Drought response and irrigation: Overcoming *lacunae* in impact assessment and decision making

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Abstract: Climate change, increasing demand, higher environmental standards and inelastic water supply suggest that future drought response in Southern Europe will demand more frequent and intense irrigation restrictions. In this context, there is a pressing need to better understand the economic impacts of irrigation restrictions, including their microeconomic and economy-wide repercussions. This paper presents a methodological framework that connects a bottom-up model working at an agricultural district level with a regionally-calibrated top-down model to address this need. The bottom-up approach consists of a multi-attribute Revealed Preference Method, and the top-down approach of a multiregional supply and use model that combines non-linear programming and input-output modelling techniques. To the best of our knowledge, this is the first time both models are connected. Methods are illustrated with an application in the Lower Po River Basin (LPRB) in Italy. Despite its growing drought exposure and inflating agricultural losses, drought management in the Po River Basin is informed through a hydrological model that does not consider economic objectives or restrictions. Results show that irrigation restrictions constrain farmers to rely on less water intensive and/or rainfed crops, which are typically characterized by lower gross margin, labor intensity and GVA. As the water availability constraint is strengthened, trading GVA off for water conservation becomes costlier. A hypothetical water conservation/irrigation restriction target of 25 Mm^3 would cost EUR 0.26/m^3; 50 Mm^3, EUR 0.29/m^3; 100 Mm^3, EUR 0.33/m^3; and 150 Mm^3, EUR 0.41/m^3. On average, the GVA losses estimated for the LPRB using the microeconomic simulation represent 58.6% (Emilia Romagna) and 79.7% (Italy) of the GVA losses estimated using the macroeconomic simulation. This highlights the relevance of the inter-sectorial linkages within and among the Italian regions, suggesting that microeconomic models need to be complemented with macroeconomic models in water policy appraisals

1. Introduction

Southern Europe is becoming drier (EC, 2012; IPCC, 2014). Adverse climatic conditions may reduce rainfed agricultural production and farmers are likely to adapt by increasing their irrigation demand. With *high confidence*, water demand for crop irrigation is expected to increase by more than 40% up to 2080 (IPCC, 2014), further strengthening the irrigation expansion trend of the last 50 years (EEA, 2009). Declining runoff and groundwater resources in Mediterranean catchments are unlikely to meet expanding irrigation demand (IPCC, 2014), giving rise to more frequent and intense drought events (EC, 2012; EEA, 2012a). Higher environmental standards (EC, 2000), competition with other economic uses (EEA, 2012b) and the hastily increasing costs of new supplies (EEA, 2012a; Randall, 1981) suggest that future drought response will demand more frequent and intense irrigation restrictions (EC, 2012; OECD, 2014). In this context, there is a pressing need to better understand the economic impacts of watering restrictions, including their microeconomic and economy-wide repercussions (OECD, 2013; UN, 2014; WEF, 2015).

Decision Support Systems (DSS) at different geographical scales play a key role in this respect, providing the data to inform water resources management (Girard et al., 2015). DSS use simulation and optimization models to explore the benefits of alternative management strategies following agronomic, hydrological or economic criteria, or a combination thereof (hybrid approaches, e.g. hydroeconomic) (Harou et al., 2009; Singh, 2012). Economic objectives and constraints have been used in DSS since the 1960s (Maass et al., 1962; Rogers and Smith, 1970). Increasing prominence of economics in water resources management came as a reaction to the inability of conventional engineering approaches to address the incremental costs of water provision, which eventually led to inelastic supply in several basins and called for a better understanding and representation of the drivers and dynamics of demand (Randall, 1981).

