CROP ROTATION IN THESSALY: BIO-ECONOMIC MODELING FOR EFFICIENT FARM MANAGEMENT

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ABSTRACT

This paper explores alternatives to cotton mono-culture in Thessaly, examining various rotations suitable to regional characteristics. Different farm management practices are considered applied to two types of soil. Current practices as well as best management practices (BMP) are compared, based on biological growth model estimations. Economic performance and environmental effects such as water deficit due to irrigation and nitrogen leaching are evaluated for a typical farm. Quantification of trade-offs between economic and environmental objectives, is attempted through bio-economic modeling. This approach can provide important information to farmers for selecting rotations and management practices but also to public decision makers for establishing agri-environmental measures.

RÉSUMÉ

Cet article explore les alternatives à la monoculture du coton en Thessalie, en examinant diverses rotations de cultures, adaptées aux caractéristiques régionales. Différentes pratiques de gestion d'exploitation agricole sont considérées, appliquées à deux types de sol. Les pratiques courantes aussi bien que des Pratiques de Gestion Optimale sont comparées, sur la base d'estimations du modèle biologique de croissance de plantes. Les performances économiques ainsi que les effets environnementaux, concernant l'irrigation et le lessivage de nitrates sont évalués pour l'exploitation de base. La quantification des arbitrages entre les objectifs économique et environnementaux est tentée à l'aide du modèle bio-économique. Cette approche peut fournir des informations importantes aux agriculteurs, pour le choix des rotations et des pratiques de gestion, mais également aux décideurs publics pour l'établissement des mesures agro-environnementales.

1. INTRODUCTION

Sustainability of resources is usually in conflict with profit maximization and is often neglected when short-term rent prospects prevail. This is the case in agriculture, given the long gestation periods of manifestation of environmental pollution, and the difficulties of determining pollution sources (non-point source pollution phenomena). In Thessaly, one of the most dynamic and endowed agricultural regions of Greece, cotton cultivation has significantly expanded these last fifteen years to cover more than 0.4 Gha today. Security of prices and public investments in irrigation infrastructure incited private investment concerning irrigation and mechanization of cultivation. As a result, traditional rotation schemes were abandoned and cotton mono-culture has dominated arable cropping, with negative effects on the environment from increased input use, namely fertilizers, water and pesticides. Aggregate cotton quantities produced have overwhelmed the Common Agricultural Policy maximum guaranteed quantities triggering co-responsibility penalties, resulting in lower subsidies on cotton price. This fact combined with unexpected events that often cause serious damage to harvests (exposed to excessive risk as farm income depends largely on one crop) raised farmers discontent and pushed them to seek alternative crop rotations for arable land.

A recent study, based on survey data on a sub-region of Thessaly plain, comparing 1989 and 1997 periods (Rozakis et al., 1999) has found evidence of farm income decrease. This is mainly due to the lower prices at the farm level in constant drachmas. Subsidies to cotton have decreased from 200 to 120 in the last five years in current Drs because of increased co-responsibility levies as produced quantities have boosted. On the other hand, excessive use of inputs are required to compensate soil impoverishment to keep cotton yields at high levels. Cotton mono-culture is in the origin of both these phenomena. Water over-consumption, nitrogen leaching and soil erosion related to intensive cultivation have caused negative environmental effects. These effects may result in increased costs to the farmers (aquifers depletion means deeper and more expensive drills, erosion affects soil productivity etc.) and to society (pollution of drinking water). As a matter of fact, nitrate groundwater pollution has been already observed in the plain of Thessaly (for instance in Nikea, which is among the few areas in Greece where EU norms of 50 mg N/l of groundwater(¹) are exceeded).

In order to attenuate negative environmental effects more reasonable farmer's management practices have been proposed which usually result in reduced profits. This paper examines alternative rotation schemes in order to estimate differences in input use, output produced and income generated as well as the extent of support needed to incite farmers shift to more sustainable alternatives. The first part of this paper consists of a detailed description of the case study physical environment that determines the actual and potential agricultural production. Potential yields are calculated for

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(¹) Increased nitrate levels impose external costs through drinking water contamination and eutrophication. This has led to the EC directive of 1991 which sets surface water and ground water nitrate concentration standards (Council Directive concerning the protection of waters against pollution caused by nitrates from agricultural sources, EC Official Journal, L375, 1).

the most important arable crops in the region by means of a comprehensive, deterministic crop growth model. In the next section, biological plant growth model and economic dimension are integrated through mathematical programming. Alternatives have been evaluated on the basis of single or multiple criteria. Main findings and discussion conclude the paper.

