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A tradeoff analysis between socio-economic efficiency and environmental performance of irrigated agriculture

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Abstract: European irrigated agriculture is very important in economic, social and environmental terms. A linear programming model that simulates the farmers' behaviour in cropping selection was used to evaluate the impact on farm performance of intervention measures, namely: 1) volumetric pricing; 2) abstraction quota restrictions that might be used to ration water and/or increase water use efficiency. The consequences of these policy mechanisms were evaluated, using two conflicting objectives. The first objective enabled to maximise the farmers' profit, while the second one represents the regulators' perspective, to ration water more efficiently by minimising the irrigated water use. The tradeoff analysis between the socio-economic efficiency and the environmental performance revealed the fragility of the farming systems in water scarcity. The results highlight the need for a more careful balance of water conservation and rural development objectives. The approach is illustrated using a case study on irrigated agriculture in East Midlands of England.

Keywords: bi-objective model; agricultural planning; sustainability; irrigation; licensing; water pricing.

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1 Introduction

It is evident that all OECD countries rely mostly on regulatory requirements to address environmental issues in agriculture (OECD, 2010). Environmental regulations and water efficiency standards are the most common public policy instrumentsimposed to irrigated agriculture to promote structural changes to facilitate a sustainable development (Stevens, 2011). Both the European legislation (EU, Water Framework Directive 2000/60/EC) and the national legislation (Water Act, 2003) seek to ensure better abstraction control and greater environmental protection. Nevertheless, it is extremely important to evaluate the feasibility and the impact of the potential alternative policy instruments onthe irrigated agriculture.

In England, water resources are managed by the Environment Agency (EA, 2013). Insome parts of England like the East Midland district,spray irrigation may account less than 1% of the total water abstracted, however, this water is necessary for the production of high value vegetables and potatoes when resources are most limited. Moreover, given that this water is used by crops or lost by evaporation, it is appreciated to have a much greater impact on the environment compared to other abstraction where water is returned after it has been used (EA, 2009). Growing pressure on water resources is leading to increasing restrictions on abstraction for irrigation and consideration of the use of economic instruments, such as increased abstraction charges and/or tradable licences, to restrict demand and encourage wiser use of water (EA, 2009). There are, however, significant concerns regarding the impacts that such legislation might have on the sustainability of production, particularly in key agricultural commodity sectors, such as the potato industry (BPC, 2003).

From a methodological point of view, our approach is based on multiobjective programming, which tries to simultaneously optimise several conflicting objectives. The problem analysed here can be deduced from the variety of criteria that are taken into account by farmers when they are planning their productive activities. Thus, resource allocation at the farm level (land, water, labour, etc.) implies the simultaneous optimisation of several conflicting criteria, and the simulation of more realistic decision-making processes will lead to a closer scenario simulation and, consequently, provide the necessary information for a more rational policy-making procedure.

The use of multicriteria programming techniques to aid decision-making is inherent in studies undertaken to solve farm management problems (Romero and Rehman, 2003). Therefore, the multiobjective models can be considered as the rule rather than the exception to support decision-making in agriculture (Davijani et al., 2016; Galán-Martín et al., 2016; Lalehzari et al., 2016; Ortuno and Vitoriano, 2011). The construction of models to simulate farmers' behaviour is associated with a tradeoff between the model's capability to provide numerical results for policy evaluation and its coherence with basic economic principles (Gutiérrez-Martín et al., 2014). Bournaris et al. (2015) present a goal programming model that supports irrigation water-use and eco-friendly decision process in agricultural production planning. Manos et al. (2006) use utility functions in a multiobjective framework to analyse the farmers' behaviour and the socio-economic and environmental implications of alternative fertiliser pricing policies. Bartolini et al. (2010) present a multiobjective optimisation model to find optimal water distribution scenarios in irrigated agriculture. Gomez-Limon and Martinez (2006) propose a multiobjective model at basin level to determine the optimal crop mix on irrigated farmland taking into consideration the irrigation water market and farmers' welfare.

Our aim is to explore the likely impact of two alternative intervention measures, namely abstraction quota restrictions and volumetric pricing that may beutilised to ration water and/or increase water use efficiency. We evaluated irrigation using selected economic, social and environmental indicators of performance, including the value of water used for irrigation. The consequences of the intervention measures were evaluated, using a bi-objective linear programming model that was developed to simulate the farmers' decisions in response to policy changes. For a selection of scenarios, the set of optimal solutions is discovered and tradeoffs between the policy objectives are presented along with their associated production patterns. The tradeoff analysis is fundamental to multicriteria models and derives from the idea that resources are limited. Accordingly, to obtain more of one scarce resource, an individual or society collectively must give up some amount of another scarce resource. This procedure is based on the principle of opportunity cost. Our tradeoff analysis applies these principles to derive information about the sustainability of irrigated agriculture, by quantifying the inter-relationships among sustainability indicators implied by the intervention measures in irrigated water use and the economic behaviour of farmers.

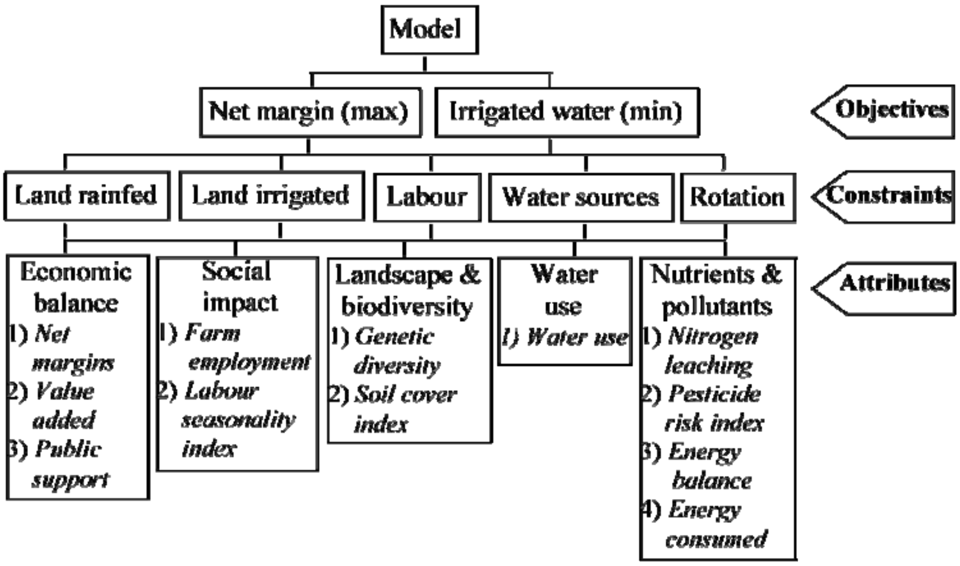
The originality of our approach lies more in the purpose to investigate and clarify the complex relationships and interactions between socio-economic efficiency and environmental performance of irrigated agriculture. Indeed, the interest of this article lies in the association of different disciplines relating to the problems of land use, water management and environmental protection by investigating the role of sustainability indicators in improving practices and outcomes. Yet, our approach is quite innovative as it aims to provide descriptive models rather than normative farm or regional planning, as most of the models found in the literaturedo.

