



Tradeable Nitrogen Abatement Practices for Diffuse Agricultural Emissions: A ‘Smart Market’ Approach

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Abstract

Markets in pollution permits for managing environmental quality have been advocated by economists since early 1970s as a mechanism that can deliver pollution reduction targets at lower cost to regulated entities than traditional uniform command-and control approaches. This study explores whether a ‘smart market’ cap-and-trade scheme between non-point sources can offer meaningful, robust and policy amenable, advantages over alternative approaches for nitrogen management in a realistic setting: 6504 individual farms in Limfjorden catchment, Denmark. The scheme involves multilateral trading of nitrogen emission rights among farms via changes in agricultural land management practices under a catchment-level cap on total nitrogen load. In this, the first exploration of non-point to non-point smart market nitrogen trading in a real setting, we estimate efficiency gains compared to uniform command-and-control regulation, explore the robustness of these gains in the face of non-participation, and reflect on farmers’ potential acceptance of the trading market in comparison with its command-and-control analog: spatially-targeted regulation, implemented via location-specific limits on nitrogen leaching. Results indicate that the smart market has the potential to substantially reduce the cost of meeting the catchment’s nitrogen reduction target. For a 21.5% reduction from baseline nitrogen load, the market delivers cost savings of 56% (DKK273 million, €36.6 million) compared to uniform regulation, with participating farms realising a mean net benefit of DKK 723/ha (€ 97/ha). Market performance is relatively robust against transaction cost; when delivering a 21.5% reduction in nitrogen load to Limfjorden, approximately 70% of the overall efficiency gain could be retained if only 24% of farms engaged with the market.

Keywords Land use · Diffuse pollution · Leaching · Linear programming · Simulations · Water Framework Directive · Water quality trading

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1 Introduction

Excessive nitrogen leaching from agricultural catchments is one of the main causes of eutrophication of marine and coastal areas around the world (Vilmin et al. 2018), with enclosed marine areas being particularly vulnerable. Abatement of nitrogen emissions to marine and freshwater systems downstream has been at the core of water policy in intensive agricultural regions for decades (Greenhalgh and Selman 2012; Corrales et al. 2013; Duhon et al. 2015; Ribaud and Shortle 2019). These policies have come at a substantial cost to regulated entities and society generally (Keiser and Shapiro 2018). Implementing nitrogen abatement policies that provide flexibility to farmers with respect to the choice of abatement options could significantly reduce the societal costs of meeting water quality targets (Greenhalgh and Selman 2012; Corrales et al. 2013, 2017; Shortle 2013). One way of achieving this is via a nitrogen trading scheme.

A nitrogen trading scheme can be designed to specifically address the challenge of cost-effective management of excessive nitrogen loadings to receiving waters (Crutchfield and Letson 1994; Kerr et al. 2007; Fisher-Vanden and Olmstead 2013), provided that the scheme operates with a fixed cap on the total nitrogen load reaching the receptor. Under such a scheme, emission sources are each provided with an initial allocation of nitrogen leaching rights at-source, such that the sum of those leaching rights across all sources does not exceed the required nitrogen load cap at the receptor, when accounting appropriately for the proportions of at-source leaching that will be removed (primarily) via denitrification, biological uptake or sedimentation when passing through soil, water, rivers, lakes and wetlands on its way to the receptor (Højberg et al. 2015). Here, following Van Breemen et al. (2002), Windolf et al. (2011) and Højberg et al. (2015), we use the term ‘nitrogen retention’ to describe the proportion of at-source leached nitrogen that is removed by natural processes before it reaches the receptor. Each source can, if it wishes, trade away from its initial allocation of nitrogen leaching rights. If a leaching right holder has access to low-cost abatement options, they may find it more profitable to abate some of their emissions and sell their excess leaching rights to sources with higher abatement costs who are looking to buy additional leaching rights to avoid the need to undertake on-farm abatement. By allowing leaching rights to be traded between emission sources, the total cost of meeting the required nitrogen load cap at the receptor can be minimised.

Upon receiving its initial leaching rights, and knowing its existing farming activities and soil type(s), an emission right holder would consider their suite of possible land management and land use options to determine the quantity of leaching rights they require. The link between land management practices, land uses and at-farm nitrogen leaching is informed by biophysical models (e.g. Andersen et al. (2012)). Farmers undertake nitrogen abatement by changing the combination of land management practices on their farm to reduce at-farm leaching. Purchases and sales of leaching rights in the market are managed to ensure that the nitrogen load cap at the receptor is not exceeded.

Potential gains from trade arise because of the inherent heterogeneity between farms in the cost-effectiveness with which changes in land management practices deliver nitrogen abatement at-farm. Heterogeneity may arise, for example, because of differences between farming businesses in the types of crops grown, soil productivity, climate, and scale of operation. Heterogeneity in the cost-effectiveness of abatement is further increased when there is inter-farm variability in the biophysical processes that link management practices and land uses to at-farm leaching, and in N-retention from farm to the receptor (Claassen et al. 2008). Designing policies that recognise and incorporate

spatial heterogeneity in the cost-effectiveness of abatement can further reduce the societal costs of attaining water pollution targets (Hasler et al. 2014, 2019; Konrad et al. 2014; Smart et al. 2016; Refsgaard et al. 2019; Czajkowski et al. 2021).

A cap-and-trade '*smart market*' multilateral trading framework has been proposed that can account for spatial variation in the cost-effectiveness of abatement actions and provide easy ('low transaction cost') market access to facilitate trading (Prabodanie et al. 2010, 2014; Raffensperger et al. 2017). Smart markets can handle biophysical and hydrological heterogeneity across a catchment, and set appropriate spatially-specific prices for supply and purchase of pollutant emission rights that reflect the spatially-specific impact of emissions from different locations on receiving water quality (Prabodanie et al. 2014). A smart market is an auction mechanism based on an optimisation model that was first demonstrated by McCabe et al. (1991). In the context of nitrogen regulation, a smart market is a centrally managed, online marketplace where a periodic auction is cleared using an optimisation process that maximises the gains from trade on receipt of *bid-to-buy* and *offer-to-sell* schedules in nitrogen loading rights at the receptor from market participants (Prabodanie et al. 2010; Raffensperger et al. 2017). Optimisation is implemented via a linear programming model that incorporates relevant spatial heterogeneity in nitrogen retention by ensuring that, in aggregate, trades do not exceed the desired nitrogen load cap at a single or multiple receptors (Prabodanie et al. 2010; The Wetlands Initiative 2014; Raffensperger et al. 2017).

Theoretical expositions of a smart market as a viable trading approach have been presented for efficient allocation of instream river flows (Murphy et al. 2009), ground water (Raffensperger et al. 2009; Raffensperger 2011), impervious cover (Raffensperger and Cochrane 2010), nitrate emission rights (Prabodanie et al. 2009, 2010, 2014;), sediment discharge rights (Pinto et al. 2013) and air pollution emissions rights (Willett et al. 2014, 2015). However, to the best of the authors' knowledge, with the exception of Raffensperger et al's (2017) case study in Big Bureau Creek, Illinois, U.S.A that simulates hydrologically-grounded smart market trading in nitrogen load between *point sources* (sewage treatment plants) as buyers and *non-point sources* (farmers installing nitrogen treatment wetlands) as sellers, all prior expositions of smart markets to manage nitrogen runoff in agricultural settings have been essentially theoretical, typically comprising less than 10 notional trading entities.

Given the potential advantages of the smart market, escalating concern globally regarding nitrate pollutant loads (e.g. Rockström et al. 2009), and the absence of a prior case study at real-world scale and complexity of a smart market that features *non-point* nitrogen *sources* (i.e. farms) as both buyers and sellers of nitrogen loading rights, here we explore whether a smart market can offer meaningful, and policy amenable, advantages over conventional 'command and control' regulation for nitrogen management in a real setting.

We simulate the operation of a smart market between farms as non-point source buyers and sellers of nitrogen loading rights at the receptor in a real, whole-of-catchment biophysical setting: 6504 actual farms comprising 56,556 individual land parcels of mixed farmland that drain to Limfjorden, a coastal fjord cutting through northern Jutland in Denmark. The research questions we address with this simulation are:

1. What level of efficiency gain could a smart market offer over traditional uniform 'command and control' regulation in the Limfjorden catchment – and to what extent do these gains persist as the nitrogen load cap for Limfjorden is tightened?

2. How robust are smart market efficiency gains in Limfjorden likely to be in the face of non-participation in market trading (as might be induced by different levels of transaction cost)?
3. Are there particular features of Limfjorden's agricultural landscape which support delivery of efficient and robust outcomes from a smart market trading in nitrogen loading?

In addressing these questions, the paper contributes to the evolving literature on smart market applications for water quality management by providing *the first simulation of smart market nitrogen trading among non-point sources at whole-of-catchment scale using empirical data*, including quantification of the potential efficiency gains from trading. It also contributes to literature that seeks to quantify the potential impact of non-participation and contributes to the ongoing debate regarding how farmers might respond to introduction of different policy mechanisms for practical management of water quality in agricultural settings.

2 Methods

2.1 Study area description

The Limfjorden catchment (Fig. 1) covers an area of 505,600 hectares of which 493,600 hectares are arable land, including permanent pasture. The agricultural area is dominated by cereal production comprising mainly spring barley, winter wheat and grass in rotation (Table 1). Representing 19% of Danish agricultural area, land in the Limfjorden catchment is predominantly privately owned and comprises 6504 farms. In recent decades, water quality in the fjord ('the receptor') has declined significantly (Tomczak et al. 2013). Nutrient enrichment has led to eutrophication and frequent occurrences of algal blooms (chlorophyll *a* observations) (Carstensen et al. 2007, 2013), hypoxia, reduced water clarity and loss of biodiversity including macroalgae and fish species (Hinsby et al. 2012). To improve water quality in the fjord, and with reference to the European Union's Water Framework Directive, a 2021 target nitrogen (N) load reduction of 3,627 tonnes has been established (MFVM 2016).¹

Average nitrogen retention for the Limfjorden catchment is 64.9%, (Andersen et al. 2012), i.e. on average, for every 100 kg N leached from farms' root zones, 64.9 kg N is decomposed in the soil and in ground- and surface waters so that only 35.1 kg N reaches the fjord. Knowing the target N reduction required at the fjord (3627 tonnes), the catchment area (505,600 ha), and average retention (64.9%), an average reduction of approximately 20 kg N/ha is required at the farms' root zones. This average 20 kg N/ha target reduction

¹ Nitrogen is considered the primary water pollutant of concern for Limfjorden. We do not include phosphorus in our study because Limfjorden and other estuaries and fjords in Denmark do not yet have target reductions for phosphorus loads from agriculture. Furthermore, measures undertaken in agriculture to reduce phosphorus losses have to be linked to very specific phosphorus loss pathways and spatial locations from which there are phosphorus loss risks. For Danish conditions these pathways and risks are described in Andersen and Heckrath (2020). The specific spatial characteristics of the phosphorus loads reduce the potential for using market-based instruments for regulation of phosphorus losses. However, as noted by Bernhardt (2013), phosphorus reduction should be approached carefully because interactions between phosphorus and nitrogen can inhibit the capacity of lakes to denitrify when input phosphorus loads are reduced—thus inadvertently increasing nitrogen loads delivered to coastal waters.