2. METHODOLOGY: THE BIO-ECONOMIC MODEL

The economics of crop rotations has been linked to LP models since the early years of linear programming. The crop rotation concept involves the exploitation of jointly beneficial interactions among individual crops. Modeling techniques used include predetermined rotation schemes but also methods that permit flexibility to the choice of rotations (El-Nazer and McCarl, 1986). Data on consequences of preceding crops and management strategies can be provided by biological models (Johnson et al., 1991) or estimated through regression techniques (El-Nazer and McCarl, ibid). Environmental problems have been extensively analysed by agricultural economists using mathematical programming methods (i.e., Moxey and White, 1994). Abundant literature exists on soil erosion, nitrate pollution and scarcity of water where multi-objective methods assist to determine trade-offs and to compare policy tools (Young et al., 1991, Pan and Hodge, JAE 1994, Zekri and Romero, 1992).

The incorporation of bio-physical models to farm economic models could provide information on ecological impact as well as effects on farm income of cultivation practice changes. Production functions are expressed in agronomic terms. This approach is already largely applied in the context of mathematical modeling to set-up bio-economic models (see for example Deybe, 1993, and Louhichi et al., 1999). It can go beyond traditional environmental economics paradigm and subscribe to ecological economics as it is based on multi-disciplinary work simulating co-evolving natural and socio-economic systems.

In this paper an integrated bio-economic model has been constructed having rotation activities as variables. These are defined here in terms of explicit crop sequences as presented in section 3.2 for the case study. Interactions of crop sequences under different rotations imply specific crop yield/input relationships. A SUCROS-based (Danalatos, 1993) crop-growth simulation model is used to predict crop yields that depend on preceding crops under different input levels (Supit et al., 1994). The crop growth model is based on a hierarchical order of land quality analyses and simulates system performance by the intercepted radiation, the temperature and the availability of water. The dynamic simulation of land use systems behavior employs the "state variable approach", in which dependent variable values are steady for the duration of every interval and reflect the state of the system. All values are adjusted after completion of the calculations of an interval. With this technique, interactions between quality-requirement combinations, positioned at different hierarchical levels, are accounted for automatically. The outcome of the calculations is biomass production figures, which serve as reference at lower hierarchical level, and corrections are made for the particular nutrient availability of the soil to reach this production potential. The model, which is based on QLE-Approach (Driessen and Konijn, 1992) was calibrated for Greek circumstances and applied for annual crops in Greece (Danalatos, 1993).

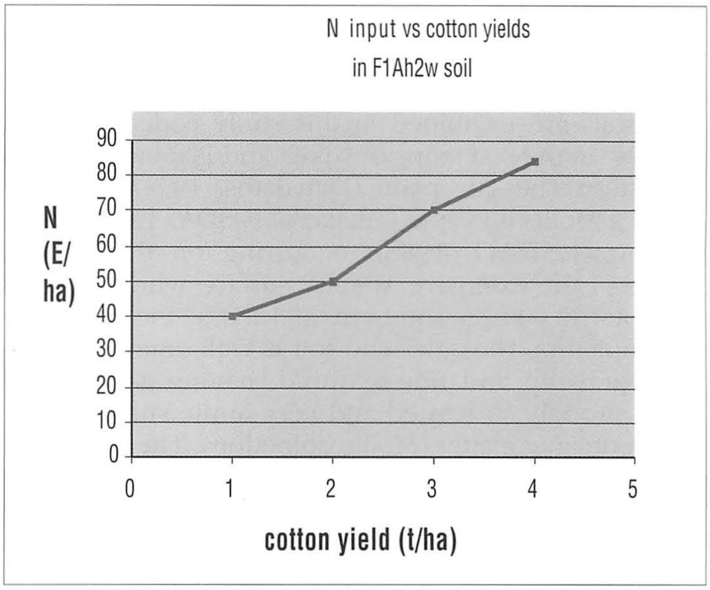

Figure 1.- Nitrogen input vs cotton yield response curve.

