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Analysis of nitrate pollution control policies in the irrigated agriculture of Apulia Region (Southern Italy): A bio-economic modelling approach

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Abstract

Nitrate leaching is one of the many forms of environmental pollution resulting from irrigation and intensive agriculture. In this work, a method of combining an agronomic simulation model (EPIC) and a mathematical multi-objective programming model is used to analyse the effects of three agricultural policies on farmer's revenue and nitrate leaching. An evaluation of the net social costs associated with the different policy measures is also given. The farmer's behaviour in different policy scenarios was studied in terms of selected crops, irrigation technique and method, and adopted management practices with focus on farm management practices and water application efficiency. Irrigation water pricing, subsidies to adopt improved management levels, and taxation on the use of nitrogen fertilizer were examined. A trade-off emerges between the levels of nitrate leaching and net farmer's revenue more pronounced for nitrogen tax policies than for water pricing. The results obtained indicate that nitrate leaching can be reduced by about 40% with an associated net social cost of 269 €/ha for the water pricing policy, 183 €/ha for the tax on fertilizer and 95 €/ha for subsidies to high efficiency management.

Keywords: Nitrate pollution; Agricultural policy; Agronomic model; Multi-objective model

1. Introduction

Agricultural activities might generate negative impacts on the environment.

Irrigation can affect the environment by favouring the adoption of intensive agricultural practices and boosting high cash crops with associated use of increasing amounts of water, fertilizers and pesticides (IEEP, 2000). Still, chemical-based pollution in agriculture is not exclusively related to irrigation.

Water pollution from agriculture is defined as non-point source pollution. Actors involved are numerous and it is a quite complex matter to define how and when polluting agent moves into the water bodies and who the polluters are.

The strong site-specific dimension of this phenomenon significantly affects the types of tools to be used to control it and their efficiency (Westra and Olson, 2001).

Economic theory has long since identified the control mechanisms of externalities – the main economic category by which the theme of pollution is tackled – but economic control instruments cannot be readily implemented nor can their efficacy be promptly assessed (Shortle and Dunn, 1986).

Policy mechanisms used for agricultural non-point pollution control are direct regulations (i.e. standards on the amount and use of potential pollutants and production practices) and pricing policy like taxes or subsidies. Taxes and subsidies can be applied directly to the polluting emissions ("effluent" taxes or subsidies) or based on some emission proxies like polluting inputs or certain agricultural practices ("influent" taxes or subsidies). Much less used are other economic incentives like tradable permits and contracts (Hahn, 2000), although the combined use of subsidies and contracts between farmers and some public

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agencies are increasingly adopted as it is the case of the European agri-environmental policies (Horan and Shortle, 2001).

Many studies have shown the potential role of water price policies in modifying farm-level irrigation decisions towards more environmentally friendly choices (Gardner and Young, 1988; Dinar et al., 1989; Varela-Ortega et al., 1998; Berbel and Gómez-Limón, 2000; Mimouni et al., 2000). Irrigation water seems to have all the attributes that make it a good base to design policy instruments for non-point pollution control: it is (i) correlated with environmental conditions, (ii) enforceable at reasonable cost and (iii) targetable in time and space (Braden and Segerson, 1993).

Many of the numerous studies addressing the economic theory of non-point pollution control (Deybe, 1994; Bouzaher et al., 1995; Teague et al., 1995; Dalton and Masters, 1997) have used a bio-economic modelling approach that combines biophysical and economic models to fit the complexity of the relationships between agriculture and environment. Still, studies conducted in the Mediterranean region are very few (Boussemart et al., 1996; Flichman et al., 1995; Flichman, 1997; Louhichi et al., 1999; Mimouni et al., 2000), in spite of the increasing severity of environmental problems in this area.

In the present work, and for the first time, this approach is applied to irrigation efficiency. We focused on the possible effect of improved farm management practices on water application efficiency and nitrate leaching reduction.

This paper reports the results of a study that analysed the farmer's behaviour in different policy scenarios in terms of strategies adopted when changing selected crops, irrigation techniques, irrigation methods and management practices to improve water application efficiency.

Water application efficiency (e_a) is defined as the ratio of the amount of water that effectively reaches the crop root zone (W_r) to the amount of water applied to the field (W_a), i.e.,

$$e_a = W_r/W_a \quad (1)$$

Our final objective was to assess the effects of different policy measures on farmer's revenue and nitrate leaching level and to evaluate their net social costs.

The policies examined include a gradual increase in the water price by unit of water consumed, a subsidy to the adoption of high level management practices and a tax on the use of nitrogen fertilizer in crop production.

In the investigated region (Apulia, Southern Italy), irrigated land covers 361,000 ha equal to 25% of total agricultural land and irrigated agriculture produces 1663 million euro (1997 data) representing 54% of the total value of the regional agricultural production (INEA, 2001).

Climatic conditions and the type of cultivated crops (high value crops such as vegetables, salads and soft fruits) make irrigation a must for the farmers to obtain acceptable revenue and, in turn, irrigated intensive agriculture makes these regions greatly exposed to severe nitrate leaching impacts (IEEP, 2000).

2. Study area

The study was carried out in a flat area farm, of almost 100 ha in Apulia region, typically grown with sown crops, cereals and some vegetable crops like tomato essentially used for processing.

