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Analysis of policy instruments for control of nitrate pollution in irrigated agriculture in Castilla y León, Spain

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Abstract

Irrigated agriculture is one of the most important sources of nitrate pollution of water resources. For this reason, during the past decade, various policies have been proposed in order to prevent this negative impact of farming activities. The aim of this work is therefore to analyze the effects of the joint application of the last Common Agriculture Policy (CAP) reform with different policy instruments designed to mitigate nitrate pollution. To this end, models based on Positive Mathematical Programming have been developed to enable simulating irrigators' productive behaviour in the event of the implementation of these instruments. The results indicate that the latest CAP reform (partial decoupling of subsidies) will by itself lead to an important reduction in nitrate pollution. If this reduction is not regarded as being sufficient, other specific policy instruments could further reduce this source of pollution. In this sense, the most suitable one could be the application of nitrogen fertilization quotas.

Additional key words: agricultural policy, economic instruments, environmental policy, positive mathematical programming.

Resumen

Análisis de instrumentos políticos para el control de la contaminación por nitratos de la agricultura de regadío en Castilla y León (España)

La agricultura de regadío es una de las principales fuentes de contaminación por nitratos de los recursos hídricos. Por este motivo en los últimos años han surgido diferentes políticas encaminadas a evitar esta externalidad negativa de la actividad agraria. En este sentido, el objetivo de este trabajo es analizar los efectos de la aplicación conjunta de la última reforma de la Política Agraria Común (PAC) y diferentes instrumentos políticos mitigadores de la contaminación por nitratos. Para ello se han empleado modelos de simulación basados en la programación matemática positiva, los cuales permiten simular el comportamiento productivo de los regantes frente a la hipotética implementación de tales instrumentos. Los resultados obtenidos ponen de manifiesto que esta externalidad negativa va a reducirse de forma significativa gracias a la última reforma de la PAC (desacoplamiento parcial de las ayudas). Si esta reducción no se considerase suficiente, otros instrumentos específicos permitirían una reducción adicional de esta fuente de contaminación. En este sentido el instrumento que puede resultar más adecuado es el establecimiento de límites máximos a la fertilización nitrogenada.

Palabras clave adicionales: instrumentos económicos, política agraria, política ambiental, programación matemática positiva.

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Abbreviations used: AL (agricultural labour), CAP (common agricultural policy), CMO (Common Market Organization), EEA (European Environment Agency), EU (European Union), IA (irrigated area), LP (linear programming), MIMAM (Spanish Ministry of the Environment), NBAL (nitrogen balance), OECD (Organisation for Economic Co-operation and Development), PMP (positive mathematical programming), PUBR (public-sector revenue), SFP (single farm payment), TGM (total gross margin), WATER (water use), WFD (Water Framework Directive).

Introduction

Average fertilizer consumption in the EU-15 is 174.1 kg ha year^{-1}. This high application rate of fertilizers, combined with its often inappropriate use, generates a surplus of nitrogen in the soil of 83 kg N ha year^{-1} (OECD, 2008). This causes water pollution by nitrates, one of the most serious environmental problems in developed countries (OECD, 2005). In Spain the general situation is not so worrying, because fertilizer consumption (121.5 kg ha year^{-1} average) and the nitrogen balance (33 kg N ha year^{-1} average) are considerably lower than those of the EU-15 (MIMAM, 2006; OECD, 2008). Nonetheless, these national average data hide the problem linked to irrigated agriculture, an agricultural subsector which makes intensive use of these fertilizers and is the main source of diffuse contamination of water resources in Spain (MIMAM, 2000). Indeed, a separate analysis of this type of agriculture confirms that both nitrogen consumption and nitrogen balance are very high, even exceeding the European average (Gómez-Limón *et al*., 2007; MIMAM, 2007). The environmental impact of such situation is evident, given that in Spain most of the declared nitrate-vulnerable zones are located in irrigated areas and their surroundings (MIMAM, 2006).

Given this problematic scenario, the national authorities face the challenge of designing and implementing the necessary instruments to minimize the impact of agriculture as the main source of diffuse pollution of water resources (Martínez and Albiac, 2004). During the past two decades, therefore, various policies at EU level have been implemented to deal with this situation, as pointed out by the EEA (2005). It is worth highlighting some of these policies, namely: a) the Nitrate Directive, which has the principal objective of reducing nitrate pollution of water resources caused by agriculture, b) the new Common Agricultural Policy (CAP) in which, since its 1999 reform (Agenda 2000) subsidies to farmers are conditional on the fulfilment of a set of environmental requirements, and c) the Water Framework Directive (WFD), which seeks to implement new hydrological plans leading to a 'good ecological status of waterbodies'.

The theoretical study of nitrate pollution control policies began in the eighties with the seminal works of Griffin and Bromely (1982), Shortle and Dunn (1986) and Segerson (1988). Since then, the scientific community has performed intensive studies of this problem. Among recent works in this field, those of Martínez and Albiac (2006), Segerson and Wu (2006), Aftab *et al*. (2007), Semaan *et al*. (2007) and Suter *et al.* (2008) are worth mentioning. In brief, this literature points out that policies designed to reduce nitrate pollution of agricultural origin can be implemented in various ways, in particular through the use of taxes and/or subsidies, the setting of emission quotas and the application of certain market instruments. For a detailed discussion of this issue, see Shortle and Abler (2001).

Within this general framework, the main objective of this study is to analyse the economic, social and environmental impacts of the implementation of different policy instruments aimed at reducing nitrate pollution (nitrogen fertilization quotas, eco-tax for nitrogen fertilizers, irrigation water pricing and the limitation of the surface for intensive nitrogen activities) within the context of the new CAP, which was established after the Mid-Term Review. The comparative analysis was carried out by means of a case study of the irrigated area (IA) of Arévalo-Madrigal in the province of Ávila in central Spain, an agricultural system potentially vulnerable to nitrate pollution. For this purpose, a methodology based on the positive mathematical programming has been developed, in order to simulate farmers' behaviour when facing the new CAP scenario and the various policy instruments considered. The study aims to provide informative support for decision makers when designing and implementing the programme of measures for inclusion in the new hydrological plan for the Duero river basin, which must be approved before 2010, as required by the WFD.

The next section of this paper shows a description of the agricultural system studied. The third section provides a detailed presentation of the methodology adopted for the empirical application and the origin of the information used to feed the models built, while the fourth describes the specific formulation of the simulation models used for each of the policy instruments being considered. The fifth section synthesizes the results of these simulations, while the sixth outlines the most relevant conclusions reached.

Case study

The IA of Arévalo-Madrigal covers 13,662 ha in the southern part of the Duero river basin in the Province of Ávila. This agricultural system is located in the Spanish

North Plateau, at an average altitude of 900 m and with a typical continental climate; long, cold and relatively wet winters followed by short hot and dry summers. The annual rainfall is low, averaging less than 450 mm. Irrigated agriculture is the only alternative to the typical rain-fed cereals monoculture in this area, allowing summer crops to be grown.