A mixed-integer LP model (**Annex I**) is formulated maximizing net farm income subject to agronomic and resource constraints (integer variables: rotations). To exclude complicated and not realistic rotation combinations, only one rotation can be selected for each type of soil along with cotton or maize mono-culture assuming that each parcel's soil quality is homogeneous. Land and water availability constraints are considered. Irrigation techniques are mutually exclusive.

Then detailed data on rotations are introduced in the model that can maximise farm income or minimise environmental impacts for a particular area with specific types of soils and management techniques and propose the optimal scheme. Environmental objectives can be water economy and N-input reduction. Nutrient input can be used as proxy of potential nitrate pollution. Results can be taken into account in the model transformed in discrete alternatives or piece-wise linear functions introducing binary variables to represent Nitrogen-yield relationship (**Figure 1**). The module of multi-criteria analysis that assists in exploring the consequences of the farmer's preferences and trade-offs between criteria is based on the "reference point" method (section 4).

3. CASE STUDY

3.1. Soils and management

Two soils are examined in this study coded 2Mt and F1Ah2w in the soil maps of Nikea and Platanoulia areas in eastern Thessaly plain (Danalatos, 1993). The first soil is a Mollisol (Typic Calcixerol [USDA, 1975]; Calcic Chernozem [FAO, 1988]) occurring on the bottom slopes of the extensive Tertiary surface which extends at about 40,000 ha southern of Larissa, the main city and capital of Thessaly. The soil is well drained, somewhat gravelly and fine-textured, having a 30-45 cm thick, strongly structured and very fertile surface layer, rich in organic matter (Mollic epipedon). The soil is currently used for wheat and occasionally (if water is available) for irrigated corn, maize and sugar beets, or potatoes.

The second soil (F1Ah2w) is an Alfisol (USDA, 1975), representing the higher soils on the Pleistocene terrace, i.e. an extensive, very gently sloping paleo-flood plain (of the Peneios river) covering half of the plain north of Larissa. The soil is deep, moderately well drained and clay textured. It contains an argillic horizon near or at the surface (surface erosion) over a calcic horizon at 70-90 cm depth. The soil is classified as Calcic Haploxeralf (USDA, 1975) or Calcic Luvisol (FAO, 1988). The soil is currently use for irrigated cotton, orchards (pears, almonds) or vineyards. On the Pleistocene terrace, irrigation water availability is not a limiting factor.

Irrigation management techniques such as overhead irrigation with large (gun) rotating sprinklers and drip irrigation are used alternatively as they involve different investment and operating costs and also result in different water consumption per hectare considered in this study. Irrigation with traveling guns became very popular in the last two decades because it involves minimum effort by the farmer. Important disadvantage is the high operating pressures involved resulting in high rainfall intensities and incipient ponding on many of the Thessaly soils including the soils on the Pleistocene terrace. Drip irrigation was applied at first in orchards (pears, apples, etc.) and vineyards of Thessaly producing excellent yields. From 1988 only few progressive cotton farmers applied drip irrigation in Thessaly. Today drip-irrigated cotton is common practice in many cases, resulting in a general increase in water efficiency and yield in the Thessaly region during the last decade.

The biological growth model provides non-linear relationships of N input vs. yields, based on the base uptake and the recovery fraction of the applied nutrient. These characteristics are approximated based on the measured chemical data of the soils considered (organic matter content in the various soil layers). N input - yield relationship for a particular type of soil is illustrated in Figure 1.