The water pricing criteria adopted in the investigated area is a binomial and block-rate tariff, which consists of a fixed fee farmers pay to the Consortium per hectare of cultivated area and a variable tiered fee that depends on consumption. Such water pricing is applicable in that the on-demand pressurized distribution network is equipped with water meters.

Average rainfall is around 460 mm/year, with maximum temperature reaching 31 °C in July and minimum temperature of 5 °C in January and February. The soil is 120 cm deep, it has an average bulk density of 1.3 g/cm^3 and an average texture throughout the profile with 45% sand, 42% clay and 13% silt on weight basis. It contains 1.24% of organic matter with a pH of about 8.5 and a cation exchange capacity of 290 mmol/kg. The field capacity and wilting point are 39% and 21%, respectively, of the total available water.

Five crops were grown – wheat, sorghum, sunflower, tomato and sugar beet – and the following was considered: (i) three irrigation regimes or techniques corresponding to a first level of deficit irrigation (T1), a second level of deficit irrigation (T2) and full irrigation (T3) plus the rain-fed regime for wheat, sunflower and sorghum (Table 1); (ii) three irrigation methods, surface, (R1), sprinkler (R2) and drip (R3); (iii) three management levels, low (M1), medium (M2) and high (M3). Management levels were defined according to some operations performed and equipment used such as: land levelling, days of expert consultation, number of water meters and tensiometers, pressure regulators, volumetric valves and water markers. Different levels of nitrogen fertilizer application were also considered and set on the basis of the actual fertilization practices in the area. In particular, wheat received a total of 120 kg-N/ha during the crop season and for each irrigation regime (T), with 45 kg-N/ha applied at sowing and 75 kg-N/ha applied at the shooting stage. Sorghum received a total of 100 kg-N/ha in the rain-fed case (T0 – half applied at sowing and half at the shooting stage) and a total of 200 kg-N/ha in all the other irrigation regimes (T1–T3 – equally distributed during the crop season and at each irrigation event). Sunflower

Table 1
Reference water (mm) and quantity of N (kg/ha) for each crop and technique

	T0		T1		T2		T3	
	W_r	N	W_r	N	W_r	N	W_r	N
Wheat	–	120	90	120	160	120	300	120
Sorghum	–	100	180	200	250	200	400	200
Sunflower	–	70	210	80	350	100	600	120
Sugar beet	–	–	250	150	450	200	700	200
Tomato	–	–	180	150	330	200	500	200

Table 2
Water application efficiency for irrigation method and level of management

Method	Level of management		
	Low	Medium	High
Surface	0.50	0.65	0.80
Sprinkler	0.65	0.75	0.85
Drip	0.70	0.85	0.95

received 70, 80, 100 and 120 kg-N/ha for the rain-fed and the three irrigation regimes T1–T3, respectively. Also in this case, for the rain-fed case, the total N was applied in two equal amounts at the beginning and in the middle of the crop season, while in equal share and at each irrigation event for the other irrigation levels. Sugarbeet and tomato received 150 kg-N/ha in T1 and 200 kg-N/ha in both T2 and T3, equally distributed and at each irrigation event. The total N applications are summarized in Table 1.

Combinations of the three irrigation methods (R) and three management levels (M) determine nine different levels of water application efficiency (e_a) varying from 0.50 to 0.95 (Table 2), although in two cases the water application efficiency was identical (0.65 and 0.85). The water application efficiency values attributed to the different combinations of irrigation methods (R) and management levels (M) were defined on the basis of local experimental observations, expert knowledge from local extension service specialists, and well-established scientific bibliography (Pruitt et al., 1984; Howell, 2003; Playán et al., 2005). An additional 100% application efficiency case ($e_a = 1$) was also included, so that a total of eight water application efficiency levels were simulated with each technique (T), compounding an overall 24 (8×3) treatments to be investigated for each crop in terms of both yield and nitrate leaching (Table 3).

3. The methodology

This study combines a biophysical model and a mathematical programming model at the farm-level, to generate a "bio-economic" model that analyses the entire farming system, including nitrate leaching as one of the environmental parameters associated with different agricultural techniques.

The first step consists in applying an agronomic simulation model that considers crop growth interaction with the climate, soil and agricultural practices (including irrigation). The model allows estimating crop production and nitrate leaching associated with different scenarios following the direction of a research developed during the last decade in several countries, such as Europe, USA, and Australia (Flichman and Jacquet, 2002).

The second step is to use the output of the biophysical model – crop production and nitrate leaching – as input for the economic model together with other economic data such as prices of products and costs of production factors (like water, labour, fertilizers and irrigation system equipment). For each scenario, the economic model generates the farmer's revenue and the crop distribution by irrigation technique, irrigation method and management level. Based on the selected crop distribution, the level of nitrate leaching is obtained. The adopted methodology couples the agronomic simulation model (EPIC) with a multi-objective programming model (MOPM). It gives a multi-scenario analysis showing the effects of changing water price or applying subsidies and taxes on farmers' revenue and

Table 3
EPIC simulation results for different water application efficiency levels and techniques