Denmark with the Limfjorden catchment area

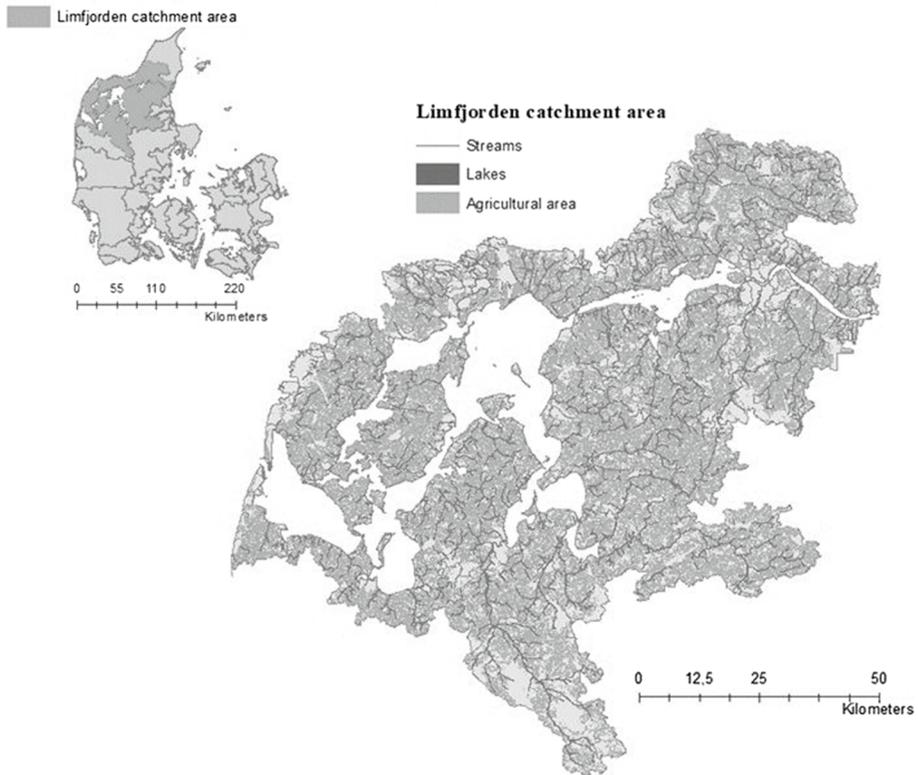


Fig. 1 Study area in Limfjorden catchment illustrating agricultural areas, lakes and streams

in at-farm leaching (~26% reduction from a calculated baseline of 79 kg N/ha leaching,² corresponding to a baseline nitrogen load of ~14,000 tonnes at fjord) is considered feasible for the types of farming undertaken in the catchment, given their cost profiles and available abatement measures (Hasler et al. 2019). Therefore, in this study, the smart market scheme is simulated for target total reductions of between 2 and 32% in at-farm leaching.³ N reductions beyond this range would need to be implemented through additional agricultural and non-agricultural measures.

² Baseline nitrogen leaching for the catchment was calculated knowing the area and crop rotations of individual farms (Data source: the General Agricultural Register and the Danish Husbandry register, collected by the Ministry of Environment and Food), crop-specific leaching estimates (Andersen et al. 2012), and nitrogen retention mapping (Windolf et al. 2011; Blicher-Mathiesen et al. 2014).

³ Recent load estimations, based on monitored and modelled data (MFVM 2016) suggest that baseline leaching in the Limfjorden catchment is somewhat lower than the calculated baseline used in this study. However, since the objective is to explore the operation of a smart market in a real agricultural context, we present simulation results for nitrogen abatement from our calculated baseline.

Table 1 Land use in Limfjorden catchment

Crop type category	Area (ha)	Percentage distribution
Permanent pasture	40,570	8.1
Energy crops/Willow	1487	0.3
Forest	1122	0.2
Uncultivated area	4504	0.9
Fruit and vegetables/nursery	1544	0.3
Area out of rotation	3042	0.6
Spring crops		
Oats	10,279	2.1
Spring barley	95,814	19.1
Corn	45,062	9.0
Winter crops		
Winter barley	22,578	4.5
Winter wheat	148,896	29.7
Winter rape seed	30,489	6.1
Rotational grass	95,146	19.0
Total area	500,533	100.0

2.2 Data

To simulate the operation of trading between farms in at-farm N leaching rights we need to know how Limfjorden's farmers would choose to configure N abatement practices to deliver feasible, least-cost stepwise reductions in nitrogen leaching from their farms. This information is used to produce the farm-specific bid-to-buy and offer-to-sell schedules in nitrogen loading rights at the fjord that are key inputs to the linear program that solves for smart market equilibrium. For our market simulation, we produce this farm-level dataset of minimum-cost leaching solutions by following a two-step process. The first step uses a specially modified version of the previously published, Limfjorden calibrated, TargetEconN 'social planner' cost-minimisation model (Hasler et al. 2019; Filippelli et al. 2020). To generate input data for our market simulation, the TargetEconN model framework has been adapted to model N abatement at a farm-scale so that it can estimate expected nitrogen leaching and the abatement costs incurred when applying the least-cost package of abatement measures to achieve a specified reduction in nitrogen leaching from a farm (see Appendix 1 for a fully detailed description, including data sources and a formal definition of the optimisation objective for the farm-scale modification of TargetEconN). The modified, farm-scale version of TargetEconN identifies the minimum-cost set of abatement measures to apply to a farm's fields to achieve a given reduction in farm-specific at-farm N leaching. The four abatement practices considered in this study are catch crops, reduced fertiliser applications, set aside, and restored wetlands. We run the modified, farm-scale TargetEconN model for a range of different at-farm N leaching limits. For each farm, we find the cost-minimised mix of N abatement measures for achieving each of the following levels of at-farm N leaching in kg/ha: 53, 56, 59, 61, 64, 67, 69, 71, 72, 74 and 76. For each of these N leaching limits, the modified farm-scale TargetEconN reports farm-specific minimised abatement costs and the farm-specific levels of N leaching achieved. The farm-specific data that are taken forward from TargetEconN to the smart market simulation thus

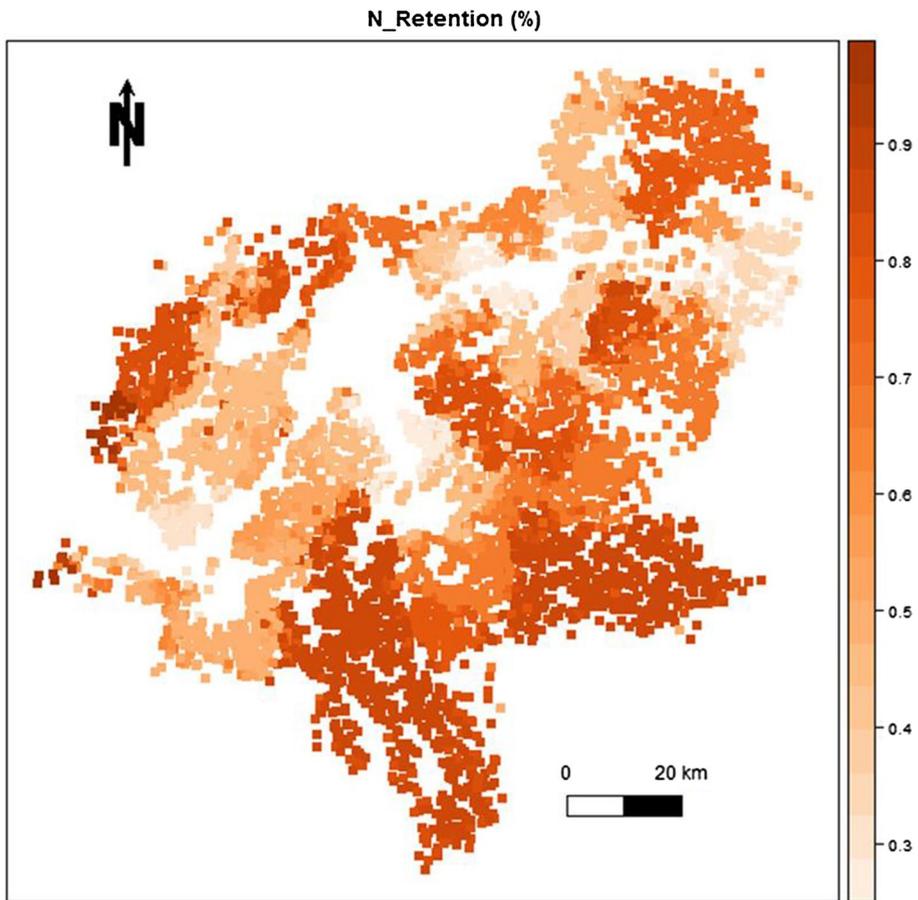


Fig. 2 Area-weighted retention for farms in the Limfjorden catchment

comprise a set of farm-specific at-farm N-leaching loads and (minimised) abatement costs for tightening at-farm N leaching limits from 76 kgN/ha down to 53 kgN/ha. Incremental abatement costs arising for each farm under the least-cost schedule of abatement practices that deliver the specified incremental reductions in at-farm N leaching generate the information required to produce the farm-specific *bid-to-buy* and *offer-to-sell* schedules for each of Limfjorden's 6,504 farms, as required for market simulation. In a second step, fine resolution retention mapping for Limfjorden's 90 sub-catchments (Windolf et al. 2011) is used to convert nitrogen leaching at-farm into nitrogen loads delivered to the fjord⁴ (Fig. 2).

⁴ We allocate a nitrogen retention percentage for each farm according to the dominant retention sub-catchment for the land parcels belonging to the farm.

2.3 Smart Market Trading Scheme

This section describes the smart market design and operation as proposed by Prabodanie et al. (2010), adapted for on-ground implementation of a smart market in tradable nitrogen abatement practices in the Limfjorden catchment, under a total load cap at the fjord, as the receiving water. The traded commodity in the nitrogen market for Limfjorden is N loading rights at the fjord. A maximum limit of N loading at the fjord is set as a binding cap and corresponds to environmental regulator's water quality target. Having set the N loading cap at the fjord, and knowing farm-specific farm-to-fjord nitrogen retention, the regulator allocates this cap amongst all farms as a *uniform initial per hectare allocation* of at-farm leaching rights such that the sum of N leaching from farms' root zones, accounting appropriately for their N retention, matches the desired N cap at the fjord. At-farm N leaching rights confer to the holder the right to leach the specified quantity of N (in kgN/ha) from their farm's root zone during the trading period. The trading period is one year in this study. A farm is required to hold enough permits to cover its intended N leaching, given its planned land use and land management for the year, and accounting for the set of nitrogen abatement practices (if any) that it will be implementing.

Each farm, having received its initial allocation of at-farm nitrogen leaching rights, can *choose* to trade away from this initial position by buying or selling N leaching rights in the market. Any farm that was previously leaching more than the initial allocation it received can choose to either implement abatement measures that will reduce leaching to comply with the farm's initial allocation, or buy sufficient additional leaching rights from the market to cover leaching in excess of that initial allocation. Conversely, any farm for which at-farm leaching is below its initial allocation can choose to sell unused leaching rights to the market. Whether or not a farmer chooses to buy (or sell) additional leaching rights depends on the costs they would save (incur) by implementing fewer (implementing more) abatement practices, together with the expenditures incurred in purchasing (revenues received from selling) the relevant quantity of leaching rights. Trading between farmers occurs when one farmer's maximum willingness to pay (WTP) for additional leaching rights is higher than another farmer's minimum willingness to accept (WTA) compensation for undertaking additional abatement. Farm-specific maximum WTP and minimum WTA for the incremental steps in leaching rights that correspond to stepwise changes in management practices and land use are determined from the farm-specific incremental abatement costs and incremental reductions in leaching, as described previously (Sect. 2.2).

