Spatial modelling integrating agricultural production, costs and hydrology for nitrogen policy assessments - a catchment apporach

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Abstract
Nutrient loads cause eutrophication, and the non-point characteristics of this pollution problem has been studied for decades. Efforts have been made to reduce nutrient loads and eutrophication in Europe, US and elsewhere, but additional actions are required to achieve *good* water quality aimed for in water quality policies. Spatial data describing the relationships between biophysical and hydrological factors and agricultural production have been used to develop an ecological-economic model of the non-point pollution and the spatial configuration of the costs to reduce the loads. The model has been developed to analyze the cost-effective choice of abatement measures taking the nonpoint and diffuse distribution of the loads of nitrogen to the sea into account. The model is a cost-minimization model at a fine spatial resolution which identifies spatial distributions of the cost-effective implementation of abatement measures. The model is developed to analyze and compare the costs and effects of uniform regulation versus spatially differentiated implementation of abatement measures, as well as how model assumptions affect the model solutions. Both types of analyses are regarded important for the use of this type of models in policy advise.

Key Words
Catchment modelling, spatial regulation, cost-effective abatement measures, agriculture, water quality policies

Introduction
The non-point pollution problem caused by nitrogen loads has been studied for decades, and in parts of Europe such as Denmark nitrogen loads from agriculture has been intensively regulated, but continues to be a major environmental problem of policy concern. In the 1990's, the N loads from Danish watersheds to the coastal areas were among the highest in Europe (Maar et al 2016). Measures undertaken as part of National Water Action Plans and the implementation of the European Water Framework Directive (WFD) (EC, 2003) have reduced the N-loads by about 50% (Maar et al 2016), but there is still a gap between the current status of the coastal waters and the WFD-targets. Filling this gap requires costly abatement in agriculture and of other sources of nutrient loads. Research into cost-minimizing solutions is therefore regarded as an important contribution to reduce the money spend by the regulating authorities and production losses of landowners and other parties.

Until now Danish nitrogen policies have, as in many other countries, included uniform regulations and instruments. In Denmark one of the most significant measures has been fixed quotas restricting nitrogen fertilizer application to a level below economic optimum, but this regulation is now abandoned to allow for more differentiated regulation of farmers. Other measures used in the current policy include catch crop requirements for all farms, as well as voluntary measures such as set-aside, where agricultural land is withdrawn from cultivation, restoration of wetlands, cultivation of energy crops, forestation and investments in technologies to improve the utilization of animal manure. To reduce costs of water quality improvements it has been argued that more targeted regulation, taking heterogeneity in both costs and natural conditions into account, should be implemented, allowing for cost effective non-uniform implementation.

It is widely recognized that there are a number of challenges in designing and implementing this type of non-uniform targeted non-point regulation. Due to the diffuse nature of non-point sources the monitoring and regulation of nitrogen loads at the agricultural field scale are prohibitively expensive and technically demanding (Griffin and Bromley 1982; Shortle and Dunn 1986).

Since monitoring the sources of pollution is difficult modelling could be an instrument to guide regulation and cost-effective distribution of the abatement. Recent developments in modeling and optimization approaches, using detailed spatial physical and economic data, can be used to, at least partly, to solve the nonpoint regulation problem by proposing more cost-efficient reductions of nutrient loads to the aquatic environment. Such models, taking heterogeneity in natural conditions and costs into account, have been developed and demonstrated in recent studies, such as Rabotyagov et al (2014) and Konrad et al (2014)).

The present study introduces an integrated biophysical and economic model framework developed to analyze and model cost-effective abatement policies for regulating agricultural non-point pollution from a Danish coastal catchment area.. The model system, named TargetEconN, is calibrated for the Danish catchments to the fjord ‘Limfjorden’, with the aim to identify nitrogen abatement programs that take the heterogeneity of natural conditions as well as abatement costs within the catchment, into account.

The model

The model TargetEconN for the Limfjord Catchment is a social planner model set up to minimize the costs of reducing the nitrogen loads to the fjord, choosing the most cost-effective abatement measures to reduce these loads. The model is built on similar principles as the models developed in Konrad et al (2014) and Hasler et al (2014).

