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An integrated PMP model to assess the development of agro-energy crops and the effect on water requirements

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Abstract. This paper presents an integrated model for the economic and environmental assessment of the use of natural resources when new activities (i.e. biomass crops for energy production) are introduced into the farm production plan. The methodology is based on the integration of positive mathematical programming (PMP) with the AquaCrop model developed by FAO. PMP represents farmer decision processes and evaluates how farms react to the biomass-sorghum activity option at different price levels. AquaCrop evaluates the relationship between water needs and biomass production and assesses the effect of the land allocation on water requirements at regional level. The integration of these two models assists global policy evaluation at regional level as it makes it possible to identify the economic threshold for biomass crops, the change in land allocation and total water requirement. The model can help policy makers to evaluate the impacts of variations in crop profitability and market innovations on farm profitability, land use and water consumption and the sustainability of the market scenario.

Keywords. Agroenergy economics, Positive Mathematical Programming, water demand, AquaCrop

JEL codes. C61, Q42, Q24, Q25, Q51

1. Introduction

Farmer interest in agro-energy production is mainly due to the high level of financial subsidies for renewable energy production. European strategy against climate change indicates agriculture as one of the main sectors that should contribute through specific actions to achieve the objectives established for 2020 (European Commission, 2010). The 2014-2020 CAP reform also states that European agriculture can play a major role in mitigating global warming through new entrepreneurial vision and the substitution of fossil energy with renewable energy (European Commission, 2009). Agro-energies are thus considered as an instrument to enhance energy security, reduce greenhouse gas emissions and raise farm income (Petersen, 2008). Agricultural biomass and agronomic management are the main resources to generate environmentally virtuous processes on farms.

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Despite the theoretical advantages for European society, the threats as well as the benefits of agro-energy need to be carefully evaluated. On one hand, agricultural biomass used for producing fuel, heat and electricity has favourable effects on the environment, but on the other hand, it can determine end-consumption competition and excessive pressure on natural resources. Biofuel gives rise to concern about the sustainability of the non-food supply chains. Rising demand for biofuel has led to widespread exploitation of arable land for growing first and second generation biofuel crops. According to the internal biofuel strategy, 10% of total transport fuel should be biofuels (biodiesel or bioethanol) in European Union (EU) by 2020 (European Commission, 2006). If this is considered in terms of available land surface, the risk of agricultural land overexploitation is real (Zezza, 2008).

Another example of how renewable energies can contribute to a sustainable society is biogas. Biogas in the Po Valley, in Italy, is very profitable as a result of large public subsidies and very short payback time, and is expanding rapidly. Most of the biogas plants maximize economic performance using biomass that in part originates from waste such as slurry and agroindustrial wastes, and often from specialized crops, in particular maize. About 200 ha of dedicated crops are used in a biogas plant of 1MW. This type of agro-energy farms present a low level of crop diversification, which brings the risk of creating monoculture requiring intensive use of pesticide. They also use large quantities of water for irrigation for the entire plant growing cycle. Overexploiting resources means reducing agricultural commodities for food and feeding purposes but also jeopardizing the equilibrium of the ecosystem. Soil depletion, biodiversity reduction, aquifer pollution and water scarcity are important concerns which need to be taken into consideration alongside global warming. Paradoxically, it sometimes appears that it is necessary to sacrifice the environment in order to save it (Doornbosch and Steenblick, 2007).

To produce food and fibre, EU agriculture takes about 50% of the available fresh water, while at global level this percentage is 70% (OECD, 2010). The rapid growth of agro-energy poses the need for management of irrigation water in order to avoid excessive pressure on the resource and water crisis in drought periods (OECD, 2010). Increasing demand for water from other economic sectors and society worsens the problem of water scarcity. In line with the EU Water Framework Directive (WFD) (Directive n. 2000/60/EC), Member States will have to apply administrative and economic tools for saving irrigated water and controlling the use of water for agriculture. The objective of the WFD is threefold: protect water resources, optimize water use and sustain agricultural productivity. As a limited resource, water should be managed through appropriate economic instruments to drive user behaviour to improve efficiency in water distribution and application. WFD encourages the use of a set of economic instruments, including the tariff system and the market for water entitlements to rationalize water allocation, which might assign an economic value to water. Without an explicit value, users pursuing private interests will use water as a free access resource compromising its sustainable exploitation (Hardin, 1968). But if water is perceived as a scarce resource and an economic good, farmers have to compare alternative crops to identify those maximising farm income and minimizing the cost of the water consumption (García-Vila and Fereres, 2012; Bazzani *et al.*, 2007; Bazzani *et al.*, 2004; Ward and Michelsen, 2002). The problem becomes particularly important in Mediterranean regions and in drought periods (Howell, 2001).

Agricultural biomass production for agro-energy supply chain is an alternative that farmers are increasingly considering in their decision making, but according to the type of crop it has a big effect on water availability. In the case of sorghum for second generation bioethanol production, water consumption for irrigation is not high, but in other cases, like maize for biogas, where maize is intensively cultivated, it can be much higher.

Evaluating the impact of agro-energy production on land and water use can support policy makers in planning intervention to optimize the use of scarce resources. Local water management authorities in particular need to be made aware of likely farm allocation decisions and the potential water consumption of agro-energy crop development. This information supports water distribution planning and implementation of tools to regulate water for irrigation. To support policy and management decisions, quantitative models based on mathematical programming (MP) are usually implemented.

The literature shows that MP can be used for farm management and policy assessment. MP models generate an optimization process of an objective function subject to a set of constraints and can be implemented following normative and positive approaches. The normative approach can be considered the "classical" MP tool for farm management. The characteristics of normative MP models are related to the level of knowledge about the farmer technological set, prices and costs and farmer assumptions in a suboptimal condition. The model requires a large amount of technical and economic data. A normative MP model will typically identify optimal production level and the optimal use of inputs to maximize revenue or minimize costs. These models have a prescriptive character, they indicate what the decision maker ought to do in order to optimise his objective and they do not reproduce what he is actually doing. Normative models are useful for their capacity to predict the use of inputs. In the case of water, demand can be calculated for single farms or for groups of farms. For groups of farms, models can reproduce water supply nodes in order to reorganize the network and water allocation more efficiently (Harou *et al.*, 2009; Bartolini *et al.*, 2007; Rosengrant *et al.*, 2000; García-Villa and Fereres, 2012).