The structure of this paper is as follows. Section 2 presentsthe mathematical programmingmodel and describes the conceptual settings of the tradeoff analysis. Section 3 describes the case study and data sources. Sections 4and 5 present the main findings and discuss the results of the empirical analysis. Finally, our conclusions are given.

2 Multicriteria mathematical programming

The linear programming model that addresses the impacts of water pricing and abstraction quota restrictions on agricultural irrigation is outlined in Figure 1.

Figure 1 Objectives, constraints and attributes of the bi-objective model



The detailed mathematical formulation of the developed model is as follows:

2.1 Decision variables

The key variable is X_C^K which is defined as the hectares dedicated to crops *c* of irrigation type *k*, where *k* = {*I*: Irrigated, or *R*: Rainfed}. The remaining decision variables are: CL_t, the hours of casual labour during the peak months *t* = {1,…,12}; *Ws*, the tons of water used according to water source were *s* = {Surface Summer, Surface Winter, Ground Summer, and Ground Winter}.

2.2 Objectives

Maximisation of net margin, which is defined as the difference between revenue and total (variable and fixed) costs:

$$\begin{aligned}\max \sum_k \sum_c X_c^k \cdot GM_m^k - \sum_k \sum_c X_c^k \cdot \left(MVC_c^k + MFC_c^k\right) \\ - \sum_t CL_t \cdot HourPay - \sum_s W_s \cdot TC_s\end{aligned} \quad (1)$$

were, the first term of (1) represents the gross margin, the second term is the fixed (MFC_c^k) and variable (MVC_c^k) machinery costs for crop *c* of type *k*. The following term concerns the casual labour costs (were: *HourPay* is the payment per hour for seasonal labour) and the last term represents the water resource related costs (TC_s). Note that net margin is a good estimator of profit, given the commercial nature of irrigation investment and the fact that contractors are engaged in many farm operations, it is deemed a more appropriate estimator of relative profitability. Thus, the maximisation of profit in the short-run is equivalent to the maximisation of net margin.

Satisfaction of irrigation water demand, then the objective to be minimised is:

$$\min \sum_{c} X_C^I \cdot WATERDEM_c \tag{2}$$

where $WATERDEM_c$ is the quantity of water required by irrigated crops in the farming system.

Major Constraints

Land restriction for rainfed crops (including set aside):

$$\sum_{c} X_c^R \leq LAND_R \tag{3}$$

where $LAND_R$ represents the total cultivation area for rainfed crops.

Land restriction for irrigated crops:

$$\sum_{c} X_c^I \leq LAND_I \tag{4}$$

where $LAND_I$ represents the total cultivation area for irrigated crops.

Water demand and water sources:

$$\sum_{c} X_c^I \cdot WATERDEM_c = \sum_{s} W_s \tag{5}$$

Labour demand for every month t:

$$\sum_{k} \sum_{c} X_c^k \cdot LAB_{\mathrm{ct}}^k \leq A.V.L.R._t + CL_t \forall t \tag{6}$$

where LAB_{ct}^k represent the hours of labour needed for the for the type k of crop c during month t and $AV.L.R.t$ represent the hours of labour provided by regular employees during month t.

All decision variables must be non-negative:

$$X_{\mathrm{c}}^k, \mathrm{AV.L.R.}_{\mathrm{t}}, CL_t, W_s, I_m \geq 0 \ \forall c, k, t, s, m \tag{7}$$

2.3 Rotation and set aside constraints

Let C represent the complete set of corps c cultivated in the farming system that described in Section 3. In that case C = {*SWH*: Spring Wheat, *WWH*: Winter Wheat, *WWH2*: Winter Wheat 2, *WBA*: Winter Barley, *OSR*: Oilseed rape, *FBN*: Field Beans, *CPS*: Peas (combined), *SBG*: Sugar beet, *POT*: Potatoes, *VPS*: Vining peas, *SA*: Set aside} then we have:

Crop rotation for potatoes (once every six years):

$$\sum_k \sum_c X_c^k \geq 6 \cdot X_{POT}^I \tag{8}$$

Since potatoes should be cultivated at most once every six years in the same land, at most 1/6 of the total land is dedicated to potatoes, while at least 5/6 of the total land is dedicated to all the other crops. Similarly, the next constraints represent same features.

Crop Rotation for Combined crops (can be cultivated on the same land once every 2 years):

$$\sum_k \sum_c X_c^k \geq \left(X_{POT}^I + X_{SBG}^I + X_{VPS}^I \right) \tag{9}$$

Crop rotation for sugar beet (once every four years):

$$\sum_k \sum_c X_c^k \geq 4 \cdot \left(X_{SGB}^R + X_{SBG}^I \right) \tag{10}$$

Crop rotation for field beans, peas (combined), oilseed rape (once every five years) and for Vining peas (once every three years):

$$\sum_k \sum_c X_c^k \geq 5 \cdot \left(X_{FBN}^R + X_{CPS}^R + X_{OSR}^R \right) + 3 X_{VPS}^I \tag{11}$$

Compulsory land (ha) for set aside:

$$X_{SA}^R = 1/10 \cdot \left(LAND1 + X_{WWH}^I \right) \tag{12}$$

Land dedicated to 2nd crop of winter wheat (Winter Wheat 2):

$$X_{WWH}^R + 0.5 \cdot X_{WWH2}^R + X_{SWH}^R + X_{WBA}^R + X_{WWH}^I \leq LAND1 + LAND2 \tag{13}$$

2.4 Attributes

The term 'attribute' is often used in multicriteria models to denote any relevant indicator that the analysis considers. These variables neither constrain the model nor are considered for optimisation by the decision maker, but they are relevant measures for the policymakers and the society to quantify the impact of the policy scenarios in the system performance. The above bi-objective model has been developed in order to provide the attribute values directly from the decision variables.