Economic models used in DSS typically work at two levels: micro- and macroeconomic. Microeconomic modeling follows a bottom-up approach and typically works at a farm or agricultural/irrigation district scale. Farmers may decide on crop mix and timing, water application and capital stock, in order to optimize[1] an objective function within a domain defined by a number of constraints. Most models rely on single-attribute objective functions that maximize the utility derived from profit, the case of Linear Programming, Expected Utility and Positive Mathematical Programming (Heckelei et al., 2012; Howitt, 1995). There is also an expanding literature on Revealed Preference Models (RPM) that make possible the use of both single- and multi-attribute utility functions (Gómez-Limón et al., 2016; Gutiérrez-Martín and Gómez, 2011; Pérez-Blanco et al., 2015b; Rodrigues et al., 2013). Multi-attribute utility functions are consistent with observed farmers' behavior and scientific research, which suggest that decision-making is

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[1] An alternative to optimization is simulation. However, the usual approach to solve water management problems from microeconomics is optimization (Harou et al., 2009; Singh, 2012).

largely driven by the multiple attributes of objects (including but not limited to profit) and related farmers' beliefs (Bergevoet et al., 2004; Läpple and Kelley, 2013; Lynne, 1995; Poppenborg and Koellner, 2013). Other advantages of RPM as compared to alternative methods include metrics for performance evaluation, a clear economic rationale and a supple specification that makes feasible the use of both linear and non-linear functional forms (Gómez-Limón et al., 2016; Gutiérrez-Martín et al., 2014; Gutiérrez-Martín and Gómez, 2011a).

Macroeconomic modeling follows a top-down approach and describes the operation of the economy at a regional (Carrera et al., 2015; Dixon et al., 2011; E E Koks et al., 2015; Pérez-Blanco and Thaler, 2014), national (Bosello et al., 2012; Ciscar et al., 2011) and even global scale (Hertel, 1997; Lenzen et al., 2012, 2013). The two most common used models to assess the economy-wide impacts of environmental changes are Computable General Equilibrium (CGE) and Input-Output (IO) models. In CGE models, agent behavior is calibrated from observed economic flows registered in Social Accounting Matrices. These models often follow a Walrasian framework, investments are saving-driven and agents minimize private expenditure to attain a given utility level (Bosello et al., 2014; Parrado and De Cian, 2014). IO models, on the other hand, reflect the economic interdependencies between sectors and regions within an economy through intermediate supply and final demand, based on linear relations (Koks et al., 2015). Alternative approaches combine non-linear optimization with IO modelling techniques. As shown in Oosterhaven & Bouwmeester (2016) and Baghershad & Nobel (2015), the combination of IO modeling with optimization techniques allows for a more flexible modelling framework when dealing with economic disruptions. Such a framework provides the simplicity of IO modeling (i.e. Leontief production function), but also allows for some more flexibility which is available in CGE modeling (Oosterhaven et al. 2013).

Most DSS operationalize economic concepts combining microeconomic and engineering models using a holistic or modular approach. Holistic approaches represent farmers using piecewise exogenous benefit functions that relate water use to profit, and then solve both models at once to represent causal relationships and interdependencies. Modular approaches run the two models independently, which increases the probability of convergence on an optimal solution and the level of detail in each sub-field (Harou et al., 2009; Heinz et al., 2007; Singh, 2012). Computationally demanding macroeconomic models are typically run independently and combined with engineering models using a modular approach (see e.g. Carrera et al., 2015; Grames et al., 2016). Although micro- and macroeconomic models have been widely used to inform drought management, DSS include one or another and connected micro- and macroeconomic models are rare (Pérez-Blanco et al., 2016). This paper presents a methodological framework that utilizes a modular approach to connect a multi-attribute RPM with a macroeconomic model that combines non-linear programming and IO techniques. The latter will be further referred to as the MRIA (MultiRegional Impact Assessment) model (Koks and Thissen, 2016). The multi-attribute RPM and the MRIA model present a series of advantages over alternative approaches, and can be coupled with relatively low computational requirements. To the best of our knowledge, this is the first time both models are connected.

Methods are used to assess the economic impacts of seasonal irrigation restrictions, including their microeconomic and economy-wide repercussions. This is resolved in two stages: in the *first stage*, the multi-attribute RPM is calibrated and a series of simulations are run to estimate the impacts of irrigation restrictions on the income of farmers; in the *second stage*, estimated income impacts are adapted and imported into the MRIA model to calculate the economy-wide repercussions across sectors and regions. The exercise is illustrated with an application in the Lower Po River Basin (LPRB) in Northeastern Italy. Despite its growing drought exposure and inflating agricultural losses (Mysiak et al., 2013; PRBDA, 2015), irrigation restrictions in the Po River Basin is informed through a hydrological modeling that does not include information on the economic impact of irrigation restrictions. By means of a thorough representation of farmers' preferences and response and related economy-wide repercussions, this research can be used to estimate the abatement costs of droughts. Authors intend to leverage on this research and its outcomes to strengthen ongoing collaboration with basin authorities and advance towards the development of a modular hydroeconomic model comprising sound micro- and macroeconomic principles[2].

