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Influence of soil and climate heterogeneity on the performance of economic instruments for reducing nitrate leaching from agriculture

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HIGHLIGHTS

- We analyze the influence of soil and climate heterogeneity on economic instruments.
- Cluster analysis was used to group same crops located in different areas.
- We assess the impact of instruments in terms of social welfare and farmers' income.
- The most efficient instrument is tax on emissions followed by tax on fertilizer.
- However, cost-effectiveness can be different between clusters of the same crop.

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ABSTRACT

Economic instruments can be used to control groundwater nitrate pollution due to the intensive use of fertilizers in agriculture. In order to test their efficiency on the reduction of nitrate leaching, we propose an approach based on the combined use of production and pollution functions to derive the impacts on the expected farmer response of these instruments. Some of the most important factors influencing nitrate leaching and crop yield are the type of soil and the climatic conditions. Crop yield and nitrate leaching responses to different soil and climatic conditions were classified by means of a cluster analysis, and crops located in different areas but with similar response were grouped for the analysis. We use a spatial economic optimization model to evaluate the potential of taxes on nitrogen fertilizers, water prices, and taxes on nitrate emissions to reduce nitrate pollution, as well as their economic impact in terms of social welfare and farmers' net benefits. The method was applied to the Mancha Oriental System (MOS) in Spain, a large area with different soil types and climatic conditions. We divided the study area into zones of homogeneous crop production and nitrate leaching properties. Results show spatially different responses of crop growth and nitrate leaching, proving how the cost-effectiveness of pollution control instruments is contingent upon the spatial heterogeneities of the problem.

1. Introduction

Nitrogen is the main polluter of groundwater in Europe (EC, 2010) and worldwide, mainly because of the intensive use of fertilizers in agriculture, and we can expect that past fertilizer strategies will impact for many decades the quality of groundwater bodies (Schlesinger, 2009). It is now widely accepted that nitrogen management demands integrated approaches to improve water quality (Sutton et al., 2011; Oenema et al., 2011). By integrating natural sciences and economics in decision making, environmental protection and resource use efficiency can be enhanced (Hall et al., 2001). This integration would benefit from a multicriteria framework that helps to assess the trade-off relationships between agronomy and the environment (Koo and O'Connell, 2006, 2007; Cardenas et al., 2011). To decrease nitrogen emissions from agriculture, a series of environmental policies and legislation have been implemented in the European Union and all around the world. One example is the EU Nitrates Directive that aims to reduce nitrate leaching from agriculture, which is already producing some positive results although with large regional differences (Velthof et al., 2014; EC, 2011). Policy mechanisms for agricultural non-point pollution control include not only direct regulations (i.e., standards on the amount and use of potential pollutants and production practices) but also economic instruments. Economic instruments can be defined as incentives for adapting individual decisions to collectively agreed goals (De la Camara et al., 2013). Taxes and subsidies can be applied directly to the polluting emissions through “effluent” taxes or based on emission proxies like polluting inputs “influent taxes” or subsidies. There have been even some preliminary experiences on the implementation of economic instruments for nitrate pollution control in Europe (Rougoor et al., 2001; Nam et al., 2007) and in different OECD countries (Vojtech, 2010).

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There is already a very extensive literature on the economics of non-point pollution, pioneered by the seminar papers by Griffin and Bromley (1982) and Shortle and Dunn (1986). The contribution of economic instruments like fertilizer taxes to nitrate pollution control has been theoretically analysed (see reviews by Shortle and Horan, 2001, 2013), although some instruments cannot be readily implemented nor can their efficiency be promptly assessed (Shortle and Dunn, 1986). Segerson (1988) analysed the effectiveness of instruments based on measurements of ambient pollution instead of effluent or input instrument, given the difficulty to monitor individual pollution actions in practical terms.

Many studies have also shown the potential role of water price policies in modifying farm-level irrigation decisions towards more environmentally friendly choices (Varela-Ortega et al., 1998; Berbel and Gómez-Limón, 2000). Some authors (Horan and Shortle, 2001) found instruments based on irrigation water to be more cost-efficient than instruments based on the use of nitrogen fertilization, while others (Martínez and Albiac, 2004; Semaan et al., 2007) have shown that water pricing might be rather inefficient to abate emissions. Although the EU Water Frame Directive (WFD) only explicitly refers to water pricing, other economic instruments as fertilizer taxes have been also widely studied. For many authors, fertilizer taxation is one of the more efficient measures to reduce nitrate emissions (Pan and Hodge, 1994; Martínez and Albiac, 2004; Semaan et al., 2007). Lally et al. (2009) compared regulation on nitrogen application versus taxes on fertilizer and concluded that a tax on inorganic nitrogen would impose a larger compliance cost on farmers and on public authorities than would a regulatory measure. Economic incentives can also induce voluntary agreements (Segerson and Wu, 2006).