The selected attributes are based on the social, economic and environmental indicators proposed by the OECD (2001) and the agri-environmental indicators developed by the Commission of the European Communities (2006) to monitor the environmental concerns into the common agricultural policy. The attributes were grouped under the following five general sustainability components: Economic balance; Social impact; Landscape and biodiversity; Water use; and Nutrients and pollutants. The corresponding agricultural sustainability attributes along with their definitions are presented in Table 1.

Table 1 Definition of model attributes

Attribute	*Definition*
Economic balance	
Netmargins	Net revenues (margin) in £/ha
Valueadded	Net revenues less support in £/ha
Publicsupport	Area payments, direct subsidies, agri-environmental payments in £/ha
Social impact	
Farm employment	Totallabour hours (per month)
Labour seasonality index	Variance of monthly labour hours
Landscape and biodiversity	
Genetic diversity	Number of crops cultivated in the farm
Soil cover Index	Percentage of crop area covered by plantation
Water use	Volumes of water used in m^3/irrigable ha
Nutrients and pollutants	
Nitrogen leaching	Estimate of nitrogen emissions (kg/ha) to surface water
Pesticide risk index	Calculated by the model developed by Hollis and Brown (1994)
Energy balance	Energy produced by crop minus energy consumed
Energy consumed	Energy used by crop(fertilisers, pesticides, seeds, labour, electricity and fuel use, and machinery replacement and maintenance)in MJ/ha

2.5 Multiobjective method

In order to analyse the tradeoffs between the conflicting objectives of the problem described above, we apply the constraint method (Steuer, 1986). This method optimises one of the objective functions while the others are required to have specified upper bounds. The upper bounds of these constraints are given by the ε-vector and, by varying it, the exact Pareto frontier can be generated.

Specifically, the impact of abstraction quota restrictions (licence mechanism) was studied by initially estimating the maximum water demand for irrigation when its availability is not restricted. Then the Pareto solutions were generated by consecutively reducing the water availability (compared to maximum needed) by 10%. Alternatively, using the other intervention measure (price mechanism) the Pareto solutions were generated by consecutively increasing water fee to Regulator by 0.25 and 0.025 £/m^3 for summer and winter water, respectively.

The model was calibrated using primary data collected from the surveyed farms described belowand validated against the actual behaviour of farms seen as a combination of farming activities (rotation and irrigation choices). Validation experiments showed as well that the bi-objective model outputs were close enough to the real world outcomes. In addition, a sensitivity analysis was also performed in the constructed model, which confirms that the values of parameters estimated are reasonably robust.

3 Description of the case study and data sources

The production of field scale vegetables using irrigation is important on the lighter soils of the East Midlands of England. Potatoes and sugar beet are the main irrigated crops (Table 2). Crop rotations require a minimum six years between potato crops and four years between sugar beet. Cereals are the main break crop in the irrigation cycle. Most irrigation involves mobile rain guns and booms. The overall average farm size for mixed cropping farms is 193 ha, and 320 ha for those farms of 200 ha and above (Seabrook and Johnson, 2002).

Table 2 Typical cropping pattern for East Midlands farm

	% of land
Cereals	56.37
Oilseed rape	3.46
Potatoes	2.90
Sugar beet	8.93
Vining peas	2.72
Protein peas	3.81
Winter beans	2.22
Horticultural crops	0
Other sale crops	3.43
Total sale crops	83.89
Temporary grass	0.81
Permanent grass	4.20
Fodder crops	0
Rough grazing	0
Total forage	5.01
Bare fallow/land let/set aside	7.87
Woodland	0.84
Buildings and roads	2.39
Total area	100

Source: Seabrook and Johnson (2002)

Information on crop yields, crop prices, crop area-payments, labour and machinery costs are taken from a range of sources, notably Nix (2000, 2002), Leiva and Morris (1997) together with data from a national farm survey of irrigation practices (Weatherhead and Danert, 2002). Crop prices and yields are derived from trends over the preceding five year period using published sources (DEFRA, 2002), assuming premium quality for the irrigated crops (Weatherhead et al, 2002).

Irrigation needs (expressed as depths of water applied) for each crop type have been estimated using an irrigation scheduling water balance model irrigation water requirements (IWR) developed by Hess (1996). Irrigation costs included both fixed and variable costs and were calculated according to the water source (surface or ground water) and storage system (none, reservoir lined and unlined), while only trickle irrigation was considered as infield system.

Estimates of nitrogen and phosphorus emissions (kg/ha) to surface water are obtained using an export coefficient model (Abdelsafae, 1998) in accordance with industry recommended application rates, and taking into account local soil and climatic conditions (ABC, 2000; Nix, 2000, 2002). Estimates of energy inputs, including fertilisers and pesticides, seeds, labour, electricity and fuel use, and machinery replacement and maintenance are obtained from various published literature, including ABC (2000), Audsley (1997), Chadwick (1999), Hülsbergen et al. (2001), Nix (2000, 2002) and Wells (2001). The pesticide risk index was calculated by the model developed by Hollis and Brown (1994) taking into account the industry recommended application pesticide rates for each crop.

This availability of water was based on the average values (the 10th driest year in 20 irrigation years). The financial performance of irrigation is very sensitive to the prices obtained for irrigated crops. As previously mentioned, most irrigation in England is focused on quality assurance (Morris et al., 1997). A review of potato, vegetable, fruit and salad crop prices showed that prices for first quality produce are typically 40% to 50% above prices for average or second grade produce (DEFRA, 2016). However, in this case study, it was assumed that farmers for their irrigated crops attain overall average prices without the additional premium associated with first quality.

