent on how much of the nutrients are retained by natural processes before reaching

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[1] Not including water bodies affected by atmospheric deposition.

[2] More information on (European Commission EC, 2000) Annex V.

https://doi.org/10.1016/j.ecolecon.2022.107549
Received 29 July 2021; Received in revised form 3 June 2022; Accepted 15 July 2022
Available online 27 July 2022
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the ultimate receiving water bodies. The retention level is in turn affected by physical characteristics such as soil composition and distance to the water body (Andersen et al., 2001). Moreover, since environmental damage from the leaching is localized, environmental targets may also be geographically specific, limiting the potential market size. These bio-physical intricacies add complexity to the design and application of efficient economic instruments. Adding to the mix is also an inherently complex socioeconomic landscape, producing overall what Shortle and Horan (2017, p.01) term "a wicked challenge for economic instruments". A comprehensive analysis of the topic can be found in that study and also in Horan and Shortle (2011), Kostel et al. (2014), OECD (2012) and Shortle and Horan (2008).

1.1. *Tradable permit schemes*

Tradable permit schemes are often heralded as an effective mechanism to reduce the emission of pollutants cost-efficiently. Permit trading between emitters allows for flexibility in the allocation of abatement efforts, leading to cost-efficiency gains derived from the spatially differentiated marginal costs and benefits of implementing emission reducing measures throughout the area covered by the market.

Such schemes are widely covered in the literature and some have been implemented worldwide with mixed results (Narassimhan et al., 2018; Schmalensee and Stavins, 2017; Sovacool, 2011). In the most widely used environmental trading market, i.e. the carbon trading markets, emissions are mostly under the control of the emitter, they can be accurately measured for each participating point source and the spatial distribution of the emissions is not relevant for the fulfillment of the environmental goal due to carbon being a uniformly mixed pollutant. This means that there is little uncertainty with regard to the environmental damage caused by individual polluters and also that the market space does not need to be geographically restricted.

When the trading units (damaging emissions) are easily identifiable and measurable, and the market size is large enough, transaction costs, typically associated with exchange costs and monitoring costs, can be kept at acceptable levels. In such textbook markets, the regulator needs only to have knowledge of the environmental constraint, or the maximum emission load allowed, and can let emitters trade using knowledge of their own economic landscape (Horan and Shortle, 2011).

Implementation of Water Quality Trading Markets (WQTM), however, has been challenging (Greenhalgh and Selman, 2012; Selman et al., 2009; Shortle, 2013). Since the majority of polluting emissions (i.e. nitrogen emissions) come from non-point sources, dealing efficiently with relevant complexities is essential for designing a successful scheme. Inevitably, regulators need to address the challenges related to enforceability of reductions of diffuse emissions. This includes the quantification of the emissions (and the uncertainty in their measurement); the feasibility of an enforceable cap; and the perceived fairness in the allocation of reduction requirements among market participants (both point and non-point sources). The spatial variability of abatement costs and abatement effectiveness (due largely to variability in nitrogen retention) also needs to be addressed with sufficient certainty and legitimacy to improve cost-efficiency and to be accepted by market participants. The effort needed to set-up and run such a system involves both compliance and transaction costs related to obtaining, verifying, and transferring permits (DeBoe and Stephenson, 2016). These costs can rise to levels where they outweigh the gains from trade to participants, which may lead to low market activity (fewer participants) and low efficiency of the market scheme (Kostel et al., 2014; Stavins, 1995).

Literature on non-point source pollution and WQTMs have argued that policies can be tailored to confront the inherent complexities in regulation of non-point pollution. Recommended policy choices include setting up a proxy system where emissions are estimated for each abatement measure, easing monitoring requirements (Horan and Shortle, 2011; Kostel et al., 2014; Shortle and Horan, 2008); spatially targeting measures to improve cost-efficiency (Greenhalgh and Selman, 2012; Kostel et al., 2014; Shortle and Horan, 2008); and enabling and incentivizing emitters to participate in the market (Greenhalgh and Selman, 2012; Kostel et al., 2014). Combining these features in the design of policy instruments could prove effective for regulation of agricultural emissions.

Low participation is a particularly important issue for WQTM, and compliance and transaction costs levels can be a relevant factor for participation, acting as a barrier to entry (Greenhalgh and Selman, 2012). In a market design where a cap on emissions is enforceable and where market-like policies and incentives are present (Stephenson and Shabman, 2011; Stephenson and Shabman, 2017), it is a reasonable assumption that higher and more evenly distributed gains from trade may lead to higher participation. Real world implementation of WQTM have however demonstrated that high potential gains are not sufficient to ensure high participation (Stephenson and Shabman, 2017) and an enforceable cap is in most cases a challenging proposition. In this study, we evaluate a hypothetical market where these and other barriers to trade are not directly accounted for and farmers are assumed to participate in the market if it is in their economic interest to do so, correcting for transaction costs.

1.2. *Mussel farming as a nutrient reduction measure*

It has been proposed that mussel farming, when optimized for mitigation purposes, has the potential to reduce nitrogen concentrations at a competitive cost when compared to land-based measures (Filippelli et al., 2020; Gren et al., 2009, 2018; Kotta et al., 2020; Petersen et al., 2016b; Petersen et al., 2014). Gren et al. (2009) examined the cost-effectiveness of including mussel farming in combination with 20 other abatement and mitigation measures across 24 basins in the Baltic Sea and concluded that, for a wide range of reduction targets, mussel farming reduced total costs. Filippelli et al. (2020), in a case study that investigated mussel farming's potential to reduce the total cost of achieving WFD targets in Limfjorden, Denmark, reported cost reductions in two out of three catchments. While mussel farming can potentially reduce the costs of achieving water quality policy targets, current evidence suggests that effective mussel based nutrient abatement is not economically viable without a further economic incentive (Filippelli et al., 2020).

In a WQTM context, introducing mussel farming to the mix of available measures may prove cost-efficient and improve market efficiency. Mussel farms can add a substantial supply of N-permits to the market at competitive prices, reducing costs and increasing market liquidity. In catchments with high reduction requirements, demand for N-permits may exceed supply, as stricter reduction targets mean farmers face potentially higher mitigation costs and thus have higher demand for permits (Hansen et al., 2019). Therefore, integrating land-based reduction measures and mussel-based mitigation can potentially reduce costs and provide liquidity to improve market efficiency.

1.3. *Smart markets for water quality*

For our study, we use a smart market for water quality (SMWQ) approach for designing our WQTM. First developed by Prabodanie et al. (2010) and recently applied in a hypothetical study by (Hasan et al., 2022) in Denmark, the approach is based on an optimization model proposed by (Mccabe et al., 1991) as a mechanism to clear the market to produce equilibrium price and quantity given the bids (i.e. demand) and offers (i.e. supply) submitted by market participants under a defined total load cap. The approach can, in theory, account for the spatial interactions that arise from the dispersed nature of non-point pollution while also potentially reduce transaction costs. SMWQ has been proposed for trading nitrogen between point and non-point sources as well as trading between non-point sources (Hasan et al., 2022; Prabodanie et al., 2010; Raffensperger and Milke, 2017; Ranga Prabodanie et al., 2014). However, to the best of the authors knowledge, there is no record in the literature of analysis of a smart market mechanism where land-based farmers and marine-based farmers trade in the same market.