3.2. Crop rotations

Alternative crop rotation examined here present some heterogeneity as they include cotton and maize monoculture and different rotations involving in addition wheat and barley. Intensive rotation schemes are also considered as they behave interestingly regarding soil erosion. The following rotations were considered:

I. Cotton mono-culture

II. Maize mono-culture

III. C-C-C-W three years cotton and one year wheat

IV. C-C-C-M three years cotton and one year maize

V. C-M-C-M one year cotton one year maize

VI. C-B x 4 intensive rotation of cotton with barley as

Table 1 ***Inputs and output for basic crops in different rotation conditions (in values) for a specific soil type (2Mt) and irrigation system (drip) in a farm of average size (7 ha).***

soil type: 2Mt	Cotton		Maize		Durum wheat/ barley	
	monoculture	in rotation	monoculture	in rotation	intensive	in rotation
Variable Expenses						
Fertilisers	1824	1551	2132	1812	572.727	573
Seeds	795	795	636	636	361	361
Pesticides	737	516	547	465		
Harvest	1273	1273	955	811	636	636
Electricity for irrigation	1020	1020	1655	1407	510	510
Fuel and lubricants	1063	1063	785	785	323	323
Interests of wc	503	466	503	444	180	180
Amortisation machines	5767	5767	5767	5767	5378	5378
Maintenance & insurance	1140	1140	1140	1140	1061	1061
Fixed paid costs	***987***	***987***	***987***	***987***	***920***	***920***
Yield (tons/ha)	2.40	2.52	13.00	13.65	5.00	8.00
Price (euro/ton)	733	733	167	167	150	150
Sales	***1759***	***1847***	***2170***	***2278***	***750***	***1200***
Subsidies per ha			***497***	***497***	***498***	***498***
Farm income*	***245***	***372***	***656***	***827***	***-359***	***91***

* When in rotation fixed paid costs are shared by all activities so that corresponding farm income figures are higher than these appearing in this table.

Note: all monetary values are in € except figures in bold characters expressed in €/hectare.

winter crop

VII. M-W x 4 intensive rotation of maize with wheat as winter crop

VIII. C-W-M-B x 2 intensive rotation of all four crops

Cotton mono-culture is currently the most common cultivation on the flat to slightly undulating Thessaly soils where supplemental irrigation water is available. It covers almost half of the total cotton cultivated area in Greece.

Maize mono-culture is practiced in some areas with fertile soils with high water availability.

Thessaly is one of the areas where cotton suffers from *Verticillium dahliae*. The disease could be brought under control by introducing rotations with winter wheat and/or maize. A three-year cotton - one-year wheat (crop rotation III) or maize (crop rotation IV) would therefore be suggested in the area. However they are practiced in only few cases apparently due to the lower profit from the wheat cultivation or the lack of water needed for a reasonable maize production.

Crop rotations VI, VII, and VIII are intensive by means of harvesting two crops in the same year. The second crop would then be either short-period wheat or barley; these winter crops will be sown in the period from mid-November to mid-December and harvested in late April, when the field will be prepared for the sowing of the summer crop before the beginning of May.

3.3. Farm management under water deficit.

First of all, farm incomes are calculated for each crop on different rotation, soil, management technique, and input levels. Based on series of data such as these shown in **Table 1** (that contains elementary information for all crops participating to rotations), farm income for suggested sequences of crops (rotation schemes) can be calculated using a spreadsheet linked to the biological development model. Thus, water quantity consumed, nutrient input and pesticide use can be calculated for all rotations.

Farm income analysis shows that intensive rotations (M-W x 4 and C-W-M-B x 2) are the most profitable followed by maize and cotton mono-cultures. However, these options require important input quantities, regarding scarce resources such as water. Values of income and water consumption are presented in **Table 6 (Annex II)**. It is supposed first that there is no limiting factors so that results correspond to yield potential levels (Yield Oriented Agriculture(2) scheme as referred in de Koning and van Diepen, 1992). Then, fertiliser and pesticide input is decreased to give "input limited production" (ILP)(3).

The present work attempts to implement the bio-economic approach in a particular context. Taking into consideration all rotation combinations about 50 alternatives have been evaluated (8 rotations x 2 irrigation techniques x 2-3 N input-yield combinations in average). Analysis focus on an area of 7 ha (a typical hypothetical farm) that is located on the 2Mt type of soil. A parametric solution of the model would give the optimal (max farm income) rotation under diminishing water availability(4). This iterative process has indicated 8 interesting rotations out of 44 for various water deficits. The last column in **Table 2** shows the income loss per cubic meter resulted by consecutive restrictions to water consumption.