To exemplify this smart market scheme further, consider a 25-ha farm (Farm A) with an N retention of 0.6 that has been allocated nitrogen leaching rights of 69 kgN/ha at its root zone (corresponding to 690 kg N loading rights at the fjord). Farm A's lowest-cost abatement measure to comply with its initial allocation of at-farm N leaching rights is to implement set aside. With the smart market in place, instead of being forced to implement set aside, Farm A can *bid to buy* additional N loading rights at the fjord (which can be expressed as N leaching rights at the farm by dividing by the N loading rights at the fjord by $(1 - \text{the farm's N retention coefficient})$, i.e. dividing by $(1 - 0.6) = 0.4$). Purchasing additional loading rights would deliver a cost saving to Farm A if the requisite quantity of additional N leaching rights at Farm A can be purchased from the market for less than the cost to Farm A of implementing set aside.

Once an initial uniform per hectare allocation of N leaching rights has been determined by the market manager, farmers submit *bids-to-buy* extra leaching rights (at-farm)

or *offers-to-sell* (unused) at-farm leaching rights to the smart market manager.⁵ The smart market manager is the entity appointed by the regulator to manage the smart market. As described in Raffensperger et al. (2017), the market manager is responsible for retaining data on leaching right holdings and transfers, leaching right prices, hydrology, retentions, nitrogen load and concentrations at specific monitoring points; managing the common pool of loading rights from submitted bids and offers; and clearing the trading market in N loading rights at the fjord using a linear program. Farmers who trade at-farm leaching rights are in effect, implicitly buying and selling from this common pool of N loading rights at the fjord (Raffensperger et al. 2017).

2.4 The Linear Program

A linear program is used to solve for an N-loading price at the fjord by accepting a set of farmers' *bids-to-buy* and *offers-to-sell* such that the catchment-wide total net gain from trading in leaching rights is maximised, subject to not exceeding the N loading cap at the fjord, and given the initial allocation of at-farm N leaching rights. This N leaching right allocation problem is modelled for a single time period of one year⁶ and it is assumed that farmers submit *bids* and *offers* which truly reflect their own 'least-cost' choice of land management practices to achieve incremental changes in at-farm leaching⁷ (Prabodanie et al. 2010). The following mathematical model is adapted from the descriptions provided by Prabodanie et al. (2010, 2014). In this model, nitrogen leaching from each farm is weighted by a farm-specific coefficient, d_i (where $d_i = 1 - \text{retention}_i$) to produce the overall nitrogen load at the fjord. Each landholder who manages a particular farm is regarded as a decision-making unit (DMU).

Indices

$i = 1, \dots, N$ participants or DMUs

$k = 1, \dots, K$ bid or offer steps or 'tranches' in the bid / offer schedule for each DMU i . (The number of bid and offer steps need not be the same for all DMUs because in a mixed farming catchment, each DMU can only feasibly move to a limited number of other land use(s) by implementing particular farm-specific abatement measures.)

Parameters

A_i = initial allocation of at-farm N leaching rights to DMU i .

⁵ In a practical implementation (as opposed to our simulation) farmers would use a spatially-specific look-up table, webpage or smart phone 'app' to determine the N-leaching from different management practices and land uses on their farm. They would then use this information to decide which combinations of management practices and land uses on their farm would give them the lowest cost options for keeping N-leaching within different limits.

⁶ For wetlands and set aside abatement measures, the contract length would cover multiple years. In this case, farmers would vary their submitted bid and offer schedule according to the agreed contract for each year. The auction is cleared once every year following submission of bids and offers at the beginning of that auction period.

⁷ These are precisely the outcomes provided to our smart market simulation by TargetEconN.

(initial per hectare allocation of at-farm leaching rights multiplied by the land area of the farm)

$$d_i = (1 - N_retention_i) \text{ where } (0 \leq d_i \leq 1)$$

= increase in N load at the fjord, from a one unit increase in N leaching at farm i

L = the maximum nitrogen load at the fjord ('the cap')

U_{ik} = upper bound on size of k th bid tranche placed by DMU i

($U_{ik} > 0$ for buy steps, $U_{ik} < 0$ sell steps)

P_{ik} = price associated with k th bid or offer step placed by DMU i

Decision variables

b_{ik} = purchases/sales of at - farm N leaching rights by DMU i from k th bid or offer step

q_i = maximum at - farm nitrogen leaching allowed to the root zone for DMU i .

(q_i must exactly match the total number of

at - farm leaching rights held by DMU i after market clearing)

μ_i = price of at-farm N leaching rights for DMU i ,
given as the shadow price of constraint T2 .

Objective function for the N-market overall

$$\text{Maximise } \sum_{i=1}^N \sum_{k=1}^K P_{ik} b_{ik}, \text{ subject to}$$

Upper bounds on bids and offers from each DMU

$$\text{If } U_{ik} \geq 0, 0 \leq b_{ik} \leq U_{ik}, \text{ else } U_{ik} \leq b_{ik} \leq 0$$

$$\text{for all } i = 1, \dots, N \text{ and } k = 1, \dots, K \quad (T1) : \alpha_{ik}, \theta_{ik}$$

Compliance constraints for each DMU

$$q_i - \sum_{k=1}^K b_{ik} = A_i \quad \text{for all } i = 1, \dots, N \quad (T2) : \mu_i$$

Water quality constraint at the fjord (receptor)

$$\sum_{i=1}^N d_i q_i \leq L \quad \text{for all } i = 1, \dots, N \quad (T3) : \delta$$

The linear program maximises the joint total surplus (or net benefit) to buyers and sellers from participating in the market. The coefficients P_{ik} in the objective function indicate how much each unit of at-farm N leaching rights is worth to the buyer/seller (Prabodanie et al. 2014). In the Limfjorden data, the P_{ik} are calculated as the difference in total abatement costs between two adjacent abatement positions divided by the corresponding change in nitrogen leached (at the farm). The objective function maximises net gains from trading in at-farm N leaching rights assuming that the bid and offer schedules are true reflections of the abatement cost and at-farm leaching outcomes following decisions to opt for particular land uses and abatement practices on each farm (Prabodanie et al. 2010, 2014).

An upper bound on each bid/offer (T1) ensures that the quantity of leaching rights bought or sold during a particular trade does not exceed the maximum quantity offered for trade in that tranche by each DMU. The compliance constraint (T2) specifies the relationship between the quantities of bids/offers accepted (b_{ik}), the maximum at-farm nitrogen leaching allowed (q_i) and the initial allocation of at-farm N leaching rights (A_i) for each DMU. The maximum at-farm nitrogen leaching allowed (q_i), net of bids and/or offers accepted (b_{ik}), must match the initial at-farm allocation of leaching rights for each DMU i (A_i). The water quality constraint (T3) ensures that the total nitrogen load cap at the receptor is not exceeded. Nitrogen leaching from each DMU i is weighted by $d_i = (1 - \text{DMU } i\text{'s retention coefficient})$ to determine the corresponding level of nitrogen loading that reaches the fjord.

As described in Prabodanie et al. (2010), the variables shown to the right of the constraints (α_{ik} , θ_{ik} , μ_i , and δ) are the associated shadow prices. The shadow price for the compliance constraint for each DMU (μ_i) indicates the change in total net worth from market trading (i.e. the change in the value of the objective function) which would arise if DMU i were to receive one more unit (kg) of at-farm N leaching rights. To prevent DMU i from leaching this additional nitrogen, it should be charged a shadow price, μ_i , such that the equality of marginal cost and marginal benefit holds under a binding cap. This μ_i is therefore the price that the market manager should charge DMU i for the right to leach an additional 1 kg of nitrogen from their farm (Prabodanie et al. 2010).

The shadow price δ on the water quality constraint at the fjord (T3) represents the marginal change in the value of the objective function (i.e. the increase in the total net benefit realised from market trading) which would result if the nitrogen load cap at the fjord were to be relaxed by 1 kg (Prabodanie et al. 2014). Following the same logic, for the constraint at the receptor to bind, the price of nitrogen loading at the receptor should equal its shadow price δ , again re-aligning with the notion that marginal benefit equals marginal cost at the receptor.

The dual formulation of the linear programming problem shows that DMU i 's price is given by $\mu_i = d_i \delta$. This indicates that the price paid for at-farm N leaching rights supplied to, or the price paid for at-farm N leaching rights bought from, DMU i is adjusted by the linear program according to the impact that at-farm nitrogen leaching from DMU i has on the binding total nitrogen load constraint at the fjord. DMU-specific prices will *not* be equal across market participants because nitrogen leaching from different farms has different impacts on nitrogen load at the fjord, depending on farm-specific N retention through the drainage network (Fig. 2). The dual formulation of the linear program shows that, for accepted bids, the farm-specific price of leaching rights μ_i will always be less than, or at most equal to, the relevant *bid-to-buy* price submitted by permit buyer i . Similarly, for accepted offers, μ_i will always be greater than, or at least equal to, the relevant *offer-to-supply* price submitted by permit supplier i (Prabodanie et al. 2010) (see Appendix 2 for

a more detailed description on bids, offers, DMU-specific prices and DMU-specific gains from trade under the smart market mechanism).

2.5 Trading Scenarios

The smart market in tradable nitrogen abatement practices in Limfjorden catchment is simulated initially assuming *full participation* (i.e. *zero transaction costs*). Smart market operation is simulated across a range of *uniform initial allocations* of at-farm N leaching rights, corresponding to different N load caps at the fjord. At-farm N leaching rights are converted to N loadings at the fjord using farm-specific retention (Fig. 2).

In our simulation, initial allocation is set to be *equal* across all farms on a per hectare basis. Given this uniform initial allocation, we compare abatement cost outcomes with and without trading. The no-trading scenario provides total abatement cost under *uniform command-and-control* regulation. The market equilibrium outcome after trading provides minimised total abatement cost under the smart market. Market performance is assessed by reporting the following metrics: market price of a unit of N loading at the fjord, number of buyers and sellers, total abatement costs with and without trade (i.e. under the smart market vs. under uniform per hectare regulation), gains from trade in aggregate (i.e. the reduction in total N abatement cost across the catchment under the smart market in comparison to uniform regulation), and farm-specific gains from trade. We simulate the market under a tightening cap, implemented by stepwise reduction of the uniform per hectare initial allocation of at-farm N leaching rights. The loosest cap simulated is set at a uniform initial allocation of 76 kgN_leached/ha at-farm; this represents a reduction of 2.25% from the baseline total N load of 13.8 million kgN at the fjord. The tightest cap is set at a uniform initial allocation of 53 kgN_leached/ha at-farm, corresponding to a 31.83% reduction from the baseline N load at the fjord.

The potential impact of non-participation is analysed by considering the financial gains that individual farm businesses realise through trading. We re-run the market with reduced participation on the assumption that farmers with low gains from trade will be less likely to participate because the modest gains they achieve through trading may not be sufficient to cover their transaction cost in engaging with the market (Stavins 1995; Collentine 2006). The potential impact of non-participation induced by different levels of transaction cost is quantified by re-running the simulated market with participation limited to only those farmers whose farm-specific gain from trade exceeds 15,000, 25,000 or 50,000⁸ DKK. These gains correspond to approximately 1.7%, 2.8% and 5.5% of the annual operating profit of the average farm in North Jutland⁹ (Statistics Denmark 2020). For each re-run of the market, we record the reduction in the aggregate gain from trade.