A SMWQ can work similarly to modern electricity markets, where buyers and sellers submit bids to a central market authority (Raffensperger et al., 2009; Raffensperger and Milke, 2017; Ranga Prabodanie et al., 2014). It is a centrally mediated, multilateral trading system. The centralized nature of the system and its use of linear programming to clear the market allows it to incorporate the necessary spatial factors readily available at high resolution, such as local retention and crop choices; and single or multiple local environmental targets (Raffensperger and Milke, 2017; Ranga Prabodanie et al., 2014). The mechanism also allows the use of nitrogen reduction measures as proxies for emissions reductions, partly overcoming the problem of accurately measuring the tradable unit (nitrogen emissions) (Horan and Shortle, 2011). As described in Prabodanie et al. (2010), the central market manager is responsible for enforcing contracts, guaranteeing payments, providing anonymity when needed, enforcing market regulations, and ensuring good market operations overall. The central market manager does not need information on private costs and benefits of market participants. As a result, the framework can deliver a multilateral trading platform that makes use of available scientific information and guarantees users' rights while potentially decreasing transaction costs (Kostel et al., 2014).

1.4. Aim of the paper

Building on earlier work from Hasan et al. (2022), we simulate a hypothetical WQTM in a catchment located in northern Denmark using the SMWQ framework described above. We build on Hasan et al.'s work by including mussel farmers in the trading market and setting up scenarios with decreasing levels of participation (−10%, −20% and − 30%) by agricultural farmers.

By integrating agricultural farmers and mussel farmers, we seek to assess the effects of such integration on a water quality trading market and the costs of mitigating non-point source pollution using a smart market approach. Additionally, by setting-up scenarios with decreasing levels of participation, we seek to estimate the effects, in our study area, of an important concern regarding WQTMs – low participation. Both contributions offer novel additions to the literature and have important policy implications for the design of instruments to improve

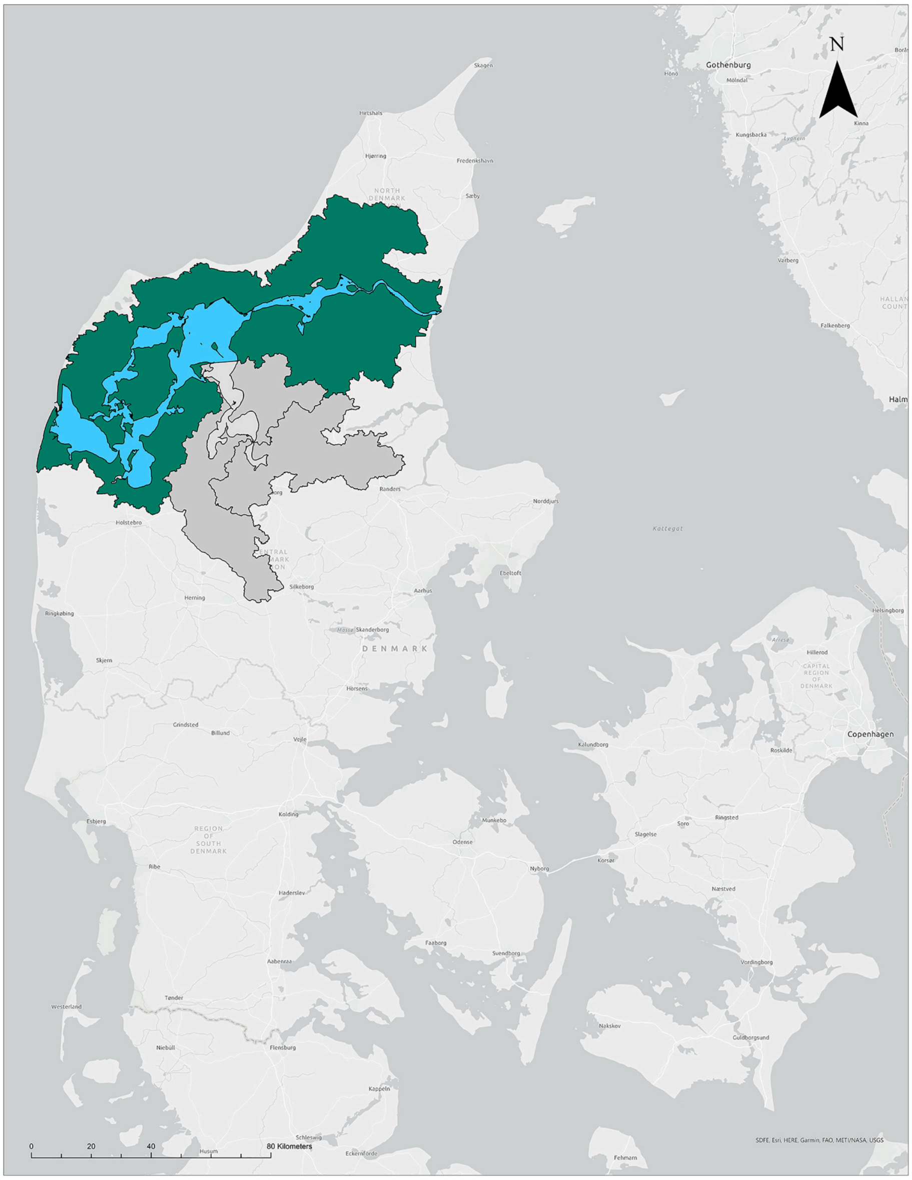

Fig. 1. Limfjorden catchment. The sub-catchment depicted in green is the study catchment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental conditions in coastal and marine areas.

2. Material and methods

2.1. Study area

Located in Jutland, northern Denmark, Limfjorden is a fjord of approximately 1500 km^2. Its catchment area covers roughly 7600 km^2, >20% of the country's area. The fjord area is formed by several basins parted by shallow and narrow sounds. The total volume of water is approximately 70km^3, its maximum depth is 28 m and its mean depth is 4.9 m. It connects the North Sea on the west and the Kattegat on the east. It has a constant flow of high salinity water (32–34 psu) from the west, low salinity (19–25 psu) water from the east and fresh water from the surrounding catchment. Overall, it is considered a high salinity water body (Ministry of Environment, 2011; Wiles et al., 2006).

The Limfjorden catchment area is used primarily for agriculture, with 6504 farms covering 66% of the land area. Natural areas such as lakes, wetlands, bogs, heathland, and meadows make up 12%, forests cover 10% and urban areas and infrastructure cover 12%. Due to the high nutrient input from surrounding areas, mostly from agricultural run-off, Limfjorden has become a eutrophic water body. There are three catchments from which nutrients flow to Limfjorden and the overall water body is thus divided into three sub areas linked to these catchments. For this study, we focus on the largest catchment (Fig. 1), which is linked to the water bodies of Nissum Bredning, Thisted Bredning, Kås Bredning, Løgstør Bredning, Nibe Bredning and Langerak. Their total water area is 1278 km^2 (Ministry of Environment, 2011).

Each sub area of Limfjorden has its own set of environmental indicator targets and nitrogen reduction targets in accordance with the WFD goal of all European waters reaching good ecological status. The area linked to the sub catchment in focus for this study is currently categorised as in "poor ecological status" and was assigned a nitrogen load reduction target of 2122.1 tons per year in 2016 (*Agency for Water and Nature Management*, 2016). The load reduction target from 2016 is used in this study because updated targets for 2021 are not yet available.

With regards to mussel production, Limfjorden is generally well suited to sustain relatively high productivity levels. This is due primarily to high salinity, which positively affects mussels' filtration rates, and high quantities of nutrients coming from the surrounding agricultural lands, which raises primary production and phytoplankton biomass. Low levels of chemicals and microbiological contamination complete the favorable conditions for mussel production in Limfjorden (Petersen et al., 2014; Riisgård et al., 2014; Riisgård et al., 2013).

