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

Peña-Haro, Salvador[1]; Garcia-Prats, Alberto[2]; Pulido-Velazquez, Manuel[3]

[1] Institute of Environmental Engineering, ETH Zurich, Wolfgang-Pauli-Strasse 15, CH-8093 Zurich, Switzerland

[2] Department of Hydraulics and Environmental Engineering, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain.

[3] Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain.

Abstract Economic instruments can be used to control groundwater nitrate pollution due to the intensive use of fertilisers 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.

Key words *economic instruments, soil and climate heterogeneity, nitrate leaching*

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., 2012). 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 the agronomy and the environment (Koo and O'Connell, 2006 and 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 (Velhof et al., 2014; EC, 2011). Policy mechanisms for agricultural non-point pollution control include 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) .

There is already a very extensive literature on the economics of nonpoint 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 have been theoretically analysed (see reviews by Shortle and Horan, 2001 and 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 Gomez-Limon, 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 (Martinez 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 nitrates emissions (Pan and Hodge, 1994; Martinez 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 (Martinez 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; Martinez 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 maximization of farmer's net benefits from crop production computed as:

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

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); 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:

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

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:

$$SW = \prod - \mu \cdot l_c \qquad (3)$$

where Π is the total private 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 and 2006).

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

$$Y_c = a + b \cdot W_c + c \cdot W_c^2 + d \cdot N_c + e \cdot N_c^2 + f \cdot W_c \cdot N_c \quad (4)$$

Nitrate leaching is estimated using the following quadratic function:

$$L_c = g + h \cdot W_c + i \cdot W_c^2 + j \cdot N_c + k \cdot N_c^2 + l \cdot W_c \cdot N_c \quad (5)$$

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 (Rosemburg, 2004). The two-step cluster analysis (SPSS Inc., 2001; Zhang et al., 1996 and Chiu et al., 2001) was designed to handle very large data sets 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 was 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 independent or associated. The chi-square indicator is calculated as:

$$\chi_p{}^2 = \sum_i \sum_j \frac{(\mathrm{E_{ij}} - \mathrm{O_{ij}})^2}{E_{ij}} \quad (5)$$

where E_{ij} is the expected frequency for the cell in the i_{th} row (1 to R) and the j_{th} column (1 to C). O_{ij} is the observed frequency for the cell in the i_{th} row (1 to R) and the j_{th} column (1 to C).

Different indicators of dependence can be used to describe the degree which the values of one variable predict or vary with those of the other variable. Herein we used Goodman and Kruskall's Lambda, Pearson's contingency coefficient and Cramer's V to analyse dependency.

Cramers'V (V) is a measure of association independent of the sample size, useful for comparing multiple χ^2 test statistics; it is generalizable across contingency tables of varying sizes. It is not affected by the sample size and therefore, very useful in situations where a statistically significant chi-square is expected as a result of large sample size instead of any relevant relationship between the variables. It is interpreted as a measure of the relative strength of an association between two variables. The coefficient ranges from 0 to 1 (fully dependent).

$$V = \sqrt{\frac{\phi^2}{k-1}} \tag{7}$$

where: $\phi = \sqrt{\frac{\chi_p{}^2}{N}}$ and N are total counts in the table and k is the number of rows or the number of columns, whichever is less.

Goodman and Kruskal's Lambda (λ) measures the percentage improvement in predictability of the dependent variable (row variable or column variable), given the value of the other variable:

$$\lambda_a = \frac{\sum_j \max\left(O_{ij}\right) - \max\left(n_j\right)}{N - \max\left(n_j\right)} \tag{8}$$

where n_i and n_j are respectively the row and column marginal totals

The Pearson's Contingency Coefficient (PC) is a measure of association that is independent of sample size. It ranges between 0 (no relationship) and 1 (perfect relationship). For any particular table, the maximum possible indicator depends on the size of the table (a 2 × 2 table has a maximum of 0.707), so it should only be used to compare tables with the same dimensions (as in our case).

$$PC = \sqrt{\frac{\chi_P^2}{\chi_P^2 + N}} \quad (9)$$

3. Case study.

3.1. Description of the study area

The Mancha Oriental System (MOS), with a surface area of 7260 km^2, is one of the largest groundwater bodies in Spain. It belongs to the Jucar River Basin (JRB) and encompasses parts of the provinces of Albacete, Cuenca and Valencia. With an average altitude of 700 m above sea level, the region has a Mediterranean-continental semiarid climate with noticeable fluctuations in daily and seasonal temperatures. The mean monthly summer temperature is about 22°C, while during the winter it is about 6°C. Mean annual precipitation (1940–2010) is about 360 mm. The most important surface water body is the Jucar River (Fig. 1). The annual water withdrawal, through more than 2500 pumping wells, has been increased from around 100 Mm^3 in 1982 to 400 Mm^3 in 2002 (CHJ, 2005). Agriculture is the main use of groundwater, using around 90% of the total abstractions (360 Mm^3/year).