⁸ 50,000 DKK is equivalent to approximately € 6723 or US\$ 7600 at exchange rates on 12th December 2021 (https://www.nationalbanken.dk/en/statistics/exchange_rates).

⁹ In Danmarks Statistik's data *operating profit* for the farm is defined as the value of *gross output* minus *total costs*. *Gross output* is defined as "Income from sales of the production, including internal feeding stuff and seeds for sowing, work performed for others, changes in the value of livestock and stocks, payment-in-kind to private individuals and paid labour and direct subsidies." *Total costs* are defined as: "Costs linked to the generation of gross output, including stock reductions of feeding stuff, fertilizers and other intermediate products. Costs of financing and family remuneration are excluded." (Danmark Statistik 2021, pp 104–105).

Table 2 Outcomes of market trading simulations

Baseline load when there is no restriction imposed on leaching = 13.8 million kgN at receptor	76	74	72	71	69	67	64	61	59	56	53
Uniform initial allocation of N leaching rights (kgN/ha leached at farm)	2.25	4.82	7.39	8.68	11.25	13.82	17.68	21.54	24.11	27.97	31.83
Reduction from baseline total N load at receptor (%)	17.37	30.43	51.18	66.25	83.23	96.23	112.95	135.22	164.89	224.91	321.62
Nitrogen price at receptor (DKK/kgN load at fjord)	3439	3572	3330	3501	3551	3352	3423	3205	2940	2411	1680
Number of buyers	1914	2361	3156	2997	2947	3145	3076	3294	3563	4093	4824
Number of sellers	113.77	186.68	189.60	246.27	309.25	310.54	430.47	487.36	551.33	602.17	663.80
Total abatement costs with no trade (DKK million)	5.57	11.78	23.82	34.22	60.98	92.89	148.56	213.94	266.79	369.22	510.80
Total abatement costs with trade (DKK million)	108.20	174.90	165.78	212.05	248.27	217.65	281.91	273.42	284.54	232.96	153.00

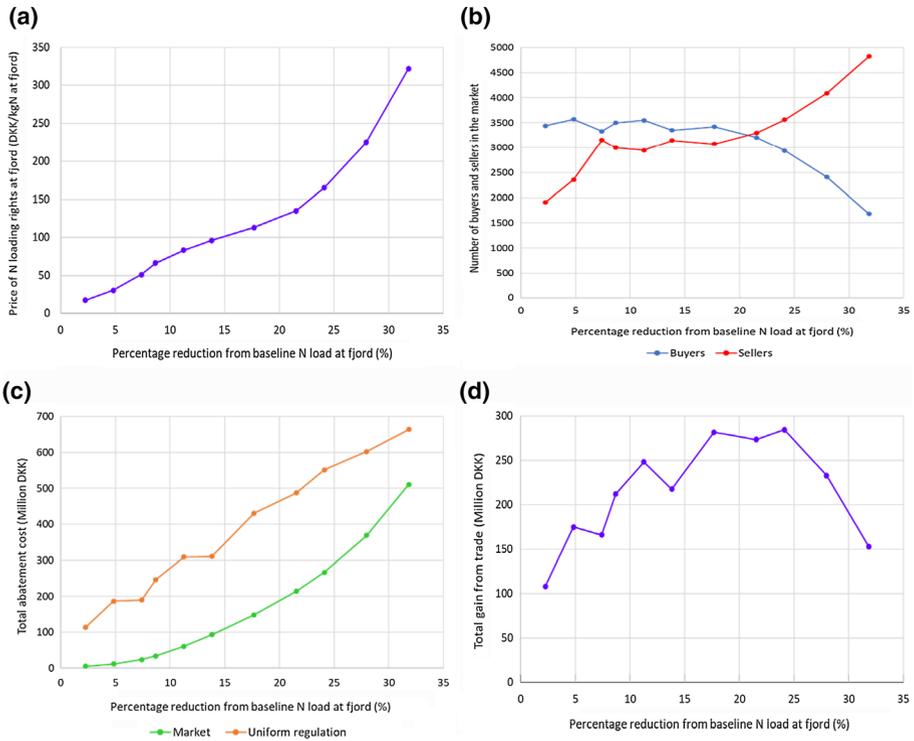


Fig. 3 Outcomes of market trading simulations plotted against reduction in total N load at the fjord

3 Results

3.1 Smart Market Simulations with Full Participation and Zero Transaction Costs

Results from 11 rounds of trading simulations as the load cap at the fjord is tightened are summarised in Table 2 and Fig. 3. As expected, the equilibrium price for N loading rights at the fjord rises as the reduction from baseline N load increases (Fig. 3a). The number of buyers is greater than the number of sellers at low N reductions from baseline (Fig. 3b); however, once the load reduction exceeds 18%, the number of buyers reduces rapidly as the N loading price at the fjord rises further. Total abatement cost under the market (assuming full participation) is considerably lower than under uniform regulation at all levels of cap simulated (Fig. 3c). The total gains from market trading are highest in absolute terms for N reductions of between 18 and 24% from baseline, (Fig. 3d). Across this range, assuming full participation, the market reduces total abatement cost for the Limfjorden catchment by between 66 and 52% compared with uniform regulation (for N reductions of between 18 and 24%, respectively). These are very considerable cost savings.

To further investigate market operation, we explore farm-specific outcomes for a 21.5% total N reduction from baseline; approximately the level of N load reduction required for the catchment. Figure 4 shows demand and supply curves at market equilibrium in this situation with full participation. Under these conditions, all but five of the catchment's 6,504 farms realise a net benefit from trading (Table 2). Substantial proportions of buyers and

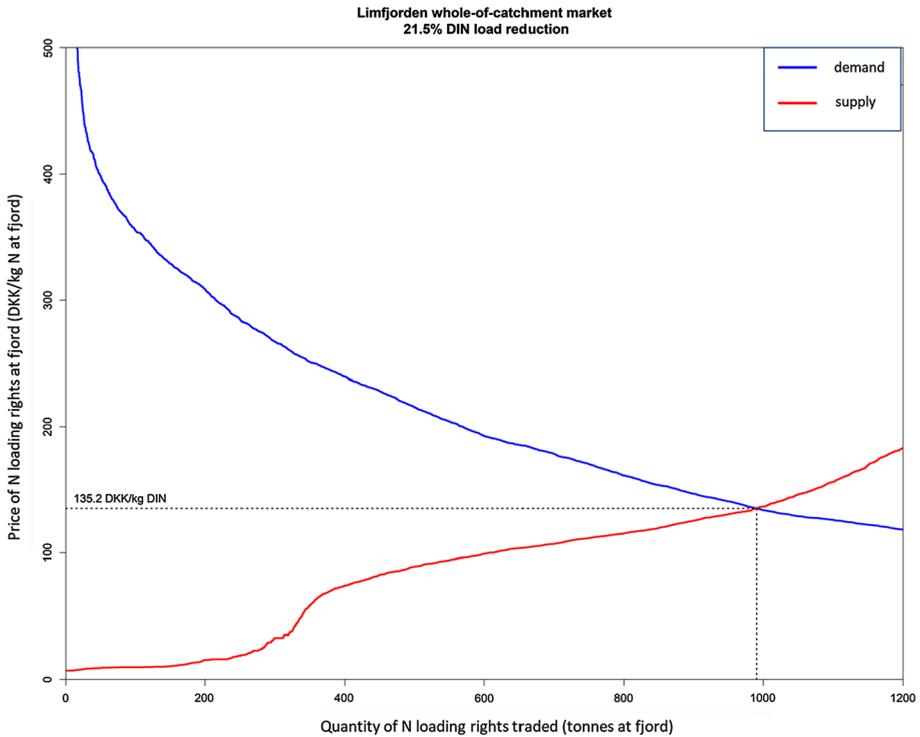


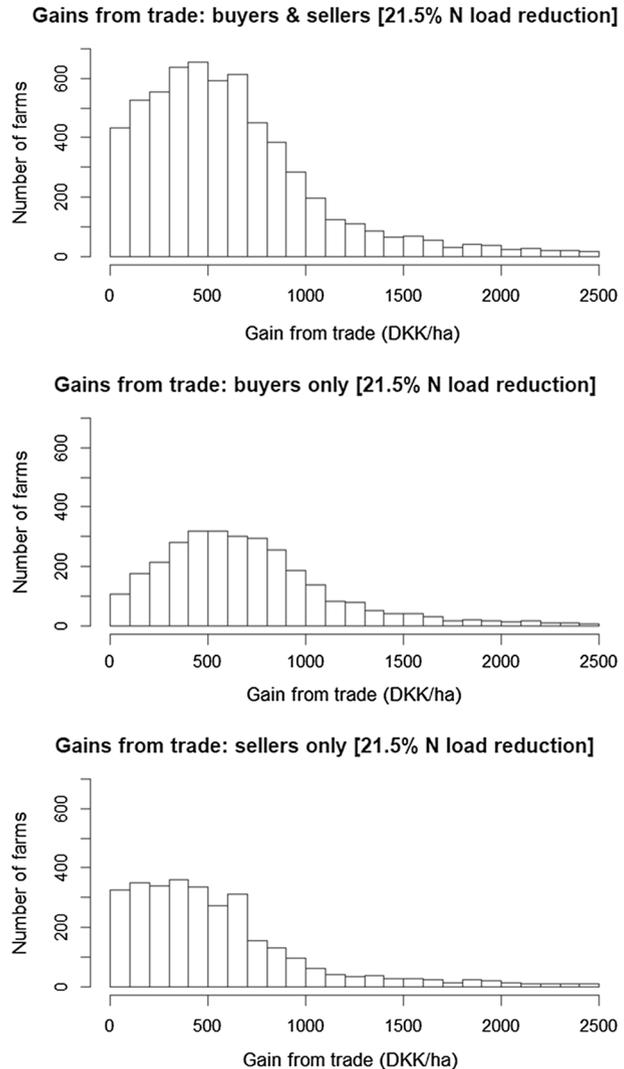
Fig. 4 Demand and supply curves for at-fjord N loading rights in the simulated Limfjorden smart market under full participation, at market equilibrium under a load cap that reduces N load at the fjord by 21.5% from baseline

sellers realise farm-specific per hectare gains from trade of 500 DKK/ha or above (Fig. 5), although gains are generally higher for buyers than for sellers. For perspective, a gain of 500 DKK/ha corresponds to 20% and 60% of the typical gross margin achieved from winter wheat and spring barley, respectively, (the two most widely planted cereal crops) grown in the Limfjorden catchment on non-irrigated sandy soil with N input from artificial fertiliser (the soil and N-input combination that covers the largest proportion of the catchment's land area) (Table 3).

The prices of at-farm leaching rights (Fig. 6) vary inversely with N retention (Fig. 2) because leaching from low retention areas has a bigger impact on the binding load constraint at the fjord. A tighter load cap (e.g. 21.5% reduction on baseline N load at the fjord) results in higher at-farm prices for leaching rights, reflecting their increasing scarcity.