According to the above, we assume that licensed quantities of water were adequate to meet crop water requirements. The irrigated area, set at 50% of the command area, was constrained by system capacity and crop rotation requirements. The farming system was then subject to incremental restrictions on water availability and to increases in water abstraction charges. The key characteristics of the case study are presented in Table 3.

Table 3 Characteristics of the East Midlands case study farming system

Location	Midlands, (Gleadthorpe) , average annual rainfall 622 mm; Max Et 3.6 mm/day; soils sandy loams
Area	300 ha
Command area	300 ha
Irrigated area/year	150 ha
Cropping options	Rainfed: winter wheat 1st crop, winter wheat 2nd crop, spring wheat, winter barley, winter field beans, winter oil seed rape, combined peas, sugar beet, set-aside
	Irrigated: winter wheat, potatoes, sugar beet, vining peas
Crop constraints	Rotation for cereal/ non-cereal break crops; potatoes once every six years; Sugar beet once every four years; field beans, peas (combined), oilseed rape once every five years; vining peas once every three years
Water supply	Borehole (40%) and surface (60%) sources. Summer 60% Winter 40% of total licenced quantities
Irrigation system	Unlined reservoir for winter storage, mobile hose-reel system. 25mm capacity, 7 day interval
Typical irrigation water depths mm	125–220 mm on potatoes depending on needs
Labour and machinery	1 worker at least regular labour plus casual for peak periods, fully mechanised system

Table 4 Farm performanceaccording to selected sustainability indicators when the price of water fees is increasing*

Water price (£/m^3/)		*Economic balance*			*Social impact*		*Landscape and biodiversity*		*Water use*	*Nutrients and pollutants*			
Summer	*Winter*	*Net margins (£/ha)*	*(Value added) (£/ha)*	*Public support (£/ha)*	*Farm employment (hrs/ha)*	*Labour seasonality index*	*Genetic diversity*	*Soil cover index*	*Water use (m^3/irrigable ha)*	*Nitrogen leaching (Kg N/ha*	*Pesticide risk index*	*Energy balance (MJ/ha)*	*Energy consumed (MJ/ha)*
0	0	824.6	704.5	120.1	20.3	32.1	5.0	4.7	1,058.3	26.2	1,05.3	9,1597.0	2,0362.3
0.01688	0.00169	818.9	698.8	120.1	20.3	32.1	5.0	4.7	1,058.3	26.2	1,05.3	9,1597.0	2,0362.3
0.05	0.005	809.3	689.3	120.1	20.3	32.1	5.0	4.7	608.3	26.2	1,05.3	8,9657.9	2,0051.4
0.15	0.015	790.3	658.2	132.1	19.8	37.4	5.0	4.8	553.3	26.8	1,09.6	9,4020.1	2,0367.7
0.75	0.075	773.1	631.7	141.5	19.4	41.2	5.0	4.8	516.7	28.3	1,11.5	9,6163.1	2,0518.7
16.75	1.675	359.8	209.3	150.5	17.9	41.8	5.0	4.8	417.4	28.7	1,08.9	9,3954.8	2,0087.3
17.25	1.725	351.5	169.2	182.3	12.4	58.1	5.0	4.7	66.8	29.8	99.5	8,6156.8	1,8563.7
20.5	2.05	341.2	152.9	188.3	11.4	67.2	4.0	4.7	0.0	30.1	97.7	8,4672.2	1,8273.6

Note: *For the cases where the increase the price of water fees resulted to changes to water use.

Table 5 Farm performance according to selected sustainability indicators when water availability is constrained

Water availability	*Economic balance*			*Social impact*		*Landscape and biodiversity*		*Water use*	*Nutrients and pollutants*			
	Net margins (£/ha)	*(Value added) (£/ha)*	*Public support (£/ha)*	*Farm employment (hrs/ha)*	*Labour seasonality index*	*Genetic diversity*	*Soil cover index*	*Water use (m^3/irrigable ha)*	*Nitrogen leaching (Kg N/ha*	*Pesticide risk index*	*Energy balance (MJ/ha)*	*Energy consumed (MJ/ha)*
100%	818.9	698.8	120.1	20.3	32.1	5.0	4.7	1,058.3	26.2	105.3	91,597.0	20,362.3
90%	818.1	698.1	120.1	20.3	32.1	6.0	4.7	952.5	26.2	105.3	91,141.0	20,289.1
80%	817.4	697.3	120.1	20.3	32.1	6.0	4.7	846.7	26.2	105.3	90,684.9	20,216.0
75%	817.1	697.0	120.1	20.3	32.1	6.0	4.7	793.8	26.2	105.3	90,456.9	20,179.5
70%	816.7	696.6	120.1	20.3	32.1	6.0	4.7	740.8	26.2	105.3	90,228.8	20,142.9
60%	816.0	695.9	120.1	20.3	32.1	6.0	4.7	635.0	26.2	105.3	89,772.7	20,069.8
50%	812.6	674.3	138.3	19.6	39.8	6.0	4.8	529.2	27.8	110.9	95,439.5	20,460.2
40%	730.3	580.3	149.9	18.0	41.8	5.0	4.8	423.3	28.6	109.0	94,096.2	20,104.4
30%	635.8	476.2	159.5	16.3	43.5	5.0	4.8	317.5	29.0	106.2	91,740.2	19,646.7
25%	588.4	424.1	164.3	15.5	45.0	5.0	4.7	264.6	29.2	104.8	90,562.1	19,417.9
20%	541.1	372.0	169.1	14.7	47.2	5.0	4.7	211.7	29.4	103.4	89,384.2	19,189.0
10%	446.5	267.8	178.7	13.0	54.2	5.0	4.7	105.8	29.7	100.5	87,028.2	18,731.3
0%	341.2	152.9	188.3	11.4	67.2	4.0	4.7	0.0	30.1	97.7	84,672.2	18,273.6