2.2. Data

2.2.1. Agricultural farms

In the smart market, agricultural farmers can choose between abatement measures with different effectiveness and costs. To calculate the costs of measures, we use information on the crop composition of each farm to calculate the forgone gross margin after applying the measure. In the next paragraphs, we present a summary of the data used and its sources. For a complete description of the dataset used in this study, including information on land parcels, crop type distribution, gross margins per crop type, leaching estimates and retention, see Hasan et al. (2022). The data on mussel production and costs are based on Filippelli et al. (2020) and are briefly outlined below.

Data sources are the Danish husbandry register, the Danish general farm register, the Danish agricultural advisory service (SEGES), the national nitrogen model (Højberg et al., 2015) and selected publications. An overview of the data inputs and sources is presented in Table 1 and described below.

The Danish general farm register and the Danish husbandry register provide data on crop composition and fertilizer application at the land parcel level. Land parcels have a mean area of 9 ha in the study area.

Table 1
Data description.

Data Description	Spatial unit	Year	Source(s)
Crop composition	Land parcel[a]	2011	Danish General Farm register. Data is used to manage farmers' applications for the EU single farm payment.
Crop-specific gross margins	Individual crop, per soil type and use of organic or inorganic manure.	Average 2011–2013	SEGES: gross margin budgets. http://Farmtalonline.dlbr.dk
Fertilizer application at field level. Livestock production.	Land parcel	2011	Danish General Farm register. Data is used to manage farmers' applications for the EU single farm payment. Data from the Husbandry register collected annually by Danish authorities for cross-compliance control of Danish farmers.
Nitrogen retention	Catchments with a mean size of 15 km^2	2015	Højberg et al. (2015)
Leaching coefficients. Kg N from the root zone.	Per measure, soil type, use of manure.	Estimates based on data updated until the publication of the report in 2012.	Andersen et al. (2012)
Estimated cost of mussel production	18.8 ha standard mussel farm.	2014/2019	Petersen et al., 2014; Taylor et al., 2019; Filippelli et al., 2020

[a] A land parcel is a geographic unit which consists of one or several single fields. The fields linked to the land parcel can be owned by one of more farmers. Based on data from the Danish General agricultural Land Register (GLR).

Gross margins are available from http://www.farmtaonline.dlbr, managed by SEGES (Danish Agricultural Advisory Service). It is calculated per individual crop, soil type and use of fertilizer. The availability of data on crop composition and gross margins allows us to calculate the costs of the abatement measures as the foregone income from applying a measure to a specific field plus its implementation costs.

Nitrogen retention levels are taken from the latest Danish national nitrogen model (Højberg et al., 2015). The model provides estimates of nitrogen retention coefficients for the whole country and is divided in areas of 15km^2, on average. Leaching coefficients come from Andersen et al. (2012) and are calculated as the difference in the amount of nitrogen loss from the root zone before and after the implementation of measures. This is influenced by crop type, soil type, topography and the use of fertilizer. The available agricultural abatement measures for this simulation are catch crops, reduced N fertilization, set aside and restored wetlands. These measures are part of existing annual agricultural reporting for the EU Common Agricultural Policy support and therefore these data are accessible.

Mussel farms.

Mussel farm characteristics and production costs are based on Filippelli et al. (2020), Holbach et al. (2020), Petersen et al. (2016a), Peterson et al. (2015) and Taylor et al. (2019). A standardized 18.8 ha farm is used for nitrogen reduction potential and cost calculations. An overview of the information on the size, costs and nitrogen reduction potential of mussel farms can be found in Appendix 1. Potential areas for mussel cultivation and nitrogen uptake have been mapped for the entire coastal area around Denmark, and the potential carrying capacity for mussel farming has been modelled based on data on chlorophyll content, temperature, water flow and salinity, as well as risk of eider duck foraging and starfish attacks (Holbach et al., 2020; Bruhn et al., 2020). The carrying capacity map was used in the present study to set the productivity levels (N reduction per year) of the mussel farms. The models in Holbach et al. (2020) were developed and validated with measurement data from experimental farms in Skive fjord (another sub catchment in the Limfjorden) and Horsens fjord. The productivity of mussels in terms of produced biomass and the nutrient extractions estimates for the rest of the Danish fjords and coastal areas are extrapolated using the validated model and are therefore more uncertain (Bruhn et al., 2020; Holbach et al., 2020). Results on the productivity and nutrient extraction of the experimental farms are reported in Taylor et al. (2019).

Data from the most effective long-line mussel farm type with a high density of long-lines (30 cm between the lines) has been used. Each mussel farm has an area of 18.8 ha and is capable of producing 1260 tons of mussels per year (67 t/ha year^{-1}). Harvested mussels have a nitrogen content of 1.4% on average, which means that each farm has the potential to capture 17.9 tons of N per year (Holbach et al., 2020; Taylor et al., 2019). The cost to run a farm of this size is estimated to be 98,736 DKK per year. Mussel farming for mitigation purposes is optimized for biomass production, resulting in a higher density of the lines and smaller mussels – decreasing its value for human consumption (Petersen et al., 2015). It is assumed that the mussels do not generate a waste product but that they are utilized for fertilization in the agricultural sector and that the shells are used in road construction at zero additional costs, as has also been assumed by others (Petersen et al., 2015). Given the productivity estimates for the catchment, the production costs of mussels to reduce 1 kg of nitrogen is estimated to be 104 DKK. These estimates are now used in the Danish catalogue of marine mitigation measures (Maar et al., 2020).

2.3. *The modeling approach*

To simulate the SMWQ we use information on the expected behavior of participants – buyer's maximum willingness to pay for a permit, seller's minimum willingness to accept for a permit, and the corresponding quantities of permits demanded and supplied. We assume zero compliance and transactions costs related to participation in the market. With parcel-level data on their current nitrogen leaching and the cost and effectiveness of the abatement measures available to them, we are able to model buyers' and sellers' economically rational choices when confronted with different leaching limits (at farm level). These leaching limits (i.e. initial allocation of permits) are set following a grandfathering approach.

Thus, as a first step, we model agricultural farmers' choices when faced with a limit on nitrogen leaching at their farms and the available nitrogen reducing measures (eqs. 1, 2 and 3). These choices translate into bids-to-buy and offers-to-sell permits, which are then used as inputs for the second step - the SMWQ simulation (eqs. 4, 5, 6 and 7). Each N-permit allows the holder to leach 1KgN at farm level, which translates into less than 1KgN of leaching rights at the fjord (the receptor), depending on the farm-to-fjord nitrogen retention. The modeling framework is based on previous work, see Hasan et al. (2022) for further information.

2.3.1. *Step 1 – modeling of agricultural farmers' bids and offers*

In step 1, we run a cost-minimizing mixed-integer linear programming model to optimize each agricultural farmer's choice of measures in order to comply with their leaching limits. Farmers will base their willingness to pay or to accept payment for permits on the cost-effectiveness of the measures available to them, their leaching limit and their current leaching. The optimization model is an adaptation of the TargetEcoN model developed by (Hasler et al., 2019; Konrad et al., 2017; Konrad et al., 2014).

The model equations are described and explained below.