Contrasting market outcomes from markets with 4.8% and 21.5% reductions on the total N load at the fjord, Fig. 7 compares the size and spatial distribution of net trades (in kg N_{leached}/ha), showing buyers of at-farm leaching rights in blue, and sellers in red. A larger number of farms sell N leaching rights when the load cap is tighter (see also Table 2). This is a consequence of the higher prices being offered to farmers, particularly in locations

Fig. 5 Distribution of farm-specific gains from trade in the N-trading market with a 21.5% reduction from baseline leaching of 13.8 million kgN at the fjord, (equivalent to a uniform initial at-farm leaching allowance of 61 kgN_leached/ha)



with low retention¹⁰ (Figs. 2, 6). The market is working to reduce N leaching from these 'problem' locations. Market action incentivises redistribution of N leaching across the catchment so that it aligns more closely with the spatial distribution of retention (Fig. 2). This acts to increase overall nitrogen use efficiency, moving nitrogen from 'lossy' locations (where retention is low) to 'less lossy' locations (where retention is high).

¹⁰ Recall from the dual formulation of the linear programming problem in Sect. 2.4 that the farm-specific price for N leaching rights (μ_i) is given by $\mu_i = (1 - \text{retention}_i)\delta$. Thus, farms with low retention have at-farm leaching prices that are closer to the market equilibrium price of N loading rights at the fjord (δ). The converse is true for farms with high retention.

Table 3 Gross margins (DKK/ha) for each crop type (arable land only)

Crop type category	Gross margin in DKK/hectare, average 2011–2013					
	With manure ^a			Without manure		
	Clay	Sandy soils	Sandy soils (irrigated)	Clay	Sandy soils	Sandy soils (irrigated)
Spring crops						
Oats	3515	1615	1615	2543	625	625
Spring barley	4663	1905	2008	3535	830	775
Corn	4495	2512	2815	2667	729	658
Winter crops						
Winter barley	5998	2710	1956	5040	1811	9602
Winter wheat	8819	3609	3609	7509	2508	508
Remaining area						
Winter rape seed	5971	2396	2396	4893	1443	1443
Rotational grass	5000	3880	3756	2813	1787	1462

^aSet aside of manured areas is costly for various reasons, however only loss of the higher gross margins compared to non-manured areas, is taken into account in the current study. Area for manure application is required for fulfilment of the so called “harmony rule”, introduced to comply with the EU Nitrate Directive (Council Directive 91/676/EEC). The harmony rules impose a limit on maximum livestock density per hectare. Reducing the operational farm area due to set aside puts pressure on the farm to utilise other areas for application of manure or to set up manure-spreading agreements with other farmers. In the case study data, 69% of the area is harmony area, fertilised with manure. The remainder is either not fertilised with manure but suitable for manure application (free-harmony area, 28%), or not suitable for manure application (3%)

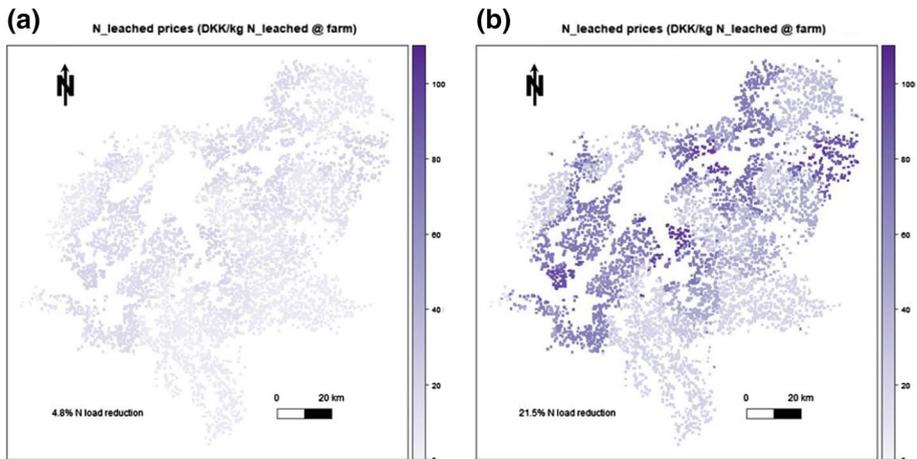


Fig. 6 Farm-specific prices of at-farm N leaching rights under load caps that deliver **a** 4.8% and **b** 21.5% total N load reduction at the fjord

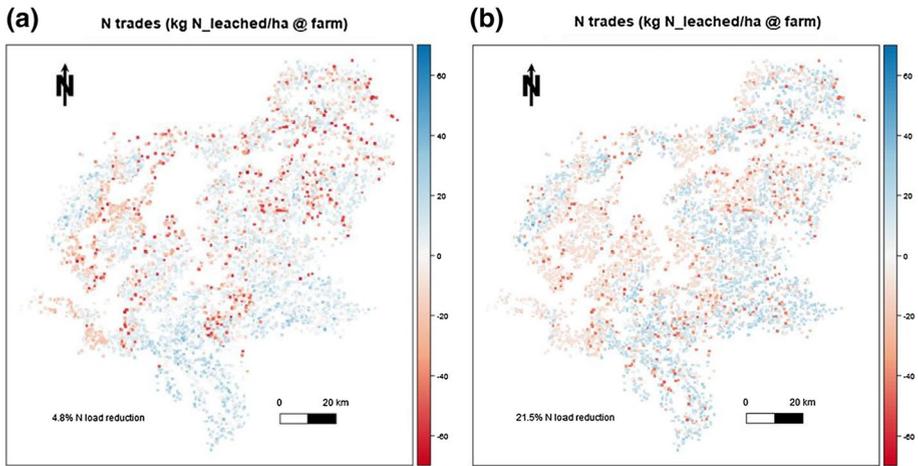


Fig. 7 Net trades in kgN/ha_leached at-farm for **a** 4.8% and **b** 21.5% total load reduction at the fjord. Buyers of at-farm leaching rights in blue, sellers in red. For perspective, indicative at-farm N leaching for winter wheat and spring barley grown on sandy soil is 84 and 94 kgN/ha, respectively (Table 4)

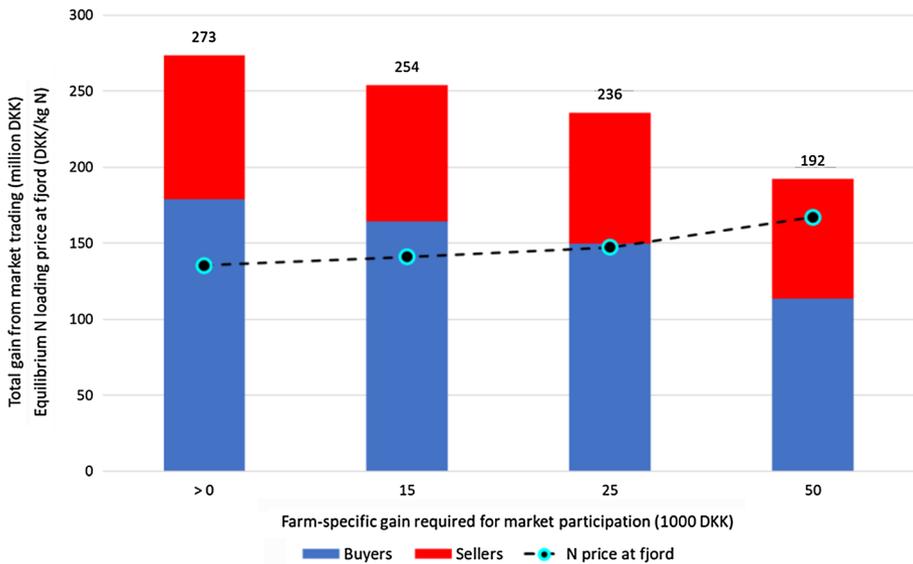


Fig. 8 Total gain from market trading (compared with uniform command and control), under different thresholds for farm-specific gain from trade as a threshold for market participation. Equilibrium N-loading price at the fjord (DKK/kgN at the fjord) is also shown

3.2 Non-participation

We explore the potential impact of farmers’ non-participation (as might be induced if the gain from trade is insufficient to cover transaction cost) by considering farm-specific gains

from trade. Again, we explore outcomes under a load cap that reduces baseline N load at the fjord by 21.5%.

Under this load cap, if the threshold condition for market participation is that the farm business has simply to realise a gain from trading (i.e. the threshold for market participation is 'any gain greater than 0 DKK'), all except five of the catchment's 6504 farms trade in the market and the resulting whole-of-catchment gain from trading is 273 million DKK (i.e. for the same overall load cap at the fjord, the difference in total abatement cost under market trading and uniform regulation is 273 million DKK) (Table 2 and Fig. 8). Buyers acquire the larger share of these gains (Fig. 8), consistent with the histograms in Fig. 5.

Raising the threshold farm-specific gain for market participation in three steps from >0 DKK up to 50,000 DKK per farm (Fig. 8), the total gain from market trading reduces, but only modestly. With farm-specific gains of 15,000, 25,000 and 50,000 DKK as thresholds for market participation, 93%, 86% and 70% of the maximum achievable 273 million DKK gain is retained by those farmers who remain in the market. With these participation thresholds in place, 93%, 86% and 70% of the maximum gain is retained with only 56%, 42% and 24%, respectively, of original participants still trading in the market. Thus, simulation results suggest that the market can still deliver substantial abatement cost savings (compared with uniform regulation) even under high percentage levels of non-participation.

4 Discussion

4.1 Efficiency Gain from Market Trading

This study has simulated trading in nitrogen abatement practices, implemented via a smart market mechanism in Limfjorden, a mixed agricultural catchment comprising 6504 farms in northern Denmark. To the best of the authors' knowledge, this is the first investigation of a cap and trade smart market between non-point agricultural nitrogen sources of this scale in a real setting. In Limfjorden, under load caps that are representative of the desired level of N load reduction at the fjord, simulation results suggest that a smart market could provide savings of between 66% and 52% in total abatement cost compared with uniform command and control regulation. Our estimated cost savings are in line with those of Corrales et al. (2017) who estimated cost savings of 76% and 45%, relative to command-and-control regulation, for (modelled) phosphorus trading between point source domestic and industrial wastewater facilities and non-point sources of runoff from agriculture and urban areas in two sub-catchments draining into Lake Okeechobee in the US.

These findings are encouraging, but the literature—and learnings from practical implementation of nutrient trading, albeit not via a smart market approach—suggest that concerns regarding non-participation, transaction costs and the spatial resolution and spatial scale of market operation should also be considered (Shortle and Horan 2013; DeBoe and Stephenson 2016). In addition, the enforceability of trading-based solutions have been questioned because of concerns regarding observability and monitoring (Hoag et al. 2017). Recently, spatially-targeted regulation, implemented via location-specific limits on N leaching, has been proposed for cost-effective management of N losses from agriculture in Denmark and the Baltic Sea region (Hasler et al. 2019; Refsgaard et al. 2019; Czajkowski et al. 2021). Below, we reflect on how the smart market solution will likely perform in the face of these challenges. We also discuss potential advantages of the smart market approach over spatially-targeted regulation.

4.2 Impact of Non-participation on Market Outcomes

Our market simulation indicates that a high proportion of the total gain from trade is likely to be retained with only modest market participation (70% of the maximum gain retained with only 24% participation). Farm-specific gains from trade (Fig. 5) and the market equilibrium demand and supply curves (Fig. 4), reveal that this is because a large proportion of the total gains from trade accrue to a relatively small number of participants. Nevertheless, non-participation in trading schemes and, more generally, in initiatives to improve agricultural management practices is a well-recognised problem that merits careful consideration.

