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Research article

Spatially differentiated strategies for reducing nitrate loads from agriculture in two Danish catchments

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ABSTRACT

Nutrient loss from agriculture is the largest source of diffuse water pollution in Denmark. To reduce nutrient loads a number of solutions have been implemented, but this has been insufficient to achieve the environmental objectives without unacceptable repercussions for agricultural production. This has substantiated the need to develop a new approach to achieve nitrogen (N) load reduction to the aquatic environments with lower costs to farmers. The new approach imply targeting N leaching mitigation to those parts of the landscape which contribute most to the N-loadings. This would involve either reducing the source loading or enhancing the natural reduction (denitrification) of N after it is leached from the root zone of agricultural crops. In this study, a new method of spatially differentiated analysis for two Danish catchments (Odense and Norsminde) was conducted that reach across the individual farms to achieve selected N-load reduction targets. It includes application of cover crops within current crop rotations, set-a-side application on high N-load areas, and changes in agricultural management based on maps of N-reduction available for two different spatial scales, considering soil type and farm boundaries as spatial constraints. In summary, the results revealed that considering spatial constraints for changes in agricultural management will affect the effectiveness of N-load reduction, and the highest N-load reduction was achieved where less constraints were considered. The results also showed that the range of variation in land use, soil types, and N-reduction potential influence the reduction of N-loadings that can originate from critical source areas. The greater the spatial variation the greater the potential for N load reduction through targeting of measures. Therefore, the effectiveness of spatially differentiated measures in term of set-a-side area in Odense catchment were relatively greater compared to Norsminde catchment. The results also showed that using a fine spatial N-reduction map provides greater potential for N load reductions compared to using sub-catchment scale N-reduction maps.

1. Introduction

In Denmark, agricultural activities is the major contributor of nitrate to the coastal waters. This is a consequence of the large extent of agriculture (more than 60% of land is farmed) and short distances between agricultural source areas and the coastline (Dalgaard et al., 2014). This has resulted in deterioration of the quality of groundwater and surface waters. Since 1985, several action plans have been implemented in Denmark to reduce N discharges from point sources and diffuse losses from agriculture (Kronvang et al., 2008). In particular, the implementation of the EU Nitrates Directive required accounting for the fertilizer value of N in manure, and limiting N application to what was required for crop yield and N removal (Van Grinsven et al., 2012). The N-regulation in Denmark was until 2015 based on N fertilizer quotas for field application based on crops and soil type, time management rules for slurry and manure application and mandatory cover crops (Dalgaard et al., 2014). Although measures like wetlands, buffer strips and 2 m riparian zones along streams and lakes are to some extent site specific, current regulation of N fertilization is mainly input-based and applied uniformly for the whole of Denmark.

This N-regulation in Denmark is largely applied without considering the required N-load reduction targets for a given catchment and the spatial variability in the natural N-reduction in

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groundwater and surface waters on the flow pathway to the sea, whereby nitrate is naturally transformed to N_2 under anaerobic conditions (Dalgaard et al., 2014; Mikkelsen et al., 2010; Refsgaard et al., 2014). The current regulation has proven successful in terms of improving the N efficiency in farming systems and reducing nitrate leaching (Kronvang et al., 2008; Jacobsen et al., 2017). Implementation of these policies in Denmark have reduced the N-leaching by app. 50% since 1990 (Dalgaard et al., 2014; Jacobsen, 2009; Mikkelsen et al., 2010); but current N-loadings to marine environments are for most catchments still considerably above environmental acceptable levels set by the Water Framework Directive (WFD), and these loadings may be expected to increase in the future due to climate change (Jeppesen et al., 2011). Therefore, developing and implementing a new, targeted and differentiated regulation of agricultural use of N (NLK, 2013) and improved management of N in agriculture is seen as necessary to achieve a sustainable balance between the production of food and other biomass, and the unwanted effects of N on water pollution (Dalgaard et al., 2012).

The Food and Agriculture Package agreed by the Danish Parliament in 2016 aims to allow more optimal fertilization of crops while introducing targeted measures to reduce N loadings to groundwater and surface waters. However, this policy for more targeted measures is still not implemented. Currently, the main focus for enacting a new regulation in Denmark is based on differentiating the agricultural N management according to the spatial variation in groundwater N-reduction, a result of geological heterogeneity in the subsurface. This is expected to be a more cost-effective approach than a uniform management approach (Jacobsen and Hansen, 2016; Refsgaard et al., 2014). This new approach of N-regulation could be different between different types of fields and farms as also suggested in other parts of the world (Whittaker et al., 2017). On the fields with low groundwater N-reduction, higher impacts on the N-loading will be obtained from applying N-leaching measures, resulting in higher cost effectiveness. Although farms are the key decision making units (Happe et al., 2011), regulation of N strictly at the farm or field level may not provide optimal solutions for each individual farmer. Therefore, in order to provide policy makers with the necessary information for responsible political action, research should address the possible environmental impacts of spatially differentiated N-mitigation strategies and regulation at landscape scale while also considering constraints imposed at farm scale for implementing such strategies.