	Water application efficiency levels															
	0.50	0.65	0.70	0.75	0.80	0.85	0.95	1.00	0.50	0.65	0.70	0.75	0.80	0.85	0.95	1.00
	Yields (ton/ha) at 12% moisture								Leaching (kg/ha)							
	T1								T1							
Wheat	4.4	4.3	4.1	4.0	3.9	3.9	3.8	3.8	31	22	19	17	15	13	10	8
Sorghum	5.2	5.0	5.0	4.9	4.9	4.8	4.7	4.7	151	124	117	110	103	97	86	80
Sunflower	3.7	3.7	3.7	3.6	3.6	3.5	3.5	3.4	57	39	35	32	29	27	24	22
Sugar beet	64.8	59.6	57.6	55.2	53.2	51.2	47.6	46.8	58	42	37	33	30	26	19	17
Tomato	86.0	78.0	74.0	72.0	68.0	66.0	64.0	62.0	103	83	77	71	65	59	47	45
	T2								T2							
Wheat	4.6	4.6	4.6	4.6	4.5	4.4	4.3	4.1	59	45	40	36	32	28	23	22
Sorghum	5.2	5.3	5.3	5.3	5.2	5.2	4.9	4.9	167	150	139	130	122	114	100	93
Sunflower	3.9	4.0	4.0	4.0	3.9	3.9	3.7	3.7	80	66	62	58	54	50	45	42
Sugar beet	72.8	71.6	70.0	68.0	65.6	63.6	60.0	58.4	68	59	58	57	55	53	47	44
Tomato	96.0	96.0	94.0	94.0	92.0	90.0	86.0	86.0	81	67	63	59	57	55	47	41
	T3								T3							
Wheat	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.1	67	63	60	60	58	55	48	45
Sorghum	5.0	5.4	5.4	5.4	5.4	5.4	5.4	5.4	181	163	158	155	150	145	127	121
Sunflower	3.7	3.9	3.9	4.0	4.0	4.2	4.3	4.4	102	86	82	78	75	71	66	55
Sugar beet	74.4	75.2	75.6	75.6	75.6	75.6	75.6	75.6	65	57	56	55	53	51	46	43
Tomato	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	118	107	103	99	93	87	71	64

nitrate leaching. The net revenue of the farmer is the economic variable to be maximized, while nitrate leaching is chosen as a proxy variable for the environmental impact on water bodies. Finally, the cost-effectiveness of various non-point pollution abatement policies is analysed.

3.1. The agronomic model

The EPIC model is thoroughly described in Williams et al. (1984, 1989). It uses a daily time step to simulate crop growth, soil water balance, erosion, pesticide and nutrients movement with water and sediment. Among all the uses of EPIC, we focused on crop productivity and nitrate leaching.

The version used was the EPICPHAS real time (EWQTPR), developed at Toulouse (France) from the original version of EPIC (Cabelguenne et al., 1990). Its crop growth module runs on a time scale of one day, following a stepwise procedure with the derivation of potential dry matter increments of the day as function of leaf area index (LAI) and the climatic variables (solar radiation and air temperature) of the previous day. On the basis of such potential dry matter increment of the day, the model calculates the corresponding water and nutrient potential demand. By evaluating the actual water and nutrient availability to the crop, the model is able to assign a stress index between 0 (full stress) and 1 (no stress) for each limiting resource. The minimum value of these stress indexes, representing the most limiting factor, lower the potential growth of that day to the actual dry matter growth by acting either on LAI (vegetative stage) or on Harvest Index (HI, when the reproductive stage has been reached). The capacity of EPICPHAS to distinguish different sensitivity to stresses depending on the crop stages has increased the accuracy of the crop growth simulation. Further enhancement of the model accuracy has been obtained by having the rooting system simulation capable of adapting the extraction pattern of water from the soil to the different species-specific root characteristics. After calibration of the main crops and soil parameters, the model was tested for accuracy of crop growth and yield as well as for moisture content in the soil and nitrate leaching simulations. While the accuracy for growth and yield simulations of wheat, sorghum, sunflower, sugarbeet and tomato was tested also in few other experimental trials (Jones et al., 1988; Cabelguenne et al., 1988; Steduto et al., 1995), the nitrate leaching was specifically tested for the soil and water management conditions of the present work. The overall accuracy of crop yield simulation of EPIC varied between 9% and 17% depending on the crop under investigation and the water management regime. The overall accuracy of nitrate leaching simulation of EPIC varied between 12% and 21%, depending mainly on the water management regime. It was observed that surface runoff was the main weak component of the soil water balance simulation, while leaching was much more accurate. Therefore, the accuracy performance is considered sufficient to value the comparison between the treatments of the present work.

The techniques (T1–T3) are defined on the basis of the amount of water that effectively reaches the plant root zone independently of the efficiency level of the irrigation system. This amount of water is termed *reference water*, which is the same as W_r of Eq. (1). The *applied water* (W_a) is the amount of water applied to the field considering a given water application efficiency level e_a so that

$$W_r = W_a \times e_a \tag{2}$$

3.2. The economic model

The applied economic model is a mathematical multicriteria model having the twofold objective of maximizing the farmer's revenue and minimizing the risk.

Following the mean-standard deviation analysis (Hazell and Norton, 1986), the maximised objective function (U) of the model is:

$$Z - \varphi \times S_v = U, \tag{3}$$

where Z is the average net revenue of the farmer (€), φ is the coefficient for the risk aversion parameter, S_v, is the standard deviation of the revenue distribution generated by the variability of yields under different weather conditions (states of nature) and the variability of prices (states of market) and U is the expected farmer's utility.

