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Potential benefits of farm scale measures versus landscape measures for reducing nitrate loads in a Danish catchment

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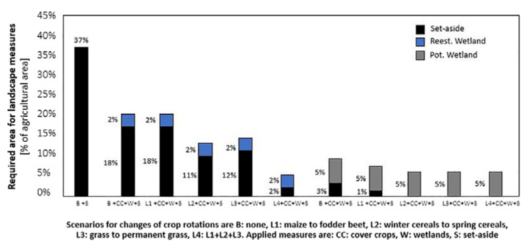
HIGHLIGHTS

- N-load reductions exploit farm and landscape measures and variation in groundwater nitrate reduction.
- Nitrate leaching from farmland is reduced by changes in crop rotations and using cover crops.
- Including potential wetlands eliminated the need for set-aside to achieve reduction target.
- Effectiveness of farm scale measures is affected by farm type, soil type and groundwater N-reduction.
- Establishment of wetlands depends on landscape features.

GRAPHICAL ABSTRACT



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ABSTRACT

To comply with the EU Water Framework Directive, Denmark must further reduce the nitrate (N)-load to marine ecosystems from agricultural areas. Under the anticipated future spatially targeted regulation, the required N-load reductions will differ between catchments, and these are expected to be mitigated by a combination of land and water management measures. Here, we explored how the expected N-load reduction target of 38% for a Danish catchment (River Odense) could be achieved through a combination of farm and landscape measures. These include: (a) N-leaching reduction through changing the crop rotation and applying cover crops, (b) enhancing N-reduction through (re)establishment of wetlands, and (c) reducing N-leaching through spatially targeting of set-aside to high N-load areas. Changes in crop rotations were effective in reducing N-leaching by growing crops with a longer growing season and by allowing a higher use of cover crops. A combination of wetlands and changes in crop rotations were needed for reaching the N-load reduction target without use of set-aside. However, not all combinations of wetlands and crop rotation changes achieved the required N-load reduction, resulting in a need for targeted set-aside, implying a need for balancing measures at farm and landscape scale to maximize N load reduction while minimizing loss of productive land. The effectiveness of farm scale measures is affected by farm and soil types as well as by N-reduction in groundwater, while the possibilities for using wetlands for decreasing the N-load depends on landscape features, allowing the establishment of wetlands connected to streams and rivers.

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1. Introduction

Despite a successful history of more than 30 years for aquatic action plans and policies aimed at reducing the level of nitrogen (N) loads from human activities in Denmark (Kronvang et al., 2008; Dalgaard et al., 2014; Jacobsen et al., 2017), current N-loads to marine environments are still considerably above environmental acceptable levels set by the Water Framework Directive (WFD). The basis of Danish water quality policies has until recently been nationwide reduction targets for root zone N-leaching from primarily agricultural sources, combined with specific measures to achieve the targets (Ærtebjerg et al., 2003; Jacobsen et al., 2017). This has been implemented via a uniform regulation regime involving mandatory measures (e.g., maximum N fertilizer rates, time restrictions for slurry and manure application, mandatory cover crops, constructed wetlands, and buffer strips and 2 m riparian buffer zones along streams and lakes), which successfully resulted in an almost 50% reduction in agricultural N-leaching from the mid-1980s to 2003 (Naturstyrelsen, 2005, 2014a, 2014b). Nevertheless, N-leaching is still a major concern, especially in relation to the quality of coastal waters (Naturstyrelsen, 2014a). There is thus a need for further reducing N-loads to many marine areas. This is primarily a consequence of the large extent of agricultural lands (more than 60% of Denmark) and short distance between agricultural lands and the coastline (Dalgaard et al., 2014; Hashemi et al., 2018a). Also, the uniform regulation with statutory maximum N fertilizer rates, set below the production-economic optimum, have contributed to halting agricultural yield progress in Denmark, which has been a primary concern of the farming industry (Dalgaard et al., 2014).

The Food and Agriculture Package agreed by the Danish Parliament in 2016 aimed to allow production-economic optimal fertilization of crops while introducing new targeted measures for reducing N-loads to the aquatic environments (Hashemi et al., 2018a). However, the policy of targeted measures were by 2017 still not implemented, since achieving additional N-load reductions through spatial targeting is no simple task (Hashemi et al., 2018a). The present focus in Denmark for enacting a new policy of differentiated agricultural N mitigation is based on the spatial variation in groundwater N-reduction (i.e. the redox reaction where nitrate is reduced to N_2, primarily under anaerobic conditions), a result of geological heterogeneity in the subsurface geology. This is expected to be a more cost-effective approach than a uniform N management regulation (Jacobsen and Hansen, 2016; Refsgaard et al., 2014), in particular when this is combined with (re)establishment of wetlands to enhance N-reduction in surface waters.