The IA comprises 1,133 farms, for an average irrigated farm size of 12.1 ha. The predominant crops in the zone are cereals (maize –*Zea mays* L.–, barley –*Hordeum vulgare* L.– and wheat –*Triticum aestivum* L.) covering 69.3% of the total surface area. Industrial crops (sugar-beet –*Beta vulgaris* L.– and sunflower –*Helianthus annuus* L.) are also important, occupying 22.4% of the IA. Other relevant crops are potatoes (*Solanum tuberosum* L.) and alfalfa (*Medicago sativa* L.), covering 2.4% and 1.2% of the IA, respectively. The remaining cultures, such as legumes and vegetables, are of minor importance. The water used by irrigated agriculture is supplied by an important groundwater body, Hydrogeological Unit 02.17, also known as '*Los Arenales*' aquifer. Because of the origin of the groundwater source, pumping is required to obtain water. The existence of these pumping systems explains why the predominant system for irrigation in this zone is based on sprinkler technology, which is used to irrigate all crops in the area.

The increasingly intensive use of groundwater for farming in this area is jeopardizing the sustainability of this water resource, in both quantitative and qualitative terms, as extraction has surpassed natural inflow, resulting in over-exploitation of the aquifer. This situation has led to the suspension of new permits for water extraction since 1998. The agricultural system utilises a network of 14 stations for quality control managed by the public authority in charge of water use (*Confederación Hidrográfica del Duero*), which regularly report data on groundwater nitrate concentration (see *www.chd.es*). The data reveal that the average values of nitrogen concentration in the groundwater below the study area during 2003-2007 have ranged between 10 and 30 mg NO_3^- L^{-1}, although during summer periods these concentrations have reached maximum values ranging between 55 and 65 mg NO_3^- L^{-1}. It should also be pointed out that this Hydrogeological Unit mentions problems of arsenic pollution, also of agricultural origin. Both types of pollution have led to the suspension of the water supply for human consumption in 26 municipalities located inside or near this IA (Fernández *et al.*, 1998).

Methodology

Policy scenarios and instruments analysed

CAP scenarios

Two CAP scenarios have been considered. The first represents the previous policy situation, derived from the application of Agenda 2000 ("*CAP-2000*" scenario), which is considered as the baseline scenario in order to compare the other results. The second scenario analysed refers to the CAP reform introduced by the European Council in 2003 and which came into force in Spain in 2006. This reform introduced the partial decoupling of direct subsidies to herbaceous crops as its main novel aspect. This scenario also contemplates the implementation of the new reform of the Common Market Organization (CMO) of sugar in 2009. This scenario is labelled "*CAP-reformed*". The characteristics of the two scenarios are as follows:

- "*CAP-2000*" *scenario*. This scenario represents the CAP framework in effect until 2005/2006, whereby public support to the agricultural sector was effectuated via direct payments per unit area of €63.00 Mg^{-1} of theoretical county yields for cereals and oilseeds. In the case of protein crops, payments increased to a limit of €72.50 Mg^{-1}.
- "*CAP-reformed*" *scenario*. This scenario is characterized by the partial decoupling of the payments received in the previous scenario. Therefore, the producers of herbaceous crops receive a direct coupled payment (linked to crop area) equal to 25% of the support received previously (€15.75 Mg^{-1} for cereals, oilseed and protein crops). The remaining 75% of the support became part of the Single Farm Payment (SFP) that would be received annually by farmers regardless of their crop mix (for further details, see García Álvarez-Coque, 2006). Moreover, this new scenario includes the restructuring of the sugar sector promoted by the new sugar CMO. In this new scenario, the sugar sector is thus characterized by: a) a decrease in the sugar-beet selling price from €48.00 Mg^{-1} (*CAP-2000* scenario) to €40.00 Mg^{-1}, b) the integration of sugar-beet into the SFP, which now also includes annually €11.00 Mg^{-1} delivered during the biennium 2004-2005, and c) the compulsory abandonment of 50% of production, with farmers being compensated with €40.00 Mg^{-1} delivered as average during the period 2004-2008.

Policy instruments for nitrate pollution control

Taking into account the various policy instruments that would theoretically be suitable for diffuse nitrate pollution control (Martínez and Albiac, 2004, 2006; Semaan *et al*., 2007) and the particular characteristics of the IA analysed (private irrigation initiatives and groundwater resources), for this study the following four alternative policy instruments have been selected as the most interesting ones for their potential implementation:

- *Instrument 1* proposes restrictions on the consumption of nitrogen fertilizers (nitrogen fertilization quotas). For the implementation of this policy instrument five different maximum levels of nitrogen fertilization are proposed: 120, 100, 80, 60 and 40 kg N ha^{-1}. These figures were chosen considering that current average nitrogen fertilization in the IA is 136.0 kg N ha^{-1}. Thus, the first level (120 kg N ha^{-1}) would be fixed in order to assure that most farmers will be under this average. Lower quotas would force further decreases in nitrogen use by farmers.
- *Instrument 2* suggests the implementation of an "ecological" tax on the use of nitrogen fertilizers, targeted to reduce nitrogen demand for agricultural production. Five different levels of application of this eco-tax have been considered, ranging from €0.20 to €1.00 per kilogram of nitrogen applied in fertilization. These values were chosen considering current application of this instrument in the different European countries where it is implemented (Sweden, Austria and Finland; see Nam *et al*., 2007).
- *Instrument 3* considers the introduction of volumetric water pricing. Water and nitrogen are one of the most important inputs in irrigated systems, being both characterized by limited substitution (their use can be adjusted by a von Liebig production function, as explained in Paris and Knapp. 1989, Paris, 1992 and Knapp and Schwabe, 2008). This is why water pricing (reducing water demand) is at the same time an instrument to reduced nitrogen use. Following this rationale, six price levels were selected for the simulation of this policy instruments, ranging between €0.01 and €0.06 m^{-3}, in a hypothetical attempt to implement the cost recovery principle as set out by the WFD in the Duero basin (Gómez-Limón and Riesgo, 2004; Riesgo and Gómez-Limón, 2006).
- *Instrument 4* proposes limiting the cultivated area of the most nitrogen-intensive crops, which are the potentially most polluting ones. In this case study, this restriction would affect sugar-beet, maize and potato, which nitrogen requirements are above 200 kg N ha^{-1}. Thus, five different simulation scenarios are proposed, which limit the maximum area of this set of crops to 25, 20, 15, 10 and 5% of the total available.

Decision-making heterogeneity and cluster analysis

Modelling farming activity at agricultural system level (or at any other level that deals with a set of individual farms) implies problems of aggregation bias. Indeed, modelling a set of farms in a unique programming model overestimates the mobility of resources, allowing the modelled farms to combine resources in proportions that are not possible in the real world (Hazell and Norton, 1986). This aggregation bias can only be avoided if the farms included in the models fulfil strict homogeneity criteria (Day, 1963): technological homogeneity, pecuniary proportionality and institutional proportionality.

The IA under consideration as a case study is located in a single agricultural county and uses a single source of water. Hence, bearing in mind soil-quality homogeneity, and technological, institutional and market characteristics, it could be considered that the case study area is an analytical unit that fulfils the above-mentioned homogeneity criteria. Thus, it might seem reasonable to assume similar behaviour for all farmers in the study area, which would mean that the operation of the policy instruments being considered could be analysed through a single simulation model with relatively small problems of aggregation bias. However, this assumption must be rejected, since experience demonstrates that the behaviour of individual farmers can differ widely due to the heterogeneity of crop cost and/or the disparity in their objectives. This explains why farmers operating in the same agricultural system, with similar resources availability, invest in a wide range of crop plans (Gómez-Limón *et al*., 2004). For this reason, in order to avoid the aggregation bias in simulation, it is needed the classification of farmers into homogeneous groups with regard to their crop mixes. For this purpose, the most appropriate statistical technique is cluster analysis, which utilises farmers' actual crop mixes as classification criteria (Berbel and Rodríguez, 1998).