Objective function: (Eq.1)

$$Min_{x_{n,j}} V = \sum_{n}^{N} \sum_{j}^{J} Cost_{n,j} {*} Pot_{n,j} {*} x_{n,j} \tag{1}$$

Subject to:

Constraint 1: (Eq.2)

$$\sum_{n}^{N} (Area_n {*} Leach_n) - \left(\sum_{n}^{I} \left(Area_n {*} t \right) \right) = E_f \tag{2}$$

Constraint 2: (Eq.3)

$$E_f \leq \sum_{n}^{N} \sum_{j}^{J} Effect_{n,j} {*} Pot_{n,j} {*} x_{n,j} \tag{3}$$

where n, $n \in \{1, 2, \ldots, N\}$, represent the individual fields within a farm; j, $j \in \{1, 2, \ldots, J\}$, denote the available nitrogen reduction measures for field n; and t, $t \in \{1, 2, \ldots, T\}$, stands for the initial nitrogen leaching allowance for a farm, in KgN/ha. $Cost_{n,\ j}$ denotes the cost, in DKK/ha, of implementing measure j on field n. The area of each field is represented, in ha, by $Area_n$. The leaching at the root zone in each field is given, in KgN/ha, by $Leach_n$. The effectiveness (KgN/ha) and potential (ha) of a specific measure j on a specific field n are represented by, respectively, $Effect_{n,\ j}$ and $Pot_{n,\ j}$. E_f denotes a farm's nitrogen reduction target in KgN and $x_{n,\ j}$ is a binary variable indicating whether a measure is adopted or not.

Eq. 1 is then the objective function, and we seek to minimize the cost (V) of complying with the leaching limit by choosing the best combination of measures and fields. Eq. 2 determines the required nitrogen reduction (E_f) per farm to comply with its limit (i.e. its nitrogen leaching allowance). The equation subtracts the total nitrogen leaching limit for a farm ($\sum_n^N (Area_n * t)$) from its current total nitrogen leaching ($\sum_n^N (Area_n * Leach_n)$) and returns the required reduction (E_f) in KgN. Eq. 3 then forces the actual nitrogen reduction per farm to be equal or greater than the required target. The binary variable ($x_{n,\ j}$) determines which measures j, if any, are implemented on each of the farm's fields. By varying t in eq. 2, we find the corresponding reduction targets (E_f) for the different initial leaching allowances. Using that information in conjunction with eq. 3, it is possible to create bid and offer schedules for N-permits for each farm (consisting of $n \in \{1, 2, \ldots, N\}$ fields) in the market.

The binary control variable in the model implies that any given measure can only be applied to an entire field, which can lead to overshooting of the reduction targets. To generate more smooth marginal abatement costs estimates, we split each field into four 'sub-fields', allowing a mitigation measure to be applied to 25%, 50% or 75% of a field.

2.3.2. *Step 2 - modeling of mussel farmers' offers*

The second step addresses the offers from the mussel farmers. As described in Section 2.2, in this study, we model all of the mussel farms as having an area of 18.8 ha, being capable of capturing 17.9 tons of N per year and having a yearly cost of 98,736 DKK/ha (approximately 1.9 M DKK per farm). Consequently, each mussel farmer (assuming they own one farm) will submit only one offer to sell 17,900 permits (1 permit = 1kgN) at a minimum offer price of 104 DKK per permit. Permit offer price and quantity will thus be uniform across all mussel farmers. Mussel farmers are defined by $m \in \{1, 2, \ldots, M\}$.

2.3.3. *Step 3 – Simulation of the SMWQ*

In the third and last step, we simulate a *SMWQ* using the smart market approach. The objective of the smart market is to maximize the net gains from trade (i.e. to buyers and sellers in combination). Its constraints are the maximum nitrogen load at the receiving water body and the individual leaching limits for each agricultural farm. The market is simulated by running a linear programming model using the output from step 1 as one of its inputs for participating agricultural farms, and the offer price and quantity for mussel farmers from step 2. The inputs from step 1 comprise agricultural farmers' schedules for both demand (bids) and supply (offers) of N-permits, whereas the inputs from step 2 comprise only mussel farmers' offers for supply of N-permits. We also have access to data on farm locations, farm area and nitrogen retention.

Knowledge of nitrogen retention on agricultural land is central to the design of a SMWQ. The intensity of this retention depends on soil properties and distance to the receptor. Since retention coefficients will vary for agricultural farms in different locations, so will farms' contribution to the total allowable load at the receiving water body. Therefore, the retention level for each farm will impact the actual environmental damage caused by its emissions. As the N-permit price for each agricultural farm will reflect the true damage that the farm's emissions are causing to the receiving water body, the at-farm N-permit price will be weighted by the (inverse of) nitrogen retention between each farm and the fjord. Mussel farmers will not add to, but instead remove, the nitrogen load at the receiving water body. The linear programme outlined below details how markets are cleared, given the submitted bids-to-buy and offers-to-supply N-permits, all operating within the load cap at the receptor. Market simulations are undertaken with and without mussel farms' participation. The formulation of the linear programme was taken from Prabodanie et al. (2010), adapted appropriately to this current application and informed by a similar application outlined in Hasan et al. (2022) for the same case study area.

Objective function (Eq. 4)

$$Max\sum_{i=1}^{I}\sum_{k=1}^{K}P_{ik}b_{ik}, \text{subject to} \tag{4}$$

Limits on bids-to-buy and offers-to-sell for each participant (Eq. 5)

$$\begin{aligned}&If\ U_{ik}\geq 0, 0\leq b_{ik}\leq U_{ik}, else\ U_{ik}\leq b_{ik}\leq 0\\ &\quad for\ all\ i=1,\dots,I; and\ k=1,\dots,K\end{aligned} \tag{5}$$

Water quality constraint at the receiving water body (Eq. 6)

$$\sum_{i=1}^{I}(1-r_i)q_i\leq L \text{ for all } i=1,\dots,I\ (S1):\delta \tag{6}$$

Compliance constraints for each participant (Eq. 7)

$$q_i-\sum_{k=1}^{K}b_{ik}=A_i \text{ for all } i=1,\dots,I\ (S2):\mu_i \tag{7}$$

where i, $i\in\{1,2,\dots,I\}$, represent the market participants and k, $k\in\{1,2,\dots,K\}$, denote the number of bids-to-buy or offers-to-sell for each participant. The initial allowance of N-permits, for each participant, is given by A_i and the retention coefficient at farm level is denoted by r_i.

Eq. 4 is the objective function. It seeks to maximize the gains from trade, or the total net benefit to participants in the market, for buyers and sellers in combination. In this equation, $P_{i,\ k}$ represents the price each participant would be willing to buy or sell N-permits, which are the bids-to buy or offers-to-sell obtained in steps 1 and 2. Their bids and offers will be accepted if the N-permit price is lower than their bid-to-buy price (for buyers) or if the N-permit price is higher than their offer-to-sell price (for sellers).

Eq. 5 describes the limits on the bids-to-buy and offers-to-sell quantities submitted by each participating agricultural and mussel farm. The quantities bought or sold by each participant in each transaction is represented by $b_{i,\ k}$. Values are positive when participants buy and negative when they sell. Therefore, the model is seeking to maximize the difference between the buyers' maximum willingness to pay and the sellers' minimum willingness to accept. In so doing, the pollution reduction target is achieved at least aggregate cost by moving reduction measures to farms where they are less costly to implement.

Eq. 6 specifies the water quality constraint. Total nitrogen load reaching the water body must be lower or equal to the required limit (L). Nitrogen that leaves the agricultural farms (q_i) is partially retained ($1-r_i$) before it reaches the receiving water body (the receptor) i.e. only a proportion of q_i reaches the receptor. Inclusion of mussel farms whose locations are at the receptor (i.e. $r_n=0$) means that total removals of nitrogen by mussel farms are *additional* to the load cap L, or equivalently, total nitrogen loads from agricultural farms at the receptor net of total loads removed by mussel farms is equal to L.