As we assume that Z is normally distributed, then for a specific value of φ, say φ_0, $U = Z - \varphi_0 \times S_v$ identifies a particular fractile of the Z distribution for each farm plan and represents the minimum expected revenue with a certain probability that depends on the risk aversion value. For example, if $\varphi, = 1.65$, then $U = Z - 1.65 \times S_v$ identifies the 5% Z fractile. A 5% Z fractile is the value of Z which will be exceeded 95% of the time. Risk aversion coefficient was kept constant in all simulations. Its value was fixed at 1.65 to calibrate the results of the model to the initial situation.

Z, the average net revenue is calculated through the equation:

$$Z = \sum(Y \times P + S_b) - \sum(C_O + C_m + H_L \times C_L + F_N \times C_N + C_e) - T \times A - P_w \times V_w \tag{4}$$

where P is the average price of crops (€/ton), S_b are the subsidies given to certain crops (€/ha), C_O is the production cost of the crop (€/ha), C_m is the cost of management for each level and crop (€/ha), C_L is the cost of 1 h of labour (€), C_N is the cost of one nitrogen fertilizer unit (€/kg) and C_e is the capital cost of the irrigation equipment (€/ha) calculated as fraction of its revaluated purchase value. H_L are the hours of labour needed for each technique, F_N is the amount of nitrogen fertilizer (kg of urea per ha), T is the fixed tariff for irrigation (€/ha), P_w is the price of 1 m^3 of water (€/m^3) and V_w is the total quantity of water applied (m^3).

In Eq. (4), Y is the crop yield for each technique (tons/ha). It is endogenously generated by the economic model through the equation:

$$Y = Y_{max} - ((Y_{max} - Y_{min})/R_{coef} \times A) \times X \tag{5}$$

where Y_{max} is the maximum yield obtained with the minimum cultivated area (tons/ha), Y_{min} is the minimum yield obtained with maximum cultivated area (tons/ha), R_{coef} is the rotation coefficient for each crop (%), A is the total area (ha) and X is the actual cultivated area (ha). Y_{max} and Y_{min} were calculated as 1.05% and 0.95%, respectively, of the yields obtained with EPIC. A variation of ±5% of the average yield has been determined on the base of local experience and represents the range of yield variation that occurs when the cultivated land area increases from about one fourth of the total to the total. Therefore, Eq. (5) was introduced to account for crop yield variation that occurs with the variation in the cultivated surface according to the law of diminishing return.

The rotation coefficient, R_{coef}, was introduced for each crop to simulate actual agronomic practices by which some crops cannot be grown the following year on the same piece of land to avoid problems in nutrition and exposure to some pathogens.

We assume that price variations are independent of yield variations and, since we had not enough data to estimate directly the standard deviation of prices, the procedure was to generate random prices, respecting the observed range of price variation.

The risk is represented by the standard deviation of revenue in different states of nature and states of market. The model will then choose the optimal solution that yields the highest net revenue at low risk.

Considering the prevailing conditions in this region, we decided to introduce neither a labour nor a capital constraint.

3.3. The policy scenarios

The first policy measure we analysed was a gradual increase in water price starting from a value of 0 €/m^3. We considered sixteen different water prices up to 0.39 €/m^3. In the real situation, with the above described water pricing system, the average price of water is around 0.10 €/m^3.

The second policy measure analysed was a subsidy to certain agronomic practices that induce a reduction in nitrate leaching. These practices are the medium management level (M2) and the high management level (M3) that have higher water application efficiency.

According to the results of the agronomic model, nitrate leaching decreases shifting from low to medium and high irrigation management level for all the crops, with techniques and irrigation methods being constant. Since both M2 and M3 require additional costs for equipment and labour, a subsidy was introduced to cover part of such costs and to encourage their adoption. For the adoption of M2, two levels of subsidy – 103 and 155 €/ha – were tested. These values correspond to minimum and maximum values for the adoption of this management level: with a subsidy lower than 103 €/ha all the land is cultivated under M1, while with a value equal to or higher than 155 €/ha, M2 is adopted all over the land. For the adoption of M3, a further level of subsidy – 165 €/ha – was introduced to induce farmers to adopt this management level over the whole cultivated land.

Combining these three levels of subsidies, six subsidy schemes were simulated: (103,103), (103,155), (103,165), (155,103), (155,155), (155,165) €/ha. Each of them includes the amounts of subsidy given to the farmer for each hectare of cultivated land under the medium and the high management level, respectively.

The third analysed measure was a tax on N. Seven levels were considered from 0.52 to 3.15 €/kg, with a resulting increase in the nitrogen price from 0.23 to 3.38 €/kg.

The baseline considered is the real situation with the binomial and block-rate water price system described above, a net revenue of 1193 €/ha and nitrate leaching of 54 kg-N/ha. The actual water price incorporates no environmental consideration.

4. Results and discussions

4.1. Agronomic model results

Yield and nitrate leaching resulting from the simulation of the agronomic model, referred to the different crops, irrigation techniques and water application efficiency levels are reported in Table 3.

The relationship between Y and W_a is a classical production function that reflects the law of diminishing returns. Its range can be divided into three stages: at stage 1 the output increases more than proportionally with the increase of the variable input; at stage 2 output increases at a decreasing rate; finally, at stage 3 output decreases because too much variable input is being used in comparison with the available fixed inputs. The absolute decline in yields, typical of the third stage of the function, can be more marked (sunflower) or less marked (tomato). In the example of wheat, the relationship is shown in Fig. 1.