Farm income is plotted against water consumption (figure 2) illustrating Table 2 results. Eight efficient(5) solutions are found among alternatives (which not surprisingly coincide to the rotation selected by the parametric process of decreasing water availability). The slopes of line segments connecting efficient solutions represent trade-offs to be paid to move from one point to the other. One can observe that the most practiced rotation, that is cotton mono-culture irrigated by travelling gun, is not an efficient one. A farmer that has water limitations can chose a most profitable alternative,

Table 2 ***Efficient points derived by the ε-constraint method.***

	Rotation	Income	Water Q	Trade-off
		€/ha	m³/ha	€/ m³
17*	M-W x 4 (G)	1608	11340	
19	C-W-M-B (G)	1237	10530	0.458
3	Maize (G)	1214	8100	0.009
25	Maize (D)	969	6300	0.136
11	C-M-C-M (D)	635	5670	0.530
14	C-C-C-M (D)	457	5355	0.565
15	Cotton (D)	244	5040	0.676
16	C-C-C-W (D)	229	4410	0.024

* Code numbers of rotations correspond to those of Table 6 in the Annex II
(in parenthesis irrigation system is noted D: drip, G: travelling gun).

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(2) Growth models adjust potential yield levels by introducing site specific factors (radiation, temperature etc.). Depending on input use (water, nitrogen, phosphorus) attainable levels are determined equal or lower to the potential ones. YOA is supposed to use input quantities without restriction to reach potential yield levels (de Koning et al., 1992).

(3) In this exercise, one scenario of ILP is used where fertiliser and pesticide use is limited by 30 and 15 percent respectively. ILP crops in rotations are followed by "ext" noting extensive cultivation.

(4) In order to find all solutions under diminishing water availability, we maximised income subject to varying lower bounds of water consumption (ε_k). More precisely, we solved parametrically (for different values of ε_k) the following model:

Max $z_1(x_{s.r}) + \rho\, z_2(x_{s.r})$ (1)
subject to $z_2(x_{s.r}) \geq \varepsilon_k$ (2)
and $x_{s,r}$ (x: rotation, s: soil type, r: irrigation technique) belongs to the feasible space, where ρ is a small positive value.
The objective function is slightly modified in order to discard weakly efficient solutions. Next, ε_k are parametrically varied from the best to the worst possible value for objective k (k=2,...,n). This approach becomes quickly prohibitive when the number of objectives grows. In our case the number of objectives is limited and a more general model would include 3 to 4 economic and environmental criteria, which remains manageable.

(5) *Efficient or non-dominated solutions*: feasible solutions such that no other feasible solution can achieve the same or better preformance for all the criteria under consideration and strictly better for at least one criterion.

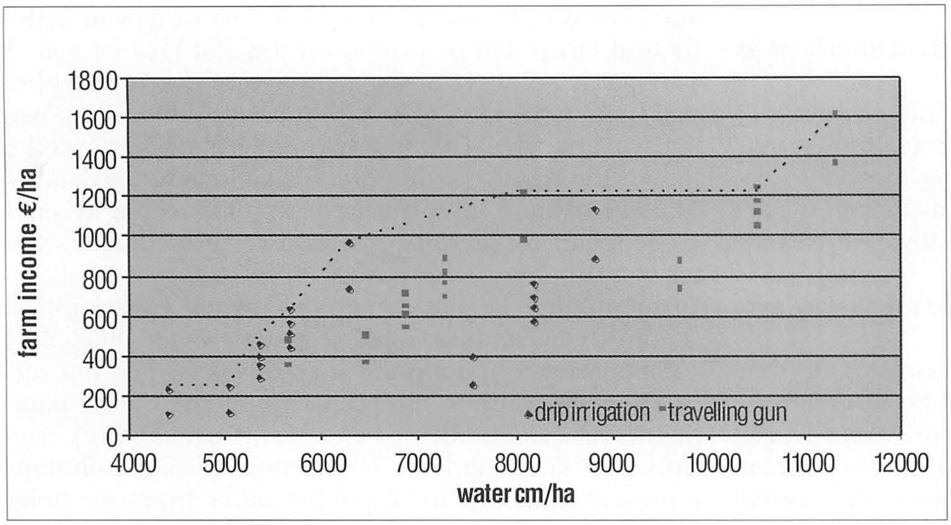

Figure 2 - Bi-criteria decision space: Income versus water consumption.

maize (drip) that requires even (somewhat) less water, situated at point 1. Alternative (C-M-C-M (G)) is less profitable but as it requires less quantity of water it cannot be rejected if both profitability and water economy are to be satisfied.