Since the early 1970s to nowadays, the increase of irrigated crop areas and the subsequent rise of water abstractions has induced negative environmental impacts in the area. The groundwater table has decreased in some regions from 60 to 80 m between 1970 and 2002, (Moratalla et al., 2009), which has impacted the connected surface water bodies. In this regard, a reduction of groundwater discharges into the Jucar River has been observed, leading to the conversion of some gaining reaches of the river into losing reaches, and to wetlands degradation and desiccation and river flow depletion. Irrigated crop development has also led to significant negative consequences on the quality status of the aquifer because of fertilizer use. Nitrate concentrations in groundwater of 125 mg/l have been measured at certain locations (Moratalla et al., 2009). The aquifer has been declared as a nitrate vulnerable area by the Castilla-La Mancha regional government (DOCM, 2003).

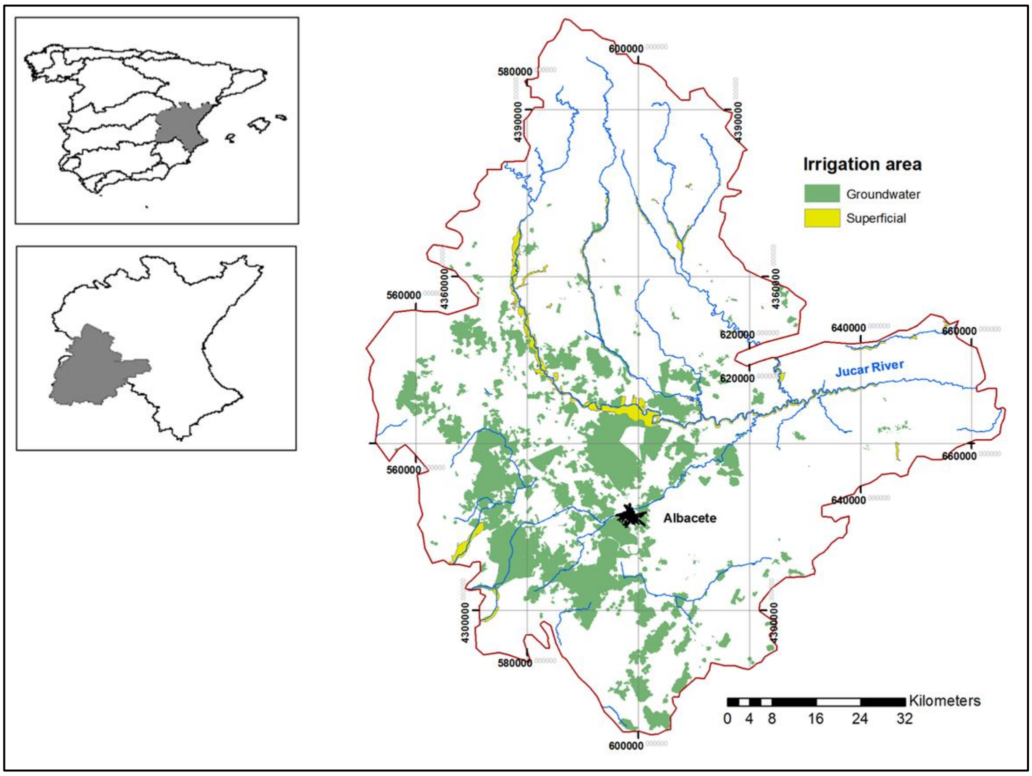


Figure 1 Study area.

In large areas like the MOS, different climate and soil conditions can be found. Nine climatic zones were defined using ten weather stations (Fig 2a). Stations in the north of the MOS have an average precipitation around 100 mm higher than the ones located in the south. The more rainfall is the more leaching it should be expected (Table 1).

Table 1 Average annual precipitation in mm (2000-2009).

Villanueva	Albacete	Montilleja	Tarazona	Almansa	Pozo Cañada	Gineta	Sanchon	El Picazo
405	323	373	382	342	332	339	424	424

The Digital Soil Map of the World (FAO, 2007) from the International Union of Soil Sciences was used to define the soil zones. Four soil zones were derived according with the soil type. Soil Bg10-2a in the centre and south west end of the MOS is a gleyic cambisol, while the three other soil types (Bk46-2a, Bk47-2/3b and Bk45-2bc) belong to the family of calcic cambisols (Fig. 2b).