Table 6 Crop Pattern when water price (£/m^3)is increasing*

Summer water price		*RAINFED crops*									*IRRIGATED crops*			
		1st winter wheat	*2nd winter wheat*	*Spring wheat*	*Winter Barley*	*Winter field beans*	*Combined peas*	*Winter oil-seed rape*	*Sugar beet*	*Set aside*	*Winter wheat*	*Potatoes*	*Sugar beet*	*Vining peas*
0	0	136.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.6	0.0	50.0	75.0	25.0
0.01688	0.001688	136.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.6	0.0	50.0	75.0	25.0
0.05	0.005	136.4	0.0	0.0	0.0	0.0	0.0	0.0	75.0	13.6	0.0	50.0	0.0	25.0
0.15	0.015	150.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	15.0	0.0	50.0	0.0	10.0
0.75	0.075	150.0	0.0	0.0	0.0	0.0	0.0	9.1	75.0	15.9	0.0	50.0	0.0	0.0
16.75	1.675	150.0	0.0	0.0	0.0	0.0	0.0	17.8	75.0	16.8	0.0	40.4	0.0	0.0
17.25	1.725	150.0	0.0	0.0	0.0	0.0	0.0	48.7	75.0	19.9	0.0	6.5	0.0	0.0
20.5	2.05	150.0	0.0	0.0	0.0	0.0	0.0	54.5	75.0	20.5	0.0	0.0	0.0	0.0

Note: *For the cases where the increase the price of water fees resulted to changes to water use.

Table 7 Crop Pattern when water availability is constrained

Water availability	*RAINFED crops*									*IRRIGATED crops*			
	1st winter wheat	*2nd winter wheat*	*Spring wheat*	*Winter Barley*	*Winter field beans*	*Combined peas*	*Winter oil-seed rape*	*Sugar beet*	*Set aside*	*Winter wheat*	*Potatoes*	*Sugar beet*	*Vining peas*
100%	136.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.6	0.0	50.0	75.0	25.0
90%	136.4	0.0	0.0	0.0	0.0	0.0	0.0	17.6	13.6	0.0	50.0	57.4	25.0
80%	136.4	0.0	0.0	0.0	0.0	0.0	0.0	35.3	13.6	0.0	50.0	39.7	25.0
75%	136.4	0.0	0.0	0.0	0.0	0.0	0.0	44.1	13.6	0.0	50.0	30.9	25.0
70%	136.4	0.0	0.0	0.0	0.0	0.0	0.0	52.9	13.6	0.0	50.0	22.1	25.0
60%	136.4	0.0	0.0	0.0	0.0	0.0	0.0	70.6	13.6	0.0	50.0	4.4	25.0
50%	150.0	0.0	0.0	0.0	0.0	0.0	6.0	75.0	15.6	0.0	50.0	0.0	3.4
40%	150.0	0.0	0.0	0.0	0.0	0.0	17.3	75.0	16.7	0.0	41.0	0.0	0.0
30%	150.0	0.0	0.0	0.0	0.0	0.0	26.6	75.0	17.7	0.0	30.7	0.0	0.0
25%	150.0	0.0	0.0	0.0	0.0	0.0	31.3	75.0	18.1	0.0	25.6	0.0	0.0
20%	150.0	0.0	0.0	0.0	0.0	0.0	35.9	75.0	18.6	0.0	20.5	0.0	0.0
10%	150.0	0.0	0.0	0.0	0.0	0.0	45.2	75.0	19.5	0.0	10.2	0.0	0.0
0%	150.0	0.0	0.0	0.0	0.0	0.0	54.5	75.0	20.5	0.0	0.0	0.0	0.0

4 Results

The overall impacts of both mechanisms to reduce water use incrop pattern and farm performance, according to selected sustainability indicators are presented in Table 4 to Table 7.

More specifically, according to Figure 2, which displays the changes on irrigated crop pattern, and Figure 3, which presents the marginal value of water at different levels of use compared to the unconstrained situation, it is evident that the price mechanism cannot easily achieve specific reductions of water consumption. For example, water demand is 1058 m^3/irrigable ha when winter water fee is £0.00169/m^3 and 608 m^3/irrigable ha at £0.005 /m^3. Setting the winter water fees by 0.075 £/m^3 (and making summer water not available because of its high price) it results in reducing the water use by almost 50%, as vining peas and irrigated sugar beet are very sensitive to water price and are marginally more profitable than rainfed alternative crops. However, the winter water fee should be as high as £1.725/m^3 to reduce further the water use, because potatoes benefit a lot from being irrigated in terms of quality and yield gains.

Figure 2 Irrigated crops pattern of water licence quantity restrictions and abstraction charges (see online version for colours)

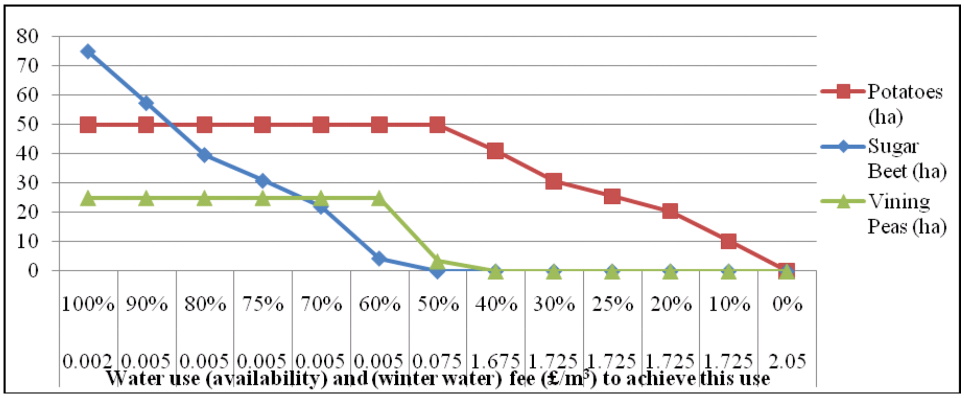


Figure 3 Water demand (expressed as a percentage of unrestricted water requirements, i.e. 1058 m^3/irrigable ha), by theoretical abstraction charges (see online version for colours)