Positive MP models, or positive mathematical programming (PMP) (Howitt, 1995; Paris and Howitt, 1998; Heckelei *et al.*, 2012) are used on the other hand for policy assessment when the size of inputs and variable costs are not precisely known. In a context of poor information, they can predict farm use under the hypothesis that the observed production level is considered optimal by the entrepreneur. Variation in output market price, or in specific coupled (or decoupled) payments, leads to a new optimal production level. The main feature of positive MP models is to calibrate, for a given farm, the observed production level and to estimate a non linear cost function that reproduces the cost of the inputs. The technological matrix defines the productivity level for the observed crops and activities. PMP typically identifies the cost that economic agents are willing to pay in order to be optimal at the observed level. These models can be developed for a single farm or a group of homogeneous farms belonging to a large region (Arfini and Donati, 2011).

While normative MP models can describe in great detail the technological level and predict the use of inputs, they meet difficulties assessing the impacts of new market and policy scenarios when many farms in a region are considered. This is because of the difficulty in collecting and differentiating technological information among farms. By contrast, positive MP models can easily estimate the cost of technology and thus assess the impact of new market and policy scenarios for a large group of farms. Such farms usually belong to large samples such as FADN which do not collect micro information related to the input use of each farm activity. For PMP models, the drawback is the lack of information related to the physical use of inputs. There are two possible strategies in order to provide information on input use: i) consider in PMP models the use of specific inputs (Helming and Peerlings, 2003), although there is the problem of considering different technological sets and input-output relationships for many farms; ii) integrate PMP models with other methodologies that consider more specifically input-output relationships for some specific inputs.

Water as an input can be introduced into MP models (including PMP) in various ways: i) water is considered as a constraint with fixed water requirement coefficients (Graveline and Mérel, 2012; Cortignani and Severini, 2009; Medellin-Azuara *et al.*, 2010); ii) water is included within the production function linking crop yields to water application (García-Villa and Fereres, 2012; Graveline and Mérel, 2012) through the introduction of biophysical information including local environment characteristics (García-Villa and Fereres, 2012; Cortignani and Severini, 2009). In particular, a model estimating the relationship between yields and water use has recently been developed by FAO: AquaCrop. AquaCrop (Steduto *et al.*, 2009) permits evaluation and simulation of yield responses with regard to water application for a group of crops. It takes account of specific information on climate conditions, soil characteristics and irrigation management.

PMP has shown to be very efficient for policy analysis purposes (Heckelei *et al.*, 2012) and particularly for assessing the introduction of a new crop in the production pattern of a group of farms (Arfini and Donati, 2013). The present analysis was conducted considering new activities as "latent" information that the entrepreneur can use for maximizing the objective function. PMP provides results using small amounts of information on the latent crop (yield and market price) without a detailed description of the technological set for all the inputs. It was used to evaluate the farmer's ability to choose agricultural activities not observed in the base year (Röhm and Dabbert, 2003; Blanco *et al.*, 2008; Arfini and Donati, 2013)

This paper presents an integrated framework of models answering research questions on assessment of impact of a new activity (e.g. agro-energy crops) on the agricultural production plan of a region. The assessment considers key issues for policy makers: land use, supply variations, territorial specialization, economic impact and environmental implications of the change in water use by farmers. The framework integrates micro-based PMP and the AquaCrop model. More specifically the goal is to assess the effects of the introduction of sorghum for biomass production on land and water allocation in the province of Parma, in Emilia Romagna region in northern Italy. The model simulates different market scenarios for sorghum in order to evaluate the level of sustainability and policy implications at different market prices.

The paper consists of five sections. The first discusses PMP methodology using latent crop information. The second presents the AquaCrop model, adapted to the characteristics of the area under investigation and the purpose of this research. The third section describes the integration of the models and their structure. The fourth presents results of simulations using AquaCrop. The fifth section presents the main results and their implications for policy. In the conclusion, opportunities for future research are discussed.

2. PMP model with latent information

PMP appeared in the world of MP quite recently thanks to the pioneering studies of Howitt (1995) and Paris and Arfini (1995). Its impact on agricultural economists was important in generating a wide field of literature that has led over time to more sophisticated modelling. Various elements have influenced the development of PMP models over time: research objectives, characteristics of available information, number of farms in the sample, number of farms that are represented by the models, level of representativeness of the data at regional level, method of calibration, method of estimating the non linear cost function as well as theoretical assumptions underpinning the models. Two distinct strands can be seen in the literature: the first considers PMP as a calibration method (Howitt, 1995; Heckelei and Wolff, 2003), while the second considers PMP as a method of estimating variable costs (Arfini and Paris, 1995; Paris and Howitt, 1998; Paris and Arfini, 2000; Paris, 2012). This paper follows the approach proposed by Paris (2012), where PMP assesses the impacts of market scenarios and agricultural policy by estimating the variable cost function associated with the use of inputs.

As regards the PMP models that consider latent information, the background hypothesis is based on the assumption that farmers have knowledge of a set of information regarding production activities, which is larger than the set of information that can be observed from the production plan. Some of this farmer information comes from their previous experience, some from the experience of their neighbours or from advice on new crops given by experts (agronomists). The economic and technological information regarding activities that are perceived as more costly or more risky will not be used in the production plan, but will remain latent until it becomes economically useful.

The decision to change the production plan or technological choices is usually motivated by variables such as risk aversion, level of technical knowledge, availability of capital, family structure, age of the farmer, the presence of support agencies in the territory, etc. All these variables affect the farmer's decision process and lead to the selection of a certain combination of crops. Why does a farmer produce soft wheat and alfalfa and not, for instance, tomato and sugarbeet, which are produced on other farms in the area? The farmer could potentially insert tomato and sugar beet into his production plan, but he does not currently produce them because they are not profitable for his farm. Until they become profitable, information is "latent" in the sense that it is known by the farmer but not used.

Economic information related to farm crops identified as "latent" can however be introduced into a PMP model in two different ways:

1. as "latent technology", when a given crop is adopted only by a group of farms in the sample: each farm belonging to the same sample is cross-linked with the others through a common set of cost function parameters and shares the same technology. Because there is self-selection, a given crop existing in the production pattern of farm "A" can be adopted by farm "B" if there is economic advantage;
2. as "latent crop", when the information is related to a given crop that does not exist in the farm production plan for any farms belonging to the sample.

Of course, in the real world farmers are not alone. They are in an environment characterized by different production decisions deriving from different production possibilities, among which the farmer selects what he assumes to be the best solution. The main driving force that leads farmers to select one production plan and not others is the cost function associated with each activity. The total cost function is the economic measure of the available technology and all the other factors. The total cost includes all variable costs perceived by the farmer for each activity. Some of these costs are clearly registered by bookkeeping and identified as explicit costs, while others are only perceived by entrepreneur and are implicit costs of the decision. Farmer behaviour can be formally reproduced by a production plan where the observed activities are accompanied by latent activities.