In order to develop a typology of producers, a survey was carried out among producers, with the aim of gathering information on crop mixes that would allow the farmers' production to be characterised. This information enabled to apply cluster analysis, taking Euclidean squared distance as a measure among actual crop mixes (vector crop area expressed in percentages). The Ward or minimum variance method was utilised as the aggregation criterion.

The simulation technique: positive mathematical programming

Positive mathematical programming (PMP) is a modelling technique developed by Howitt (1995) which allows calibrating Linear Programming (LP) models using the information contained in dual values. PMP has been widely accepted by economists as a means of analysing policy scenarios and instruments affecting farming activities. A large number of Spanish studies that use PMP include those of Calatrava and Garrido (2001), Júdez *et al*. (2001), Arriaza and Gómez-Limón (2003), Atance and Barreiro (2006), Oñate *et al*. (2007) and Iglesias and Blanco (2008).

The PMP assumes that the productive activity observed in a given farm or set of farms is a consequence of the farmer's profit maximization behaviour. Thus, the differences observed among farmers are due to the different production costs faced by each one of them. On the basis of this assumption, this mathematical programming technique attempts to estimate the costs of different crops, which permits the same crop mix distribution as the one observed in the real world to be obtained through a mathematical programming model.

The PMP calibration described by Howitt (1995), also known as the "standard PMP approach", is based on three steps. The first step consists of building a LP model in order to obtain the dual values variables for each of the activities (crops) considered. The following step uses the dual values variables to calibrate the cost function of the individual crops. Finally, the cost function parameters are used to define a new objective function for the PMP model. Thus, the LP model developed in the first step is transformed into a non-linear programming model that will reproduce the base year crop distribution, and can be used to simulate future or hypothetic scenarios which would lead into new productive behaviour.

However, this primitive focus has been strongly criticized, and some important shortcomings of this technique have been identified (Heckelei and Britz, 2005; Henry de Frahan *et al*., 2007). This led to further development of the PMP with the aim of mitigating the drawbacks of the original method. In this respect, the works of Paris and Howitt (1998), Heckelei and Britz (2000), Júdez *et al*. (2001), Paris (2001), Paris and Howitt (2001), Preckel *et al*. (2002), Britz *et al*. (2003), Heckelei and Wolff (2003) and Röhm and Dabbert (2003) are of particular relevance.

Within the context of PMP development, Röhm and Dabbert (2003) present an extension which permits a higher degree of substitution between similar crops (called 'variant activities'), rather than between other less close crops (activities). These variant activities are taken into account in order to obtain more realistic results. Thus, the concept of variant activities can be applied to the same crop that is grown under different techniques, as well as to crops from the same family which are equally well adapted to local conditions and are equally susceptible to the same pests (Röhm and Dabbert, 2003).

The mathematical formulation of this extension of the PMP can be summarized as follows. Bearing in mind the different activities (i) and the possible variants (j), the initial model takes the following formulation:

$$Max\ TGM = \sum_i \sum_j \left(p_{i,j} \cdot y_{i,j} - c_{i,j} + s_{i,j}\right) x_{i,j} \qquad [1a]$$

Subject to:

$$\sum_i \sum_j \left(x_{i,j}\right) \le \sum_i \sum_j \left(x^0_{i,j}\right) \qquad [1b]$$

$$\sum_j \left(x_{i,j}\right) \le \sum_j \left(x^0_{i,j}\right)\left(1+\varepsilon_1\right) \quad \forall i \qquad [1c]$$

$$x_{i,j} \le x^0_{i,j}\left(1+\varepsilon_2\right) \quad \forall i,j \qquad [1d]$$

$$x_{i,j} \ge 0 \qquad [1e]$$

$$\varepsilon_2 > \varepsilon_1 \qquad [1f]$$

Eq. [1a] represents the LP model objective function, where *TGM* is the total gross margin (assuming profit maximization). The *TGM* is calculated as the sum of the gross margins resulting from each activity. For this reason, the objective function is logically a function of the area allocated to each crop, $x_{i,j}$ (hectares devoted to crop *i*, with variant *j*). These $x_{i,j}$ are considered to be the decision variables of the model. In order to calculate the *TGM* it is also necessary to have the following technical coefficient data: price ($p_{i,j}$), yield ($y_{i,j}$), variable cost ($c_{i,j}$) and CAP direct subsidies, coupled to the production per unit area ($s_{i,j}$) for each crop that can be regarded as alternatives.

The above-mentioned model presents a set of constraints, which can be interpreted as follows. Eq. [1b] limits the total agricultural land available, where $x^0_{i,j}$ represents the crop mix observed in the base year. Eq. [1c] represents the constraints for total activities, ε_1 being a small positive number. Finally, Eq. [1d] represents the constraints for the variant activity, with ε_2 another small positive number that must satisfy Eq. [1f].

The addition of Eqs. [1c] and [1d] forces an optimal solution in the LP model which reproduces the activities observed in the base year ($x^0_{i,j}$). As a result of the introduction of the final two constraints, the model solution generates the dual values for the different activities. Eq. [1c] produces the dual values of activities λ_i and Eq. [1d] indicates the dual values of the variant activity $\lambda_{i,j}$. Nonetheless, as in the primal the number of constraints exceeds the number of variables, some of the variables have dual values equal to zero. This circumstance is observed in the dual value of the least profitable activity (λ_i) and in the dual value of the least profitable variant activity ($\lambda_{i,j}$). Nevertheless, this situation can be solved by calibrating the least profitable crops, at the same time changing the dual values obtained previously (see Röhm and Dabbert, 2003).

Once the transformed dual values have been obtained, Eq. [2] represents the general objective function for a PMP model, taking into account the variant activities:

$$Max\ TGM = \sum_i \left\{ \sum_j \left[GM_{i,j} x_{i,j} + \lambda_i x_{i,j} \left(1 - \frac{x_{i,j}}{x^0_{i,j}} \right) \right] + \lambda_i \sum_j x_{i,j} \left(1 - \frac{\sum_j x_{i,j}}{\sum_j x^0_{i,j}} \right) \right\} \quad [2]$$

From this equation, after a series of transformations, Eq. [3] emerges, being the extended version of the PMP:

$$Max\ TGM = \sum_i \sum_j \left\{ x_{i,j} \left[y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x^0_{i,j}} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \vec{x}^0_{i,j}} \vec{x}_i \right) + s_{i,j} - c_{i,j} \right] \right\} \quad [3]$$

This extended version of PMP has been also criticized, particularly because of the implicit subjectivity in the definition of the groups of variant activities, considering that this grouping might influence the response of the models (Blanco *et al*., 2008). However, the extended version of the PMP method has been widely adopted by the scientific community, and is the technique chosen for several recent studies: Key and Kaplan (2007), Schmid *et al*. (2007), Wirsig *et al*. (2007) and Henseler *et al*. (2008).