Eq. 7 refers to the dynamics at farm level. Each participant is initially allocated a leaching allowance A_i, where $A_i\geq 0$ and $A_i=0$ for agricultural and mussel farms, respectively. If leaching from an agricultural farm is higher than its allowance, the farm needs to buy N-permits ($b_i>0$) to compensate. Conversely, if leaching from an agricultural farm is lower than its allowance, it can sell N-permits ($b_i<0$). Mussel farms participating in this market receive zero initial allowance, $A_i=0$, and their retention is set at zero, $r_i=0$. In this instance, Eq. 7 implies that total leaching (q_i) from mussel farms is negative and equal to the number of N-permits sold.

Each mussel farm can remove a fixed quantity of N per year from the water body where it is located (Section 2.2; Holbach et al., 2020; Taylor et al., 2019). Each mussel farm can thus sell a fixed quantity of N permits per year. For mussel farmers (in the simulation), the economic decision is on whether or not to set-up a mussel farm for mitigation. Agricultural farmers can also choose to implement more abatement measures than required and sell the resulting excess N-permits if it is cost-efficient for them to do so.

The parameter δ, shown in eq. 6, is the shadow price of the water quality constraint. It represents the marginal change in the objective function that would result from an increase of 1 KgN in the allowed nitrogen load to the receiving water body. For the farm level compliance constraint (Eq. 7), the associated shadow price, μ_i, represents the marginal change in the objective function if agricultural farm i were allowed to leach an additional 1KgN at farm level or if mussel farm i were able to remove an additional 1 kgN.

As the N-permit price for each agricultural farm must reflect the true damage that the farm's emissions are causing to the receiving water body, it will be weighted by the nitrogen retention of each farm (Kolstad, 2011) – the higher the retention, the less a farmer has to pay for one permit. μ_i represents the price of permit for participant i such that $\mu_i=\delta$ * ($1-retention_i$) where δ represents the shadow price of the nitrogen load limit at the receptor. Agricultural farmers will face a permit price that equals μ_i, while mussel farmers, who are already removing nitrogen load in the receiving water body and are not affected by nitrogen retention (i.e. $r_i=0$), will be paid a permit price equal to δ.

2.4. The modelled scenarios

The effects of integrating mussel farmers into the SMWQ are analysed using 2 scenarios: without mussels and with mussels. Additionally, to test the effects of differing participation levels by agricultural farmers in the market, both scenarios have three sub-scenarios where we reduce agricultural farmers' market participation by 10%, 20% and 30%.

For all scenarios, agricultural farmers are required to adhere to their individual limits on nitrogen leaching at farm level. Additionally, farmers are required to collectively reduce total nitrogen load to the receiving water body by 2122,100 KgN per year, or 27.4% of the current load. The reduction target is taken from the most recent available Danish River Basin Management Plan for 2015–2021 (*Agency for Water and Nature Management,* 2016). Consequently, farmers are required to implement abatement measures and/or engage in the permit market in order to comply with their individual load limits. The 'with mussels' scenario introduces mussel farms to the WQTM, allowing them to contribute to the nitrogen load reduction goal.

A grandfathering approach is used, where initial permit allocation is based on past leaching levels (Fig. 2). After calculating the share of the total nitrogen leaching at the root zone that each farm is responsible for,

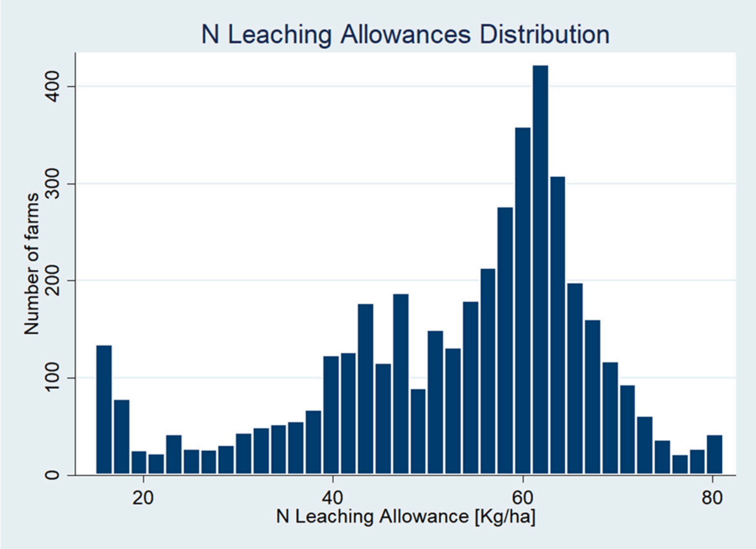

Fig. 2. Distribution of N leaching allowances.

new allocations are distributed respecting the initial proportions.[3] As mentioned above, the total load to the receiving water body is reduced by 27.4% to comply with the catchment's cap without inclusion of mussel farms as market participants. Inclusion of mussel farms in the market would allow the nitrogen load from agricultural farms to the fjord to be increased by 17.9 tons of N per mussel farm (assuming that the N-credits offered by the mussel farm are actually purchased by agricultural farmers).

For the reduced participation scenarios, we systematically remove 10%, 20% or 30% of agricultural farmers participants from the market. Assuming that farmers' willingness to participate is positively correlated with their gains from joining, we remove the farmers who realised the lowest gains from trade when running the simulation with full participation (for both scenarios - with and without mussel farmers). For the scenarios with mussels, we use the long-term mussel productivity estimation, which results in the 104 DKK/KgN offer price. The removed agricultural farmers who would have gained <140 DKK/ha, 325 DKK/ha and 536 DKK/ha for reduced participation of 10%, 20% and 30%, respectively, in the scenario without mussels; and 158 DKK/ha, 384 DKK/ha and 585 DKK/ha for reduced participation of 10%, 20% and 30%, respectively, in the scenarios with mussels.

The agricultural farmers who choose not to participate in the market are still required to comply with their original leaching limits. They will implement the necessary measures to reduce emissions (modelled in step 1, section 2.2) and their costs will be added to the total costs for the scenarios.

3. Results

For all the scenarios and sub-scenarios, total abatement costs without trade are around 542 million DKK. Overall, the simulation results suggest that substantial reductions in total abatement costs can be achieved through a SMWQ between non-point pollution sources i.e. agricultural farmers and that additional cost savings can be achieved by including mussel farms in the market as point sinks (Table 2).

3.1. *Full participation*

For the scenario without mussel farmers and with full participation from agricultural farmers, total abatement costs with permit trading are 189.9 million DKK. The permit price at the receptor is 156 DKK/kgN and the total cost reduction achieved by the trading scheme is 65%. Total permit sales add up to 135.7 million DKK. The quantity of permits bought is 3602 tons (1 N-permit = 1KgN leaching at the farm), while permits sold adds up to 1810 tons (at the farm).[4] Total gains from trade are 352.4 million DKK, with buyers gaining 289.8 million and sellers 62.6 million. The number of buyers in the market is 3069 and there are 1131 sellers.

When integrating agricultural farmers and mussel farmers, in a market with full participation, total abatement costs after trade are 167.3 million DKK, a reduction of 69.2% due to trade. When compared to the scenario without mussel farmers, total costs are 11.9% lower.

The number of mussel farms for the scenarios with full participation reaches 52. This is the number of farms required to reach the reduction goal cost effectively with a permit price per KgN at the receptor of 104 DKK. When there is no cheaper option to buy N-permits, the smart market will keep matching buyers' bids to mussel farmers' offers until the reduction target is reached or until there are no more mussel farms available. Evidently, there is a limit on the possible number of mussel farms in Limfjorden. However, 52 farms, or 978 ha, represents only a small fraction of the total available area in the water body (Holbach et al., 2020).