This alternative is a non-dominated or *efficient* solution in the Pareto sense, in multi-objective analysis terminology. If the farmer decides to reduce its water consumption, he can cultivate rotation C-M-C-M realising 335 €/ha less income for a quantity of 630 m³/ha saved, in other words, for each € lost (only) approximately 2 m³ of water per hectare can be saved.

4. MULTICRITERIA ANALYSIS AND RESULTS

A standard approach to proceed when more than one objectives are involved is to optimise the weighted sum of individual objectives. In this case study, no matter what combination of weights in the two dimensional space is selected, some efficient solutions (in Table 2) are never selected as it is shown in Table 3. Moreover, when supplementary objectives enter the decision space, efficient solution number increases and the weighted sum objective function may miss a lot of them that may be interesting for the decision maker. As a matter of fact in this simplified model of 44 alternative rotations, the bi-criteria space contains 8 efficient, as seen in previous paragraphs whereas the tri-criteria one counts 30 efficient solutions out of 44 (Table 6 in the Annex I).

Table 3 ***Bi-criteria optimization robustness.***

	Rotation	Income	Water Q	Weight Income	Weight Water
		(€/ha)	m³/ha	%	%
17*	M-Wx4 (G)	1608	11340	90-100	0-10
3	maize (G)	1214	8100	89	11
25	maize (D)	969	6300	72-88	12-28
16	C-C-C-W (D)	229	4410	0-71	29-100

* Code numbers of rotations correspond to those of Table 6 in Annex I.

Beside the above caveat, it is extremely difficult to give a relative importance (weight) to each criterion (Romero, Rehman, 1989), so an alternative approach is needed to cope with this problem. An interactive approach which allows an exploration of the efficient solutions and of possible trade-offs among criteria seems more appropriate than any method aggregating a priori the criteria. For this purpose we implemented an interactive multi-criteria method based on a reference point approach (Wierzbicki, 1982). Basically, this approach projects aspiration levels expressed on the criteria onto the efficient frontier resulting in a solution corresponding to a specific tax exemption scheme. The exploration is supported through an interactive adjustment of the aspiration levels on the basis of solutions generated at previous iterations. This approach has been used in various contexts, in particular in contexts involving environmental aspects (Sourie et al., 1999) as it presents the advantage of optimising over physical units.

Projection of aspiration levels expressed by the DM is performed by optimising a scalarising function (s) that aims at satisfying the following requirements:

- s must generate efficient solutions only
- all efficient solutions may be generated by s

The first requirement is easily met since we work on the subset of efficient solutions (30 out of 44). In order to satisfy the second requirement, we selected the following scalarising function derived from the weighted Chebychev norm:

$$s(z,\overline{z})=\max_{b=1\ldots p}\{\lambda_b(Z_b\ Z_b)\}$$

Table 4 ***Three objective pay-off matrix.***

Objectives	Net income	Water Q	Ninp
Optimised objective			
Farm income	**1710**	12000	1304
WaterQ	229	**4410**	510
Ninp	103	**4410**	**350**

$$\left(\lambda_h = \frac{1}{(\overset{*}{Z}_h - \boldsymbol{n}_h)}\right)$$

and $\bar{z}$ reference point representing aspiration levels
p number of criteria (objectives)
z^*_h maximum value on criterion h (ideal point)
n_h minimum value on criterion h, over the efficient set of solutions (nadir point)

Optimising separately for each criterion results in quite different strategies. The pay-off matrix presented in Table 6, illustrates conflicts among strategies as well as possible trade-offs and provides useful information in a synthetic way.

Optimisations performed for three objectives resulted in the following pay-off matrix.

One can observe that the minimum water consumption point can be achieved using two different income and N-input combinations. Environmental objectives are considered separately against income and give different "transformation curves".

Supposing that preferences are expressed through an additive and separable utility function weights attributed to each objective and results are shown in the Table 6. It is observed that when weights on environmental objectives change different solutions are proposed whereas importance attributed to the economic objective remains stable.