Economic, social and environmental attributes

Irrigated agriculture is closely linked to economic, social and environmental issues (Gómez-Limón *et al*., 2007). Bearing this in mind, as well as the main objective of this work, a set of indicators that enable the effects of the individual proposed policy instruments to be quantified has been chosen:

- *Economic impact*. This impact will be measured by the total gross margin obtained by farming activity (*TGM*). This indicator is the difference between income (sales and subsidies, both coupled and decoupled included in the SFP) and total variable costs. The gross margin can be regarded as a valid estimator of the private profitability in the agricultural activity, which is measured in € ha^{-1}.
- *Social impact*. Agricultural labour (*AL*) demand can be considered as a social indicator that enables the contribution of the agricultural sector to rural development and territory balance (population settlement, income distribution, etc.) to be quantified. The measurement unit of this indicator is work-days ha^{-1}.
- *Environmental impact*. This impact is measured via two indicators. The nitrogen balance (*NBAL*), used as an indicator is calculated by the difference between nitrogen inputs and outputs. The difference represents the amount of nitrogen leached into the surrounding environment, which in turn is an indicator of the environmental impact of irrigated agriculture on water quality. This indicator is expressed in kg N ha^{-1}. The second indicator is the water use (*WATER*), quantified in terms of volume of water per irrigated hectare. This indicator allows the quantitative pressure to be measured in m^3 ha^{-1}, that exerted by agriculture on the aquifer.

All the above-mentioned indicators have been calculated by using technical coefficients per unit area (ha) for each crop *i* and variant *j* (for further details, see

OECD, 2001; and Bazzani *et al*., 2004). The final value obtained for each simulated policy scenario and economic instrument has been derived from farmers' optimal crop plans ($x_{i,j}$) based on the models built for each case.

Data sources for feeding the models

The data needed to feed the simulation models were gathered from primary and secondary sources. Secondary data were extracted from the *Anuarios Agroalimentarios de Castilla y León* (CAG, various years). In particular, data regarding prices and yield productions were collected from this official source. Primary data were obtained from two surveys. The first focused on agricultural technicians working in the IA (agricultural extensionists, farmers' organization advisors, university teachers and researchers), and was aimed at collecting information about production techniques and input prices. A total of seven experts were consulted. The second survey focused on irrigators working in the IA, and this collected information about crop mix, structural variables of farms and socio-demographic characteristics of the farmers. A total of 62 farmers were interviewed.

Modelling

Typology of farms

As a result of the cluster analysis (see Section "Decision-making heterogeneity and cluster analysis"), three different homogeneous groups were defined, as can be observed in Table 1. The main features of the different farm types identified are summarized as follows:

- *Cluster 1*. This first group includes 31% of the farmers interviewed, representing 68% of the area of the IA. This group is characterized by middle-aged farmers (around 50 yr old) who manage large irrigated farms (an average of 115 ha per holding). The main crops of this farm type are winter cereals (wheat and barley), covering about 70% of the irrigated area. This group has been labelled as "*large cereal growers*".
- *Cluster 2*. The second group of farmers comprises about half of the farmers sampled, representing around 30% of the total irrigated area. This group consists of older farmers, with an average age of 54 yr, who manage medium-sized irrigated farms (an average of 31 ha). The characteristic crop mix mainly includes of winter cereals and sugar-beet, representing 65% and 21% respectively of the irrigated area. This group has been labelled as "*cereals and sugar-beet growers*".
- *Cluster 3*. This third homogeneous group comprised 19% of the farmers, and they worked only 2% of the IA. This group profile is characterized by irrigators with an average age of 50 years, who manage small farms (average of 6 ha). The main crop in this farm-type is sugar-beet, covering 93% of the total irrigated area. This group has been labelled as "*small sugar-beet growers*".

The proposed modelling approach was then individually implemented for each cluster. In order to obtain results at the IA level, the individual results were aggregated by weighting the sum of the land represented by each farm type, in order to minimize aggregation bias regarding the whole IA results (see Section "Decision-making heterogeneity and cluster analysis").

Modelling baseline scenario (*CAP-2000*)

In order to build the simulation models for each farm type it was necessary to take into account the area given over to each crop in the area, as decision variables ($x_{i,j}$). Before enumerating the decision variables selected, and taking into account the PMP extension followed, the group of irrigated winter cereals was defined in terms of two different variant activities[1]: irrigated wheat and irrigated barley. The activities chosen for modelling were thus defined as follows: irrigated winter cereals (x_1), with the two variants of irrigated wheat ($x_{1,1}$), and irrigated barley ($x_{1,2}$), rain-fed wheat (x_2), rain-fed barley (x_3), maize (x_4), irrigated sunflower (x_5), rain-fed sunflower (x_6), sugar-beet (x_7), potato (x_8), irrigated alfalfa (x_9), rain-fed alfalfa (x_{10}) and set-aside (x_{11}). It is worth noting the usefulness of the inclusion of rain-fed crops as alternatives, with the purpose of increasing the flexibility of the model, allowing farmers the option of ceasing irrigation and

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[1] For the case study presented in this work, the rain-fed crops have not been adopted as variant activities, because the crop mix observed in the base year did not present these activities.

Table 1. Main features of the different farm types in the irrigated area (IA)

Code	Label	Percentage over total farmers in IA	Percentage over total surface of IA	Average size per holding (ha)	Main crops
G1	*Large cereal growers*	31.2%	68.4%	115	Winter cereals, maize, and sugar-beet
G2	*Cereals and sugar-beet growers*	50.0%	29.5%	31	Winter cereals and sugar-beet
G3	*Small sugar-beet growers*	18.8%	2.1%	6	Sugar-beet

introducing these crops as in rain-fed areas, as happens in the real world.

The objective function for the *CAP-2000* scenario is adjusted to the principle of profit maximization, as presented in Eq. [3]. This objective function, however, was subjected to the following constraints[2]:

Surface constraint:

$$\sum_i \sum_j x_{i,j} \le SUR \qquad [4a]$$

Alfalfa rotation constraint:

$$x_9 + x_{10} \le 55\% \cdot SUR \qquad [4b]$$

Sugar-beet CAP constraint:

$$x_7 \le \frac{\textit{sugar-beet quota}}{\textit{sugar-beet yield}} \qquad [4c]$$

Potato market constraint:

$$x_8 \le \textit{ historic maximum value} \qquad [4d]$$

Alfalfa market constraint:

$$x_9 + x_{10} \le \textit{historic maximum value} \qquad [4e]$$

This is the model from which the calibration parameters λ_i and $\lambda_{i,j}$ were estimated, allowing for the simulation of the *CAP-reformed* scenario and the different policy instruments for nitrate pollution control (see Section "The simulation technique: positive mathematical programming").