Under full participation, total revenues from permit sales decrease by 4.3% when moving from without mussels to with mussels, reaching 129.8 million DKK, as mussel farms offer relatively cheap N-permits. Mussel farmers receive 73.2% of total permit sales. The quantity of permits bought increases by 27.6%, to 4597 tons of nitrogen, when moving from without mussels to with mussels under full participation, resulting in an increase in the total gains from trade from 352.4 to 375.0 million DKK; an increase of 6.4%. While buyers increase their share of the gains from 82.2% (289.8 M DKK) to 95.3% (359.2 M DKK), the share of the gains that accrue to sellers falls from 17.8% (62.6 M DKK) to 4.2% (15.8 M DKK) when comparing between full participation without and with mussels.

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[3] For some farms the reduction in leaching is infeasible using only the measures considered in this study. They have been allocated their minimum leaching level. Also, no farm is allocated <15 kgN/ha initially since that is considered close to natural leaching levels. There were 304 farms incapable of complying with their allotted reduction, from a total of 4239.

[4] The quantity of permits bought and sold differ due to the difference in N retention affecting buyers and sellers. At the receptor, permit purchases and permit sales are in balance - so the load cap still holds (Eq. 6).

Table 2

Results of the simulations for markets operating with a load cap that represents a 27.4% reduction on current total N-load to the receptor. Comparison of markets with and without mussel farms; and different levels of participation of agricultural farm.

		Without Mussels				With Mussels			
		Full Participation	10% out	20% out	30% out	Full Participation	10% out	20% out	30% out
Number of mussel farms		–	–	–	–	**52**	**50**	**41**	**36**
Costs without trade (M DKK)		542.3	542.1	541.9	542.2	N/A	N/A	N/A	N/A
Costs with trade (M DKK)		**189.9**	**191.8**	**203.4**	**224.2**	**167.3**	**169.3**	**182.7**	**205.4**
Cost savings (%)		**65.0%**	**64.6%**	**62.5%**	**58.6%**	**69.2%**	**68.8%**	**66.3%**	**62.1%**
Cost red. After mussels (%)		–	–	–	–	**11.9%**	**11.7%**	**10.2%**	**8.4%**
Permit price at receptor (DKK/kgN)		156	153	151	143	104	104	104	104
Total permits bought (t)		3602	3486	3113	2617	4597	4476	3920	3308
Total permits sold (t)		1810	1706	1441	1167	1493	1418	1183	951
Tot. permits sold by mussels (t)		–	–	–	–	913	885	732	630
Total permit sales (M DKK)		135.7	127.6	110.3	87.2	129.8	124.5	104	85.6
Tot. p. sales by mussels (M DKK)		–	–	–	–	95.0	92.0	76.1	65.6
Gains from trade (M DKK)	Total	**352.4**	**350.3**	**338.5**	**318.0**	**375.0**	**373.0**	**359.6**	**336.9**
	Buyers	**289.8**	**291.4**	**285.7**	**274.4**	**359.2**	**357.8**	**345.6**	**325.6**
	Sellers	**62.6**	**58.9**	**52.8**	**43.7**	**15.8**	**15.3**	**14.0**	**11.3**
# of Buyers		3069	2939	2697	2407	3607	3444	3105	2752
# of Sellers		1131	876	694	560	646	421	327	251

The gains from trade for sellers decrease sharply when mussel farms are introduced to the market, as they outcompete the agricultural farms as permit suppliers. When mussel farms are able to offer nitrogen reduction at a lower cost than agricultural farmers, buying bids will continue to be matched to their offers-to-sell at their production costs. When mussel farms enter the market, the total number of buyers increases by 17.5%, to 3607, and the number of sellers decreases by 42.9%, to 646. This is because a standard mussel farm has an N abatement potential that is much higher than the N load that can be abated through mitigation actions on a typical agricultural farm. Consequently, when mussel farms deliver cost-effective abatement, they will outcompete many agricultural farms as suppliers of N permits. A standardized mussel farm has an abatement potential of 17.9 tons, whereas agricultural farms only sell 0.98 tons on average in a market with mussels, and 1.60 in a market without. Taking the difference in permit price into account an average agricultural seller receives 46,005 DKK from selling permits in a market with mussels (106,193 DKK in a market without mussels) whereas a mussel farm has a revenue of 1.86 mio DKK. Furthermore, agricultural farms may also change from being N permit sellers to being N permit buyers when mussel farms are introduced to the market.

In summary, when comparing the two scenarios under full participation, we observe that when mussel farmers are integrated in the SMWQ: total costs after trade decrease by 11.9%; total revenues from permit sales decrease by 4.3%, with mussel farmers receiving 73.2% of the total revenue and selling 61.2% of all the permits sold; gains from trade increase by 6.4%, with buyers increasing their share of the gains from 82.2% to 95.8%; the number of buyers increases by 17.5% and the number of sellers decreases by 42.9%.

3.2. Sensitivity to variation in cost of mussel production

An important driver of the cost of mussel production, and in turn the economic potential of including mussel farmers in the WQTM, is the productivity of the mussel farms and the variability in production across time and locations. For our study area, the ecological models identify a long-term productivity potential, per farm, of 17.9 t N year^{-1} while the measured data from experimental farms indicate a productivity of 19.7 t N year^{-1}. The difference is attributed to the fact that the model is estimating long-term productivity, while the measured values are subject to short-term fluctuations of local environmental conditions (Holbach et al., 2020; personal communication). If the measured productivity is considered, assuming fixed operational costs for the mussel farms, the cost to remove 1 kg of nitrogen decreases to 94 DKK.

We show full results for the modelled long-term productivity (17.9 t N farm year^{-1}) (Table 2). However, due to expected variability across time and space and the inherent uncertainty expected from empirically-based modeling, we can enrich our analysis by exploring the effects of a variation in mussel productivity (and thus its offer price) on the total cost after trade. This is important to explore the wider potential of trade when mussel productivity varies due to long-term variability between locations or short-term local fluctuations.

To explore the sensitivity of the market results to the costs of mussel production, we vary productivity to reach the higher measured value of 19.7 t N farm year^{-1} (94 DKK per KgN) and a roughly symmetrical lower value of 16.3 t N farm year^{-1} (114 DKK per KgN). We then identify the relationship between total costs of achieving the desired N-load cap in the fjord and mussel farms' productivity. Across the range of costs, a decrease of 1 t N year^{-1} reduced per farm (5.6% reduction in productivity) increases the total cost of achieving the load cap by 5.3 M DKK (3.2% of the total costs) (Fig. 3). The results suggest that even moderate variability in costs due to variability in productive potential of the mussel farms does not alter the conclusion that introducing mussel farms into the WQTM reduces the cost of reaching the desired water quality target.

3.3. Reduced participation

For all scenarios with reduced participation, we see reductions in cost savings from trade and therefore also in the gains from trade. However, these reductions are lower in percentage terms than the reductions in participation. For the scenarios with 10%, 20% and 30% fewer participants, total costs after trade increase by 1%, 7.1% and 18.1%, respectively (without mussel farming). The cost savings from including mussel farming to the set of available measures outweighs the increase in total costs observed in the 10% and 20% reduced participation scenarios. In the 20% non-participation scenario with mussels, estimated total cost is 182.7 M DKK, while for the full participation scenario without mussels it reaches 189.9 M DKK. However, 30% non-participation cannot be outweighed by introducing mussels farming as a mitigation option.