A study by Hansen et al. (2019) investigating factors determining Danish farmers willingness to participate in a hypothetical trading market found that farmers are reluctant to offer nitrogen reductions to the market. Hansen et al.'s results indicate a disparity between farmers' maximum willingness to pay for additional N leaching rights and their minimum willingness to accept compensation for supplying N leaching rights to the market. Our study derives farmers' bid to buy and offer to supply schedules for N leaching rights solely from the implementation costs and the opportunity cost of foregone gross margins from cropping. Hansen et al.'s findings may indicate that farmers ascribe additional value to retaining 'spare' N leaching rights to mitigate cropping risks that could emerge during the growing season. The value farmers ascribe to retaining this flexibility for risk mitigation elevates their minimum willingness to accept compensation for selling leaching rights. If such behaviours were to be present in a real market, the gains from trade would be smaller than our results suggest.

Using survey data on 110 farmers who successfully secured funding from the Australian Government's Reef Rescue Program for changes in land management, Coggan et al. (2014) report that, on average, private transaction cost was 38% of the payment received. Transaction costs were found to decline with previous engagement experience (Coggan et al. 2014). Although Coggan's study pertains to reverse tender programs, it nevertheless indicates that transaction costs can be substantial and could present a barrier to successful implementation of cap and trade smart markets.

Transaction costs reduce the potential gains from trade because they force a wedge between bids to buy and offers to sell leaching rights that must be overcome before trading can take place (Collentine 2006). As emphasised by Stavins (1995), transaction costs are always present in markets involving transfer of property rights because "parties must find one another, communicate and exchange information" (p. 134). However, as pointed out by Raffensperger et al. (2017), in a smart market farmers buy and sell in an online marketplace controlled by a market manager, removing the need to seek out trading partners bilaterally. Another way of reducing the transaction costs of engaging with the market is for the environmental regulator to incorporate information technology into the design of the smart market to reduce information asymmetry (Prabodanie et al. 2010). For example, the online trading platform could operate in conjunction with a smart phone 'app' similar to those available for stock exchange trading. As mentioned earlier, a spatially-specific look-up table, or a map-linked phone 'app' could also be made available to help farmers determine the N-leaching from different management practices and land uses on their farm. They would use this information to identify the management practices that would deliver the most profitable outcome for their business through market trading.

Our market simulations showed that 70% of the maximum achievable aggregate gain from trade should still be realised in the presence of a 50,000 DKK transaction cost

'wedge'. For perspective, 50,000 DKK corresponds to 5.5% of the annual operating profit of the average North Jutland farm (Statistics Denmark 2020). This suggests that in the Limfjorden setting, smart market gains from trade appear to be robust against substantial levels of transaction cost.

4.3 Features that Facilitate Trading Market Performance

The demand and supply curves in Fig. 4 for the Limfjorden smart market simulation under a load cap that reduces N load at the fjord by 21.5% from baseline, show that approximately 30% (~300 tonnes) of the equilibrium traded volume is supplied to the market at asking prices that are less than 25% of the market equilibrium price, and purchased by farmers whose willingness to pay is more than twice the market equilibrium price. These large differences between buyers' WTP and suppliers' WTA ensure large gains from trade accrue to both parties. Furthermore, trading of this first 30% of N loading rights at the fjord yields more than half of the total aggregate gain from the equilibrium quantity traded. This situation contributes significantly to the large aggregate gain from trade, and its robustness against substantial non-participation.

The following features of the agricultural landscape in Limfjorden underpin these supply and demand characteristics. Firstly, mixed farming within the catchment (cropping of spring and winter-sown cereals, permanent and rotational pasture, and livestock production (cattle, pigs and chickens)) results in considerable heterogeneity in farm-specific N abatement options. Farmers with access to low-cost abatement practices can offer N leaching rights to the market at low asking prices; conversely farmers lacking low cost on-farm abatement will be willing to pay a high price to buy additional N leaching rights. Secondly, the heterogeneity in at-farm N abatement costs is amplified when considering the cost of N loading rights at the fjord because of the high spatial variability in nitrogen retention across the catchment. In some locations N retention approaches 95%, whilst it is as low as 25% elsewhere: almost a four-fold variation. Thus, the combination of mixed farming and significant land areas of very high and relatively low N retention (Fig. 2) in Limfjorden catchment make it ideally suited for a smart market cap and trade scheme.

4.4 Comparison of Smart Market and Spatially-Targeted Regulation

Spatially-targeted regulation has recently been proposed for cost-effective management of N losses from agriculture in Denmark and the Baltic Sea region (Hasler et al. 2019; Refsgaard et al. 2019; Czajkowski et al. 2021). Spatially-targeted (mandated) regulation, implemented via location-specific limits on at-farm N leaching, is the command and control analog of the spatially-specific pricing of N leaching rights that emerges under the smart market. It is relevant to compare these two spatially-specific management approaches in terms of their static efficiency (the reduction in abatement cost achieved in comparison to uniform regulation), information requirement, dynamic efficiency (ability to retain abatement cost reductions under changing conditions), and potential acceptability to farmers.

With regard to *static efficiency*, both mechanisms should be able to deliver a particular cap on N load at the receptor for the same aggregate abatement cost; *provided that* the designer of the spatially-targeted N leaching allowances has full information regarding the costs of abatement options available to individual farmers.

Regarding *information requirement*: both mechanisms require detailed knowledge of the changes in at-fjord N loading that will follow from implementing particular

management practices at specific locations in the catchment; thus, both mechanisms need to be underpinned by rigorous biophysical and hydrological modelling at high spatial resolution. Published research from Windolf et al. (2011), Blicher-Mathiesen et al. (2014), Hansen et al. (2014), Højberg et al. (2015), and others indicates that the necessary modelling is in place for the Limfjorden catchment. However, to maximise cost-effectiveness under spatially-targeted regulation, the scheme designer will *also* require detailed knowledge of farm-specific abatement costs.

In our smart market *simulation*, farm-specific abatement costs for the four N management practices were obtained from the TargetEconN farm-specific cost-minimisation. In a *practical market*, however, knowledge of which combinations of management practices provide the least-cost solution for delivering various levels of N abatement on a particular farm would come from the farmers themselves. The smart market mechanism only requires that farmers submit *bid-to-buy / offer-to-sell* schedules for purchase / supply of N leaching rights at prices that are appropriate for their farm. To compile these schedules, farmers will need to know the least-cost combinations of N abatement practices for their farm (which we assume they would do) *and* they would also need to know the amount of at-farm N leaching that followed from implementing these practices on their fields. This information would be made available via a farm location-specific lookup table, webpage, or spatially-linked smart phone ‘app’. These information products would be supported by the robust, fine resolution spatial biophysical modelling described previously.

The fact that the smart market manager does not require knowledge of farm-specific abatement costs provides the smart market with a significant advantage over spatially-targeted regulation with regard to dynamic efficiency. Because the smart market leaves farm-level minimisation of abatement cost in the hands of farmers, outcomes from market trading should adjust automatically to changing conditions. The spatially-specific pricing of at-farm leaching rights that emerges from the smart market will adjust automatically as farmers’ bid and offer schedules change—as might occur, for example, because of changes in the relative prices of agricultural inputs and outputs. Market trading should thus continue to deliver least-cost N management under changing economic conditions in the agricultural sector. The adjustments to farm-specific leaching allowances that would be required to achieve the same outcome under spatially-targeted regulation would have to be enacted via changes to legislation. Given the political controversy that typically surrounds ‘command and control’ policies in agriculture, policy makers may be reluctant to update allowances to ensure efficient N management in the face of changing conditions.

Acceptability to farmers: There is considerable literature coverage of factors that influence the acceptability of different policy mechanisms to farmers (e.g. Zimmerman et al. 2019; Hasan et al. 2021). In particular, farmers have been found to be highly averse to losing autonomy over farm management decisions (Zimmerman et al 2019). This suggests that the smart market may provide a further important advantage in terms of potential farmer acceptability as farmers *retain* autonomy over opportunities to increase farm profits by trading N leaching rights in the market. If farmers *choose* not to trade they will have to configure their management practices to comply with a *uniform* (initial) per-hectare allocation of at-farm N-leaching rights. Uniform initial allocations are unlikely to trigger complaints that farmers in some locations are receiving ‘preferential treatment’; spatially-targeted N leaching allowances would likely be perceived very differently by the farming community. For these reasons, we suggest that a smart market approach is likely to be regarded as being more acceptable to farmers than would spatially-targeted regulation.

4.5 Spatial Scale of the Market

As explained previously, sufficient heterogeneity in at-receptor abatement costs between farms is a requirement for a cap-and-trade system to function as an active market. Another requirement for achieving the specific environmental cap at the receptor is that the trading occurs within the geographical boundary of the catchment draining to the receiving water. These two requirements might conflict, as increasing the spatial scale is likely to increase heterogeneity but also reduce the environmental specificity of the market. Trading within smaller geographical markets, each with their own cap, would provide more localised control of water quality and thus prevent pollution ‘hotspots’ forming. These smaller markets might, however, lack the heterogeneities and number of participants required to function effectively. In such situations, it could be more appropriate to consider alternative approaches to safeguard localised water quality. In their study of the Lake Taupo nitrogen trading program in New Zealand, Tabai-chount et al. (2019) found that large reductions in pollutant loads have been achieved, but this outcome has been considerably assisted by participation of an environmental trust that bought and then retired discharge allowances from farmers, thereby reducing the total allowable emissions load. This could potentially be a mechanism for achieving desired load reductions in highly sensitively sub-catchments that might otherwise be prone to hotspot issues under a market solution.

4.6 Observability, Monitoring and Compliance

The proposed smart market in N loading rights at the fjord is implemented via tradeable N abatement *practices* on-farm. This has notable advantages over a standard cap and trade mechanism in ‘N emissions’ in terms of observability, monitoring and compliance. Firstly, farmers are essentially trading in on-farm abatement actions, most of which (set aside, catch crops and wetland restoration) are directly observable by the regulator. The fourth abatement measure, reduction in nitrogen applications, can be monitored using nitrogen accounts and balances (Dalgaard et al. 2014). However, an incentive to trade fertiliser across catchments could reduce the effectiveness of this measure. Secondly, land use data, nitrogen applications and location of abatement measures are already recorded routinely as part of the Common Agricultural Policy framework and implementation of the European Union’s Nitrates Directive and the Water Framework Directive. This suggests that only modest additional cost would be required to link e.g. GIS data on fertiliser applications to central registries to allow the market operator to monitor compliance.

The proposed system does not overcome the fundamental lack of observability characterising diffuse pollution problems, as individual farm emissions cannot be definitively observed downstream. However, the available georeferenced land use data and emerging satellite based continuous monitoring capabilities (e.g. the Copernicus Earth monitoring system), combined with catchment scale crop leakage and retention modelling, can potentially provide sufficient data input to facilitate high resolution monitoring at relatively low cost.

5 Summary and Conclusion

Regulation of non-point source pollution is widely acknowledged as a challenging policy problem. Emissions from agriculture to water bodies is a prominent example where existing policy instruments such as uniform production input restrictions and technology

standards need to be supplemented with additional policy tools to meet current and future environmental objectives. A smart market trading in N loading rights at a receptor via changes in at-farm N management practices, as suggested here, might be a way forward to overcome the challenges in implementation of a cost-effective policy framework to meet water quality objectives.

Using a Danish case study, the Limfjorden catchment, we simulate a ‘smart market’ for managing diffuse nitrogen emissions. We estimate potential efficiency gains from this trading scheme compared to a uniform mandatory regulatory framework. Results indicate that the considerable heterogeneity in the farm productivity, together with wide spatial variation in nitrogen retention across the catchment, create the potential for significant reductions in the costs of meeting water quality targets. For 18–24% reductions from baseline nitrogen load at the receptor, the market delivers cost savings of more than 50% compared to uniform command-and-control regulation.