Modelling CAP-reformed scenario model

From the calibration made through the extended PMP version utilised, it is possible to build a model in which the *CAP-reformed* scenario is shaped. Eq. [5a] describes the objective function in which the new SFP scheme is included, as a consequence of the reformed CAP, calculated on the basis of subsidies historically received by the producers, and the compensation for the compulsory abandonment of sugar-beet (*SUBAB*). This additional payment of €40.00 per non-produced tonne of sugar-beet is received only once. Therefore, this amount is annualized at an interest rate of 5%, i.e. €0.80 Mg year^{-1}. Thus, *SUBAB* equals 0.80 x 50% x sugar-beet quota.

$$\begin{aligned} Max\ TGM = \sum_i \sum_j \Bigg\{ x_{i,j} \Bigg[y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x_{i,j}^0} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \vec{x}_{i,j}^0} \vec{x}_i \right) + \\ + s_{i,j} - c_{i,j} \Bigg] \Bigg\} + SFP + SUBAB \end{aligned} \qquad [5a]$$

Subject to:

Base model constraints:

$$A\vec{X} \le \vec{B} \qquad [5b]$$

Sugar-beet abandonment constraint:

$$x_7 \le 50\% \frac{\textit{sugar-beet quota}}{\textit{sugar-beet yield}} \qquad [5c]$$

In addition, as reflected in constraint [5c], it must be noted that the model for this new CAP scenario includes the compulsory abandonment of 50% of sugar-beet production by all farmers.

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[2] The set of contraints [4a], [4b], [4d] y [4e], will be represented hereaflter as $A\vec{X} \le \vec{B}$.

Modelling selected instruments for pollution control

Model for instrument 1: nitrogen fertilization quotas

This model simulates the implementation of a compulsory limit for the application of nitrogen fertilizers. The objective function for this scenario thus corresponds to Eq. [5a]. However, in order to simulate this hypothetical instrument, the model is subject to the following constraints:

Base model constraints:

$$A\vec{X} \leq \vec{B} \qquad [6a]$$

Sugar-beet abandonment constraint:

$$x_7 \leq 50\% \frac{\textit{sugar-beet quota}}{\textit{sugar-beet yield}} \qquad [6b]$$

Maximum nitrogen application constraint:

$$\sum_i \sum_j \left(x_{i,j}\right) \cdot NA_{i,j} \leq NALF_k \times SUR \qquad [6c]$$

where NA_{ij} refers to the nitrogen application for each crop, and $NALF_k$ is the nitrogen application limit for each of the suggested levels (k = 120, 100, 80, 60 and 40 kg N ha^{-1}).

Model for instrument 2: eco-tax for nitrogen fertilizers

For the implementation of an "ecological" tax on the use of nitrogen fertilizers, the suggested simulation model is represented as follows:

$$Max\ TGM = \sum_i \sum_j \left\{ x_{i,j} \left[\begin{array}{l} y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x^0_{i,j}} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \vec{x}^0_{i,j}} \vec{x}_i \right) + \\ + s_{i,j} - c_{i,j} - \left(t_N \cdot NA_{i,j}\right) \cdot x_{i,j} \end{array} \right] \right\} + \qquad [7a]$$

$$+ SFP + SUBAB$$

Subject to:

Base model constraints:

$$A\vec{X} \leq \vec{B} \qquad [7b]$$

Sugar-beet abandonment constraint:

$$x_7 \leq 50\% \frac{\textit{sugar-beet quota}}{\textit{sugar-beet yield}} \qquad [7c]$$

where t_N is the eco-tax for the nitrogen fertilizer application, whose values range from 0.20 up to €1.00 kgN^{-1}.

Model for instrument 3: irrigation water pricing

In order to simulate farmers' behaviour when facing irrigation water pricing, Eq. [8a] defines the objective function used for the simulation:

$$Max\ TGM = \sum_i \sum_j \left\{ x_{i,j} \left[\begin{array}{l} y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x^0_{i,j}} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \vec{x}^0_{i,j}} \vec{x}_i \right) + \\ + s_{i,j} - c_{i,j} - \left(t_w \cdot WR_{i,j}\right) \cdot x_{i,j} \end{array} \right] \right\} + \qquad [8a]$$

$$+ SFP + SUBAB$$

Subject to:

Base model constraints:

$$A\vec{X} \leq \vec{B} \qquad [8b]$$

Sugar-beet abandonment constraint:

$$x_7 \leq 50\% \frac{\textit{sugar-beet quota}}{\textit{sugar-beet yield}} \qquad [8c]$$

where t_w is the value of volumetric water pricing and $WR_{i,j}$ are the water requirements for crops *i,j*. In this case, t_w ranges between 0.01 and €0.06 m^{-3}.

Model for instrument 4: limitation of the surface for intensive nitrogen activities

This model simulates the application of a limitation on the cultivated area of the most nitrogen-intensive activities. The objective function for this scenario thus also corresponds to Eq. [5a]. Nevertheless, in order to simulate this instrument the model is subject to:

Base model constraints:

$$A\vec{X} \leq \vec{B} \qquad [9a]$$

Sugar-beet abandonment constraint:

$$x_7 \leq 50\% \frac{\textit{sugar-beet quota}}{\textit{sugar-beet yield}} \qquad [9b]$$

Surface limit constraint:

$$x_4 + x_7 + x_8 \leq MSL_k \times SUR \qquad [9c]$$

where MSL_k refers to the maximum area allocated to nitrogen-intensive crops, expressed in percentage terms (k = 25, 20, 15, 10 and 5%).

Results

The resolution of the models described above enabled, first, to obtain results for each of the three analyzed farm types. Subsequently, through the weighted aggregation of partial results, the results for the whole IA have been calculated. However, in order to synthesize the presentation of results, this section focuses on the analysis of the aggregated results at the IA level only, since these are the most relevant to the support of public-sector decision making. In any case, individual results for each farm type can be consulted in Appendix.

CAP-reformed policy scenario

With regard to the results of the new policy scenario (*CAP-reformed*), the first point to be highlighted is that the latest CAP reform will in itself have an important impact on groundwater quality. It is thus expected that this reform will produce a decrease of the *NBAL* indicator of about 28.0% (from 38.95 to 27.98 kg N ha^{-1}), due to two main causes: a) the decoupling of farm subsidies, which promotes the spread of agricultural production (introduction of less nitrogen-intensive activities in the crop plans) and b) the new sugar CMO reform, which has forced a considerable reduction in the area devoted to sugar-beet, one of the most nitrogen-intensive crops in this IA.

The *TGM* indicator also increased after the application of the recent CAP reform by about 4.8% compared with the baseline scenario. Although the new crop plans are more extensive and have lower added value, the introduction of SFP maintains profitability, and even increases it slightly from its level in the *CAP-2000* scenario. On the other hand, the *AL* indicator decreases substantially (-22.9%). This loss in employment is also a result of the replacement of more labour-intensive crops, e.g. sugar-beet, by other less intensive crops (rain-fed crops). Finally, regarding the impact on irrigation water consumption (*WATER* indicator), the CAP has also a positive effect on the demand for water, generating significant savings in water consumption, more specifically 37.4% of the consumption in the *CAP-2000* scenario.

Policy instrument 1: Nitrogen fertilization quotas

The results obtained for this policy instrument under the new CAP framework (*CAP-reformed* + Instrument 1) can be seen in Table 2, which shows that less restrictive limitations on nitrogen fertilization, as represented by the first two levels considered (120 and 100 kg N ha^{-1}), would generate an imperceptible decrease in nitrogen balance. In fact, the *NBAL* indicator would advance from -28.0% simply due to the application of the new CAP, to -28.4% and -31.2%, respectively. Nonetheless, this indicator is much more sensitive to more restricted fertilization quotas, producing noticeable decreases in the nitrogen balance for the remaining levels considered. This drop is above 50% for quotas of 60 and 40 kg N ha^{-1}.