We present the PMP model, articulated in three phases (Paris and Howitt, 1998), including non-observed activities, and consider, for sake of simplicity, only one farm with two sets of products: activities realized r (for $r=1,2,\ldots,R$) and latent activities l (for $l=1,2,\ldots,L$). We assume that $\mathbf{x}_r$ is the vector of the realized output quantities and $\mathbf{x}_l$ the vector of latent output quantities. The observed quantity levels for realized and latent activity are known and correspond to $\overline{\mathbf{x}}_r$ and $\overline{\mathbf{x}}_l$ respectively. Farm activity is subject to limiting factors i (for $i=1,2,\ldots,I$) and the upper bound values for each factor are included in vector $\mathbf{b}$ farm technology is provided by the coefficients of the *I by R* matrix $\mathbf{A}_r$ for the realized activities, and of the *I by L* matrix $\mathbf{A}_l$ for the latent activities. Given this information, we can develop the first PMP phase through a problem that maximizes the gross margin (GM) as follows:

$$\max_{\mathbf{x}_r \geq 0, \mathbf{x}_l \geq 0} GM = (\mathbf{p}_r - \mathbf{c}_r)'\mathbf{x}_r + (\mathbf{p}_l - \mathbf{c}_l)'\mathbf{x}_l \tag{1}$$

where $\mathbf{p}_r$ and $\mathbf{p}_l$ represent the vectors of realized output prices and latent output prices respectively, while, $\mathbf{c}_r$ and $\mathbf{c}_l$ the vectors of the exogenous specific costs for the realized and latent activities. The objective function (1) is maximized with respect to the non-negative variables $\mathbf{x}_r$ and $\mathbf{x}_l$ and is subject to the following constraints:

$$\mathbf{A}_r\mathbf{x}_r + \mathbf{A}_l\mathbf{x}_l \leq \mathbf{b} \qquad (\mathbf{y}\ \ ) \tag{2}$$

$$\mathbf{x}_r \leq \overline{\mathbf{x}}_r + \varepsilon \quad (\lambda_r) \tag{3}$$

$$\mathbf{x}_l \leq \overline{\mathbf{x}}_l + \varepsilon \quad (\lambda_l) \tag{4}$$

Constraint (2) identifies the relationship between the total demand of input to produce $\mathbf{x}_r$ and $\mathbf{x}_l$ (left hand side) and the total input supply (right hand side). The shadow prices of the binding farm resources $\mathbf{b}$ are represented by the vector $\mathbf{y}$. Constraints (3) and (4) are the PMP calibrating constraints, while λ_r λ_l are the dual values of the realized and latent activities. λ_r represents the hidden costs, i.e. the implicit marginal costs of the realized activities, and λ_l the implicit marginal cost associated with the latent activities.

In the definition of the problem (1)-(4), the latent crop is added from the first phase, assigning it a very low production level $\mathbf{x}_l$ close to zero, while the data related to the prices and specific costs are taken from market and must guarantee a condition of positive marginal profit. Yields are assumed by experts and by literature.

This first PMP setting provides dual information for realized and latent crops to be used in the second phase, where a non-linear function is estimated. We choose the following quadratic cost function

$$\frac{1}{2}\begin{bmatrix} \overline{\mathbf{x}}_r & \overline{\mathbf{x}}_l \end{bmatrix}\mathbf{Q}_{rl}\begin{bmatrix} \overline{\mathbf{x}}_r \\ \overline{\mathbf{x}}_l \end{bmatrix} \tag{5}$$

where matrix **Q** is symmetric positive semidefinite and includes parameters to be estimated by properly methods. In this work, the parameter estimation is carried out adopting the maximum entropy approach (Paris and Howitt, 1998) considering the following relationship:

$$\begin{bmatrix} \mathbf{c}_r \\ \mathbf{c}_l \end{bmatrix} + \begin{bmatrix} \lambda_r \\ \lambda_l \end{bmatrix} = \begin{bmatrix} \overline{\mathbf{x}}_r \\ \overline{\mathbf{x}}_l \end{bmatrix}\mathbf{Q}_{rl} \tag{6}$$

where the explicit and implicit costs recovered in the previous phase should be equal to the marginal cost derived from the quadratic total cost function (5). In analytical terms:

$$\begin{bmatrix} c_{r1} \\ c_{r2} \\ \vdots \\ c_{rR} \\ c_{l1} \\ c_{l2} \\ \vdots \\ c_{lL} \end{bmatrix} + \begin{bmatrix} \lambda_{r1} \\ \lambda_{r2} \\ \vdots \\ \lambda_{rR} \\ \lambda_{l1} \\ \lambda_{l2} \\ \vdots \\ \lambda_{lL} \end{bmatrix} = \begin{bmatrix} \overline{x}_{r1} \\ \overline{x}_{r2} \\ \vdots \\ \overline{x}_{rR} \\ \overline{x}_{l1} \\ \vdots \\ \overline{x}_{l2} \\ \overline{x}_{lL} \end{bmatrix} \begin{bmatrix} q_{r1r1} & q_{r1r2} & \cdots & q_{r1rR} & q_{r1l1} & q_{r1l2} & \cdots & q_{r1lL} \\ q_{r2r1} & q_{r2r2} & \cdots & q_{r2rR} & q_{r2l1} & q_{r2l2} & \cdots & q_{r2lL} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ q_{rRr1} & q_{rRr2} & \cdots & q_{rRrR} & q_{r1l1} & q_{rRl2} & \cdots & q_{rRlL} \\ q_{l1r1} & q_{l1r2} & \cdots & q_{l1rR} & q_{l1l1} & q_{l1l2} & \cdots & q_{l1lL} \\ q_{l2r1} & q_{l2r2} & \cdots & q_{l2rR} & q_{l2l1} & q_{l2l2} & \cdots & q_{l2lL} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ q_{lLr1} & q_{lLr2} & \cdots & q_{lLrR} & q_{lLl1} & q_{lLl2} & \cdots & q_{lLlL} \end{bmatrix} \tag{7}$$

As shown in Equation (7), the parameters of the **Q** matrix provide the information about the substitution and complementarity relationships among activities and, thus, between realized and latent activities (Arfini and Donati, 2013; Paris and Howitt, 1998).

The new non linear cost function estimated by using the maximum entropy technique is used in the third phase of PMP to calibrate the observed situation without the calibrating constraints:

$$\max_{\mathbf{x}_r \geq 0, \mathbf{x}_l \geq 0} \quad \mathbf{p}_r^{'}\mathbf{x}_r + \mathbf{p}_l^{'}\mathbf{x}_l - \frac{1}{2}\begin{bmatrix} \mathbf{x}_r & \mathbf{x}_l \end{bmatrix}\mathbf{Q}_{rl}\begin{bmatrix} \mathbf{x}_l \\ \mathbf{x}_l \end{bmatrix} \tag{8}$$

$$S.t. \quad \mathbf{A}_r\mathbf{x}_r + \mathbf{A}_l\mathbf{x}_l \leq \mathbf{b}$$

At this stage, all the information about latent activities is incorporated in a model that can be applied to evaluate policy and market scenarios. The model output shows the change in resource allocation (e.g. land), the marginal value of resources (dual values) and the dynamics in output levels as well as other important economic information on revenue, subsidy, total variable cost and gross margin variations.