Although environmental assessment of spatially targeted measures is important for N loading to the aquatic environments, predicting this under future land use and management is difficult. Thus, scenario studies as predictive tools have been developed to propose particular solutions for the future or explore possible reasons for specific current or past conditions (Hashemi et al., 2016). In a review of scenario studies on agricultural nutrient loadings, Hashemi et al. (2016) showed that only few studies have considered how to manage nutrient flows or considering how changes in the landscape may be used to influence both flows and transformation processes. Studies that have considered spatially targeting measures in the landscape are all recent, but they did not include differentiation due to spatial variation in groundwater N reduction.

Recently, Hansen et al. (2017) analyzed the potential benefits of spatially targeted regulations based on detailed maps of variation in groundwater N-reduction in a study area in Denmark. The study by Hansen et al. (2017) focused on decreasing the N-leaching on target areas with low groundwater N-reduction illustrating the potential benefits of implementing a spatially targeted regulation based on detailed groundwater N-reduction maps. The analysis demonstrated a clear advantage in terms of environmental effectiveness of targeting measures, and showed that this would allow higher fertilization on non-target areas without compromising the targeted N load reductions to the coastal waters. 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 and which constraints in the landscape that may limit the targeting of measures. To our knowledge, no studies have considered changes of agricultural management under different spatial and legal constraints available in the landscapes (i.e. detailed N-reduction maps in grid scale and sub-catchment scale, soil types, farm boundaries), and no study have considered high N-load areas in the landscape as target areas to apply N-mitigation measures.

With changes in the present regulation of N in Danish agriculture, there is a need to analyze the effectiveness of increased spatial targeting of N load reduction measures based on detailed local information on groundwater N reduction, and constrained by variation in soil type and farm boundaries. Therefore, the main objectives of our study were 1) to address the possibilities of targeting measures to reduce N-leaching losses to those parts of the landscape and agricultural systems, which contribute most to the N-loadings, and 2) to analyze the consequences for agriculture land area of different spatial constraints and scales to achieve specific targeted N-load reduction to coastal waters.

2. Materials and methods

2.1. Study sites

The study was conducted for two catchments in Denmark, Norsminde Fjord and Odense Fjord (Fig. 1). Norsminde Fjord is a 100 km^2 intensively farmed catchment with 67% of the area in agricultural land. The study was conducted in a sub-catchment of 85 km^2 covering the catchment area to the most downstream monitoring station (st.270035). Odense Fjord catchment has an area of approx. 1025 km^2 and is also dominated by agricultural land use. The area considered in this study is an upstream sub-catchment with an area of 486 km^2 (st.450003). Fig. 1 provides an overview of the location of the study sites in Denmark, elevation, the variation in soil type, as well as N-reduction and N-leaching.

2.2. Baseline input data

2.2.1. Land use

Just as elsewhere in Denmark, land use in Norsminde and Odense catchments is dominated by agriculture. For this study land use data for both catchments were for 2011 and is divided into two classes; agricultural and non-agricultural lands. 67% of the area in Norsminde and 79% in Odense are in agriculture. Excluding the permanent grass and natural areas, 62% of the area in Norsminde and 61% of the areas in Odense were specified as fields in rotation, primarily with arable crops. Information on crops on agricultural areas and farm boundaries were available for 2011 at field scale for both catchments from the General Farming Register (GLR in Danish). The most common crops grown in Norsminde were winter cereals with 62% of agricultural land, while only 13% was cultivated by spring cereals. The dominant crop type in Odense was cereals, with 35% in winter cereals and 20% in spring cereals. To specify each farm boundary, a polygon shapefile with unique farmer IDs for each field was available for each catchment. In this way, the boundary of a single farm was not necessarily confined to a specific part of the catchment, but may have fields scattered across the catchment and beyond. In this study 152 farms in Norsminde and 705 farms in Odense were identified, and the average farm size in Norsminde was 40 ha with a standard deviation of 64 ha and in Odense 50 ha