Putting this policy instrument into operation would also bring about a decrease in the *TGM*. As already com-

Table 2. Evolution of indicators selected for the irrigated area. Nitrogen fertilization quotas

Policy Scenario/Instrument	Indicators[1]			
	NBAL (kg N ha^{-1})	**TGM (€ ha^{-1})**	**AL (days ha^{-1})**	**WATER (m^3 ha^{-1})**
CAP-2000 (baseline scenario)	38.95	457.47	1.97	3,557
CAP-reformed	-28.0%	+4.8%	-22.9%	-37.4%
CAP-reformed + Instrument 1				
– 120 kg N ha^{-1}	-28.4%	+4.8%	-23.4%	-37.9%
– 100 kg N ha^{-1}	-31.2%	+4.6%	-25.9%	-41.1%
– 80 kg N ha^{-1}	-42.4%	+2.9%	-34.5%	-44.6%
– 60 kg N ha^{-1}	-52.7%	+0.5%	-45.3%	-54.7%
– 40 kg N ha^{-1}	-69.4%	-3.9%	-56.9%	-67.4%

[1] NBAL: nitrogen balance, TGM: total gross margin, AL: agricultural labour, WATER: water use.

mented on for the previous indicator, the first two fertilization levels do not affect the *TGM*. This impact is only significant for quotas below 100 kg N ha^{-1}. Nonetheless, the resulting decrease is moderated, and in the worst-case scenario, the application of restriction level 40 kg N ha^{-1}, it changes from +4.8% (*CAP-reformed* scenario) to -3.9%. Similarly, the implementation of the first two levels of restriction of nitrogen fertilization considered would have little impact on the *EMP* indicator. Nevertheless, the social impact of this instrument is considerable for the most restrictive levels, leading to reductions in employment of more than 50% for the 40 kg N ha^{-1} quota. Finally, with regard to the *WATER* indicator, this instrument produces a positive impact, in the sense that it leads to an additional reduction in demand for irrigation water. Because of high nitrogen use crops are also high water use, in the case of the implementation of quotas, a drop in the use of nitrogen causes a decrease in water consumption at the same time. In any case, in order to be able to observe significant additional decreases in water use, the limitation in nitrogen fertilization would need to be below 100 kg N ha^{-1}, as already pointed out for the previous indicators. In this case, the maximum reduction in the *WATER* indicator can reach -67.4% for a quota of 40 kg N ha^{-1}.

Policy instrument 2: Eco-tax for nitrogen fertilizers

The results of simulation models for this second policy instrument (*CAP-reformed* + Instrument 2) can be seen in Table 3. The implementation of an economic charge of €0.20 kg N^{-1} for nitrogen fertilizers would produce, by itself, an almost insignificant decrease in the liberation of nitrogen into the ecosystem. In fact, the *NBAL* indicator would merely decrease from -28.0% (*CAP-reformed* scenario) to -31.1%. However, higher values of this eco-tax would produce larger falls in the nitrogen balance e.g. an eco-tax higher than €0.40 kg N^{-1} would lead to a more than 50% decline in the *NBAL* indicator, reaching -64.4% for a charge of €1.00 kg N^{-1}.

This instrument would also have a negative effect on farm profitability. Thus, the implementation of an eco-tax of €0.20 kg N^{-1} would practically eliminate the increase in the *TGM* indicator caused by the CAP reform. The application of higher charges would generate negative variations of the *TGM* compared with the baseline scenario (*CAP-2000*), ranging from -3.7% (€0.40 kg N^{-1}) to -12.1% (€1.00 kg N^{-1}). It should be noted that this decrease in profitability would be produced both by the irrigators' payments of taxes (incomes transferred from private to public sector), as well as the changes in crop plans discussed above (less income from the market due to the substitution of the most value-added crops). In any case, from a public point of view the economic impact for this instrument needs to be analyzed jointly with its effects on the public-sector revenues (*PUBR* indicator) generated by the eco-tax. It thus worth pointing out that the application of different levels of eco-tax would generate a revenue to the state ranging between €20.23 ha^{-1} (€0.20 kg N^{-1}) and €48.51 ha^{-1} (€1.00 kg N^{-1}). These results show that for a low eco-tax the loss in the irrigators' net income is almost equal to the gain in public revenue. Thus, lower levels of eco-tax hardly result in overall economic lost,

Table 3. Evolution of indicators selected for the irrigated area. Eco-tax for nitrogen fertilizers

Policy Scenario/Instrument	Indicators[1]				
	NBAL (kg N ha^{-1})	**TGM (€ ha^{-1})**	**PUBR[2] (€ ha^{-1})**	**AL (days ha^{-1})**	**WATER (m^3 ha^{-1})**
CAP-2000 (baseline scenario)	38.95	457.47	0.00	1.97	3,557
CAP-reformed	-28.0%	+4.8%	0.00	-22.9%	-37.4%
CAP-reformed + Instrument 2					
– €0.20 kg N^{-1}	-31.1%	+0.3%	20.23	-25.6%	-41.1%
– €0.40 kg N^{-1}	-43.0%	-3.7%	32.48	-34.9%	-45.9%
– €0.60 kg N^{-1}	-51.8%	-7.0%	40.09	-42.1%	-51.2%
– €0.80 kg N^{-1}	-58.2%	-9.8%	45.86	-47.5%	-56.9%
– €1.00 kg N^{-1}	-64.4%	-12.1%	48.51	-52.6%	-62.6%

[1] See Table 2. [2] PUBR: public - sector revenue.

as this instrument only leads to a transfer of income from the private to the public sector. However, higher charges would involve losses in irrigators' profitability that would be greater than the increase in public-sector revenue, thus generating a negative economic impact (overall economic lost).

From a social point of view the application of the first eco-tax level would generate a slight decrease in the *EMP* indicator, because it has practically no impact on the crop plan adopted by irrigators. Nevertheless, an eco-tax above €0.40 kg N^{-1} would have a significant social impact, producing a decrease in the demand for labour generated by the agricultural system, that could be 50% higher than the baseline scenario (€1.00 kg N^{-1} eco-tax). Finally, it should be emphasised that the implementation of this policy instrument would have a positive impact on the *WATER* indicator. In fact, although the implementation of the two first eco-tax levels proposed would lead to a small reduction in demand for irrigation water, the application of an eco-tax of €0.60 kgN^{-1} or more would produce savings in irrigation water of more than 50% relative to the *CAP-2000* scenario.

Policy instrument 3: Irrigation water pricing

The implementation of water pricing in addition to the *CAP-reformed* scenario produces the results shown in Table 4. 'Soft' water tariffs (€0.01 or €0.02 m^{-3}) would result in a small additional decrease in the *NBAL* indicator, in such a way that the nitrogen balance would drop from the -28.0% obtained by implementing the new CAP alone, to -32.9% and -37.7% when the above prices are paid. However, higher water prices would generate much more significant decreases in the *NBAL* indicator. Indeed, 'hard' water tariffs (€0.05 or €0.06 m^{-3}) would reduce the *NBAL* indicator by more than 50% with respect to the baseline scenario.