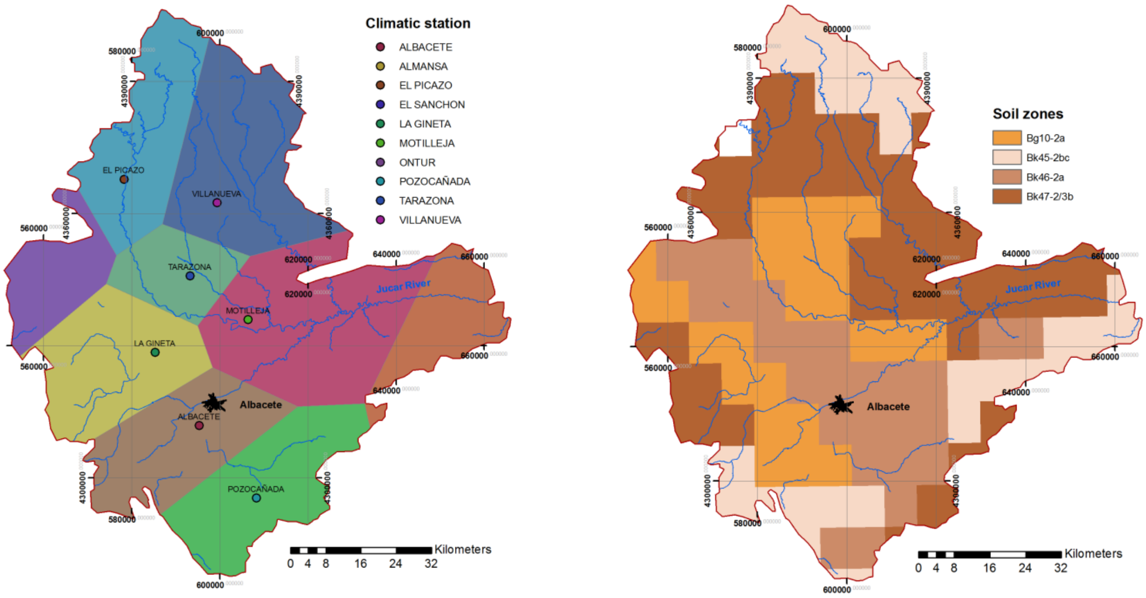


Figure 2 Climatic areas and stations (left). Soil zones (right).

Although there are 4 soil types, three of them belong to the same family having the same properties. Bg10-2a is a gleyic cambisols, it has a coarser texture than the ones belonging to the calcic cambisols (Bk codes) and has PH and cation exchange capacity considerably lower. Bg10-2a soil is more vulnerable than BK soils, and it should be expected higher leaching values.

Table 2 Soil properties in the MOS area.

Soil	% Sand	% Silt	Soil PH	Organic matter (%)	Cation exchange capacity (cmol/kg)
Bg10-2a	41.0	30.0	6.2	0.56	11.5
Bk45-2bc	33.0	38.0	8.2	0.52	19.0
Bk46-2a	33.0	38.0	8.2	0.52	19.0
Bk47-2/3b	33.0	38.0	8.2	0.52	19.0

3.2 Agronomic simulation

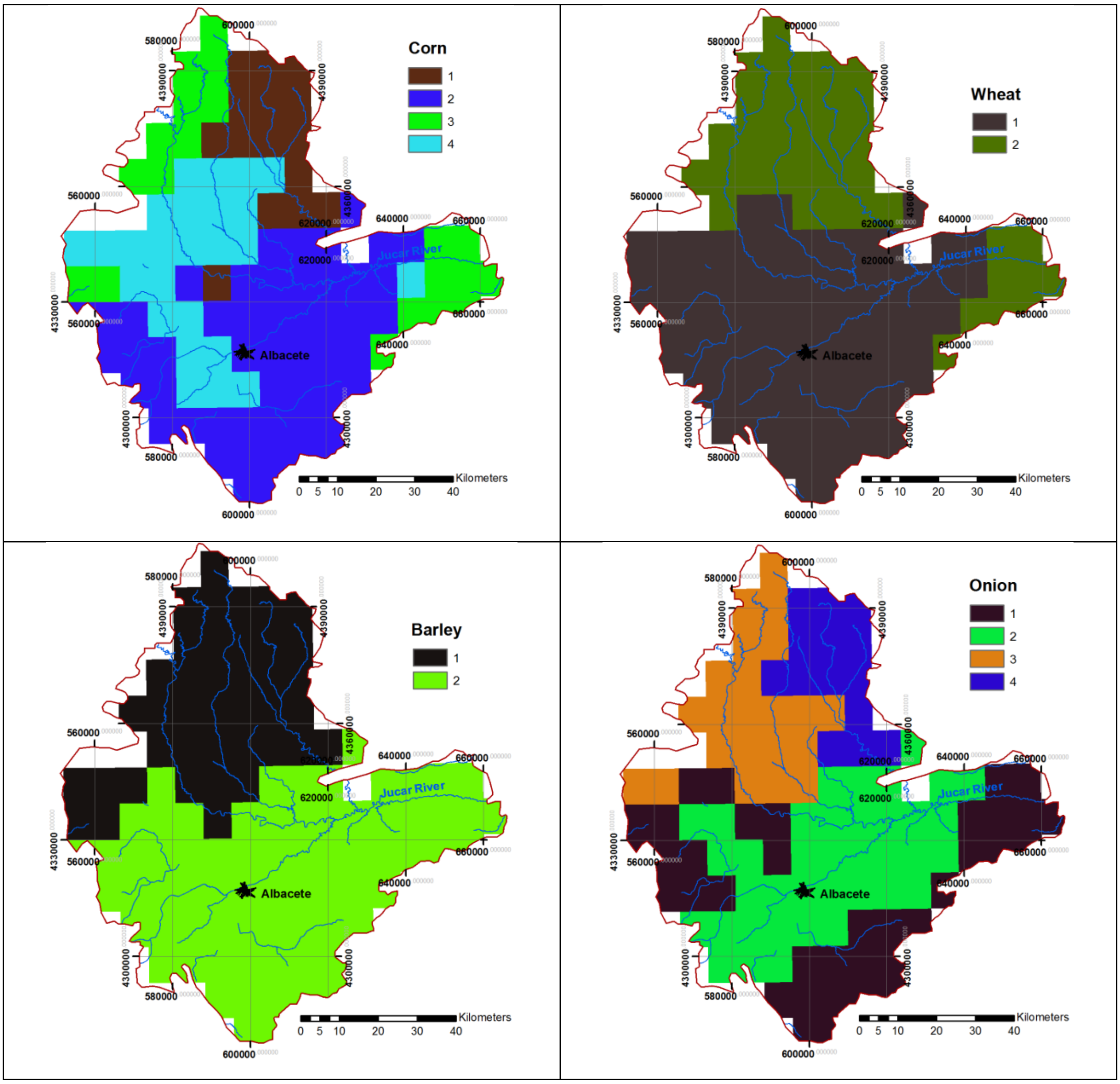
Crop yield and nitrate leaching functions (Eq. 2 and 3) specific for the MOS area were generated through agronomic simulations using the GEPIC model. GEPIC (Liu, 2009) is a GIS-based distributed version of EPIC model (Williams et al., 1983), through a loose coupling between ArcGis (Version 9.0) and the EPIC model.