Moreover, for all reduced participation scenarios, even though scenarios with mussels perform better than scenarios without them, the effectiveness of mussel farms in decreasing total cost declines as market participation decreases. Comparing scenarios without and with mussel farming, total costs decrease by 11.7%, 10.2% and 8.4% for the 10%, 20% and 30% levels of non-participation, respectively.

Mussel farms numbers drop to 38 (−10%), 31 (−20%) and 27 (−30%) under the nominated reduced participation scenarios. The lower number of mussel farms in reduced participation scenarios is due

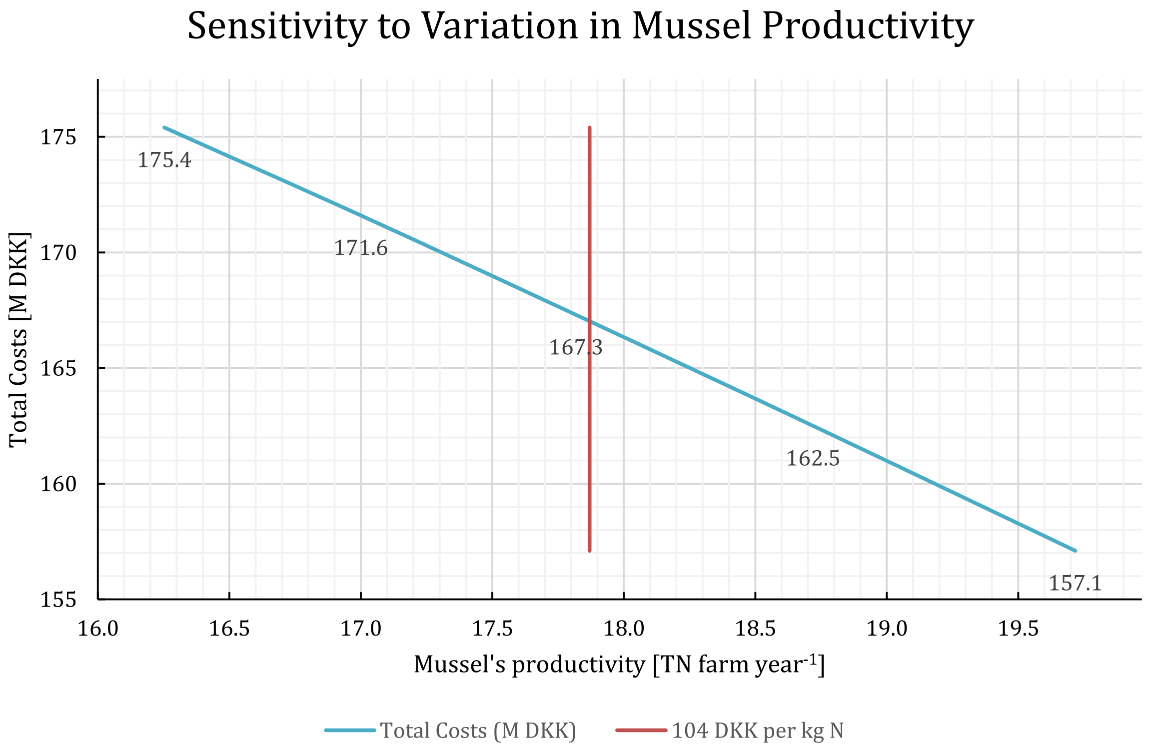

Fig. 3. Estimated total cost of meeting the desired N-load cap at the fjord for a range of mussel farms' productivities.

to the fact that the non-participating farms have to implement the nitrogen reductions required to comply with their nitrogen allocations *outside* the WQTM. Consequently, within the WQTM there is less demand for N-permits and fewer mussel farms are required to supply the market. Furthermore, as market participation decreases, only agricultural farmers who engage with the market can access low-cost N-permits from the mussel farms. This reduces the number of agricultural farmers who can benefit from this source of low-cost N-reduction, negatively impacting the mussel farms' effectiveness in reducing overall costs.

Additionally, in the case study area, trading simulation results show that farmers with low gains from trade, who are thus assumed to be less likely to participate in the market, are located in relatively low nitrogen retention areas. Consequently, the remaining participants in the reduced participation scenarios will have a higher mean nitrogen retention. Higher nitrogen retention means less nitrogen reaching the water body and thus lower overall reduction requirements for farms in the market. As N-permit prices at the receptor decrease when the reduction requirement is eased, market participants will face lower N-permit prices in lower participation scenarios. As market participants have access to lower N-permit prices, mussel farms' ability to reduce costs diminish (since their costs, and thus offers-to-sell price, do not change).

In general, however, the gains from trade depend on several factors. Agricultural farmers will gain from trade if they are given the opportunity to buy permits for less than their abatement costs or sell permits for more than the costs they incur from implementing abatement measures. On the supply side, participants on low retention soils, with relatively low N-reduction requirements and with access to relatively inexpensive N-mitigation options are likely to gain from trade as they can supply mitigation effort relatively cheaply. Alternatively, on the demand side, participants on high retention soils, with relatively high N-reduction requirements and few nutrient abatement options are likely to benefit if they can buy permits cheaply. The farmers that are least likely to gain from trade are those with a marginal cost of abatement close to the market price. These farmers could be located on high or low retention soils. It is therefore important to point out that each catchment will have its own characteristics. It would generally be the case that farmers on low and high retention soils would benefit more from the opportunities a SMWQ could generate for buying and selling permits, compared to farmers on intermediate retention soils, all other factors being equal, and therefore would be more likely to participate in a trading market.

In summary, for the lower participation scenarios, the simulation results show reductions in savings from trade and therefore in the gains from trade. Market performance measured in terms of cost savings is better when mussel farms are included in the market than when they are not. However, the effectiveness of mussel farms in lowering the total cost of meeting the total N-load reduction in the fjord declines as participation falls. We argue that a reduction in the number of agricultural farmers who can benefit from lower N-permit prices from mussel farms negatively impacts the latter's effectiveness in reducing overall costs. Additionally, we argue that lower N-permit prices, caused by reduced pressure within the market to achieve reduction targets, reduces the mussel farms' potential to reduce overall costs. Finally, we point out that each catchment will have its own characteristics and the specific findings cannot be directly transferred to other catchments.

4. Discussion and conclusion

The analysis illustrates that mussel farms have a high potential to reduce the cost of meeting marine water quality targets in the case study setting. In catchments where the marine environment is suitable for mussel production, supplementing land-based measures with marine mitigation appears to have a large cost-saving potential and is worth considering for future policy implementation. In the Limfjorden Estuary, only two of the three water bodies are suitable for mussel farming. However, even in these catchments several barriers to successful implementation exist that need careful consideration (Greenhalgh and Selman, 2012; Kostel et al., 2014).

The simulation results for Limfjorden indicate that a WQTM under a smart market approach, including land-based measures and mussel farming, has the potential to lower abatement costs to achieve the required nitrogen reduction goals by as much as 69.2%. However, catchments' environmental and economic characteristics such as suitability for mussel growth, productivity and potential nitrogen removal, spatial distribution of nitrogen retention, nitrogen reduction goal, farming activities and available abatement measures are expected to influence results elsewhere. Therefore, the results presented here should be viewed only as an indication of the potential of such integration between land and marine measures. The sensitivity analysis, which reflects realistic differences in mussel productivity between coastal and fjord locations in Denmark, provides an identification of the effect of varying productivity on the gains from trade. Potentials for mussel farming along the Danish coast are mapped (Holbach et al., 2020) and can be used for more detailed studies of the national trade potential reflecting the relative efficiency of land-based and marine-based nutrient abatement at different locations.