2. The Lower Po River Basin, Italy

The LPRB is located to the northeast of the Italian Peninsula. It comprises the lower stretches of the Po River and the sub-basins of Trebbia, Nure, Chiavenna, Arda-Ongina, Taro, Parma, Enza, Crostolo, Secchia and Panaro (the so-called *Bacini Emiliani*). The LPRB spreads throughout the provinces (NUTS 3[3]) of Piacenza, Parma, Reggio Emilia (entirely), Modena, Ferrara (most of its territory) and Bologna (marginally) in the Emilia Romagna Region (NUTS 2), and the southernmost part of the Veneto Region (Polesine, province of Rovigo). The Rovigo area and the easternmost part territories of Ferrara constitute the Po Delta Interregional Park, a UNESCO World Heritage site (UNESCO, 1999). Irrigated areas are concentrated in the southern part of the river, across the Emilia Romagna Region, and comprise 30 Agricultural Districts (ADs) (see Figure 1). ADs are groups of municipalities with similar climatic, geologic, topographic and agricultural characteristics, and are the agents in the multi-attribute RPM. Most relevant crops in the area are wheat and corn. Other relevant crops include other cereals, fruit trees and vineyards (ER Statistica, 2014).

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[2] Due to the sensible nature of the information supplied by the hydrological model, its methods and some of the model outcomes are not publicly available.

[3] The *Nomenclature des Unités Territoriales Statistiques* (NUTS), or nomenclature of territorial units for statistics, is "a hierarchical system for dividing up the economic territory of the EU" (Eurostat, 2016). In Italy, NUTS 1 refers to macro-regions; NUTS 2 to regions; and NUTS 3 to provinces.

Figure 1: The LPRB. *Source: Own elaboration*

The Po River Basin has been increasingly hit by drought events after the turn of the century. Droughts hit the basin in the years 2003, 2006, 2007 and 2015, with the State of Emergency (SoE) being declared in 2003, 2006 and 2007 for a total duration of 20 months (Mysiak et al., 2013; PRBDA, 2015). The negative consequences of droughts were especially felt in the irrigated areas of the LPRB (Mysiak et al., 2014). Climate projections indicate this trend will aggravate in the future (Coppola et al., 2014; Vezzoli et al., 2015).

Despite the medium to long term planning instruments provided for by the Italian legislation[4], drought management in the basin relies on reactive measures enacted during drought episodes (Calliari, 2011). Traditionally, drought response has followed a *Command-and-Control* (C&C) approach in which the Civil Protection Department (CPD, in Italian: *Dipartimento Protezione Civile*) sets specific water restrictions for each use, with sanctions following in case of non-compliance (GU, 1994). The 2003 drought event opened the way for the establishment of a coordinated approach, in which water restrictions are defined through consensual participatory processes in the context of a *Drought Steering Committee* (DSC, in Italian: *Cabina di Regia*). Promoted by the Po RBA, the DSC engages the regional administrations of Emilia Romagna, Lombardy, Piedmont, Valle d'Aosta, and Veneto; several Land Reclamation and Irrigation Boards; public entities supervising the operation of the great regulated lakes; the Italian Grid Distribution Operator; and major power producing companies located in the basin. The DSC builds upon the voluntary engagement of the main interested sectors, on the basis of two strategic considerations. The first is rooted in the opportunity to coordinate with other water users and delay or prevent the

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[4] These include for instance the Water Protection Plans mandated by the Legislative Decree 152/99 and the Programs of Local Action to fight Drought and Desertification (PAL, in Italian: *Piano di Azione Locale*) envisaged by CIPE's resolution 229/99.

declaration of the SoE. When the SoE is declared the CPD takes over drought management and stakeholders' needs and interests cannot be negotiated any longer (C&C). The second reason lies in the possibility of getting to know other users' current or future behavior, and act consistently so to get advantages or avoid detrimental consequences.