Low participation rates among farmers are potentially detrimental for effective market operation. Low participation rates could potentially result if a large proportion of the farms realise small gains from trade that are insufficient to overcome transaction cost. We consider this potential risk in our study and show that market performance in Limfjorden is robust against non-participation. Total gain from market trading does reduce with increasing levels of non-participation by farms with relatively small gains; however, this reduction is only modest, because a large proportion of the total gain from trade is provided by a relatively small number of high-gain participating farms. We highlight that a tradeoff exists between maximising economic and environmental performance of the cap and trade scheme. Economic performance is likely to increase with the spatial scale of the market, whereas local environmental performance may decrease as spatial scale increases.

We argue that trading schemes based on observable abatement actions have advantages over emissions- or input-based trading schemes for non-point sources, as they are likely to be less costly to monitor and control. Our simulations thus indicate smart market trading could be an effective approach for reducing the cost of nitrogen management in the Limfjorden catchment, and could potentially be implemented in practice. However, our analysis also suggests that the combination of features that make Limfjorden particularly well suited for a smart market implementation will not be universal, so the suitability of other catchments for smart market trading will need to be considered carefully.

Appendix 1: Data Development via TargetEconN

The farm-level dataset that forms the basis of the smart market simulations is produced by a two-step process. The first step involves data collation at individual land parcels and look-up tables on gross margins and leaching estimates to the root zone by crop types. We then use these two sets of information to calculate, for each land parcel: (i) gross margins (in DKK/ha); (ii) N leaching to the root zone (in kgN/ha); and (iii) the areas (in ha) within the parcel that have the potential for implementing one of four abatement practices. The second step involves aggregation of land parcels into farms, followed by implementation of optimisation program TargetEconN to identify least-cost combinations of farm-specific nitrogen abatement practices to achieve specified stepwise reductions in N emissions to the root zone. The following sub-sections describe the data development process in further details.

Table 4 Leaching estimates in kg N/ha for established crop types

Crop type category	Leaching estimate, kg N/ha	
	Sandy soils	Clay soils
Spring crops		
Oats	78	53
Spring barley	94	51
Corn	158	111
Winter crops		
Winter barley	87	60
Winter wheat	84	59
Remaining area		
Winter rape seed	114	81
Rotational grass	50	34

It is assumed that land with existing energy crops, forest and fruit/vegetables, is land with no potential for implementation of N abatement measures, as these crop types are considered to be permanent

Land Parcel Data

The farm-level dataset that forms the basis of the smart market simulations was developed from a base data of 56,556 land parcels¹¹ of varying sizes from 0.01 hectare to 578.5 hectares in the Limfjorden catchment. For each land parcel, we collate information on area, crop distribution, soil type (i.e. sand, clay or organogenic), altitude (i.e. low or high) and the type of fertiliser used (i.e. organic or inorganic) (Børgesen et al. 2009; Andersen et al. 2012). 80 percent of the catchment area comprised of sandy soils (44,312 land parcels), and the remainder are split almost equally between clay soil (10% of area; 4129 land parcels) and organogenic soil (9% of the area; 5189 land parcels). Altitude influences the water table and consequently nitrogen decomposition. The low altitude lands are typically organogenic soils. The Limfjorden catchment is primarily comprises higher altitude land (72% of the area).

Look-up Tables on Gross Margins and Nitrogen Leaching by Crop Types

Gross margins for each crop type, differentiated by soil type and use of organic or inorganic fertilisers, are obtained from Danish registers (SEGES 2017). The gross margins used in this study are average values from 2011 to 2013 (Table 3). Crop-specific leaching estimates are based on farmer's applications of N during the 2011 growing season and NLES4 modelling (Andersen et al. 2012, Andersen personal communication (Table 4).

¹¹ A land parcel is a structural geographic unit which consists of one or several single fields. The fields related to the field parcel can be owned by one of more farmers.

Table 5 Leaching from the set aside abatement measure (in kg N/ha) and reduced leaching from implementation of restored wetlands, reduced N application and catch crops abatement measures (in kg N/ha) by soil type (Andersen et al. 2012)

Abatement measure	Kg N/ha/year	
	Sandy	Clay
Restored wetlands	113	
Reduced N application ^a	0.007–12	
Set aside ^b	12	
Catch crops (without / with application of manure) ^c	34/46	16/28

^aThe effect from reduced manure application varies at a field level, depending on the amount of manure applied, crop types and the type of manure

^bFor set aside on high altitude land, the effect is estimated on clay and sandy soils as the leaching from the field withdrawn is 12 kg N/ha. For organogenic soils, the effect is half the effect on sandy soils. For set aside at low altitude land the effect for all fields is half the effect on sandy soils, as it is assumed that all low altitude areas are organogenic soils

^cThe effect from implementing catch crops on organogenic soils is 25 kg N/ha on soils without application of manure and 37 kg N/ha with application of manure

Table 6 Potential areas for implementation of each of the N abatement measures

Abatement measure	Potential area, ha	Percentage of total area
Restored wetlands—fertilised land	13,194	3.3
Restored wetlands—non-fertilised land	3477	0.7
Reduced N application	461,759	92
Set aside, higher altitude land—non-fertilised land	95,207	19
Set aside, higher altitude land—fertilised land	244,971	48
Catch crops	81,293	16
Set aside, lower altitude—non-fertilised land	41,998	8
Set aside, lower altitude—fertilised land	69,257	14

Aggregation of Land Parcels into Farms

Using Danish General Agricultural Land Register (GLR), individual land parcels are allocated to the farm that owns the largest share of that parcel. Farms that are less than 5 hectares in area are excluded from the analysis. The final dataset consists of 6,746 farms, formed from 53,630 land parcels covering an area of 500,533 ha.

Abatement Practices

The four abatement practices considered in this study are catch crops, reduced fertiliser applications, set aside, and restored wetlands. For restored wetlands, reduced N application and catch crops, leaching of N to the root zone after implementation of the abatement

Table 7 Construction and maintenance costs of each N abatement measure (Eriksen et al. 2014)

Abatement measure	Construction and maintenance cost in DKK/hectare
Set aside	Lost gross margin per land parcel+ maintenance costs 1253 DKK/ha
Catch crops	Cost for seeds, sandy soils: 252, clay soils: 197
Restored wetlands	Lost gross margin per land parcel+ implementation and maintenance costs, 1579 DKK/ha
Reduced N application	Lost gross margin due to reduced N application, estimated from use of N response functions

measure is estimated as estimated leaching in baseline from the initial crop rotation (Table 4) minus the reduction in N leaching achieved by the abatement measure (Table 5). For set aside, N leaching to the root zone is taken to be 12 kg N/ha (Table 5). The effect is estimated in total N (TN) (the dissolved inorganic nitrogen (DIN) fraction constitutes between 94% and 98% of the TN value).

For each N abatement measure, the potential is estimated at parcel scale as the share of the parcel suitable for implementation of the specific measure, based on crop allocation, soil type, manure usage and altitude. Table 6 shows the total potential for each measure according to altitude and type of fertiliser used.

Abatement Costs

Implementation costs of abatement practice is calculated as the sum of lost gross margins based on Table 3 and construction and maintenance costs (Table 7) associated with the different abatement measures.

TargetEconN

The basic framework we use to model farmer's choice of abatement measures to achieve specified reductions in N leaching is the TargetEconN model developed by Konrad et al. (2014) and Hasler et al. (2019). TargetEconN is a 'social planner' model developed to obtain minimised costs of achieving nitrogen load reductions to Limfjorden given by EU's Water Framework Directive. In this study, the model framework has been adapted to model N abatement at a farm-scale to estimate expected nitrogen leaching and the abatement costs incurred when applying the least-cost package of abatement measures to achieve a specified reduction in nitrogen leaching from a farm.

In TargetEconN, all farms within the Limfjorden catchment are given the same per-unit area initial allowance of N leaching to the root zone in kgN/ha, k , $k \in [k, \dots, K]$, equal across all farms. Each farm is then required to achieve their farm-specific N leaching target (Eq. 1):

$$\sum_i^I (Area_i * Leach_i) - \left(\sum_i^I (Area_i * k) \right) \leq E_F, \quad (1)$$

where $i \in [1, \dots, I]$ denote the fields within the farm, *Area* the area of those fields, and *Leach* the leaching to the root zone from the fields in kg N/ha. E_F is the farm-specific target

for N-leaching reduction. This target must be achieved by implementing N abatement measures.

To fulfil their leaching reduction target, the farmer can choose to implement different N abatement measures j , $j \in [j, \dots, J]$. The N leaching reduction for the farm, E_F , that results from implementation of N abatement measures is given in (Eq. 2):

$$E_F = \sum_i^I \sum_j^J Effect_{i,j} * Pot_{i,j} * x_{i,j}, \quad (2)$$

where *Effect* gives the N leached from the farm after implementation of j measures at field I , taking baseline leaching, *Leach*, into account, and *Pot* is the potential in hectares for implementation of measure j at field i . $x_{i,j} \in [0,1]$ is a binary control variable representing the choice of abatement measure j on field parcel i , ensuring that only one measure is implemented on a particular field at any one time (discrete optimization).¹²

The optimization problem facing the farmer is to choose the minimum-cost set of abatement measures to apply to the farm's fields (Eq. 3), to achieve the required reduction in farm-specific N leaching. TargetEconN thus minimizes farm-specific total abatement cost, V , subject to the N leaching reduction target defined in (Eq. 1):

$$\min_{x_{i,j}} V = \sum_i^I \sum_j^J Cost_{i,j} * Pot_{i,j} * x_{i,j}, \quad (3)$$

where $Cost_{i,j}$ is the cost of implementing measure j on field i within a particular farm.

The potential, $Pot_{i,j}$, for implementing each of the N abatement measures is binary, i.e. a given N abatement measure can only be implemented using the whole potential for the parcel. Consequently, the optimization routine might therefore over-implementation abatement for some farms (given the inflexibility in the implementation). To generate smoother abatement costs curves we have split each parcel into 0%, 25%, 50%, 75% and 100% of the implementation potential instead of only 100%. This will reduce, but not remove, the over implementation issue.

We run the model for a range of different target N leaching limits at the root zone. Thus, for each farm, we find the cost-minimized mix of N abatement measures for achieving each of the following N allowed leached to the root zone in kg/ha: 53, 56, 59, 61, 64, 67, 69, 71, 72, 74 and 76. For each of these N leaching limits, TargetEconN reports farm-specific minimised abatement costs and farm-specific levels of N leaching achieved. Farms will typically over-comply (i.e. deliver N leaching outcomes that are somewhat lower than the required target) because of the discrete (rather than infinitely variable) introduction of the different abatement measures.

The farm-specific data that are taken forward from TargetEconN to the smart market model thus comprise a set of farm-specific N-leaching loads and (minimized) abatement costs for tightening N leaching targets from 76 kgN/ha down to 53 kgN/ha. Other key characteristics of the farm such as location, farm area, main soil type, manure application regime and N retention percentage are also taken as input data to the smart market model.

¹² We allow set aside on low and high-altitude land to be implemented on the same field parcel as set aside on harmony and non-harmony areas. Also reduced N fertilisation and catch crops could possibly be implemented on the same area, however, the interaction in effects between these measures is unknown.