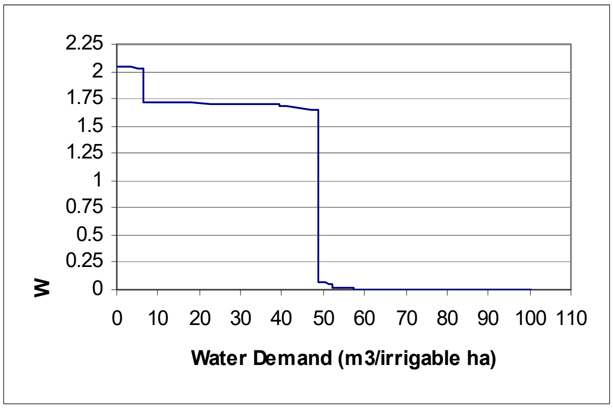
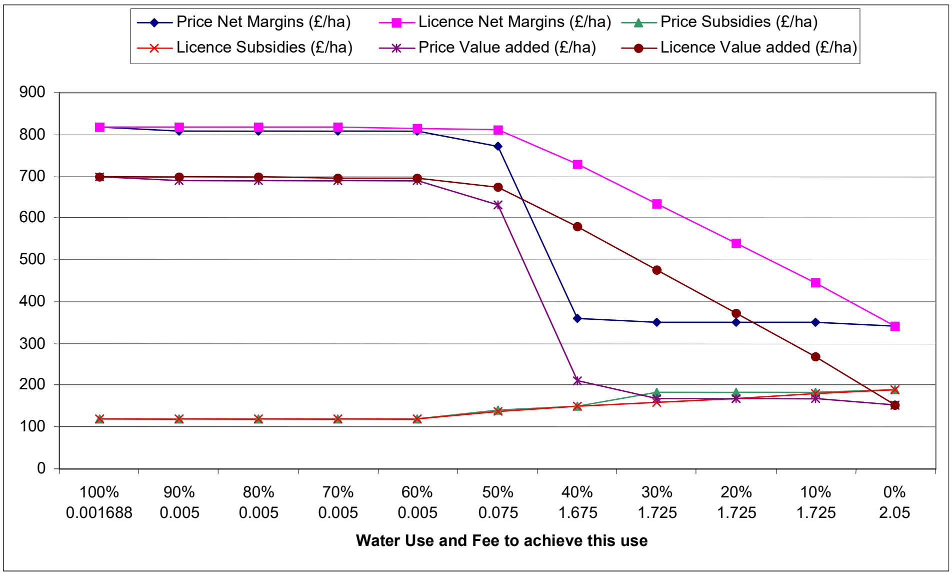


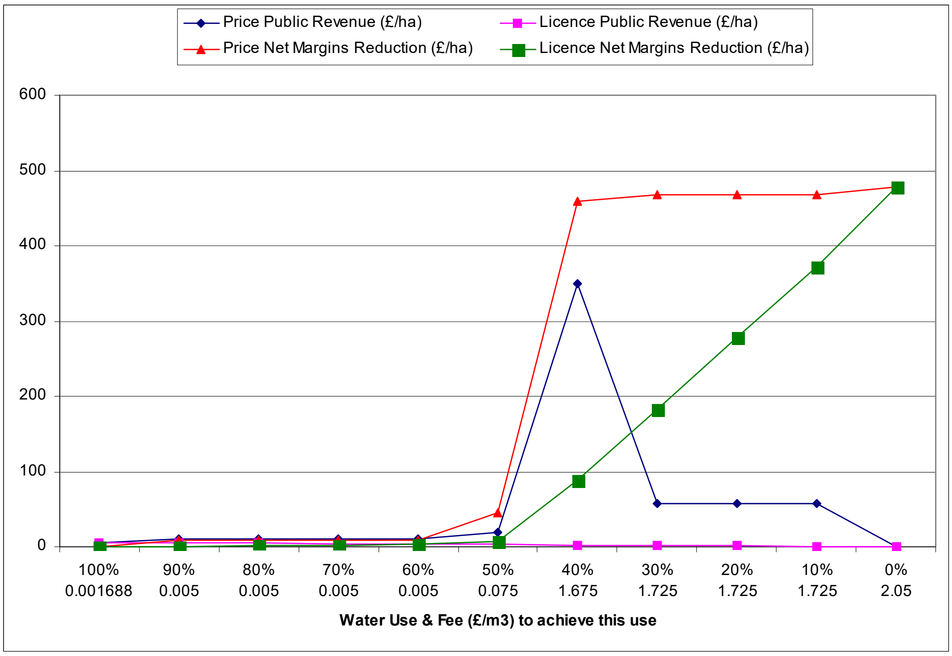
Figure 4 presents the impact of pricing and licensing interventions on farm net margins, value added and subsidies (£/ha), while the effects of water usereduction on farm net margins and Water Resource Agency revenues are displayed in Figure 4. The economic impacts of both mechanisms are almost the same when water consumption is reduced by 50%, which may be achieved by increasing the winter water price to £0.075/m^3, due the fact that irrigated vining peas and sugar beet are marginally more profitable than rainfed alternative crops. However, a reduction of water use from 50% to 40% of unrestricted water requirements would result in significant income reductions for farmers and transfer of income to the regulator in case the price mechanism is applied, as net margins drop dramatically from £773/ha when water fee is £0.075/m^{3}to £351.5/ha at £1.725/m^3 of winter water fee (Figure 4). This happens because potatoes are significantly much more profitable than their substitutes, the combinable crops. Thus, the price mechanism cannot easily achieve specific reductions of water consumption and, in fact, water consumption is stable when winter water fees range from £0.075/m^3 to £1.650/m^3 (Table 4). On the contrary, employing the licence mechanism a similar reduction in water consumption would incur a drop in net margins only from £812.6/ha to £730.3/ha. Hence, with the licence mechanism, it is feasible to attain specific reductions of water consumption, and moreover, the farm net margins are reduced in an almost linear way by the subsequent reduction of water consumption (Figure 5). Moreover, given that when reducing the availability of irrigated water, irrigated crops are substituted by combinable crops, it is inevitable that farm income would rely significantly more on subsidies, both in absolute and, even more, in relevant terms. However, subsidies are almost the same when limiting water availability by both mechanisms.