During the 2003 event, one of the most intense of the past 30 years, the DSC conducted negotiations that led to a reduction of 25-50% of irrigation withdrawals and increased water releases from alpine reservoirs and large regulated lakes. This cooperative decision of the DSC was sanctioned by a Memorandum of Understanding (in Italian: *Protocollo d'Intesa*) (PRBA, 2003). Although insufficient to restore the balance in the basin (the SoE was eventually declared), the decision brought to a progressive increase of the water flows in the Po River Estuary. Given the positive experience in 2003, the DSC was broadened in 2005 to devise a coordinated way of monitoring and anticipating future water crises (PRBA, 2005) and convened again during the 2006/2007 drought events.

Since 2003, drought management in the Po River Basin has thus been characterized by a mixed approach, relying initially on a DSC which is replaced by a C&C mechanism if drought is not resolved or aggravates. In the latter case, the DSC also plays a relevant role as an advisory committee to the CPD. Irrigation restrictions are informed by the TOPKAPI (TOPographic Kinematic APproximation and Integration) type hydrological model of the Emilia Romagna Regional Environmental and Energy Agency (in Italian: *Agenzia regionale per la prevenzione, l´ambiente e l´energia dell´Emilia-Romagna*), which has contributed to a better understanding of the consequences of irrigation restrictions or water releases throughout the basin. Yet, the absence of information on the economic impacts such decisions might have remains a major drawback of the process.

3. Revealed Preference Model

3.1. Decision-making problem

Multi-attribute utility functions depend on the attributes farmers value, which may include profit but also risk, management complexities, etc. The provision of these valuable attributes depends in turn on the decisions taken by farmers, namely the crop mix and timing, water application and capital stock. Considering every possible combination of crops and management techniques (involving timing, water application and capital) in the model as a unique crop, and introducing some restrictions and conditionals regarding capital decisions (e.g. some infrastructures affect all or large groups of crops), these alternatives can be reduced to a decision on the crop mix. Consequently, farmers are mainly focused on choosing the crop mix that maximizes the utility function within a domain:

$$\underset{x}{\text{Max}}\, U(x) = U(z_1(x);\ z_2(x); z_3(x) \ldots z_m(x)) \quad [1]$$

$$\text{s.t.:} \quad 0 \leq x_i \leq 1 \quad [2]$$

$$\textstyle\sum_{i=1}^{n} x_i = 1 \quad [3]$$

$$x \in F(x) \quad [4]$$

$$z = z(x) \in R^m \quad [5]$$

Agents decide on the crop mix $x \in R^n$. x is a vector containing the share of the surface devoted to each crop x_i $(i = 1, \ldots, n)$. Each crop i is a unique combination of crops and management techniques and has a unique combination of attributes z(x) attached. All attributes are normalized dividing by the maximum feasible value and are quantities of dimension one. Increasing the provision of any attribute has a positive impact on farmers' utility, *ceteris paribus* ("more is better"). Capital investment/disinvestment (e.g. on ligneous crops) is not allowed given the short term focus of irrigation restrictions. Agents balance the crop mix so as to maximize the utility derived from the provision of attributes subject to a series of agronomic, policy, information and physical constraints that result in a domain F(x). Physical constraints include the water resources constraint, which can be expressed as:

$$\textstyle\sum_{i=1}^{n} w_i\, x_i \leq W \quad [6]$$

Where W is the water allotted to the agent and w_i are the water withdrawals necessary to irrigate crop x_i.

The multi-attribute utility function in [1] is calibrated using a RPM. RPM follow a positive approach, meaning that the solution to the problem above is the observed crop mix actually chosen by the farmer, denoted by x^0. RPM aims to elicit a utility function that is consistent with the observed crop mix and the domain.