The model includes in all 12 abatement measures, comprising different types of abatement methods like set-aside, buffer strips and wetland restoration; nitrogen application reductions by N quota on nitrogen applications, increased utilization of livestock manure; catch crops, forestation and cultivation of energy crops. All measures are characterized by the effect on nitrogen leakage from the root zone and the costs of implementing the measure.

This implies that the modelling of costs and effects of the measures takes the spatial heterogeneity in the catchment into account by estimating the abatement costs for each measure for a specific land use units. This is done using data for the crop composition and nitrogen application at field block-level, where the field blocks include a number of agricultural field parcels belonging to a farm. In the Limfjord catchment the median size of a field block is 4.2 hectares, and the catchment holds 56,619 such field blocks.

The effects on nitrogen leakage and subsequent loads to the sea from the root zone are differentiated according to the soil type within these field blocks and retention of nitrogen in the area, i.e. the attenuation of nitrogen from the root zone to the sea. This is feasible since each field block is characterized by the composition of agricultural vegetation cover, soil type and nitrogen retention. Nitrogen retention shares are estimated for the whole catchment for the nitrogen retained in ground- and surface water, and is measured for sub-catchments of the Limfjord-catchment. The retention of N in ground- and surface water influences the effectiveness of the abatement measures by reducing the nutrient load reduction delivered to the receiving fjord.

The optimization model minimizes the costs of meeting the nutrient load reduction targets defined to achieve the water quality specified in the WFD plans for the fjord, but the model can of course also be used to model other reduction targets. These load reduction requirements are the objective of the optimization problem, and a number of restrictions are included to ensure realistic model solutions. Examples of such restrictions are the maximum implementation potential for each measure in the catchment, but also that only on measure can be implemented in each field block. This restriction is implemented to ensure that mutually exclusive measures are not implemented (in the model) at the same location. This is important to avoid over-optimistic assessment of possible policy outcomes. Some measures can be implemented jointly, e.g. implementing catch crops and nitrogen fertilizer reductions in the same field, however, the joint effect is often not known and joint implementation is therefore not considered in the model.

By specifying the costs and nitrogen load effects of each abatement measure for each field block within the catchment the optimal composition and spatial location of the abatement is modelled. The model prescribes the spatial location, as well as the scale of each measure, to achieve the most cost-effective solutions. The spatial configuration is illustrated using GIS and maps, and hereby illustrations of likely outcomes and distributions of a policy implementation can be made prior to policy decisions.

Data

The base year of the model calibration is 2011 and all prices and data for crop composition and nitrogen application are taken from this year, using register data from the General Agricultural Register, collected by the Danish Ministry of Environment and Food. The data for the modelling comprise three main categories:

- The first is the spatially explicit data on crop choice, where each field block contains information about the percent allocation to each crop, divided into these categories - winter cereals, winter rapeseed, , spring cereals and rapeseed, grass in rotation, grass outside rotation, set aside, energy crops, nature areas, forested areas, fruit and vegetables.

- The second category is the data on farm holdings distributing data on area of land cultivated for each crop and the number of livestock to each property. The livestock production is not part of the model and optimisation, but data on livestock production and distribution from the farm holding dataset is used to calculate livestock manure distribution as well as the need for area for spreading livestock manure, as this is regulated to ensure effective utilisation of the livestock manure.

- The third source of data consists of leakage and retention data, which are estimated for 483 subcatchments in Denmark by Windolf and Tornbjerg (2009). For the catchment Limfjorden there are 90 different subcatchments, where each of these subcatchments is characterised by a groundwater and a surface water retention. The retention coefficient describes the difference between the nitrogen loads leaving the rootzone as leakage, and the nitrogen compounds that reaches the river mouth and the coast. The model NLES4 (Børgesen & Greve 2009) is used for the estimation of the leakage from the rootzone for agricultural cropped areas as well as for land set-aside, , where literature is used for estimating leakage for forested and nature areas.

Conclusions: how can the model be used?

The model is suitable for scenario analysis assessing changes in reduction targets, and also for sensitivity analyses of the assumptions in the model. The assumptions used are varying to different degrees, and it is important to know how uncertainty on e.g. the retention assumptions and the assumption of other hydrological conditions affects the distribution of the abatement actions and, consequently, the distribution of costs between the farms and between subcatchments. Such scenarios can illustrate differences in cost-effectiveness and spatial distribution of abatement policies, e.g. when implementing uniform and targeted regulation. .

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