Figure 4 Impact of water licence quantity restrictions and abstraction charges on net margins and value added (see online version for colours)



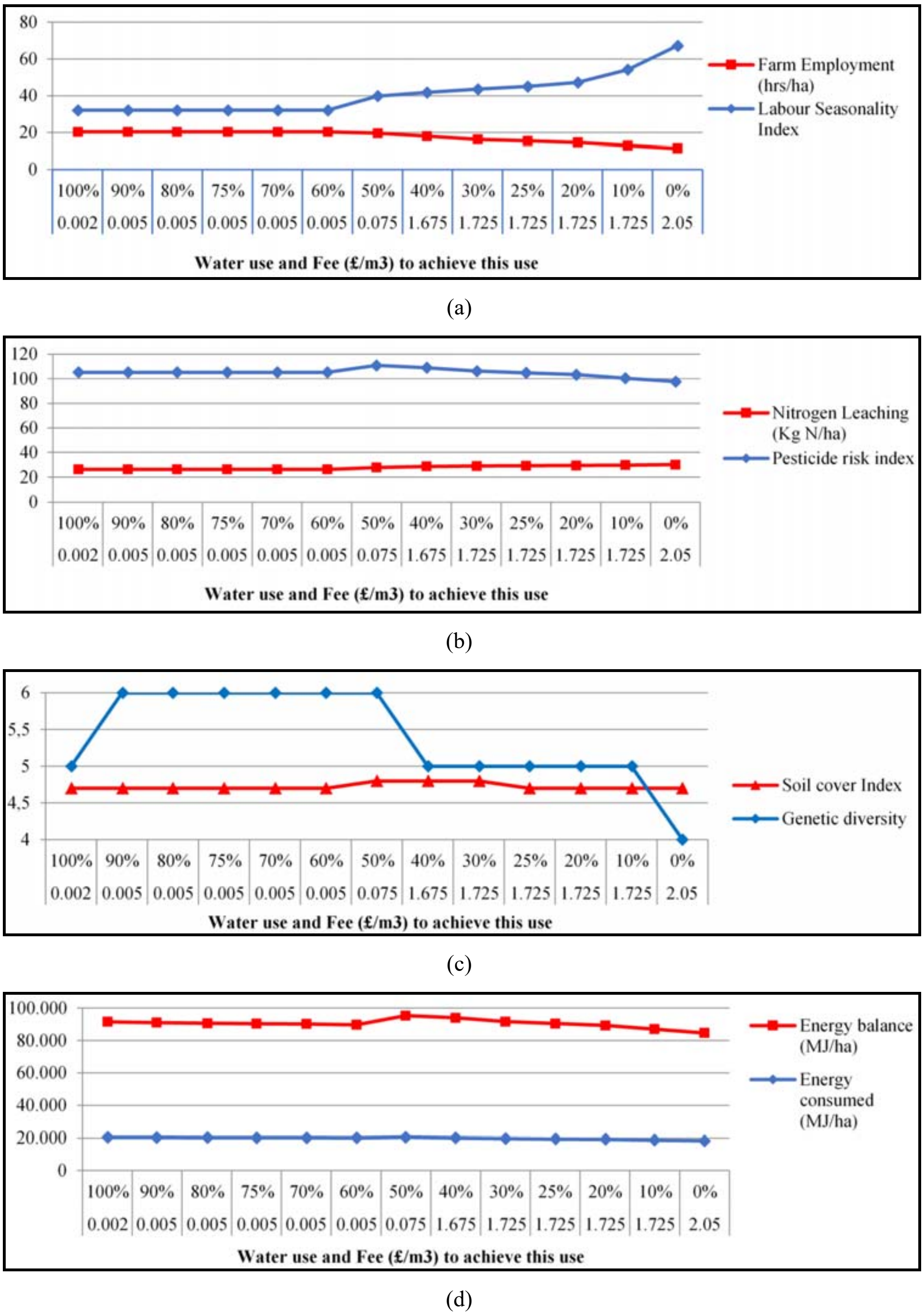
Regarding the social impacts, the labour use significantly decreases as water fees increase, because of switching from vegetables to combinable crops [Figure 6(a)]. It is stable at 17.3 hours/ha when winter water fee ranges from 17.5p/m^3 to 170p/m^3. However, there is a dramatic drop in labour use when winter water fee reaches £1.725/m^3. Labour seasonality is relatively low until the winter water fee is £1.70/m^3. In terms of the licence mechanism, labour use decreases in an almost linear trend, and it is almost 45% less when water availability is 10% than 100%. Labour seasonality initially is stable with water availability restriction up to 60%, however, it increases very considerably after that level in an almost linear trend. This is due to the replacement of irrigated crops by rainfed which display higher labour seasonality than irrigated potatoes, sugar beet and vining peas.

Figure 5 Impacts of water licence quantity restriction and abstraction charging mechanisms on incomes to farmers and water resource agency (see online version for colours)



Nitrate leaching ranges from 26 to 36 Kg N/ha, increasing initially, being stable when winter water fee ranges from 17.5p/m^3 to 170p/m^3, and reducing again at higher water fees. This is because of the changes in the cropping pattern mix [Figure 6(b)]. Pesticide leaching fluctuates a lot between 0.001688 and £0.15/m^3 of winter water fees, which reflects the level of participation of sugar beet, vining peas and oilseed rape in the cropping mix. After this point, the pesticide leaching index is rather stable. Regarding the licence mechanism, nitrate leaching ranges from 26 to 36 Kg N/ha, increasing initially and reaching a peak at 50% water availability, and reducing again to 30 Kg N/ha. This is due to the changes in the cropping pattern mix. Pesticide leaching fluctuates a lot between full and 60% water availability, which reflect the level of participation of sugar beet, vining peas and oilseed rape in the cropping mix. After this point, the pesticide leaching index is rather stable.

Figure 6 Social and environmental impacts of water licence quantity restriction and abstraction charging mechanisms, (a) farm employment and labour seasonality (b) nitrate leaching and pesticide risk (c) soil cover and genetic diversity (d) energy balance and energy consumed (see online version for colours)



Soil cover index, though fluctuating a bit between 0.075 and £1.725/m^3 of winter water fee, is rather stable [Figure 6(c)], indicating that water use restrictions have marginal effects on soil erosion risk. The number of crops included in the crop pattern initially increases from 5 to 6, when water availability reduces to 90%, however, it returns to 5 when water availability ranges from 40% to 10% and it becomes 4 when no water is available.