It is interesting to explore the decision space through successive iterations applied various weights.

Table 5 ***Results of multi-objective optimisation in parentheses percentage weights attributed to each objective.***

Objective	A	B	C
Farm income	(1608) 881	(881) 635	(881) 244
Water Q	(4410) 7290	(4410) 5670	(4410) 5040
N input	(350) 701	(701) 701	(350) 650

5. CONCLUSIONS

Analysis of alternative rotation schemes is performed using integrated biological and economic models. Economy of water and inputs when intensive rotations or mono-culture are replaced by extensive rotations compensates for income losses.

Intensive rotations increase farm income but they require higher effort and material inputs, which may become problematic in regions where nitrate pollution and water deficit phenomena are observed. The bioeconomic modeling gives interesting information to this regard.

Concerning water, for instance, it has been observed that water consumption levels over 6300 cubic meters per hectare the average per m^3 benefit of increasing water consumption is equal to 0.126 € whereas this value has an average of 0.575 € per additional cubic meter within the range of 5040 and 6300 cubic meters per hectare. In other words, within the aforementioned range a total cost of irrigation up to 0.575 € per cubic meter could be afforded by farmers whereas beyond 6300 m^3 this cost cannot exceed 0.126 € per cubic meter.

This reasoning could be useful to farmers to make decisions concerning irrigation investments but also decision makers to implement appropriate policies to curb water consumption.

When more objectives are considered a multi-objective analysis framework needs to be applied to assist the DM in the exploration of the decision space.

The reference point approach has been proven preferable to standard aggregated objective functions as it enables the DM to select among all efficient alternatives taking into account various preferences attributed to conflicting objectives.

When one attempts to satisfy simultaneously all three objectives considered in this exercise, namely maximise farm income, and minimise water and fertiliser and pesticide input, the model suggests rotation CM-CM (cotton and maize) irrigated by travevelling gun as the most interesting among all 44 rotations considered.

This is the result of a compromise selecting "closest" feasible alternative to the reference (target) point. If the DM accepts this solution and tries to improve it regarding water consumption the CMCM rotation with drip irrigation system is selected. When both environmental objectives are sought to be minimised cotton mono-culture with drip irrigation is selected. In order to achieve the absolute minimum environmental objective values the rotation CCCW, that is cotton and wheat, is preferable.

Ideally a G.I.S. should be used to provide information on parameters such as soil types, slopes and other site-specific characteristics.

Thus, Land-Classes could be defined in the context of site specific land use systems.

Input quantities and yields could then be approximated by the biological model. This way research can be pursued at the micro-regional level assisting to evaluate the efficiency of water and nitrogen use and soil conservation measures such as input or pollution taxes and land use permits. Detailed data and advanced modeling software can be exploited by the presented model for this purpose.

In terms of traditional environmental economics frame this evaluation consists in calculating positive externalities caused by changes of farm management techniques and policy measures.

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ANNEX I

Indices

r	rotation
s	irrigation system
t	cultivation technique

Parameters

C	farm income in euro per hectare
W	water consumption in cubic meters per hectare
n	nitrogen input in kg per hectare
L	total arable land in hectares in farm

Non-negative Integer Variables

χ	surface allocated to rotations
$\max z_1 = \sum_r\sum_s\sum_t C_{r,s,t,}\ \chi_{r,s,t,}$	total farm income

Subject to:

$\sum_r\sum_s\sum_t \chi_{r,s,t,} \leq L$	farm arable land constraint
$z_2 = \sum_r\sum_s\sum_t w_{r,s,t,}\ \chi_{r,s,t,}$	total water consumption per hectare for irrigation in farm
$z_3 = \sum_r\sum_s\sum_t n_{r,s,t,}\ \chi_{r,s,t,}$	total nitrogen input per hectare in farm
$\sum_r\sum_s\sum_t \chi_{r,s,t,} = 1$	mutually exclusive rotation allocation

ANNEX II

Table 6 ***Exhaustive list of rotation alternatives and results regarding objectives z_1, z_2, and z_3.***