The advantage of using GEPIC is that the input data is added in terms of GIS raster datasets, and results distributed per pixel are obtained. The basic datasets includes the DEM (Digital Elevation Model), slope, soil, climate, land use, irrigation and fertilizer. The area has 324 pixels with a resolution of 0.0833^{o}. The EPIC model, developed by the USDA-ARS and TAES, uses a daily time step to simulate the major processes that occur in soil-crop-atmosphere-management system. Potential crop yield is simulated based on the interception of solar radiation, crop parameters, leaf area index and harvest index. The daily potential growth is decreased by stresses caused by water, nitrogen and phosphorus deficiencies, extreme temperatures, and poor soil aeration (Liu, 2009). The GEPIC model was used to simulate the crop response to different fertilizer and irrigation strategies considering the different soil and climate conditions prevailing in the study area. Simulations were calibrated using the outcomes of experiments under field conditions on which the effect of water on yield was studied, developed by the ITAP (Regional Technical Institute of Agronomy of the Albacete province) during the 2000-2009 growing seasons at the experimental station “Las Tiesas” located within the MOS zone (http://www.itap.es). Planting density, potential heat units from planting to maturity, Harvest index, and Biomass-Energy Ratio (potential growth rate per unit of intercepted photosynthetically active radiation) were the parameters employed for calibrations. Paired values of yield per level of applied water in the field versus yield modelled were compared using a simple regression analysis in order to calibrate the model.

Since the main objective of the agronomic simulation was to obtain production and leaching functions, in terms of nitrogen and water use, several GEPIC simulations were performed in the following way. First, crop responses to different irrigation values were simulated while keeping the amount of fertilizer constant. Second, the amount of water was kept constant while varying the fertilizer doses. For this purpose more than 3,800 simulations per crop were run. Using this method, enough variability in crop response is guaranteed to fit the coefficients of the production and leaching functions.

3.3 Yield and leaching in homogenous areas

It is well known that nitrate leaching and crop yield are influenced by soil and climate conditions (Kissel et al., 1982). In order to assess whether the yield and leaching values (obtained with the agronomic simulations, section 3.2) of two cells of different spatial location are similar or different, we applied a two-step cluster analysis as described on section 2. The cells belonging to the same cluster define an equal-behaviour area. The zones of statistically significant differences were used to define 14 possible combinations of crop yield and nitrate leaching functions in the MOS (Table 3, Figure 3).