One concern is the evidence from surveys that farmers tend to prefer to comply with nitrogen abatement obligations by implementing measures on their own land and are generally skeptical about entering into market-based schemes (eg. O'Connell et al., 2017; Hansen et al., 2019). This would suggest that even modest compliance and transaction costs could be a barrier to successful market uptake. In this study, we estimated that 10%, 20% and 30% of participants would gain <140 DKK/ha (∼19 EUR), 325 DKK/ha (∼44 EUR) and 536 DKK/ha (∼72 EUR), respectively from engaging with the WQTM, for the scenario without mussels, and <158 DKK/ha (∼21 EUR), 384 DKK/ha (∼52 EUR) and 585 DKK/ha (∼79 EUR), respectively, for the scenarios with mussels. Determining the compliance and transaction costs faced by participants is beyond the scope of this study. However, the findings suggests that a substantial fraction of farmers would have a relatively high gain from trade compared to the payments received from other agri-environmental programmes (Hasler et al., 2022). This indicates that a market, in principle, has some degree of resilience to compliance and transaction costs. Evidence from emerging schemes has however suggested that implementation of water quality trading schemes have been very costly. Motallebi et al. (2017) estimate that the costs have been as much as 84% of the permit price. This suggests that focusing on compliance and transaction costs in development of new schemes, as well as an improved understanding of farmers reservations for engaging in this type of environmental conservation mechanism, should be a priority.

In the simulations, mussel producers are the main sellers of abatement effort when they are included in the market. As mussel farming is not financially viable on market terms, N-mitigation based on mussel production will only be viable if a trading scheme can be implemented or if compensation instruments were adopted. A potential driver for mussel farming as a nitrogen reduction measure was left out of the analysis in this study. It has been proposed that organic animal feed can be produced from the harvested mussels (Filippelli et al., 2020; Petersen et al., 2016a; Petersen et al., 2015). In that case, and assuming that the feed can be produced cost competitively, there would be a far more compelling case for mussel farming. With higher profitability, the environmental requirements to have such activity as a cost-efficient mitigation measure would be reduced.

Studies have shown that mussel meal is an adequate feedstock for piglets and egg-laying hens, with satisfactory levels of nutrients and low levels of contaminants (Afrose et al., 2016; Nørgaard et al., 2015). It has enough protein content to potentially substitute other sources of protein, such as soy and fish meal, as ingredients in animal feed. However, the process of converting harvested mussels into animal feed is still under development and, so far, results are mixed. A recent analysis of the proposed methods can be seen in Øgelund (2020). In the study, the author estimates production costs to be between 3.66 DKK and 6.76 DKK per kg. The prospect of including mussel feed production as a viable source of revenue for mussel farmers is plausible, but further research is needed.

Despite the merits regarding environmental cost-effectiveness in terms of water quality targets downstream, there are also environmental concerns about the use of mussel farming for nitrogen mitigation. Criticism often revolves around the possibility of increased sedimentation below mussel farms of organic matter from faeces and pseudo-faeces (Hedberg et al., 2018; Stadmark and Conley, 2012; Stadmark and Conley, 2011). The argument is that this can affect the biogeochemical cycles of nitrogen and phosphorus, potentially increasing the flux of nutrients from the sediment. Also, the build-up of organic matter and its subsequent decomposition can lead to oxygen depletion, affecting the benthic community and nutrient cycles.

However, such criticism has been met with counterarguments from several researchers. Several authors argue that growing and harvesting mussel biomass without nutrient input has to result in net removal of nutrients in the system, a consequence of the mass balance principle (Petersen et al., 2020; Petersen et al., 2019; Petersen et al., 2012). In other words, the increase in local sedimentation is counterbalanced by a decrease in sedimentation on a basin scale. Rose et al. (2012) also point out that oxygen depletion in the bottom area of water bodies such as the Baltic Proper and the Gulf of Finland is relatively common, and that benthic-pelagic nutrient fluxes take place even without mussels. Furthermore, the current shellfish presence in estuarine ecosystems worldwide is significantly lower than historical population densities (Beck et al., 2011). Moreover, in a recent study, Maar et al. (2021) look at the possibility of transplanting mussels from areas with frequent hypoxia events and associated decomposition of mussel tissue, to more suitable areas. Using a 3D ecological model, the study concludes that mussel transplantation can limit the intensity of hypoxia events and the negative environmental effects associated with it. The paper thus implies that choosing suitable locations for mussel production can reduce potential negative local effects.

Implementation of a market mechanism integrating land-based and marine-based nutrient reduction measures would cause a shift in abatement effort from the source of the production activity to the environmental sink – the freshwater or marine receptor. There have been discussions on whether it is desirable to introduce such 'end-of-pipe' measures instead of preventing emissions from entering the environmental system in the first place. The argument appears to be reasonable for point-sources such as wastewater treatment plants, where cost-efficient solutions are available to reduce emission at source. For non-point emissions, however, removing all emissions at their source is either impossible or not cost-efficient (Hasler et al., 2015; Petersen et al., 2016b) However, 'end-of-pipe' solutions do not provide local environmental benefits at the source and such benefits may need to be included when considering the cost-effectiveness of alternative abatement options. Additionally, a favorable argument is that mussel farming or other marine-based measures can remove nutrient released from sediments, either coming from other marine areas or accumulated through atmospheric deposition of nitrogen (Timmermann et al., 2019). Mussel farms also will have the advantage that the effect on the marine receptor is immediate, while upstream measures may have a lag in their effect on the marine environment (Hart, 2003; Kemp et al., 2009). As the urgency to comply with WFD targets becomes more pressing, the potential contribution that mussel farming offers may increase the policy support for this measure. Furthermore, as the removal of N from the water body can be easily and accurately verified by measuring the N content in the harvested mussels, this is a key advantage of this measure for a trading programme, as it helps overcome one of the main challenges in the design of instruments to control agricultural emissions (Stephenson and Shabman, 2017).

This study's results ultimately show the potential for integrating land- and marine-based farmers within one policy framework to reduce nitrogen loads in coastal and marine areas. Respecting the specificity of each catchment and its receiving water, such integration should be considered when designing instruments to improve environmental conditions in coastal and marine waters. In practice, setting binding caps on agricultural emissions matched to ecological constraints is challenging, for technical and operational reasons, but mainly for political reasons (eg. Hoag et al., 2017; Stephenson and Shabman, 2017). Agri-Environmental policies in Europe and in Denmark in particular have a long tradition using command-and-control instruments (Hasler et al., forthcoming; Dalgaard et al., 2014). Implementation challenges and administrative costs for both the farmers and the agencies related to trading schemes should not be underestimated. However, the high heterogeneity across farms and water environments, and the high costs that the agricultural sector would incur in meeting binding catchment specific water quality objectives in the European Water Framework (European Commission, 2019), could make policy innovation in this field an important topic for research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the MuMiPro project (Mussel farming, mitigation, and protein source for organic husbandry – http://www.mumipro.dk) [6150-00008B], funded by the Danish Innovation Fund (https://innovationsfonden.dk/en) and the Aarhus University Centre for Circular Bioeconomy (http://cbio.au.dk/en/). This work was also supported by the H2020 project EFFECT (Environmental public goods From Farming through Effective Contract Targeting - https://project-effect.eu) [817903].

The sponsors had no role in the study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107549.

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