3. An overview of AquaCrop

In an economic system characterized by a limited availability of resources, models that can indicate a better allocation of inputs and resources are a key to making optimal decisions. Evaluating the use of sensitive inputs for the environment, like water, becomes more complex if carried out at regional level. Specific environmental characteristic of an area (e.g. rainfall, soil characteristics, temperature, etc.) have to be associated with the technical capability of farmers and with crop profitability. Moreover, yields are the simplest expression of crop productivity, but a direct relation between yield and input use is hard to identify especially if the information is not directly registered in a bookkeeping system. Researchers have thus developed models able to create a link between yields and input use on the basis of information collected over time or by experimental methods.

One of the models which can best simulate water-limited attainable yield is AquaCrop developed by FAO (Steduto *et al.*, 2009). The model provides and predicts the crop yield according to water needs and different irrigation methods. FAO methodology considers the use of empirical production functions to evaluate crop yield response to water (Doorenbos and Kassam, 1979). The central feature is the following equation, relating yield to water used in the irrigation process:

$$\left(\frac{Y_X - Y_a}{Y_X}\right) = k_y\left(\frac{ET_X - ET_a}{ET_X}\right) \tag{9}$$

Y_X Y_a are the maximum and actual yields, ET_X and ET_a are the maximum and actual evapotranspiration, and k_y the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

The problem of water scarcity led to a different theorization of equation (9), which now separates field crops from tree crops. In particular, for field crops, FAO researchers proposed re-elaborating the equation in order to plan, manage and simulate different water management scenarios. So on the basis of work by Doorenbos and Kassam (1979), AquaCrop evolved by: i) dividing the *ET* into crop transpiration *Tr* and soil evaporation (*E*); ii) developing a model relating to canopy growth and senescence in order to estimate

Tr and its separation from *E*; iii) considering the final yield *Y* as a function of final biomass *B* and harvest index *HI* and iv) considering and separating the effects of water stress into four components: canopy growth, canopy senescence, *Tr* and *HI*.

The central equation of the new AquaCrop is thus:

$$B = WP \times \sum Tr \tag{10}$$

where *Tr* is the crop transpiration (in mm) and *WP* is the water productivity parameter (kg of biomass per m^2 and per mm of cumulated water transpired over the time period in which the biomass is produced). Equation (10) implies a shift from the seasonal or long-term evaluation used by Doorenbos and Kassam (1979) to a daily time relationship that is closer to the time scale of crop responses to water deficits.

AquaCrop considers three important aspects: soil, crop and atmosphere. Soil is considered by determining the level of fertility that can affect crop development as well as water balance. Crops and plants are measured and simulated using data relating to growth, development, and yield processes. Atmosphere is reproduced considering thermal regime, rainfall, evaporative demand, and carbon dioxide concentration. In order to better simulate reality, a wide range of parameters such as the irrigation system, water productivity, crop adjustments to stress can be modified and reflect on the final yield.

4. Model architecture

The model is divided into three parts or modules. Each module is devoted to a specific task and interfaced with the others providing the input information. Figure 1 presents a scheme where the different phases of the model are specified and linked.

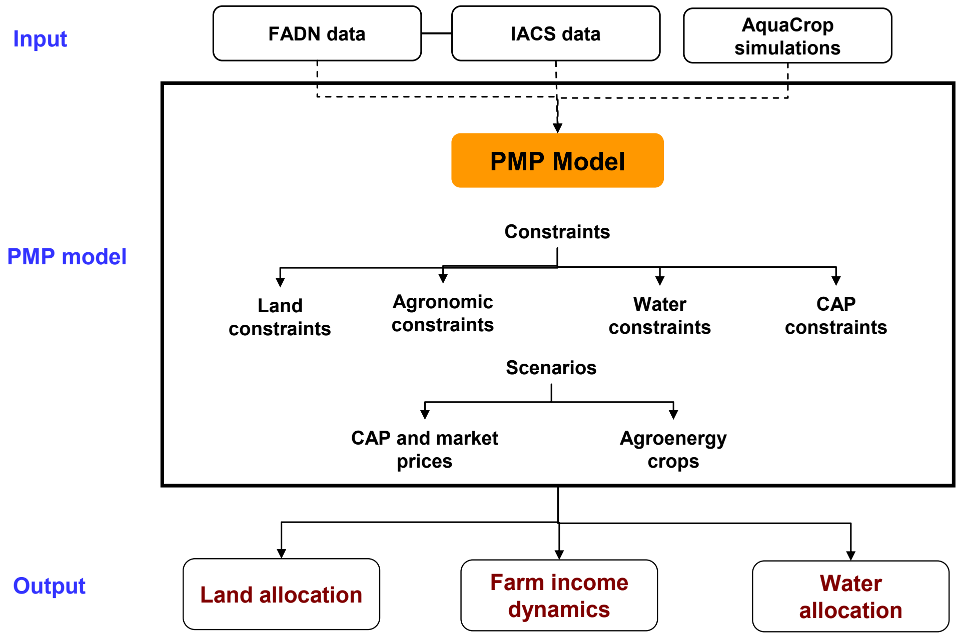
The first module provides information about the characteristics of the farms belonging to the sample and information related to the water use. In a diversified territorial context where different agronomic areas are embedded, it becomes important to cover different farm types and to truthfully represent land use and productivity levels. There is thus a compromise between minimizing the amount of data entered into the model and the need to provide enough details of individual farmer behavior and technologies and production decisions at farm level. The use of two databases providing complementary farm information is very useful: IACS (Integrated Administration and Control System) database provides information on land use of each farm, while FADN (Farm Accountancy Data Network) database provides economic[2] and technical information regarding farm type. The integration of IACS with FADN makes it possible to measure the exact dimension of agricultural production systems, gross marketable output, subsidies distributed and the amount of variable costs attributable to each process in areas smaller than NUTS3 (Arfini *et al.*, 2005).

The integration of FADN and IACS databases with AquaCrop into a single database gives a complete dataset of land use, technical and economic parameters for production processes and water use of all the farms included in the area considered by the model. The

[2] FADN Farm Accountancy Data Network, provides information for Italy at farm level on the explicit variable cost (accounting cost) per activity.

aggregation is performed at macro-farm level, i.e. farms grouped by size and farm specialization and by each agricultural area (a homogeneous altitude area belonging to the same province). More precisely, in each province three altitude levels, seven classes of size (0-10 ha, 10-20 ha, 20-30 ha, 30-50 ha, 50-100 ha, 100-300 ha, > 300 ha) and three economic sectors (arable crops, fruit and vegetables, and animal production) were considered.