The trend of the curve is the result of the water applied and the water application efficiency. With W_r being constant, the lower the water application efficiency, the higher the yields.

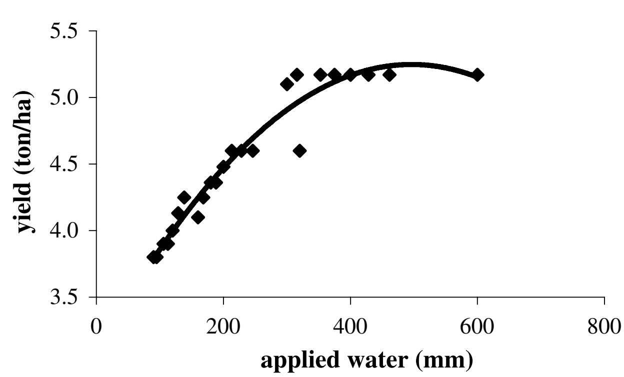

Fig. 1. Wheat yield response to applied water.

Given Eq. (1), the relationship between yields and water application efficiency is a function of two variables:

$$Y = g(W_a, e_a) \quad (6)$$

where with few exceptions for sorghum and sunflower,

$$\partial Y/\partial W_a > 0$$
$$\partial Y/\partial e_a < 0$$

For any given level of W_r, if we plot yield versus water application efficiency levels, we obtain the set of curves illustrated in Fig. 2. The figure shows that for techniques T1 and T2 the lower the efficiency levels the higher the yields. With W_r equal to 90 mm, yield response is the highest (4.4 tons/ha) at the lowest water application efficiency (0.50) and it is the lowest (3.8 tons/ha) at the highest water application efficiency (1.00). Yield responses at the remaining water application efficiency levels fall between these two boundaries. This apparently counter-intuitive result can be explained on the ground that, with deficit irrigation techniques (T1 and T2), the crop takes advantage of the received extra water due to inefficiency. Since 90 mm are considered quite insufficient to meet the seasonal wheat crop water requirements in the climatic conditions of the investigated area, the extra water applied to compensate for inefficiency is partially used by the crop. The greater the reference water, the smaller the advantage produced by extra water due to inefficiency: with 300 mm of water, the crop water requirements are fully satisfied and the previous advantage of receiving extra water by inefficient application is completely lost.

Accordingly, this effect stops with the highest water application efficiency level and with full irrigation technique. As illustrated in Fig. 2, the range of variation in yields is larger for different levels of water application efficiency under T1 and a convergence toward maximum yield is obtained at all the efficiency levels under T3.

The full irrigation technique, associated with lower levels of water application efficiency, results in excessive water supply to the plant and reduced yields. In the case of more pronounced reduction in yield, as in sunflower, yield response in T3 is completely opposite – the lowest efficiency gives the lowest yield – and yield variation for different levels of water application efficiency under T1 and T2 is smaller.

Nitrate leaching depends on W_r and water application efficiency according to the following relationship:

$$N = f(W_r, e_a) \quad (7)$$

where

$$\partial N/\partial W_r > 0$$
$$\partial N/\partial e_a < 0$$

Lower water application efficiency levels and full irrigation techniques lead to higher nitrate leaching. The example of wheat (Fig. 3) illustrates nitrate leaching for different levels of reference water and water application efficiency. The range of nitrate leaching varies from 8 to 31 kg-N/ha for T1, from 22 to 59 kg-N/ha for T2 and from 45 to 67 kg-N/ha for T3. Unlike the advantages obtained in yield response, the figure highlights that inefficiencies are always detrimental to the environment.

For all the crops and levels of reference water, nitrate leaching always increases with decreasing values of water application efficiency and rapidly increases with the increase in water applied (Fig. 4). Further, the slope of the curve in Fig. 4 is significantly steeper than the slope of the yield versus applied water curve (Fig. 1). Results are different only for tomato where nitrate leaching values vary between 45 and 103 kg-N/ha for T1, between 41 and 81 kg-N/ha for T2 and between 64 and 118 kg-N/ha for T3 (Table 3). These results may be due to the timing and amounts of irrigation applications. Under the first deficit level of irrigation (T1), water was applied in high amounts

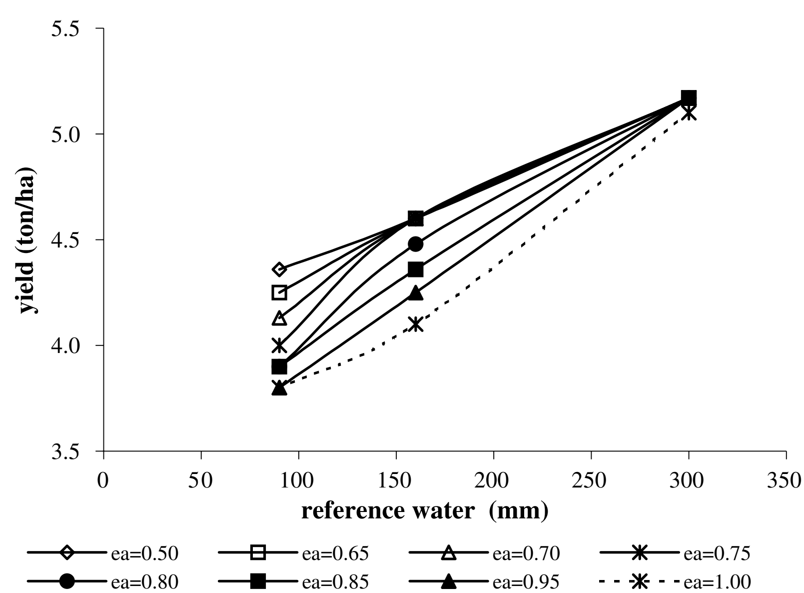

Fig. 2. Wheat yield response to reference water for different levels of water application efficiency.

