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Cost-efficient reductions in nutrient loads; identifying optimal spatially specific policy measures

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ABSTRACT

Nitrogen leakage from agriculture contributes significantly to eutrophication of freshwater and marine ecosystems, and numerous studies have focused on finding cost-effective ways to mitigate this effect. This article utilizes high-resolution data to identify a spatially targeted cost-effective reduction of nitrogen leakage, optimizing over measures as well as over locations. The use of discrete optimization techniques ensure that mutually exclusive measures are not applied on the same plot of land. The analysis is based on a case study of Odense Fjord, where spatially explicit data capture the spatial heterogeneity of the effects and costs of abatement measures. The differences in retention capacity; soil types; and current land use are particularly important factors for the spatial variation in costs and effects. The analysis highlights the importance of applying discrete optimization techniques in spatially specific analyses. We find that no unambiguous ranking of measures or spatial pattern of abatement effort can be given. Hence, landscape scale models are needed to identify optimal abatement effort. The results show that spatial targeting offers substantial improvements in cost-effectiveness compared to a uniform regulation.

1. Introduction

Freshwater ecosystems such as lakes, rivers and fjords provide society with a range of services, which depend on the quality of the surface waters. Excessive nutrient loads, as a by-product of

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modern farming practice, lead to eutrophication and oxygen depletion, and reduce the value of the services from the freshwater ecosystems [9,18,30,31]. The need to regulate leakage from agriculture has been recognized for many years, but the Water Framework Directive (WFD) has stimulated a growing interest in identifying cost-effective ways of meeting nutrient reduction targets. Cost-effectiveness of alternative policy measures has been addressed using different approaches and methods, ranging from econometric methods to linear programming models, see Fezzi et al. [13] for a comparison. For example, Fezzi et al. [12] and Hutchins et al. [21] have employed statistical methods to relate different scenarios of abatement policies to changes in farm gross margin. Another line of research builds on operations research methods, using linear or nonlinear programming to identify ways of achieving pollution reduction targets at minimum costs ([16,34,17] and [23]; see Balana et al. [4] for an overview). Using operation research methods, researchers have ranked abatement measures in terms of cost-effectiveness, but typically the analysis has been conducted at very low spatial resolution, e.g. Fröschl et al. [14] compare four different abatement measures in four different countries draining to the Black Sea.

The focus of this article is to identify the optimal spatial pattern of measures and to identify the minimum cost of achieving a pre-specified environmental target of nutrient reductions to a fresh water recipient. This optimal pattern serves as a reference point for evaluation of alternative policy options. Policy implementation is not considered in the current study, where we take the social planner's perspective to evaluate spatially uniform policies against the identified optimal cost-effective pattern of measures.

Due to spatial heterogeneity of productivity and nitrogen run-off in agricultural catchments, geographical allocation of abatement measures is widely recognized to be important for cost-efficiency considerations [5,40]. The increased accessibility of geographical information systems (GIS), as a tool for spatial data handling, has enabled researchers to access and explore higher spatial resolution data than was previously possible. This development has also influenced the literature on abatement of non-point pollution as high-resolution data has been utilized in a variety of models to evaluate abatement measures (e.g. [35,26,41,43]).

However, capturing the spatial heterogeneity in biophysical and economic characteristics in operations research is still challenging, as factors important for cost-effectiveness can vary discretely between adjacent locations, due to changes in soil type, hydrology and farm type. It may therefore be important to retain the specification of the spatial pattern of the key characteristics in the model in order to identify cost-effective measures and in order to evaluate alternative policy proposals. Furthermore, some nitrogen abatement measures are mutually exclusive (e.g. wetland reconstruction and catch crops), implying that it is important to model implementation of abatement measures on each parcel of land, to avoid overestimation of the effect that can be obtained by including a range of measures in the models.

Spatial optimization of choice of abatement measures is not new to the literature. For example, Helin (2012) develops a spatial nonlinear model to compare spatial targeting to homogenous regulation. Furthermore, the linear programming model of Khanna et al. [22] utilizes high-resolution data and includes interaction effects between locations, drawing attention to the endogenous nature of the effects of measures. These applications, however, do not keep track of land use to ensure that the same plot of land is not used more than once. Consequently, they are unable to account for mutual exclusiveness of measures on the same hectare of land. Furthermore, when models are not spatially specific, they cannot take into account that the effect of measures depends on whether they are implemented independently or jointly on the same plot of land. Many cost-minimization studies using linear or nonlinear programming to identify optimal measures for nutrient load reduction have used simplified representations to overcome this complexity. For example, the study by Fröschl et al. [14] avoids this computational difficulty by only considering four measures, which can be implemented on the same parcel of land. However, generally the effects of different measures depends on whether they are independently or jointly implemented on the same piece of land, and are therefore not additive: Disregarding this will lead to overly optimistic conclusions. This article follows an optimization approach, although in contrast with the research referenced above we identify cost-effective solution using discrete optimization techniques. We use estimates of nitrogen abatement effects and costs, which are specific to the land units, given as the largest area with