Figure 1. PMP model architecture.



The second module consists of the PMP optimization model, which estimates variable costs for all activities and assesses the impact of policy and market scenarios. There are two calibration phases: the first is obtained by n linear programming models (one for each macro-farm) adopting the calibration constraints, and the second calibration is achieved by using the non-linear cost function estimated in the second PMP phase. The second calibration allows to verify that the model reproduces the observed land allocation without calibrating constraints. Once verified, the model is ready to be implemented for the simulation phase of all sets of constraints: land, agronomic, water and policy constraints (CAP). The simulation phase considers at baseline level (year 2012) the main first pillar CAP measures, like decoupling and payment modulation. This part of the model can support modification in CAP mechanisms, such as the transition from historical to regionalized decoupling, as well as market price variation.

The third module addresses the results of the simulation. The results are stored in specific output files readable by statistical and spreadsheet software by adopting GDX routines (GAMS, 2012). These routines generate an organized output comprising calibrating checks, land and water allocation, and farm economic variable dynamics.

5. AquaCrop simulations

With regard to the research question of this paper, AquaCrop makes it possible to calculate the amount of water that each crop requires in relation to the level of observed yield. One of its key features concerns the climate characteristics of the area. The model requires information on daily maximum and minimum air temperatures, daily rainfall, daily evaporative demand of the atmosphere expressed as reference evapotranspiration, and the mean annual carbon dioxide concentration in the bulk atmosphere. The climatic parameters adopted were collected from the meteorological measurements recorded in the Emilia-Romagna region, from 1 January 2002 to 31 December 2009. For the annual carbon dioxide value, we adopted the CO_2 concentration in the Mauna Loa Observatory in Hawaii, a monitoring centre used by AquaCrop. The reference value of evapotranspiration was calculated using FAO criteria (Allen *et al.*, 1998) and parameters were determined using the FAO's model ETo-Calculator (Raes *et al.*, 2009).

In AquaCrop, the crop system is represented by five different linked and interrelated modules concerning: phenology, aerial canopy, rooting depth, biomass production and harvestable yield. Each different crop grows and develops

over its cycle by expanding its canopy and its rooting system at the same time. Table 1 shows crop growing characteristics used in the evaluation of water requirement. The six crops are the arable crops for which AquaCrop provides information for simulations on response of yield to irrigation water use.

Table 1. Crop growing characteristics adopted in the simulation process.

Crop	Sowing Date	Harvest Date	Plant Density (plant ha^{-1})
Maize	01-apr	10 August	95 x 10^3
Silage Maize	01-apr	10 August	85 x 10^3
Sorghum	13 May	11 September	200 x 10^3
Sugar Beet	10-apr	29 August	100 x 10^3
Soybean	1 May	7 September	350 x 10^3
Tomato	01-apr	19 July	35 x 10^3

The characteristics of soil (hydraulic conductivity, water content, field capacity, permanent wilting point) adopted in the study follow the standard profile suggested by the FAO model. This means that soil characteristics within the area are not differentiated.

AquaCrop also has an irrigation management component which makes it possible to operate on soil fertility and on the type of irrigation system. Standard model values were used for soil fertility, while the period and the method of irrigation were differentiated according to crop for the irrigation system (Table 2).

As noted above, the study focused on the interdependence between water requirement and biomass in order to analyze how an increase in applied irrigation water (AIW) influences the production in terms of biomass (fresh yields).

The AquaCrop model was used to generate non-linear yield response functions to AIW, able to highlight the production trend of the yield level in relation to AIW. The simulations were carried out starting with a rain-field crop, and increasing AIW by season, applying constant increments of irrigation water (different for each type of crop), in order to reach the maximum level of biomass. Table 3 reports an example of how results were organized to generate non-linear yield response functions for sugarbeet.

Table 2. Irrigation management hypothesized for each crop considered in simulation procedure.

Crop	Sowing Date	Harvest Date	Irrigation treatments	**Method**
Maize	01-apr	10 August	4	Irr.Schedule - Sprinkler
SilageMaize	01-apr	10 August	4	Irr.Schedule - Sprinkler
Sorghum	13 May	11 September	2	Irr.Schedule - Sprinkler
SugarBeet	10-apr	29 August	8	Irr.Schedule - Sprinkler
Soybean	1 May	7 September	3	Irr.Schedule - Sprinkler
Tomato	01-apr	19 July	16	Irr.Schedule - Drip

Table 3. Production level according to different AIW - Sugarbeet (t/ha).

Year	Applied irrigation water (mm)											
	0	50	100	150	200	250	300	350	400	450	500	550
2002	35.1	39.7	43.6	44.6	44.5	44.0	43.5	42.7	42.1	41.6	41.2	41.0
2003	4.2	5.2	9.7	17.1	24.8	32.4	36.5	40.1	41.8	42.8	43.0	42.2
2004	4.6	5.3	13.3	27.4	33.1	38.2	42.5	43.6	44.2	42.7	41.6	41.4
2005	14.5	18.4	27.2	33.1	38.0	41.7	44.2	45.0	44.4	42.2	41.6	41.5
2006	3.6	4.8	9.0	16.7	28.3	36.1	41.4	44.4	45.1	44.8	43.5	42.3
2007	18.7	20.9	24.2	29.4	34.1	38.0	40.6	42.3	43.4	44.2	44.2	43.4
2008	26.2	27.7	30.8	34.4	36.9	39.2	40.7	41.5	42.0	42.2	42.0	41.7
2009	4.9	7.1	13.0	20.7	28.4	34.6	39.2	41.0	42.0	42.0	42.2	42.2

From the data in Table 3 and according to the methodology proposed by García-Vila and Fereres (2012), three non-linear crop-water production functions related to the 20th, the 50th and the 80th percentile were identified. The percentile values made it possible to obtain a non-linear function (polynomial), that reports the contribution of irrigation to the production of fresh yield. Table 4 shows the values of fresh yield obtained for the different levels of AIW according to a distribution over three percentiles for sugarbeet.

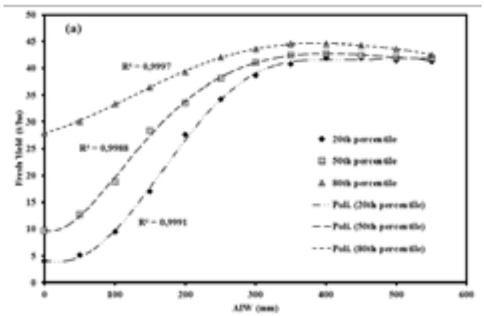
Table 4. Percentiles values from simulation for sugarbeet (t/ha).