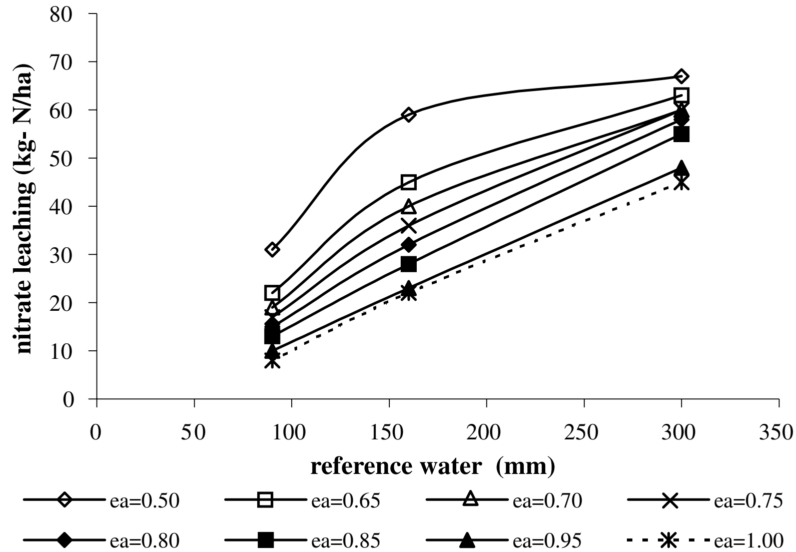

Fig. 3. Nitrate leaching for different levels of reference water and different levels of water application efficiency, in wheat.

and at large intervals, which induces more nitrate leaching as compared to the second deficit level of irrigation (T2).

The obtained results show that production and environmental objectives are conflicting. Water application efficiency being the same, the transition toward more water intensive techniques corresponds to increased yields and nitrate leaching levels. Higher farm production due to more intensive irrigation results in greater environmental impact.

On the other hand, when using deficit irrigation techniques (T1 and T2), the recovery in water application efficiency corresponds to lower yield and lower nitrate leaching level, since nitrate leaching always decreases with the increase in efficiency, whereas yields of all the crops, except sunflower, decrease with the increase in water application efficiency.

4.2. Economic model results

4.2.1. First policy scenario: water pricing

The results show a decreasing response of the net revenue of the farmer from 1672 €/ha (with a water price of 0 €/m^3) to 524 €/ha (with a water price of 0.39 €/m^3) with a reduction of about 65%. The revenue decrease is due to two concomitant factors: the changes in the use of soil by substituting water-demanding cash crops with other less yielding crops, and the increase in costs due to the rise in water price. The farmer has to pay an increased price for the water used even when the nitrate leaching reduction standard is achieved. To reach a nitrate leaching of 32 kg-N/ha, water price should be increased to 0.17 €/m^3 with a farmer's net revenue of 828 €/ha.

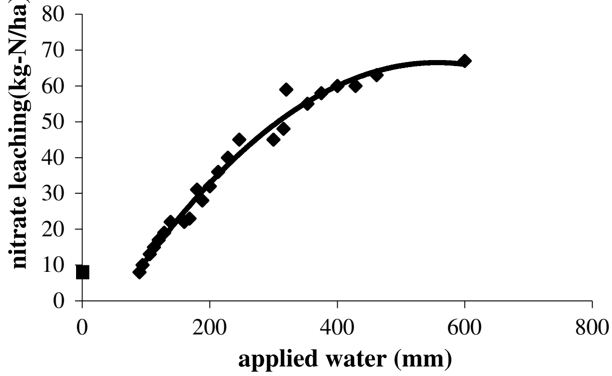

Fig. 4. Nitrate leaching for different levels of applied water, in wheat.

With the increase in water price from 0 to 0.39 €/m^3, nitrate leaching varies from 73 to 21 kg-N/ha showing a not constant water price elasticity. Significant reductions in nitrate leaching level occur for a water price ranging from 0.08 to 0.2 €/m^3. Out of this range water price policy does not affect nitrate leaching.

The farmer initially responds to water price increase by maintaining the same cropping pattern and changing only the irrigation techniques and methods. Water demand is slightly affected and the revenue loss is "transferred" directly to the public sector without any significant effect on nitrate leaching abatement.

At a later stage, the farmer responds to price increase with greater "flexibility" in his cropping pattern decision. Less water-consuming crops and some non-irrigated crops are introduced and irrigated agriculture shrinks from 100 to 20 ha. The area grown with tomato is constant and tomato still remains the most profitable crop even with a water price three times as much the actual one. Crop rotation represents the only constraint to increased tomato cultivation. At this stage, surface irrigation declines from 78% to 22% of the total area; sprinkling becomes the only irrigation method used for the full and second level of deficit irrigation technique; the low management level is gradually replaced by the high level one.