Empirical findings depend on many local conditions with respect to climate, soil and on the particular crop, and associated irrigation, tillage, and other operations (Martínez and Albiac, 2006). The cost-effectiveness of pollution control mechanisms is contingent upon spatial heterogeneities such as the type of soil (Helfand and House, 1995; Martínez and Albiac, 2006).

The objective of this paper is to develop a framework to analyse the effect of soil and climate heterogeneities on the design of efficient policy mechanisms to reduce nitrate leaching to groundwater, and to test it on the Mancha Oriental groundwater system, Spain. A spatial economic optimization model is used to assess the impacts and to estimate the cost-effectiveness of policy measures to reduce nitrate leaching using spatially variable crop production and nitrate leaching functions. Water and fertilizer prices and environmental taxes were tested in terms of impacts on social welfare, farmers' net benefits and nitrate leaching using an economic optimization model that accounts for spatial heterogeneities. Cluster analysis was used to group crop areas that, located in different soil and climatic zones, exhibit similar response to water and fertilizer application strategies.

2. Method

2.1. Spatial optimization model

A spatial economic optimization model is used to test the efficiency of policy measures to reduce groundwater nitrate contamination due to intense fertilizer use in agriculture. In order to test how farmers might response to different management policies we assume that they adjust inputs, including water and fertilizer, in order to maximize profits. In this way, the problem is defined as a maximization of farmer's net benefits from crop production:

$$\Pi = \sum_{c} A_c \cdot (p_c \cdot Y_c - p_n \cdot N_c - p_w \cdot W_c - C_c + S_s) \tag{1}$$

where A_c is the cultivated area for crop c (ha), p_c is the price of crop c (€/kg), Y_c is the crop yield (kg/ha), p_n is the price of nitrate fertilizer (€/kg), N_c is the amount of fertilizer applied to crop c (kg/ha), p_w is the water price (€/m^3), W_c is the water applied to crop c (m^3/ha), c_c includes all investments related to the cultivation of a crop except water and fertilizer (labour costs, cost of power, machinery maintenance and crop manufacturing, cost of seeds, cost of health and care) (€/ha) and s_c is the subsidy for crop c (€/ha).

To test the effect of increase water price or fertilizer price on farmer's response, the variables p_n and p_w are increased. Taxes on emissions where tested by modifying Eq. (1) as follows:

$$\Pi = \sum_{c} A_c \cdot (p_c \cdot Y_c - p_n \cdot N_c - p_w \cdot W_c - C_c + S_s - \eta \cdot l_c) \tag{2}$$

where l_c is the nitrate leached (kg/ha) and η is the tax on emissions (€/kg).

Farmers select the amount of fertilizer and irrigation that maximize their private net benefit (quasi-rent) without considering environmental externalities; and consequently, input application and nitrate emissions are not socially optimal.

In order to analyse the effect of the policy options upon the total social welfare (SW), we assess SW as the total private (farmers') net benefit, or quasi-rent (Eq. (1)), minus the damage cost of nitrate pollution (environmental externality) as follows:

$$SW = \prod - \mu \cdot l_c \tag{3}$$

where Π is the total private net benefits (€/ha), l_c is the nitrate leached (kg/ha) and μ is the unit nitrate pollution cost (€/kg). $l_c \cdot \mu$ is the term representing the damage cost from nitrogen leaching; it should represent the environmental damage costs, but in the practical absence of valuation studies to produce damage cost functions, μ is assumed to be the cost of eliminating nitrogen from groundwater (Martínez and Albiac, 2004, 2006).

The crop yield is estimated by calibrating the following quadratic function:

$$Y_c = a + b \cdot W_c + c \cdot W_c^2 + d \cdot N_c + e \cdot N_c^2 + f \cdot W_c \cdot N_c. \tag{4}$$

Nitrate leaching is estimated using the following quadratic function:

$$L_c = g + h \cdot W_c + i \cdot W_c^2 + j \cdot N_c + k \cdot N_c^2 + l \cdot W_c \cdot N_c. \tag{5}$$

The production and nitrate leaching functions are estimated using a regression analysis with simulated values from an agronomic model (Section 3.2).

2.2. Cluster analysis and soil and climate influence

Cluster analysis is a generic name for a variety of statistical methods that can be used to find out which objects within a set are similar (Romesburg, 2004). The two-step cluster analysis (SPSS Inc., 2001; Zhang et al., 1996 and Chiu et al., 2001) was designed to handle very large datasets and is implemented in the statistical package SPSS. The algorithm identifies groups of objects that exhibit similar response patterns. Two-step cluster analysis was applied to group different spatial crop areas that exhibit similar behaviour in terms of yield and leaching.

Once the cluster analysis was completed, the dependence and association of the clusters previously defined with the climate and soil condition were obtained using a cross-tabulation or contingency table analysis. A cross-tabulation is a joint frequency distribution of cases based on two or more categorical variables. The joint frequency distribution can be analysed with the chi-square statistic (χ^2) to determine whether the variables are statistically