Recently, methods for spatially targeting measures to reduce agricultural N-loads were analyzed by Hansen et al. (2017) and Hashemi et al. (2018a). Hansen et al. (2017) assessed the potential benefits of spatial targeting based on detailed N-reduction maps (i.e., a map showing how much N is removed by reduction processes in either groundwater or surface waters) in the Norsminde catchment in Denmark. They focused on decreasing the root zone N-leaching on target areas with low groundwater N-reduction, showing the potential benefits of implementing a spatially targeted regulation based on detailed groundwater N-reduction maps. However, the study by Hansen et al. (2017) only considered the optimal locations for targeted measures based on N-reduction maps, and not which specific measures to apply. Another study by Hashemi et al. (2018a) for two Danish catchments (Norsminde and Odense) showed that spatially differentiated measures plays an important role to achieve maximum N-load reduction while minimizing cost of losing agricultural production. However, the study by Hashemi et al. (2018a) only considered measures to reduce N-leaching without changing the cropping system and did not apply N-mitigation measures to increase natural N-reduction (groundwater and surface water reduction).

The second version of the Danish Water Plans under the EU Water Framework Directive was adopted on 1 July 2016 and set specific reduction targets for all larger Danish catchments. The N-load for Odense Fjord catchment in 2012 was 1653 Mg N yr^{-1}, and the new water plans set a reduction target of 38% (Danish Nature Agency, 2016). Initiatives to lower the N-load have already been implemented for this catchment; however, wetlands implemented during 2009–2015 have only resulted in a reduction of 37 Mg N yr^{-1}, consequently more will have to be done to reach the proposed reduction requirement (Danish Nature Agency, 2016). Even by using a spatially targeted strategy (i.e. changing the agricultural management by relocation of the present N-leaching) for the Odense catchment, this reduction target would still not be met as this only results in a 26% decrease in N-load (Hashemi et al., 2018a). Therefore, achieving greater N-load reductions with little effect on agricultural production will likely require a new strategy combining measures on agricultural land (e.g. set-aside, decreased fertilization, cover crops, early sowing of winter crops, conversion to perennial bioenergy crops, afforestation) with enhanced reduction of N in drainage water (e.g. riparian zones, constructed wetlands and re-establishment of former wetland areas) (Ørum et al., 2017). In addition, the location of these measures should be spatially targeted to achieve maximum efficiency. Such an approach to reduce N-loads would involve different measures in different parts of the landscape as also suggested in other parts of the world (Whittaker et al., 2017).

To our knowledge, no studies have considered a combination of reducing N-leaching at both farm and landscape scales and increasing total N-reduction at landscape scale to reach a N-load reduction target while minimizing effect on the productive agricultural area. Therefore, in order to provide policy makers with the necessary information for responsible political action, research should address the possible environmental impacts of N-mitigation measures at landscape scale compared to N-mitigation measures at farm scale for designing spatially differentiated strategies. The main objectives of our study were thus: (i) to assess the effect of potential farm and landscape measures on N-load reduction, and (ii) to analyze the consequences for the agricultural land area when using different measures to achieve the required N-load reduction from a Danish catchment (Odense River catchment) to coastal waters.

2. Materials and methods

2.1. Study site

The study area is the river Odense catchment located on the island of Funen in Denmark (Fig. 1). As a part of the total Odense Fjord catchment of 1025 km^2, this study was conducted in an intensively farmed sub-catchment of 486 km^2, covering the catchment area upstream the monitoring station at Kratholm (st.450003). The catchment drains to Odense Fjord, which is sensitive to N-loading and requires a significant N-load reduction (Danish Nature Agency, 2016). The region has a temperate and humid climate with a mean annual precipitation in Odense of 808 mm (1991–2010). Its topographical elevation varies from 12 m above sea level to 129 m above sea level. The mean annual runoff is 296 mm (1991–2010). The dominating land use in the catchment is agriculture (79%), and loamy-clayey tills are the dominant soils. An overview of the location of the study site in Denmark, elevation, soil type, total N-reduction at sub-catchment and average N-leaching (1990–2009) is provided in Fig. 1.

2.2. Baseline input data

2.2.1. Land use

Excluding the permanent grass and natural areas, 61% of the land area in the Odense catchment was in rotational crops, primarily arable crops. Information about crops on agricultural areas and farmland boundaries were available for 2011 at field scale from the General Farm Register (GLR in Danish), and this information was combined with information on the use of fertilizer and manure available from the Danish AgriFish Agency (Dalgaard et al., 2002). The most common