Irrigation system: rotation	Farm income (€/ha)	Water Q (m^3/ha)	Nitrogen input (kg/ha)	Status	Farm income (€/ha)	Water Q (m^3/ha)	Status
1 gun:cotton	490	−6480	−650	dominated by 34	490	−6480	dominated by 25
2 gun:cot(ext)	357	−6480	−350		357	−6480	dominated by 1
3 gun:maize	1214	−8100	−1000		1214	−8100	
4 gun:maiz(ext)	976	−8100	−732		976	−8100	dominated by 3
5 gun:C-C-C-W	470	−5670	−501		470	−5670	dominated by 33
6 gun:CCC(ext)W	344	−5670	−350		344	−5670	dominated by 5
7 gun:C-C-C-M	703	−6885	−626		703	−6885	dominated by 25
8 gun:CCCM(ext)	640	−6885	−569		640	−6885	dominated by 7
9 gun:CCC(ext)M	597	−6885	−435		597	−6885	dominated by 7
10 gun:CCC(ext)M(ext)	535	−6885	−378		535	−6885	dominated by 7
11 gun:C-M-C-M	880	−7290	−701		880	−7290	dominated by 25
12 gun:CM(ext)CM	756	−7290	−587	dominated by 13	756	−7290	dominated by 11
13 gun:C(ext)MCM	810	−7290	−573		810	−7290	dominated by 11
14 gun:C(ext)M(ext)CM	685	−7290	−459		685	−7290	dominated by 7
15 gun:C-B x 4	867	−9720	−902	dominated by 4	867	−9720	dominated by 3
16 gun:C(ext)Bx4	726	−9720	−647	dominated by 12	726	−9720	dominated by 3
17 gun:M-W x 4	1608	−11340	−1200		1608	−11340	
18 gun:M(ext)Wx4	1358	−11340	−972		1358	−11340	dominated by 17
19 gun:C-W-M-B	1237	−10530	−1051		1237	−10530	
20 gun:CWM(ext)B	1112	−10530	−937	dominated by 21	1112	−10530	dominated by 3
21 gun:C(ext)WMB	1167	−10530	−923		1167	−10530	dominated by 3
22 gun:C(ext)WM(ext)B	1042	−10530	−809		1042	−10530	dominated by 3
23 drip:cotton	244	−5040	−650		244	−5040	
24 drip:cot(ext)	111	−5040	−350		111	−5040	dominated by 23
25 drip:maize	969	−6300	−1000		969	−6300	
26 drip:maiz(ext)	731	−6300	−732		731	−6300	dominated by 25
27 drip:C-C-C-W	229	−4410	−501		229	−4410	
28 drip:CCC(ext)W	102	−4410	−350		102	−4410	dominated by 27
29 drip:C-C-C-M	457	−5355	−626		457	−5355	
30 drip:CCCM(ext)	395	−5355	−569		395	−5355	dominated by 29
31 drip:CCC(ext)M	352	−5355	−435		352	−5355	dominated by 29
32 drip:CCC(ext)M(ext)	289	−5355	−378		289	−5355	dominated by 29
33 drip:C-M-C-M	635	−5670	−701		635	−5670	
34 drip:CM(ext)CM	510	−5670	−587	dominated by 35	510	−5670	dominated by 33
35 drip:C(ext)MCM	565	−5670	−573		565	−5670	dominated by 33
36 drip:C(ext)M(ext)CM	440	−5670	−459		440	−5670	dominated by 5
37 drip:C-B x 4	392	−7560	−902	dominated by 1	392	−7560	dominated by 1
38 drip:C(ext)Bx4	251	−7560	−647	dominated by 2	251	−7560	dominated by 1
39 drip:M-W x 4	1134	−8820	−1200	dominated by 3	1134	−8820	dominated by 3
40 drip:M(ext)Wx4	885	−8820	−972	dominated by 4	885	−8820	dominated by 3
41 drip:C-W-M-B	763	−8190	−1051	dominated by 3	763	−8190	dominated by 3
42 drip:CWM(ext)B	638	−8190	−937	dominated by 4	638	−8190	dominated by 3
43 drip:C(ext)WMB	693	−8190	−923	dominated by 4	693	−8190	dominated by 3
44 drip:C(ext)WM(ext)B	568	−8190	−809	dominated by 4	568	−8190	dominated by 3