3.2. Calibration

Using standard microeconomic theory, the objective function parameters can be elicited for every possible set of attributes equalizing the Marginal Rate of Transformation (MRT_{kp}), i.e. the opportunity cost of trading one unit of attribute z_k off for one unit of attribute z_p (the slope of the efficient frontier), and the Marginal Rate of Substitution (MRS_{kp}), i.e. the willingness to give up one unit of attribute z_k in exchange for a unit of attribute z_p (the slope of the indifference curve of the utility function).

$$MRT_{kp} = MRS_{kp} = -\frac{\partial U / \partial z_p}{\partial U / z_k}\, ; p, k \in (1, .. m); p \neq k \quad [12]$$

The multi-attribute utility function is calibrated in two steps. In the first step, a method to reveal the efficient frontier for each pair of attributes using numerical methods is presented, and the $\mathrm{MRT}_{\mathrm{kp}}$ estimated. In the second step, the parameters of the utility function for every possible combination of attributes are elicited equalizing the $\mathrm{MRT}_{\mathrm{kp}}$ and $\mathrm{MRS}_{\mathrm{kp}}$. The relevant attributes are those that minimize the distance between observed and simulated decisions.

3.2.1. Efficient frontier and tangency point

In order to calibrate the objective function the efficient frontier needs to be defined. The efficient frontier represents the maximum provision of attributes agents can attain within the space of feasible decisions $\mathrm{F(x)}$. The efficient frontier cannot be defined with a closed function, and is obtained instead through numerical methods using an optimization procedure. For a given attribute $\mathrm{z}_k(\mathrm{x})$, this procedure finds the set of feasible crop decisions that maximize the value of attribute $\mathrm{z_p(x)}$ $(\mathrm{p} \neq \mathrm{k})$.

$$\underset{\mathrm{x}}{\mathrm{Max}}\, \mathrm{z_p(x)} \tag{7}$$

$$\text{s.t.: } \mathrm{z_k(x)} = \mathrm{c} \quad \forall \mathrm{k} \neq \mathrm{p} \quad \mathrm{c} = (0, \ldots, 1) \tag{8}$$

$$0 \leq \mathrm{x_i} \leq 1 \tag{9}$$

$$\textstyle\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{x_i} = 1 \tag{10}$$

$$\mathrm{x} \in \mathrm{F(x)} \tag{11}$$

The result is an efficient frontier in the two-dimensional space defined by $\tau_{\mathrm{z_p,z_k}}(\mathrm{X^f})$. The efficient frontier has to be convex –otherwise one of the attributes has no opportunity cost in terms of the other and can be excluded. The slope of the efficient frontier or $\mathrm{MRT}_{\mathrm{kp}}$ offers the information necessary to obtain the tangency point for the calibration of the utility function.

There are several methods that can be used to find tangency points along the frontier (Gómez-Limón et al., 2016; Gutiérrez-Martín and Gómez, 2011b; Pérez-Blanco et al., 2015a). In this paper we use a *projection* method (Gutiérrez-Martín et al., 2014), in which the optimization problem in equations [7]-[11] is solved for the observed values of $\mathrm{z_k(x)}$, i.e. $\mathrm{z_k(x)} = \mathrm{c} = \mathrm{z_k^o(x)}$. This equals to project the observed crop portfolio $\tau_{\mathrm{z_p,z_k}}(\mathrm{x^o})$ to the efficient frontier and yields two points, namely $\tau_{\mathrm{z_p,z_k^o}}(\mathrm{x^f})$ and $\tau_{\mathrm{z_p^o,z_k}}(\mathrm{x^f})$. The slope between the two projected points approximates the $\mathrm{MRT}_{\mathrm{kp}}$ and is used as the tangency point for the calibration of the utility function in the next section (Figure 2).