Farm 5: Permit Buyer

Farm area = 71.96 ha

Retention = 0.522 ($d_5 = 0.478$)

Price of N loading rights at the fjord = $\delta = 51.18$ DKK/kgN

Price of N leaching rights at Farm 5 = $\mu_5 = d_5 \times \delta = 24.46$ DKK/kgN_{leached}

Farm 5 Bid quantities (in kgN). Note: negative *bids-to-buy* denote *offers-to-sell*.

Tranche 6	Tranche 5	Tranche 4	Tranche 3	Tranche 2	Tranche 1
-364	-126	-953	567	250	412

Farm 5 Bid prices (in DKK/kgN_{leached})

Tranche 6	Tranche 5	Tranche 4	Tranche 3	Tranche 2	Tranche 1
107.67	66.00	61.03	61.03	10.42	5.48

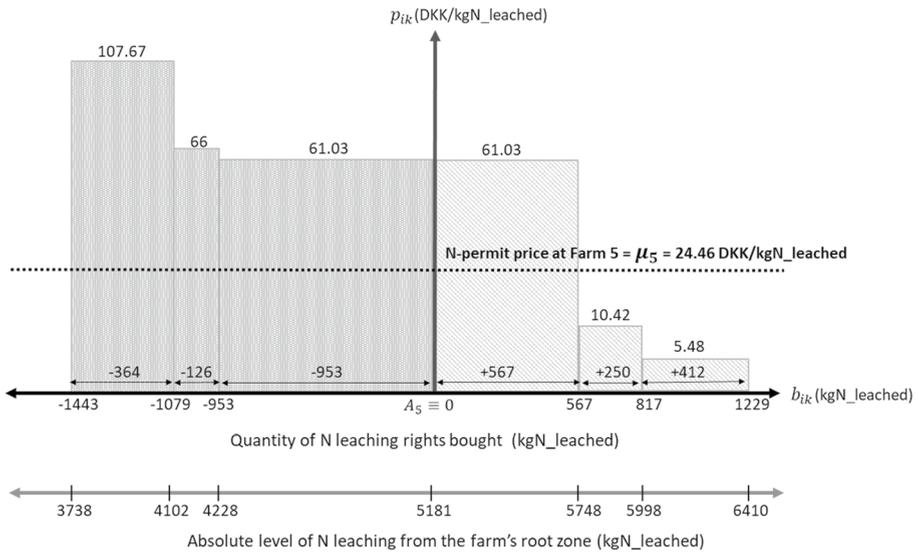


Fig. 9 Example ‘buying’ farm in Limfjorden catchment

Appendix 2: Example Illustrating How Trading in the Smart Market will Allocate N-allowances Across Traders

An example of a bid and offer schedule and the corresponding DMU-specific prices for N leaching rights for a typical DMU in Limfjorden is shown (Figs. 9 and 10) to illustrate how the gains from trade are realised in a market under a uniform N-permit allocation of 72 kgN_{leached}/ha. Figures 9 and 10 show a typical situation where, having received their initial allocation, Farm 5 and Farm 31 submitted their bid and offer schedules based on their estimated at-farm N leaching and abatement cost outlays associated with the different land use choices and N-abatement measures available to them. This process similarly occurs for the other 6502¹³ farms included in this study. The baseline N leaching to the root zones for

¹³ The original farm-level data produced by TargetEconN consist of 6746 farms, however, for the smart market simulations, we exclude all farms with retention of 0.99 or more (129 farms) and farms for which the tightest limit of 52 kgN/ha leaching is infeasible (113 farms) resulting in the final number of market participants of 6504 farms.

Farm 31: Permit Seller

Farm area = 26 ha

Retention = 0.66 ($d_i = 0.34$)

Price of N loading rights at the fjord = $\delta = 51.18$ DKK/kgN

Price of N leaching rights at Farm 31 = $d_{31} \times \delta = 17.40$ DKK/kgN_leached

Farm 31 Bid quantities (in kgN). Note: negative bids-to-buy denote offers-to-sell.

Tranche 7	Tranche 6	Tranche 5	Tranche 4	Tranche 3	Tranche 2	Tranche 1
-56	-57	-339	-48	-20	465	302

Farm 31 Bid prices (in DKK/kgN_leached)

Tranche 7	Tranche 6	Tranche 5	Tranche 4	Tranche 3	Tranche 2	Tranche 1
91.54	62.40	61.03	6.10	5.80	5.80	5.48

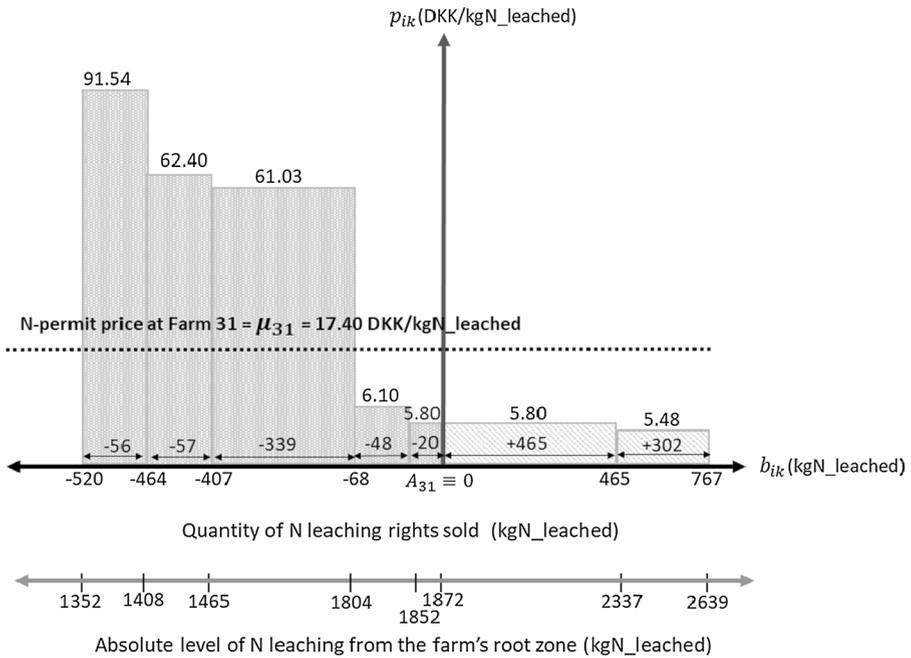


Fig. 10 Example ‘selling’ farm in Limfjorden catchment

Farm 5 and Farm 31 are 6410 kgN and 2,639 kgN, respectively. The initial N leaching allocations (at 72 kgN_leached/ha) for Farm 5 and Farm 31 are 5181 kgN_leached and 1872 kgN_leached, respectively.

Using the information on submitted bids and offers from 6504 DMUs, information on retention coefficients and target N load at Limfjorden, the smart market linear program clears the market, simultaneously maximising the total net benefit from trade to market participants. As part of the solution, a single market price for an additional 1 kg N load at the fjord (δ) emerges as the shadow price of the total N load constraint (T3). The linear program solution also contains information on farm-specific prices in the form of shadow prices for DMU-specific compliance constraints (T2). The farm-specific price for N leaching rights (μ_i) are given by the market price at the fjord (δ) multiplied by $d_i = (1 - \text{farm } i\text{'s retention coefficient})$.

In the examples shown in Figs. 9 and 10, the market price of 1 kg of N loading at the fjord is 51.18 DKK/kgN, Farm 5- and Farm 31-specific prices are 24.46 DKK/kgN leached and 17.40 DKK/kgN leached, respectively. Given their initial allocations and these on-farm prices, Farm 5 will choose to be a buyer, and Farm 31 a seller. Confronted with an N leaching price of 24.46 DKK/kgN leached, Farm 5 bought 567 kgN of leaching rights because its maximum willingness to pay for this tranche of leaching rights (61.03 DKK/kgN leached) is higher than the at-farm price it has been given. Once these additional leaching rights have been purchased, Farm 5 has a total N leaching right of 5748 kgN_{leached}. At this level of leaching rights (5748 kgN_{leached}, position with trade), compared to its baseline leaching of 6410 kgN_{leached} (i.e. when there is no regulation to limit N leaching), Farm 5 incurs an abatement cost of 4,863 DKK (obtained from the price x quantity products for bid tranches 1 & 2). These two bid tranches depict the costs incurred in implementing the two abatement measures (tranche 1, then tranche 2) required to reduce Farm 5's N leaching from its baseline level to 5,748 kgN_{leached}). Farm 5 also incurs a trade expenditure for the purchase of 567 kg of additional N leaching rights, amounting 13,869 DKK. These two costs (after-trade abatement cost and trade expenditures) represent the total costs incurred by Farm 5 after participation in N-trading.

In the 'without trade' situation, where all farms have to comply with the uniform regulation of less than or equal to 72 kgN_{leached}/ha (i.e. ≤ 5181 kgN_{leached} for Farm 5) *solely through on-farm abatement measures*, Farm 5 would have to implement on-farm abatement measures to reduce its N leaching to 4228 kgN_{leached}. This position is 953 kgN below the maximum leaching allowed under the initial leaching allocation because Farm 5 only has a particular set of abatement measures available. Utilising its available suite of measures to ensure compliance with its initial leaching allocation $A_{i=5} = 5181$ kgN_{leached}, Farm 5 actually has to reduce its leaching to 4228 kgN_{leached}. Consequently, this is Farm 5's starting position without trade. In this position, Farm 5 will incur a total abatement cost of 97,628 DKK (sum of price x quantity products for tranches 1 to 4, inclusive). As a result of over-compliance, Farm 5 holds 953 unused leaching rights. Comparing its situation with and without trade, Farm 5's gain from trade is 78,896 DKK (=total abatement cost without trade at 97,628 DKK—after trade abatement cost of 4863 DKK—trade expenditure of 13,869 DKK).

In contrast, Farm 31 is a seller of N leaching rights because with the uniform initial allocation of 72 kgN_{leached}/ha (i.e. 1872 kgN_{leached}), Farm 31's minimum willingness to accept prices for two of its *offer-to-sell* tranches (tranches 3 and 4) are lower than Farm 31's maximum willingness to pay (17.40 DKK/kgN_{leached}) (Fig. 9). In total therefore, Farm 31 sells 68 kgN_{leached} of its at-farm N leaching rights at a price of 17.40 DKK/kgN_{leached}, leaving it with 1804 kgN of at-farm leaching rights remaining. To comply with their allowance, Farm 31 will have to abate 835 kgN of at-farm leaching in total (given by the difference between the farm's baseline position of 2639 kgN_{leached} and its with-trade leaching allowance of 1804 kgN_{leached}) at a cost of 4761 DKK (sum product of price and quantity in tranches 1 to 4 inclusive). This abatement cost is partially offset by the revenue received from sales of leaching rights totalling 1183 DKK. Therefore, the net cost to Farm 31 from participating in the N trading scheme is 3578 DKK.

In the 'without trade' situation, Farm 31 would have to comply with the uniform initial at-farm leaching allowance of less than or equal to 72 kgN_{leached}/ha (i.e. 1872 kgN_{leached} in total). Given that it has only a particular set of abatement measures available, Farm 31's 'without trade' position would be to remain at 1852 kgN_{leached}. Here, the total abatement cost incurred (without trade i.e. solely through using on-farm abatement measures) is 4468 DKK and Farm 31 has 20 kgN_{leached} of unused N-permits from its initial

allocation. Thus, the gain from trade for Farm 31 is 890 DKK, given by the reduction in cost when moving from its without trade position (4468 DKK abatement cost incurred) to its with trade position (3578 DKK net abatement cost incurred).

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