The farmer pays almost totally the cost of nitrate leaching abatement in that his revenue falls severely when water demand and nitrate leaching decrease.

At a third stage farmer' choices are almost completely rigid. For a water price higher than 0.26 €/m^3 there is no response either in terms of crop pattern or of techniques or methods adopted. Water demand and level of nitrate leaching remain constant, while farmer's revenue decreases. A water price above this level is not an effective environmental policy because it only causes a transfer of revenue from the farmer to the public sector.

Together with the changes in crop pattern, techniques and methods adopted, important variations in management level also occur. To save expensive water, the farmer gradually shifts from the low level of management – dominant at the beginning – to the high level of management. As a result of these changes, the degree of efficiency by which water is used rises from 0.54 to 0.85.

The water price elasticity of both the net revenue and the nitrate leaching is not constant, so the trade-off curve of revenue versus nitrate leaching level (Fig. 5) shows three different sections, the first being of low elasticity, the second of higher elasticity and the third one completely inelastic. Two *plateaux* with increasing slope in-between are evident. Under the existing management conditions of the farm, the level of 20 kg-N/ha of nitrate leaching cannot be further decreased and the level of about 70 kg-N/ha is the highest achievable nitrate leaching.

4.2.2. Second policy scenario: high management incentives

Introducing incentives for farmers to adopt medium and high management levels we get the double result of increasing the level of revenue and lowering the level of nitrate leaching. If we compare the situation with no incentive with the final one, including an incentive of 103 € per cultivated hectare under M2 and of 165 € per cultivated hectare under M3, the net revenue rises from 1193 to 1263 €/ha with an increase of about 6%. In the final situation, the farmer adopts the most advanced management level on the whole farm area and receives a subsidy of 165 €/ha.

The nitrate leaching level reduces gradually from 54 to 33 kg-N/ha by moving from a subsidy scheme to the other. No further nitrate leaching abatement results can be achieved through this tool since with a subsidy of 165 €/ha the farmer adopts the highest management level on the whole farm area. Every increase beyond this amount would only result in a linear increase in the farmer's net revenue (Fig. 6).

The introduction of the different subsidy schemes leads the farmer to choose medium and high management levels. The adoption of M2 and M3 results in better water application efficiency, thus leading to increase the irrigated area up to 64% (against 11% in the initial situation) and to substitute T1 for T2 that change from 18% to 69% and from 62% to 12% of the whole farm area, respectively.

Total efficiency rises from 0.65 to 0.82 with considerable reduction in the amount of water used from 4070 to 2750 m^3/ha.

The increase in the water application efficiency, associated with water saving and nitrate leaching reduction, is the result of better farm management and not simply of the adoption of sprinkler and drip irrigation methods.

4.2.3. Third policy scenario: taxes on N-fertilizers

Some simulations were done levying a tax on every kilogram of N-fertilizers used. In order to reach a nitrate leaching abatement comparable with the other cases, we hypothesised a tax 10 times higher than the current price of the fertilizer.

The revenue of the farmer decreases at a constant rate from the first to the last iteration where a nitrate leaching abatement of 40% is reached; it reduces by about 40% from 1193 to 734 €/ha as the tax rises from 0 to 3.15 €/kg.

Significant abatement in nitrate leaching level is obtained only when levying a tax equal to 3.10 €/kg. To get a 40% reduction in nitrate leached per hectare the tax must be 3.15 €/kg.

N-tax generally operates through two mechanisms. First it leads to reduced fertilisation levels and thus to reduced nitrate leaching, and second it induces a substitution between different inputs of production and different agronomic practices (Vatn et al., 1997).

It is observed that until the tax reaches 2.58 €/kg neither the cropping pattern nor the adoption of different tech-

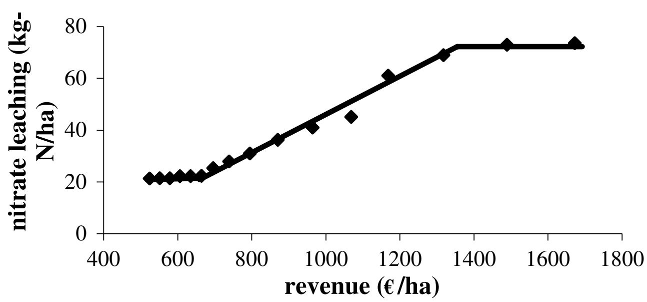

Fig. 5. Water pricing policy: trade-off between revenue and nitrate leaching.

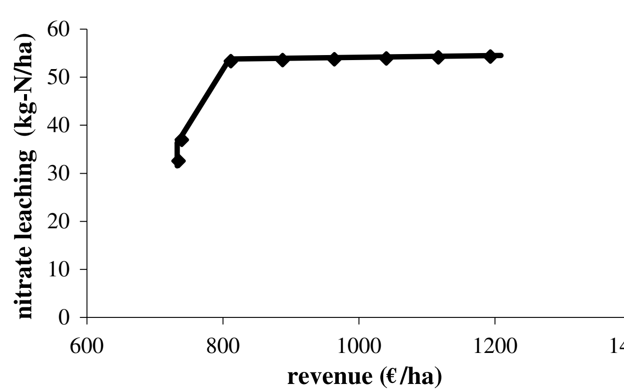

Fig. 6. High management incentives policy: trade-off between revenue and nitrate leaching.

niques, methods and levels of management change and the reduction in farmer's revenue is due to the tax payment.