When the economic impact of the implementation of irrigation water pricing is analysed, it can be observed a negative effect in the *TGM* indicator. Thus, with a water tariff of €0.06 m^{-3}, farmers' profitability would progressively decrease from +4.8% for the *CAP-reformed* scenario to up to -15.2%. As mentioned above for policy instrument 2, the decrease in the *TGM* indicator is due both to the payments made by irrigators to the public administration for water tariffs, and to the changes generated in the production plan. By comparing the loss in the *TGM* indicator with the increase in the *PUBR* indicator, it can be found that for low water tariffs this instrument basically leads to an income transfer from the private to the public sector. For higher tariffs, however, it can be appreciated how overall economic lost appear; i.e. the payments received by the authorities cannot compensate for the losses in private profitability.

On the other hand, as far as the *AL* indicator is concerned, the negative impact of water pricing needs to be emphasised, and it is worth noting that this instrument would generate additional decreases ranging from -28.1% for the lowest tariff (€0.01 m^{-3}) to -48.8% when the water price is €0.06 m^{-3}. However, this policy instrument would have a positive effect on the demand for irrigation water, producing important savings of

Table 4. Evolution of indicators selected for the irrigated area. Irrigation water pricing

Policy Scenario/Instrument	Indicators[1]				
	NBAL (kg N ha^{-1})	TGM (€ ha^{-1})	PUBR (€ ha^{-1})	AL (days ha^{-1})	WATER (m^3 ha^{-1})
CAP-2000 (baseline scenario)	*38.95*	*457.47*	*0.00*	*1.97*	*3,557*
CAP-reformed	-28.0%	+4.8%	0.00	-22.9%	-37.4%
CAP-reformed + Instrument 2					
– €0.01 m^{-3}	-32.9%	+0.3%	19.77	-28.1%	-44.4%
– €0.02 m^{-3}	-37.7%	-3.9%	34.93	-33.0%	-51.0%
– €0.03 m^{-3}	-42.9%	-7.5%	45.17	-38.1%	-57.9%
– €0.04 m^{-3}	-47.9%	-10.5%	50.90	-42.9%	-64.6%
– €0.05 m^{-3}	-52.7%	-13.0%	53.91	-46.8%	-70.2%
– €0.06 m^{-3}	-55.0%	-15.2%	58.73	-48.4%	-73.0%

[1] See Table 3.

water resources. In fact, the *WATER* indicator would display a fall of as much as 73.0% vis-à-vis the baseline scenario at water price of €0.06 m^{-3}.

Policy instrument 4: Limitation of the surface for intensive nitrogen activities

The simulations made for this policy instrument produce the results shown in Table 5. With this combination of the *CAP-reformed* policy and policy instrument 4, the nitrogen leached into the environment (*NBAL*) would hardly be reduced for the first three levels of restriction proposed (15%, 20% and 25%). This can be justified by the spread of production in the IA after the application of the last CAP reform, which has reduced, by itself, the surface allocated to sugar-beet and maize. In this sense, additional reductions in the *NBAL* indicator would require a more restrictive limitation in the surface of the potentially most pollutant crops. Thus, merely restricting the area of the most nitrogen-intensive crops by 10 and 5% would result in reductions in *NBAL* of -38.7% and -48.4%, respectively.

For the reasons mentioned above (sugar-beet and maize surface reduction caused by the last CAP reform), the implementation of the first three proposed levels of limitation of area under crop would not generate significant changes in the remaining indicators. These indicators would only be significantly affected by the introduction of restrictions around 10 or 5%. In the case of *TGM*, with these constraint values, farm profitability would be reduced by up to -0.6 and -9.8% respectively, vis-à-vis the baseline scenario. The increasingly limited application of this instrument would also aggravate its social effects (*AL* indicator). In fact, the decrease in demand for labour would reach 33.7% for the most restrictive case (a maximum of 5% of the area).

To conclude, it could also be pointed out that the implementation of this policy instrument would generate a significant decrease in the *WATER* indicator for restriction levels lower than 15%. Thus, water consumption would be reduced in more than 50% due to the limitations of the area sown for the more intensive nitrogen activities of 10 and 5%. This circumstance can be explained by the positive correlation between nitrogen and water input, as commented above (the most nitrogen-intensive crops are also those ones with the greatest water requirements).

Concluding remarks

The results of this study lead to conclude that the latest CAP reform (partial decoupling of subsidies), which has been in force since 2006, will itself lead to an important reduction in nitrate pollution in the IA studied here. Moreover, this reform will improve the environmental sustainability of agriculture by definitely reducing the demand for irrigation water demand. This will be achieved without either jeopardizing farm profitability or increasing the public cost of support for the agricultural sector. The only negative result of this reform is the reduction in agricultural labour demand, which might be a disincentive in terms of rural development and population policy. At any rate, the overall valuation of this agricultural policy reform is positive.

Table 5. Evolution of indicators selected for the Irrigated Area. Limitation of the surface for intensive nitrogen activities

Policy Scenario/Instrument	**Indicators**[1]			
	NBAL (kg N ha^{-1})	**TGM (€ ha^{-1})**	**AL (days ha^{-1})**	**WATER (m^3 ha^{-1})**
CAP-2000 (baseline scenario)	38.95	457.47	1.97	3,557
CAP-reformed	-28.0%	+4.8%	-22.9%	-37.4%
CAP-reformed + Instrument 4				
– 25%	-28.5%	+4.4%	-23.3%	-38.0%
– 20%	-28.6%	+4.3%	-23.4%	-38.1%
– 15%	-30.6%	+3.9%	-24.4%	-40.4%
– 10%	-38.7%	-0.6%	-28.5%	-50.0%
– 5%	-48.4%	-9.8%	-33.7%	-60.0%

[1] See Table 2.

These results can be extrapolated to other irrigated areas with similar characteristics: major presence of CAP subsidy-dependent crops and irrigation water from groundwater sources (high volumetric pumping cost, which renders decision-making more dependent on the relative profitability of crops). The change in CAP subsidies by itself can thus be regarded as the most impacting instrument for solving the problem of nitrate pollution in sensitive agricultural areas in inland Spain. In fact, although the main objective of the CAP is to maintain agricultural income rather than reducing nitrogen emissions, the way in which these payments are assigned (including cross-compliance implementation) is a key issue to modulate input use (production intensity) and environmental impacts of farming sector. It should also be remembered that potential environmental improvements regarding nitrogen emissions due to this agricultural policy are still not exhausted. In the future this impact could be intensified by the total decoupling of subsidies, as has been proposed for the next CAP reform, known as "Health Check", which is still to be approved.

If the reduction in nitrogen emissions due to the application of the last CAP reform, or any further reforms of this European policy, is not regarded as sufficient to solve the problem of pollution caused by agriculture, other complementary policy instruments, specifically designed for nitrate pollution reduction, could be adopted. The results of the simulations confirm that the set of instruments analysed is effective from an environmental point of view (reduction of nitrogen balance and water demand), although they could have serious negative effects on farmers' incomes and would exacerbate the negative impact on demand for agricultural labour. In any case, among the instruments analysed here, the most suitable one from a technical point of view is the application of nitrogen fertilization quotas. Indeed, for a given reduction in nitrogen balance, this instrument would have the least negative effect on the economic and social sustainability of agriculture in this IA.