Percentile	Applied irrigation water (mm)											
	0	50	100	150	200	250	300	350	400	450	500	550
20th	4.0	5.2	9.5	17.0	27.6	34.2	38.7	40.8	41.9	41.9	41.5	41.3
50th	9.7	12.8	18.8	28.4	33.6	38.1	41.0	42.5	42.7	42.5	42.1	41.9
80th	27.9	30.1	33.4	36.4	39.3	42.1	43.6	44.5	44.6	44.3	43.7	42.5

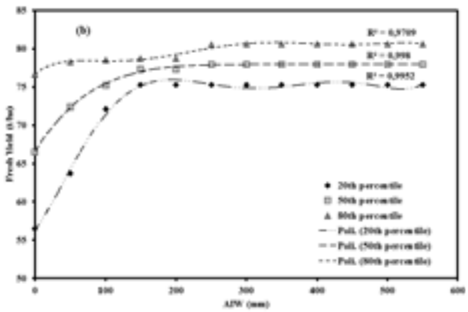
The results obtained for each crop were represented by polynomial functions in order to better describe the evolution of fresh yield production in relation to the applied irrigation water, i.e. the yield-AIW functions. In Figure 2, the vertical axis of each chart shows the level of fresh yield produced (t/ha), and the horizontal axis shows the different levels of applied irrigation water. The results demonstrate that the polynomial functions fit the simulations responses provided by AquaCrop with a high level of R^2.

Figure 2. Simulated biomass production for 8 years in response to different levels of applied irrigation water (AIW): (a) Sugar beet; (b) Silage Maize; (c) Maize; (d) Sorghum; (e) Soybean; (f) Tomato.

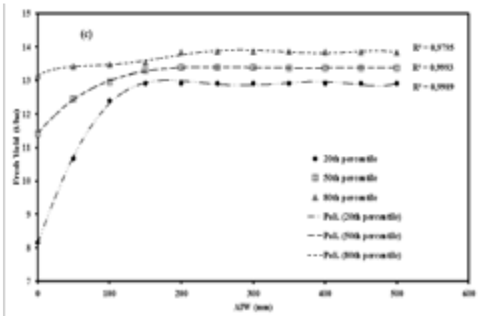
(a)



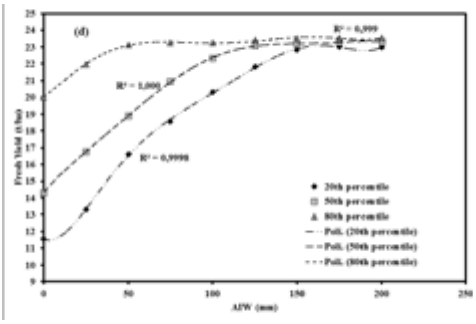
(b)



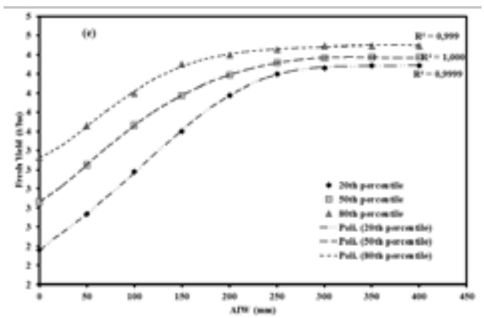
(c)



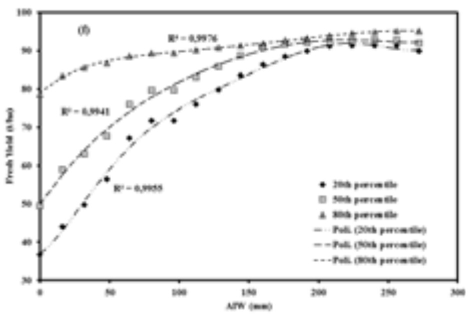
(d)



(e)



(f)



6. Impact assessment

6.1 Land allocation

The integrated model was developed in the agricultural context of a lowland area of Emilia Romagna (Northern Italy). For the purposes of clarity and brevity, the impact assessment presents the results of a homogenous area, the province of Parma. The latent crop introduced in the simulation phase was sorghum for bioethanol production. We assume that this variety of sorghum is currently not present in the regional production plan. The information concerning average yields, price and specific production cost for sorghum was taken from an experimental study promoted by the Emilia Romagna Region aiming to evaluate the possibility of building a regional supply chain for bioethanol. The results presented were developed in the framework of the "Health Check" CAP reform.

The market simulations consist of increasing the price of sorghum by 1 €/t in 200 steps, to reach the maximum price of 200 €/t. The results identify the economic threshold for sorghum, that is the starting price from which sorghum for biomass can be inserted into the production plan of farms in the province of Parma. Figure 3 shows the total area that would be grown with sorghum in the region at different level of sorghum price. The graph presents a curve that starts to increase from a level of 58 €/t, the profitable threshold for the crop. The price dynamics causes a big increase in sorghum acreage. The rotational constraints and the complementary and substitution relationships within the cost matrix prevent farm surfaces from becoming specialized in a single crop. The graphical representation of the simulation shows the different production levels with regard to different price levels, so that it is possible to identify the price to pay to producers in order to obtain a certain quantity of raw material. So, for example, if the supply chain needs 20.000 ha of sorghum, the price that should be paid to farms is more or less 108 €/t.

The simulation also shows variation in the relative incidence of sorghum compared to other crops in the regional production plan. Figure 4 highlights that the increase in the incidence of sorghum on the regional production plan is due to a big fall in the incidence of fodder crops and wheat. It is important to note that in this study, the prices of other crops are assumed to be constant throughout, but likely market price modifications would produce a change in profitability across the model, with different impacts on sorghum production responses.

6.2 Water consumption

The simulations carried out by the integrated model capture the relationships between yields and the applied irrigation water. For the six crops in Table 1, this relationship was estimated by using AquaCrop as previously described, while for the other crops information has been taken from the literature. For sugarbeet, maize, silage cereals, tomato, soya and sorghum, yields are non-linearly related to AIW, while for the other irrigated crops (e.g. alfalfa) an exogenous fixed relationship was assumed. The polynomial regressions estimated for the six crops are used in the AquaCrop model to identify the quantity of irrigated water each farm needs to obtain the observed yield. Polynomial functions from the 50th percentile were used. The difference in terms of AIW among farms is reflected in

Figure 3. Evolution of the sorghum hectares due to price variation (Parma province).