The very low price elasticity of N fertilizer consumption can be explained by the very slight differences existing between the levels of the fertilizer applications associated with the different irrigation techniques (Table 1). This means that the farmer considers it is not profitable to shift from a more water intensive irrigation technique to a less water intensive one because the reduction in crop yield would not be compensated by lower N-taxes.

With a tax higher than 2.58 €/kg, farmer's decisions start changing to reduce losses. Both tomato and sugar beet area remain constant, wheat area begins to decrease significantly and the total cultivated area drops from 100 to 50 ha. With a cost of fertilizer higher than 3.38 €/kg (price + tax) it is no longer profitable to cultivate wheat, whereas in the case of no rotation constraint, it would be still profitable to extend the area grown with tomato or sugar beet.

These variations in the cropping pattern are concurrent with a reduction in the irrigated area and in the second deficit irrigation technique against an increased use of sprinkler method (from 84% to 94% of the total irrigated area) and full irrigation techniques (from 20% to 36% of the total irrigated area). The low level management, M1, still remains the prevailing one and covers 80% of total area (it was 93% in the situation without incentives).

Quantity of water used drops from 407,000 m^3 to 273,000 m^3 equal to 4070 and 5374 m^3/ha, respectively. Unlike the previous case, efficiency level slightly rises from 0.65 to 0.69.

5. Cost-effectiveness analysis

Net social costs are defined as the algebraic sum of private and social costs related to each policy measure (Gardner and Young, 1988; Vatn et al., 1999; Schou et al., 2000; Berntsen et al., 2003). We calculated them per hectare (Table 4).

Private costs express the loss occurred in the farmer's net revenue. They cover both costs related to the changes in resources use (real costs) and the amount of taxes, increased payment for the use of input (water) and subsidies. Social costs are measured by the amount of money paid or received by the society to implement the measure. The most cost-effective policy measure will be the one leading to 40% reduction in nitrate leaching at the lowest net social cost.

The net social cost for water price policy is equal to 269 €/ha and is calculated as the losses for the farmer, equal to 365 €/ha, minus the gain in revenue for the water agency (96 €/ha).

In the case of incentives for medium and high management level, the net social cost is equal to the (algebraic) sum of the revenue gain for the farmer, equal to 70 ha, and the amount of subsidies. To reach about 40% abatement in nitrate leaching level (33 kg-N/ha), the subsidy

Table 4
Private and net social costs of the three policies

	Private costs		Net social costs
	€/ha	% [a]	€/ha
Water pricing	365	−31%	269
Management incentives[b]	−67	+6%	95
Taxes on N fertilizers	459	−38%	183

[a] Percentage on farmer's net revenue in the baseline scenario.
[b] In this case the objective of 40% reduction of the initial level of nitrate leaching – equal to 54 kg/ha – cannot be fully achieved for the reasons explained in Section 4.2.

per hectare is 165 €/ha with a net social cost of 95 €/ha. In this case, all the cost to reduce nitrate leaching is paid by the society.

The third policy measure has a social cost of 183 €/ha equal to the (algebraic) sum of the losses in the farmer' revenue, 459 €/ha, and the total amount of taxes, 276 €/ha, that represent a revenue for the society. In this case, all the cost for the nitrate leaching abatement is charged to the farmer. If the policy had stopped at a level lower than 3.10 €/kg of fertilizer it would have been completely ineffective. On the other hand, it is unrealistic to imagine a tax 10 times higher than the price of the taxed input. Both net social costs and their distribution between farmers and the rest of the society widely vary in the different scenarios depending on the type of policy measures used. Taxes place the entire cost burden on farmers whereas the society bears all costs with subsidized management improvement.

6. Conclusions

The methodological approach that combines agronomic and economic models allowed us to analyse both the environmental impact (nitrate leaching) of the agricultural production and the effect of different policies on nitrate leaching reduction.

In particular, the adopted combinations of water and nitrogen quantity and the selected nitrate leaching control measures highlighted the relationship between water application efficiency and the environmental impact.

In agreement with other authors (Gardner and Young, 1988), our results confirm that the least efficient tool to reduce nitrate leaching is the irrigation water pricing policy because of the imperfect correlation between water use and nitrate leaching, while the lowest cost method to reduce the negative environmental impact is to provide incentives for the adoption of improved management levels.

As from our results, a more flexible way to combine water and nitrogen quantity has to be explored in order to make the model less rigid in simulating the farmer's response to measures directly based on the reduction of the polluting input.

Further investigations on net social costs are recommended to include both policy monitoring and implementation costs. The implementation effectiveness of the different policies should also be taken into account because taxes and pricing are easier policies to be implemented and controlled, but farmers might not easily accept them. On the contrary, a policy supporting the adoption of higher management levels is likely the most willingly accepted by farmers but the most difficult to be implemented. Beyond the effort required to assess and control the real adoption of the different agronomic practices, successful implementation of this kind of policy involves farmer's skills, capabilities and efficient organization of the public and private farmer-oriented system of education, training and extension.

Finally, different policies are associated with different cost-sharing. The subsidy policy shares the cost between farmers and the society, while water pricing and N-tax policies charge the full cost of nitrate leaching abatement to farmers.

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