Finally, it is worth mentioning that more accurate analysis are needed in order to take also into account monitoring and transaction costs and the existence of imperfect information (Kampas and White, 2004; Ozanne and White, 2007). All of them are key issues when these policy instruments are to be implemented in real agricultural systems. Considering these additional costs, for both irrigators and the public authorities, new simulations might well modify the evaluation reached in this paper. For example, tax on fertilizers could be more preferred than a quota because it is more easily applied (lower monitoring and transaction costs). In addition, other alternative instruments designed to control nitrate pollution would be worth to be compared. In this sense, a particular agro-environmental programme could be thought in order to compensate farmers for imposing limitation to the use of nitrogen (Bartolini *et al*., 2007).

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Appendix. Evolution of indicators selected for the farms-type in the different scenarios analyzed

Policy Scenario + Instrument	Cluster 1: “Large cereal growers”					Cluster 2: “Cereals sugar-beet growers”					Cluster 3: “Small sugar-beet growers”				
	NBAL (kg N ha^{-1})	TGM (€ ha^{-1})	PUBR (€ ha^{-1})	AL (day ha^{-1})	WATER (m^3 ha^{-1})	NBAL (kg N ha^{-1})	TGM (€ ha^{-1})	PUBR (€ ha^{-1})	AL (day ha^{-1})	WATER (m^3 ha^{-1})	NBAL (kg N ha^{-1})	TGM (€ ha^{-1})	PUBR (€ ha^{-1})	AL (day ha^{-1})	WATER (m^3 ha^{-1})
CAP-2000 + no instrument (baseline scenario)															
	36.74	424.55	0.00	1.93	3,433	40.70	483.13	0.00	2.02	3,585	85.50	1,159	0.00	2.73	7,125
CAP-reformed + no instrument															
	-26.1%	+2.8%	-	-22.9%	-35.9%	-32.2%	+8.1%	-	-23.5%	-41.3%	-30.2%	+26.4%	-	-14.0%	-32.2%
CAP-reformed + Instrument 1															
– 120 kg N ha^{-1}	-26.1%	+2.8%	-	-22.9%	-35.9%	-32.2%	+8.1%	-	-23.5%	-41.3%	-51.3%	+22.7%	-	-38.4%	-51.8%
– 100 kg N ha^{-1}	-28.7%	+2.7%	-	-25.2%	-39.0%	-34.9%	+7.9%	-	-26.1%	-44.7%	-59.1%	+18.3%	-	-44.3%	-60.0%
– 80 kg N ha^{-1}	-40.3%	+1.5%	-	-33.9%	-42.1%	-45.4%	+5.7%	-	-34.8%	-48.7%	-67.3%	+12.1%	-	-50.4%	-68.0%
– 60 kg N ha^{-1}	-54.3%	-0.6%	-	-45.2%	-53.1%	-47.4%	+2.8%	-	-44.7%	-56.7%	-75.4%	+4.1%	-	-56.4%	-76.0%
– 40 kg N ha^{-1}	-68.8%	-4.5%	-	-57.2%	-66.3%	-69.9%	-2.5%	-	-55.8%	-69.0%	-83.6%	-4.5%	-	-62.5%	-84.0%
CAP-reformed + Instrument 2															
– € 0.20 kgN^{-1}	-29.8%	-2.0%	19.73	-26.1%	-40.3%	-34.0%	+3.8%	20.22	-25.3%	-43.6%	-30.3%	+23.2%	36.36	-14.0%	-32.4%
– € 0.40 kgN^{-1}	-46.2%	-5.9%	28.43	-38.6%	-45.8%	-36.0%	-0.3%	39.40	-27.2%	-46.0%	-40.3%	+20.3%	66.23	-26.7%	-46.9%
– € 0.60 kgN^{-1}	-53.3%	-9.0%	36.79	-44.5%	-52.2%	-49.2%	-4.2%	43.47	-37.7%	-49.1%	-40.4%	+17.4%	99.08	-26.8%	-47.2%
– € 0.80 kgN^{-1}	-60.5%	-11.7%	41.10	-50.4%	-58.8%	-53.5%	-7.1%	52.55	-41.5%	-53.2%	-48.0%	+14.9%	105.86	-35.5%	-47.5%
– € 1.00 kgN^{-1}	-67.7%	-13.9%	41.13	-56.3%	-65.3%	-57.8%	-9.6%	58.92	-45.3%	-57.4%	-48.3%	+12.7%	131.39	-35.7%	-47.9%
CAP-reformed + Instrument 3															
– € 0.01 m^{-3}	-31.7%	-2.0%	19.32	-28.6%	-43.7%	-35.1%	+3.9%	19.51	-26.9%	-45.6%	-40.3%	+22.7%	37.81	-26.7%	-46.9%
– € 0.02 m^{-3}	-37.4%	-6.3%	33.29	-34.4%	-51.5%	-38.1%	+0.0%	35.85	-30.3%	-50.0%	-40.7%	+19.5%	74.74	-26.9%	-47.6%
– € 0.03 m^{-3}	-43.2%	-9.9%	41.70	-40.2%	-59.5%	-41.5%	-3.5%	48.49	-33.9%	-54.9%	-41.0%	+16.3%	110.77	-27.2%	-48.0%
– € 0.04 m^{-3}	-49.4%	-12.9%	45.04	-45.7%	-67.2%	-44.9%	-6.7%	57.61	-37.5%	-59.8%	-41.4%	+13.1%	145.93	-27.4%	-48.8%
– € 0.05 m^{-3}	-54.8%	-15.2%	45.82	-49.9%	-73.3%	-48.5%	-9.5%	63.84	-40.8%	-64.4%	-42.5%	+10.0%	175.75	-28.4%	-50.7%
– € 0.06 m^{-3}	-56.6%	-17.3%	50.54	-50.9%	-75.5%	-52.2%	-12.0%	67.05	-44.0%	-68.8%	-43.2%	+7.0%	206.68	-29.0%	-51.7%
CAP-reformed + Instrument 4															
– 25 %	-26.1%	+2.8%	-	-22.9%	-35.9%	-32.2%	+8.1%	-	-23.5%	-41.3%	-55.7%	+7.6%	-	-32.7%	-59,4%
– 20 %	-26.1%	+2.8%	-	-22.9%	-35.9%	-32.2%	+8.1%	-	-23.5%	-41.3%	-60.8%	+1.8%	-	-36.5%	-64,4%
– 15 %	-27.8%	+2.7%	-	-23.7%	-37.9%	-34.4%	+7.5%	-	-24.8%	-44.1%	-65.9%	-4.8%	-	-40.3%	-69,4%
– 10 %	-36.2%	-1.2%	-	-27.8%	-47.9%	-42.1%	+1.8%	-	-29.1%	-53.0%	-71.0%	-12.0%	-	-44.1%	-74,4%
– 5 %	-45.7%	-10.0%	-	-33.0%	-58.1%	-52.7%	-8.5%	-	-34.5%	-63.1%	-76.1%	-20.0%	-	-47.9%	-79,4%