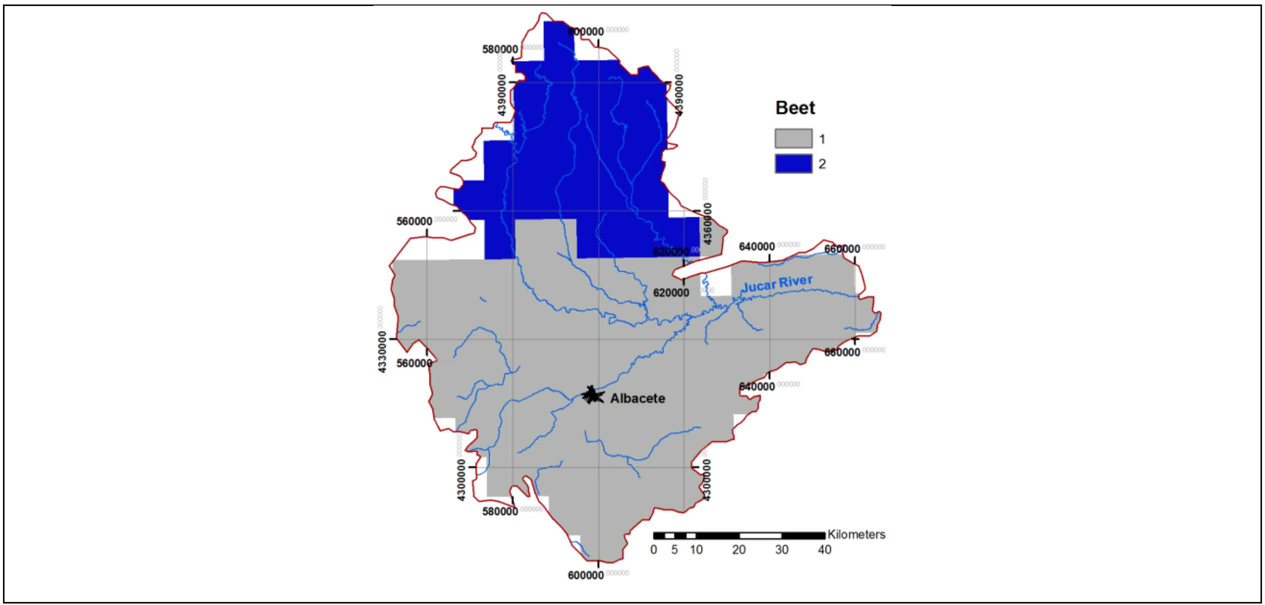


Figure 3 Spatial location of the clusters.

Table 3 Cluster analysis

Crop	Cluster	Mean Yield (as dry matter) (kg/ha)	Mean Leaching (kgNO3/ha)
Corn	1	12.60	68.12
	2	12.94	59.15
	3	12.22	76.38
	4	12.25	84,89
Wheat	1	6.35	72.32
	2	6.29	85.75
Barley	1	8.99	65.72
	2	9.65	48.97
Onion	1	7.50	62.31
	2	8.01	58.54
	3	7.09	76.71
	4	7.74	70.72
Beet	1	13.38	91.79
	2	13.57	133.44

To analyse the dependence and association of the clusters previously defined with the climate and soil condition, a cross-tabulation or contingency table analysis was applied. Table 4 shows values of a chi-square (χ^2) hypothesis test ran to determine whether or not to reject the idea that the cluster and type of soil or climatic condition classifications are independent based on the P-value. If P-value (statistical significance) is less than 0.05, we can reject the hypothesis that they are independent at the 95% confidence level.

Table 4 Indicators of association and correlation for the crop areas

	Climatic zone				Type of soil			
Crop	χ^2 **(P-value)**	λ	**P.C.**	**V**	χ^2 **(P-value)**	λ	**P.C.**	**V**
Wheat	3628.95 (0.00)	0.9862	0.7027	0.9877	1149.24 (0.00)	0.4828	0.4858	0.5558
Beet	4494.00 (0.00)	1.00	0.7071	1.00	909.22 (0.00)	0.3899	0.4102	0.4498
Corn	10672.32 (0.00)	0.8155	0.8301	0.8595	4134.96 (0.00)	0.3948	0.6797	0.5350
Onion	11046.63 (0.00)	0.9031	0.8519	0.9394	1634.32 (0.00)	0.1938	0.5305	0.3613
Barley	4419.33 (0.00)	0.9937	0.7052	0.9948	717.58 (0.00)	0.3145	0.3721	0.4008

Since the P-value in all cases is less than 0.05, we have to reject the hypothesis that clusters are independent from the type of soil and climatic zone, being climate and soil variability responsible for the definition of the cluster areas. Goodman and Kruskall's Lambda, Pearson's contingency coefficient and Cramer's V in Table 4 indicate that we can assume that equal-behaviour areas defined with the two-step cluster analysis have a high association with climatic conditions, whereas the soil properties have a moderate influence.

3.4 Crop yield and nitrate leaching functions

Once the different equal-behaviour areas with the two-step cluster analysis were defined, the coefficients of the crop yield and nitrate leaching functions were estimated. This was done for each one of the clusters previously defined. Then the parameters of equations (4) and (5) were obtained using a multiple regression statistical analysis. Figure 4 depicts corn yield and leaching functions across several clusters, clearly showing significant differences. Crop yield obtained from the agronomic simulation is expressed as dry matter. In order to transform dry matter results into fresh yield, the moisture content is taken into account. The moisture content percentages used were 12%, 12%, 15%, 91% and 85% for wheat, barley, corn, onion and beet respectively.