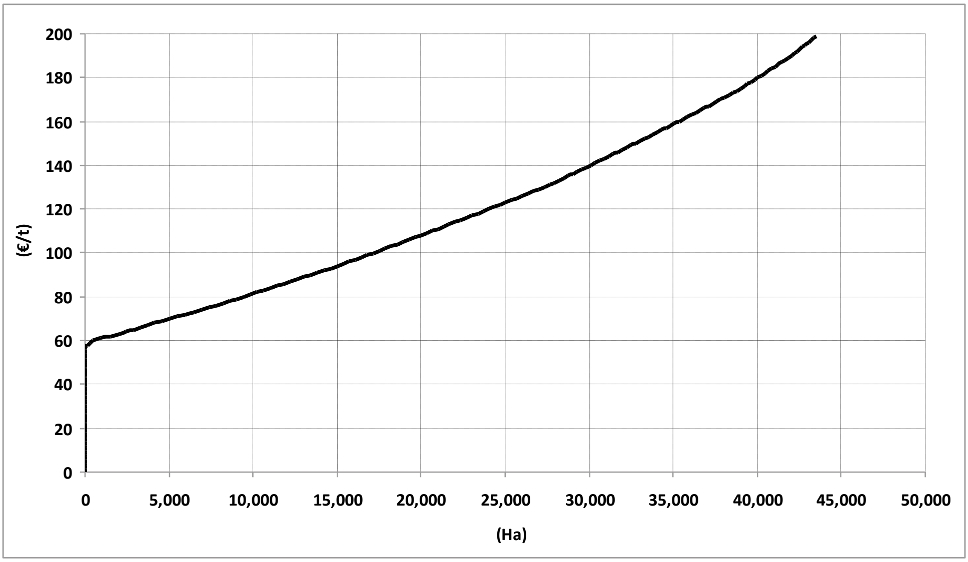
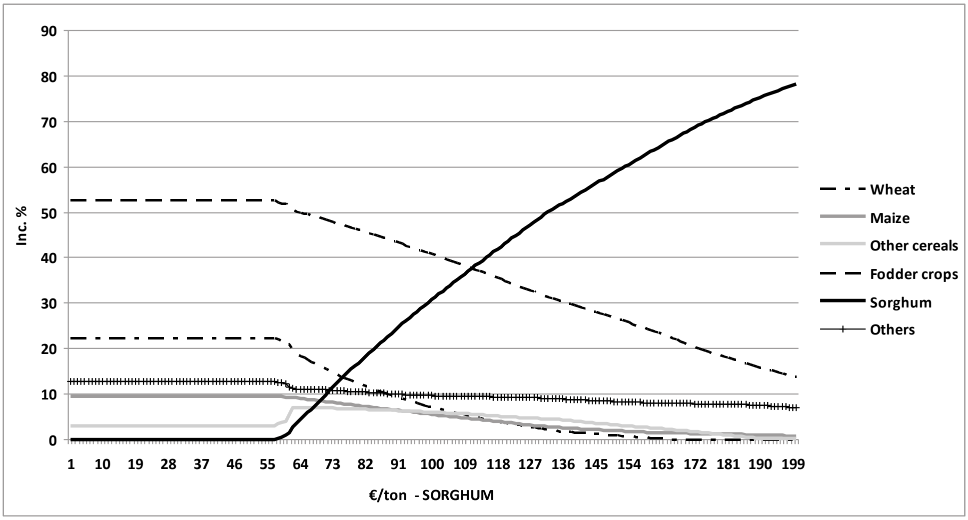


Figure 4. Evolution of the specific incidence of each crop on the regional production plan (Parma province).



the observed yield. To adapt the yield-AIW functions to the observed information, a correction factor was applied as follows:

$$yield_{n,j} = F_{n,j}(w_{n,j}) \cdot v_j \tag{11}$$

where the yield for each irrigated crop *j* (for *j=1,2,…,J*) and each farm *n* (for *n=1,2,…,N*) is derived from the non linear function obtained by AquaCrop simulations multiplied by a weighting value v_j calculated as the ratio between the average observed yield and the average yield provided by AquaCrop simulations. $w_{n,j}$ the variable related to AIW to be estimated for each farm and crop. This correction makes it possible to retain the shape of the yield-AIW function and model feasibility. In fact, the difference between observed and experimental yield data can be unavoidable (Dillon and Hardtacker, 1993; Cortignani and Severini, 2009). Table 5 presents the AIW estimated levels for the six crops simulated in AquaCrop. From experimental tests, sorghum yield is assumed to be 23 t/ha corresponding to 121.1 mm of AIW.

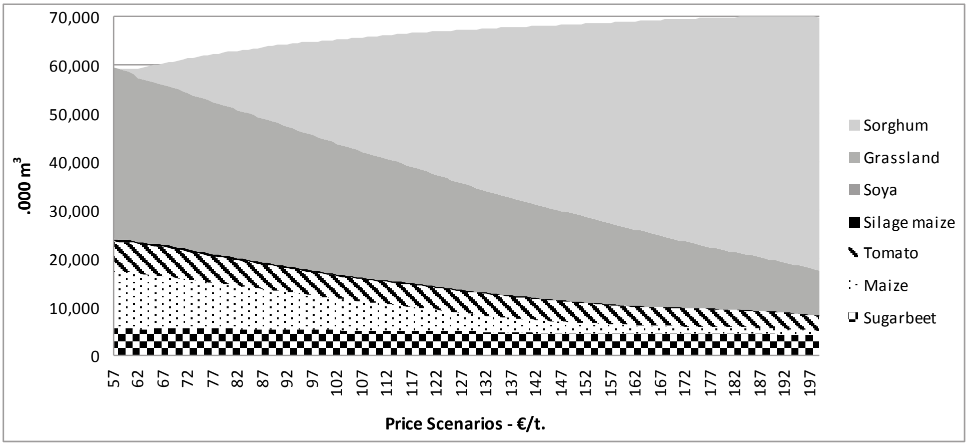
Table 5. Estimated AIW per crop in Parma province.

Area	Altitude	Farm Type	Class of Size (ha)	No. of farms	Sugarbeet	Silage cereals	Maize	Tomato	Soya	Sorghum
					AIW (mm)					
Parma	Plain	Arable crops	0-10	1233	158.8	28.3	159.8	86.9	121.6	121.1
Parma	Plain	Arable crops	10-20	452	185.4		234.5	169.4	131.4	121.1
Parma	Plain	Arable crops	20-30	175	118.8	8.9	171.7	240.7	151.6	121.1
Parma	Plain	Arable crops	30-50	129	220.4	32.1	21.2	211.2	168.0	121.1
Parma	Plain	Arable crops	50-100	97	271.9	418.9	63.7	151.3	407.8	121.1
Parma	Plain	Arable crops	100-300	20	51.4	145.2	234.5	240.7		121.1
Parma	Plain	Arable crops	> 300	1			30.1			121.1
Parma	Plain	Horticulture	0-10	10			158.6	86.9		121.1
Parma	Plain	Horticulture	10-20	6	185.4			169.4		121.1
Parma	Plain	Horticulture	20-30	8	118.8		172.1	240.7		121.1
Parma	Plain	Horticulture	30-50	14	220.4		21.2	211.1		121.1
Parma	Plain	Horticulture	50-100	10	271.9		63.7	151.3		121.1
Parma	Plain	Dairy	0-10	90			160.0	211.1		121.1
Parma	Plain	Dairy	10-20	127	185.5	630.5	234.5	160.1		121.1
Parma	Plain	Dairy	20-30	121	118.8	8.9	171.7	240.7		121.1
Parma	Plain	Dairy	30-50	180	220.4	32.1	21.2	196.3		121.1
Parma	Plain	Dairy	50-100	97	271.9	418.9	63.7	164.9		121.1
Parma	Plain	Dairy	100-300	28	51.4	145.2	234.5	211.1		121.1
Parma	Plain	Dairy	> 300	6	13.8	418.9	234.5			121.1
Parma	Plain	All	All	2804	174.6	169.3	234.5	196.4	154.7	121.1