Energy consumption and balance fluctuate relatively little between 100% and 50% of water availability, which reflects the level of participation of sugar beet, vining peas and oilseed rape in the cropping mix [Figure 6(d)]. After this point they drop by 10%, indicating that, in general, that limiting water availability by both mechanisms has little effect on energy issues.

5 Discussion

This study analysed the potential impacts of water pricing and regulation strategies on the performance of irrigated agriculture. It focused on these two water policy instruments given that voluntary actions, such as farmer agreement to limit abstractions during dry periods, might allow irrigators to devise individual coping strategies, but they usually require the threat of regulation in the background. Moreover, although public support for research, development and extension are likely to form an important part of the policy framework, they cannot readily contribute to rationing water use at the desired level.

The results of this study confirm the great value of irrigation water. From an economic perspective, compared to rainfed crops irrigated crops, in root and vegetable farming, enable farmers to attain higher net revenues per hectare, together with a lower absolute dependency on agricultural support payments. Irrigated cropping in root and vegetable farming, also, generates higher employment and, a lower degree of seasonal variation in employment, as it tends to be mechanised.

From an environmental perspective, the restriction of water availability has a marginal impact on the soil cover index and genetic diversity. Moreover, pollution risks are lower with irrigated cropping regarding nitrate leaching, as it increases by 15% in an almost linear way when water availability is constrained to zero. The contrary is the case for pesticide leaching, given that vegetables usually require higher application rates of pesticides than combinable crops, however, this reduction is around 7%. Energy consumption and energy balance are slightly reduced by 10% when all irrigated crops are removed from cropping pattern.

Water demand curve shows that the water marginal value price is initially stable, ranging from 0.29 to £0.40/m^3 when water availability is between 100% and 50%. Then it increases a lot ranging from 2.04 to £2.40/m^3 when water availability is between 40% and 0%. This is because around 50% of the water required was allocated to sugar beet and vining peas which are marginally more profitable than rainfed alternative crops. The high values of water marginal value price after this point are explained by the reduction of water used for potatoes, which benefit a lot from being irrigated in terms of quality and yield gains.

The comparison between the price and licence mechanism, when applied for water irrigation restriction, revealed that net margins and value added are considerably higher when the licence is used as an intervention mechanism to reduce water consumption than increasing water fees. Subsidies are the same for both intervention mechanisms.

Moreover, increasing the water fees results to higher net losses (public revenues – net margins reduction) than licence quotas. For example, water consumption could be reduced by 60% using licence quotas incurring £88.6/ha net losses, while with the price mechanism there would be a net loss of £467.4/ha. Thus, restrictions on abstraction licences may be a more effective and equitable mechanism to achieve beneficial change, although their enforcement may imply some additional costs. Some increase in abstraction charges, however, could help fund water resource management initiatives by the regulatory agency.

The research findings may provide useful insights to the implementation of the Regional Action Plan for the Midlands Region about Water Resources Strategy of Environment Agency (2009) which includes regional actions such as "Reflecting actual usage and licence trading" and "Water pricing" (EA, 2009). However, it should be mentioned that the Regional Action Plan for Midlands region states that "We recognise that some licences are needed for flexibility, such as water company licences that can be used in times of drought and agricultural licences which may not be used every year, and we will not request reductions on these licences" and that "Following national lead, we will work with abstractors to facilitate moves to implement alternative water pricing systems. We will try to ensure that changes to the system are fair and act as an incentive to using water resources more sustainably" (EA, 2009). Therefore, it is not surprising that it has been set a key priority for Midlands Region to "promote high-flow storage reservoirs to farmers with spray irrigation licences in over abstracted catchments to reduce current pressure on resources, increase resilience to climate change and improve biodiversity" (EA, 2009).

6 Conclusions

This paper aimed to analyse the complex relationships and interactions between socio-economic efficiency and environmental performance of irrigated agriculture. Specifically, its purpose was to investigate and clarifythe consequences concerning the rationing of water supply by examining the impacts on the sustainability of root and vegetable farms of two water policy instruments, namely restrictions on abstraction licences and increase on abstraction fees. To this end, a bi-objective linear programming model that simulates farmers' preferred behaviour was employed. The performance of the modelling tool developed suggests that it is well suited to dealing with real-world policy issues.

Our study confirms that the irrigated farm systems have substantial effects on farms' economic, social and environmental performance. More specifically, in economic terms, we can say that the irrigated farms in England have higher net margins and related farm incomes, and a lower degree of dependency on government subsidy compared to rainfed. In particular, the research results support the high marginal value of water in the East Midland case where water delivers significant benefits in terms of quality assurance on high value crops, such as potatoes. In social terms, we observe a higher employment rate and, a lower degree of seasonal variation in employment. Finally, in environmental terms, we observe the lower risk of nitrogen leaching is related to higher rates of potential pesticide pollution and in addition the higher energy consumption per ha, is related to higher net energy balance. Thus, irrigation systems appear to provide substantial economic and social benefits, but they are associated with mixed environmental performance, particularly associated with the standards of pollution control in intensive farming systems.

Altogether, the analysis revealed the fragility of the root and vegetable farming systems and the tradeoff between socio-economic indicators and environmental performance. This tradeoff can also be seen to a significant degree in the case of water as well. This highlights the need for a more careful balance of water conservation and rural development objectives.

The model developed may be a useful planning tool facilitating the competent authorities to examine alternative policy instruments and select the most appropriate that will ultimately ensure a more sustainable irrigated agriculture sector. However, since any alternative intervention to ration water supply in irrigated agriculture may be associated with additional social and economic costs to farmers, a set of effective incentives or compensations should be provided to them. Moreover, it should be mentioned that irrigation is not the single causative factor of farms' sustainable performance, as other factors beyond the scope of this study may also have an impact on it. Finally, as with any deterministic model, our research outputs are fully determined by the parameter values and the initial conditions. However, it is not feasible to know the distribution of parameter values and the high complexity of the irrigated agriculture systems would lead to extremely complex computational stochastic models.

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