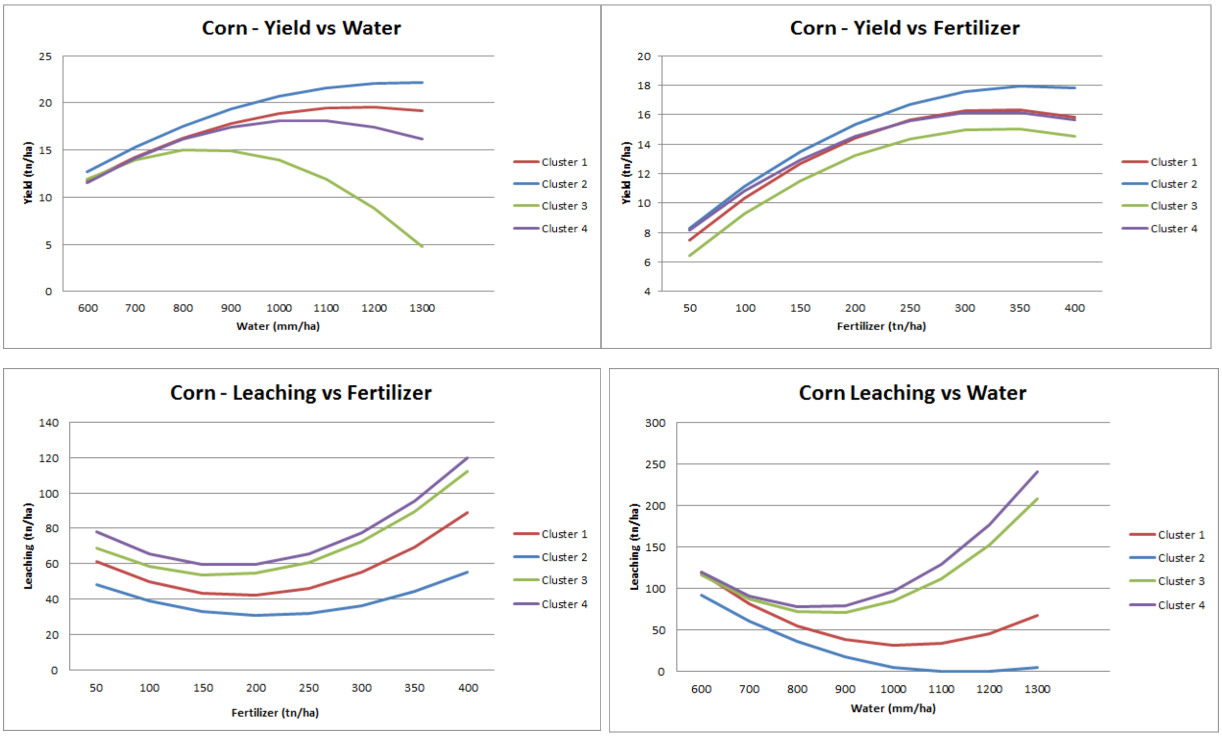


Figure 4 Corn Yield and Leaching functions.

3.5 Definition of homogenous crop response areas

The crop responses have been defined according to different soil and climatic conditions and grouped into clusters. That information was crossed with the current crop allocation map to determine the total area per crop located in the different clusters (Table 5). This area was used to determine the total amount of leaching and yield of particular combination of cluster and crop Cultivation information and spatial distribution data was obtained from the 2005 Exploitation Plan of the Central Board of Mancha Oriental Irrigators (JCRMO). 1029 administrative zones are defined where several crops are cultivated with different water applications. A simplification of this information was performed by up-scaling the administrative zones into 36 cultivation areas distributed over the MOS.

Table 5 Cultivated areas per cluster

Crop	Cluster	Cultivated area (ha)
Corn	1	8280
	2	8179
	3	8886
	4	7069
Wheat	1	8822

	2	10038
Barley	1	7430
	2	7477
Onion	1	960
	2	603
	3	878
	4	838
Beet	1	2120
	2	1480

4. Evaluation of economic instruments for groundwater nitrate pollution control.

The economic optimization model seeks to represent farmers' responses to different water and fertilizer prices and emission taxes as in a profit maximization problem. The model finds the optimal water and fertilizer application for different levels of application of each economic instrument. The optimization is constrained by a minimum and maximum amount of fertilizer use for each crop. Note that the model finds the values of fertilizer and water use that maximize total farmers' net benefit (Eq 1 and 2) in the MO area, what it is equivalent to maximize it at each cluster.

Table 4 presents the crop price, costs and subsidies considered for each one of the simulated crops. The cost term includes energy costs, consumables, and indirect and labour costs (Ministerio de Medio Ambiente, Rural y Marino, 2011). The subsidies mainly correspond to the ones provided in the context of the EU Common Agricultural Policy (CAP).

Table 6 Market price, costs and subsidies.

Crop	Crop Price (€/kg)	Costs (€/ha)	Subsidy (€/ha)
Barley	0.139	575.77	549.33
Onion	0.152	4174.34	0.00
Corn	0.173	860.38	423.45
Beet	0.048	1035.00	0.00
Wheat	0.172	650.78	598.05

MARM: Ministerio de Medio Ambiente, Rural y Marino (2011)
ITAP: Instituto Técnico Agronómico Provincial de Albacete (2010)

To evaluate the performance of the economic instruments, we compared the resulting private and social net benefits and nitrate leaching against the results corresponding to a business-asusual (BAU) scenario in which no further policies are implemented to control nitrate pollution. Additionally, we calculated the cost-effectiveness of the instruments as follows:

$$CE_i = \frac{B_0 - B_i}{L_0 - L_i} \quad (10)$$

where B_0 is the private (for the private CE index) or social net benefit (for the social CE index) in the base scenario, and B_i, the ones resulting from the application of policy i. L_0 is the leaching from the base scenario (Ton) and L_i is the resulting leaching from the scenario of policy i. Therefore, the cost-effectiveness (CE_i) index represents the (private-social) cost in M€ of a policy *i* to reduce one tonne of nitrate leached.

For the BAU scenario, the total average farmers' net benefit was estimated 131 M€/year is obtained, with a total nitrate leaching of 4809 tons.