For five crops out of six, the AIW changes according to the farm, revealing a direct relationship with the specific crop yield. But for sorghum the AIW level is the same for all farms in relation to the supposed uniform yield in the area.

The relationship yield-AIW was used to evaluate the impact of the potential introduction of sorghum for biomass production in terms of water demand. Price rises may persuade farmers to convert cereal land and grassland to sorghum with a negative effect on

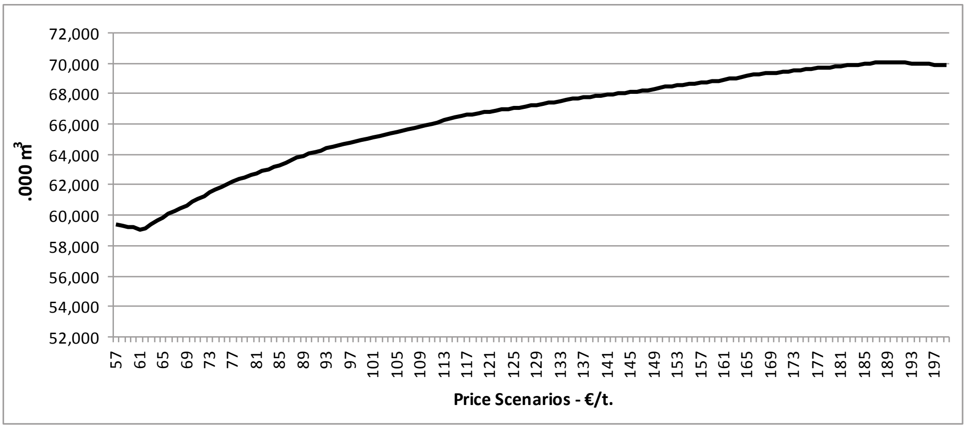
Figure 5. Irrigated water allocation.



the water consumption. In particular, the process of substitution of a non-irrigated crop, like wheat, with an irrigated crop, like sorghum, generates an increase in total irrigated water for the province of Parma. More specifically, when a price of 70 €/t for sorghum is applied, about 30% of the wheat disappears in favour of sorghum. This shift produces an increase of the total irrigated water of 2.5%, which corresponds to an increase of 1.5 million m^3 compared to before sorghum was introduced (see Figure 5).

Figure 6 shows the trend in consumption of water for irrigation. Up to a price of 61 €/t irrigated water consumption declines by 0.5%, due to a process of substitution between sorghum and grassland with high AIW. This substitution is interrupted by the demand for forage from dairy farms, represented by a specific constraint in the model.

Figure 6. Dynamics in water consumption with sorghum cultivation (province of Parma).



The model captures the impact of farm production decisions on the allocation of water, but it does not capture efficiency in the use of irrigated water. An implicit assumption of the model is that farmers in the province take the production decisions considering that water is available, and water allocation is a consequence of their decision. From this point of view, the calibrated AIW represents the willingness to use water for each crop. This implies that there are no direct constraints on the total available water per farm and, therefore that trade of water entitlements cannot be evaluated in this model.

7. Conclusions

This paper uses positive mathematical programming model to evaluate the effects of agro-energy crop cultivation on land and water allocation. The agro-energy crop is sorghum for the production of second generation bioethanol. The model simulates the introduction of sorghum as a new crop in the farm production plan in the lowlands of Parma, an agrarian region in northern Italy, and evaluates crop economic threshold and the change in farm crop set and irrigated water use. The model considers latent crop information in each farm production plan, so that in the simulation phase, new crops, such as sorghum for biomass production, are considered a new option with regard to the crops already activated in the observed situation (Arfini and Donati, 2013). The second PMP phase estimates non-linear cost functions where information about the latent crop is included. The main constraint of the model is related to the total farm land. Water appears in the third phase through the yield-AIW function which defines the relationship between crop yields and the quantity of AIW. The yield-AIW function is estimated by simulating the yield response of the crop in relation to different AIW quantities; simulations were carried out by implementing AquaCrop (Steduto *et al.*, 2009) for six crops: sugarbeet, maize, silage cereals, tomato, soya and sorghum.

The simulation results revealed the capacity of the model to evaluate the productive potential of sorghum for biomass in the region and the consequences on the regional production plan. The scenarios developed to estimate the sensitivity of the sorghum in relation to a variation in its market price made it possible to identify the price level necessary for providing a sufficient quantity of raw material to feed a second generation bioethanol supply chain. The increase in sorghum price leads to a reduction in wheat and fodder crops; maize is also affected by a process of substitution.

The PMP model makes it possible to evaluate the impact of sorghum cultivation on water consumption for irrigation. The results show that increasing land use for biomass sorghum in the lowlands of Parma province, a dairy and horticultural area, entails an increase in the total irrigated water quantity due to a decline in non-irrigated crops, like wheat. The information about water consumption will be useful for policy makers in preventing excessive demand for water in areas where the risk of drought might generate non-efficient water allocation. Furthermore, the model can evaluate the impact of the CAP on irrigation water needs as well as land use. The 2014-2020 CAP reform, which emphasized environmental objectives in agricultural policies, could also be evaluated in order to predict effects on water resources using a similar approach.

The model does however present certain limitations. The AquaCrop simulation was run on the crops included in the FAO model dataset. This is because yield-AIW functions for fodder crops, such as alfalfa and permanent meadows, have not been estimated.

Furthermore, the PMP model presented in this study does not consider an explicit water constraint, and it is thus not possible to simulate reductions in water availability and identify the dual value associated with this resource. Optimizing the model to include this information would provide a value for levels of water scarcity in certain groups of farms or areas, and would be useful in identifying an appropriate price. Finally, a water constraint in the model would make it possible to simulate the water entitlement market and put in place economic tools to make the use of water for irrigation more efficient.

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