In order to simulate the effect of a tax on nitrogen fertilizers, the fertilizer price was increased from 0.6 €/kg up to 2 €/kg, while the remaining parameters were left unchanged. The farmers' reaction to higher fertilizer prices will be to reduce fertilizer application and water use, what translate into a reduced social welfare and a lower nitrate leaching into groundwater. The highest fertilizer tax considered (2 €/kg) would reduce nitrate leaching by 1003 ton/year (21%) and farmers' net benefits would decrease in 22 M€/year (17%) due to reduced crop yields (lower income) and greater fertilizer costs. Social welfare would go down by 24 M€/year (19% reduction) considering a damage cost of 0.6 €/kg of nitrate leached (Table 5 and 6).

For assessing the potential role of water prices as economic instrument to control nitrate pollution, we simulated water price increases from 0.06 €/m^3 to 0.22 €/m^3. Higher water prices imply lower social and private (farmers') net benefits and a reduced nitrate leaching. When water price increases to 22 cents/m^3, the emission (nitrate leaching) reduction is 562 ton/year (12%) while the cost to farmers (quasi-rent losses) goes to 70 M€ (53%).

To test the influence of an emission tax on nitrogen leaching to the aquifer, we used the optimization problem that maximizes the objective function of Eq. 2 with the value of η varying from 0.5 to 1.6 €/kg. The comparison with the baseline BAU scenario shows that the private net benefits were reduced by 14 M€/year (10%), the social welfare by 7 M€ (5%) and the leaching by 693 ton/year (14 %) (Table 7).

Table 7 Performance of the economic instruments for different levels of prices/taxes. The percentage is the change with regards the BAU results)

	Price	Farmers' net benefit		Leaching		Farmers' net benefit CE	Social welfare u=0.6		Social welfare CE u=0.6	Social welfare u=1.0	
		(M€/ year)	(%)	(Ton/y ear)	(%)	(M€/100 ton)	(M€/ year)	(%)	(M€/100 ton)	(M€/ year)	(%)
BAU		131		4809			128			126	
Fertilizer price	0.7	129	- 1%	4716	-2%	2.1	126	-1%	2.7	124	-1%
	1.0	123	- 6%	4448	-7%	2.1	120	-6%	2.7	119	-6%
	1.4	116	-11%	4113	-14%	2.1	113	-11%	2.8	112	-11%
	2.0	109	-17%	3806	-21%	2.2	104	-19%	2.7	102	-19%
Water price	0.12	114	-13%	4623	-4%	9.1	111	-13%	2.4	109	-13%
	0.18	81	-38%	4352	-10%	10.8	79	-38%	1.8	77	-39%
	0.20	71	-46%	4291	-11%	11.5	69	-46%	1.6	67	-47%
	0.22	61	-53%	4246	-12%	12.4	58	-54%	1.4	57	-55%
Emission tax	0.7	124	-5%	4449	-7%	1.9	125	-2%	2.8	123	-2%
	1.1	121	-7%	4288	-11%	2.0	123	-4%	2.9	121	-4%
	1.4	119	-9%	4181	-13%	2.1	122	-5%	2.9	120	-4%
	1.6	117	-10%	4115	-14%	2.1	121	-5%	2.9	120	-5%

We can observe that, for the range of prices considered, the instrument that reduces the most the total nitrate leached to the aquifer is the fertilizer price (tax), followed by the emission tax and the lowest reduction correspond to water pricing. However, the most expensive one, in terms of forgone private benefits and social welfare losses, is water price, followed by increased fertilizer prices. Both the private and social CE indexes indicate that while emission taxes and fertilizer prices show a similar performance (around 0.02 M€/ton), the least efficient is water pricing (about 6 times less cost-efficient for the highest water price levels considered) (Table 5).

For assessing the sensitivity of the estimations of the social welfare to the u parameter, we tested the effect of an increase in that value of a 66% (from 0.6 to 1.0 €/ton of nitrate leaching damage cost) on the total welfare (right column on table 5). The changes in social welfare are just between 1 and 3%, showing the robustness of the social welfare calculation.

Influence of soil and climate heterogeneity on the economic instruments

Considering the whole extension of the MOS, the most cost-efficient measure is the tax on emissions (Table 5). This calculation involves all different soil and climatic conditions and the total cultivated area for each crop in each specific soil-climate combination (crop clusters). If we analyse nitrate leaching and private and social welfare per hectare for each one of the clusters, we can observe some significant differences in response to the economic instruments across different clusters of the same crop. For example, tax on emissions for cluster Beet-2 is far more cost-efficient (almost 6 times) than for beet-1. If we only focus on the leaching reduction per hectare, the one that reduces the leaching the least is the tax on emission,followed by water prices, and the one that reduces it the most is the fertilizer tax (Table 8).

In some cases nitrate leaching is not reduced even for high price increases, while the net benefits are significant lower as the yield decreases and the costs increase. As mentioned in section 3.3, the cluster analysis has showed that the clusters have a high association with climate conditions, whereas the soil properties have a moderate influence. Since the soil properties have a bigger influence on the nitrate leached, this means that we can expect few variations in nitrate leaching in our study region, as table 8 shows.

Table 8 Influence of soil and climate heterogeneity on economic instruments per cluster. (Δ is the difference between BAU and the maximum price for each economic instrument).

Crop	Cluster	Emission tax			Fertilizer tax			Water prices		
		Δ Farmers' net benefit (€/ha)	Δ Social welfare (u=0.06) (€/ha)	Δ Leaching (kg/ha)	Δ Farmers' net benefit (€/ha)	Δ Social welfare (u=0.06) (€/ha)	Δ Leaching (kg/ha)	Δ Farmers' net benefit (€/ha)	Δ Social welfare (u=0.06) (€/ha)	Δ Leaching (kg/ha)
Corn	C1	-3	-3	0	-560	-560	0	-1536	-1540	6
	C2	-2	-2	0	-420	-420	0	-1371	-1377	-10
	C3	-82	-81	-3	-395	-404	-14	-977	-974	-5
	C4	-124	-121	-4	-559	-560	0	-1388	-1378	-17
Wheat	W1	-65	-59	-11	-140	-157	-27	-487	-478	-15
	W2	-77	-71	-9	-155	-170	-23	-491	-484	-13
Barley	Ba1	-84	-79	-8	-215	-235	-30	-588	-573	-25
	Ba2	-58	-58	-1	-242	-246	-6	-616	-616	0
Onion	O1	-62	-62	0	-370	-371	-1	-1309	-1309	0
	O2	-64	-63	0	-471	-472	-1	-1545	-1544	-1
	O3	-90	-90	0	-401	-401	-1	-1514	-1513	-2
	O4	-195	-192	-6	-518	-523	-6	-1761	-1749	-20
Beet	Be1	-127	-97	-49	-345	-419	-116	-1152	-1136	-26
	Be2	-75	-72	-5	-254	-264	-16	-1158	-1153	-8

5. Discussion and conclusions

We have analysed the performance of three policies to reduce nitrate leaching from agriculture: fertilizer taxes, water prices, and taxes on nitrate emissions. The approach takes into consideration the soil and climate spatial variability, factors that can have a significant influence on crop yield and nitrate leaching. Different quadratic functions depending on the soil and climate conditions were derived to analyse the effects of variations of water and fertilizer applications on nitrate leaching and crop production. The analysis consisted in reproducing farmers decisions using an optimization model that maximizes farmer's net benefits from crop production under different fertilizer, water and emissions prices and comparing the changes on nitrate leaching and the corresponding economic impacts in terms of private (farmers) net benefit losses and social welfare reduction.

Dependency between clusters and soil and climate conditions has been demonstrated using the indicators of association. It was observed that the most efficient policy is the taxes on emissions followed by taxes on fertilizer. Increasing water prices showed the highest social and private CE index (due to the large private and social economic losses), although it is the one that reduced more the kgNO_3/ha leached (for the range of prices considered). This conclusion is in agreement with the findings of other authors, as for example Martinez and Albiac (2004 and 2006).

Cost-effectiveness was very different among clusters for the same crop. For specific clusters, taxes on fertilizers resulted to be more cost-efficient than taxes on nitrate emissions. This behaviour depends on the soil and climatic conditions, which are different between different regions; therefore different results can be expected for other regions.

The most important factors on evaluating the policy performance are the quadratic functions that simulate the crop yield and nitrate leaching. These functions were empirically calibrated from the simulated values from an agronomic model, which needs to be properly calibrated. However, it is not always an easy task in big areas like the MOS, given the significant variety of soils and the lack of data for the calibration and validation of such models. The largest uncertainty is found on the nitrate leaching functions, given the uncertainties on leaching estimates, the limitations of the models for its evaluation and the lack of local data for its proper assessment (Groenendijk et al., 2014 –same issue-). A sensitivity and uncertainty assessment can be carried out regarding the results of the agronomic model between the reasonable thresholds reported by the test fields and climate and soil data in the study area.

Another critical aspect that should be considered when deciding which policy to implement in order to reduce nitrate pollution is the implementation of such policy. Not always the most efficient one is the easiest to implement. While the implementation of nitrate standards is difficult because of the practical difficulties of ensuring compliance by the farmers, the application of the economic instruments will certainly have an impact on farmers' net benefits, and farmers would certainly oppose the introduction of this measure in absence of compensation for losses. On the other hand, nitrogen emissions are too costly to monitor in a systematic way, so that the policy of taxing emission is not realistic, although results could be used "as a benchmark to which alternative instruments could be compared" (Martinez and Albiac, 2006).

Nitrate pollution control is a very complex task, as it is analysis of the economic instruments, since it depends on the very particular conditions of each case study (soil, climate, and others) as well as the objectives (most nitrate leached reduction, best cost-effectiveness, highest farmers' benefits). Depending on those factors optimal measures can be different.

Further research is needed on the potential impact of differentiated polices across the different cluster areas. Heterogeneity in climate and soil conditions, and hence in the response of the crops in terms of yield and leaching, is an important source of inefficiency in the application of homogenous policies. Finally, the real impact (environmental damages) of nitrate pollution will depend on the resulting groundwater nitrate concentration and its potential transmission to surface water bodies. In order to analyse the effectiveness of different policies on groundwater nitrate concentrations, we need to relate them to fertilizer applications (Peña-Haro et al. 2010, 2011).

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