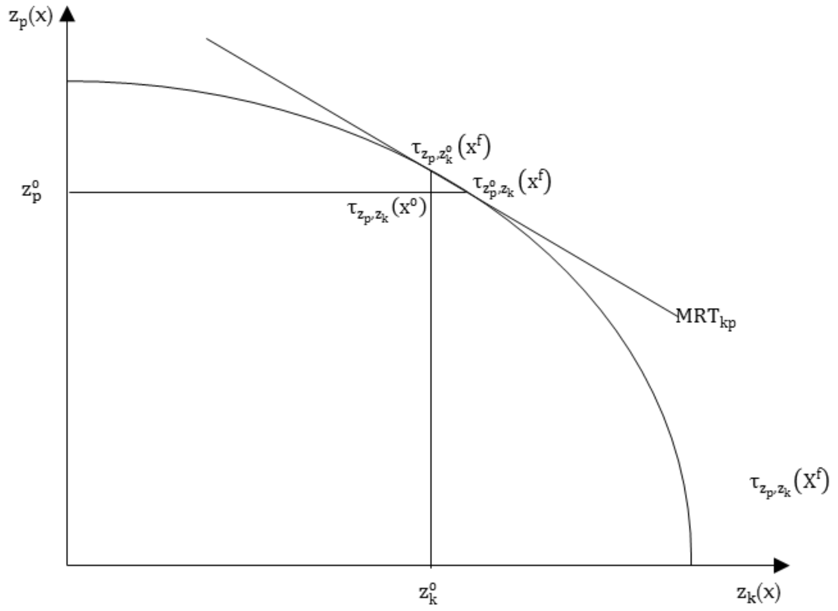

Figure 2. Efficient frontier and tangency point. *Source: Own elaboration.*

Provided agents are rational individuals that aim at maximizing their utility within the domain, and following a positive approach that equalizes the optimal and observed decisions, the observed crop portfolio $\tau_{z_p,z_k}(x^o)$ and the frontier must be close, and so must be the projected points $\tau_{z_p,z_k^o}(x^f)$ and $\tau_{z_p^o,z_k}(x^f)$. The projection method reduces the approximation error as compared to other alternatives (see e.g. Amador et al., 1998; André et al., 2010; André and Riesgo, 2007; Sumpsi et al., 1997), but still yields an error that is measured using calibration residuals (see section 3.2.3).

3.2.2. Utility function specification and parameters

A Cobb-Douglas specification was chosen for the utility function. Unlike alternative additive or multiplicative-additive specifications, Cobb-Douglas specifications have a decreasing marginal utility for each attribute and yield a global optimum (Inada, 1963). The Cobb-Douglas parameters are estimated as follows:

$$-\frac{\partial U/\partial z_p}{\partial U/z_k} = -\frac{\alpha_p}{\alpha_k}\frac{z_k}{z_p} = \text{MRT}_{kp} \qquad [13]$$

$$\sum_{p=1}^{m} \alpha_r = 1 \qquad [14]$$

This system is resolved for every possible combination of attributes, and thus the parameters of the related utility functions are elicited. The calibrated utility functions that result are used to obtain their corresponding optimum crop portfolio (x^*) and attributes ($z_p^*; r = 1, \dots, m$).

The positive approach used in RPM implies that the relevant attributes are those that more accurately resemble the observed behavior of the agent. Accuracy is assessed through calibration residuals that measure the distance between the value of observed and calibrated variables. The first calibration residual measures the distance between the observed and optimum (calibrated) crop mix:

$$e_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i^o - x_i^*}{x_i^o}\right)^2} \qquad [15]$$

The second calibration residual measures the distance between the observed and optimum (calibrated) attributes:

$$e_\tau = \sqrt{\frac{1}{m}\sum_{p=1}^{m}\left(\frac{z_p^o - z_p^*}{z_p^o}\right)^2} \qquad [16]$$

The ordinary arithmetic mean of the two metrics above is the average calibration residual:

$$e = \frac{e_x + e_\tau}{2} \qquad [17]$$

The combination of attributes that minimizes this error is the relevant one, and its corresponding utility function is used in the simulation runs.

3.3. Data

Based on a literature review on multi-attribute utility functions (Bergevoet et al., 2004; Binswanger, 1982; Chung and Lee, 2009; Delforce and Hardaker, 1985; Gómez-Limón and Riesgo, 2004; Hazell and Scandizzo, 1977a, 1977b; Just, 1975; Läpple and Kelley, 2013; Lynne, 1995; Poppenborg and Koellner, 2013; Rausser and Yassour, 1981; Rodrigues et al., 2013b), five attributes are explored. Apart from profit, these attributes include avoided risk, total labor avoidance, hired labor avoidance and direct costs avoidance (“more is better”). Attributes are described below:

-Profit (z_1), obtained as a function of the per hectare gross margin π_i:

$$z_1(x) = \sum_i x_i \pi_i \qquad [18]$$

-Avoided risk (z_2):

$$z_2(x) = x^\tau VCV(\pi(x))x - \bar{x}^\tau VCV(\pi(\bar{x}))\bar{x} \qquad [19]$$

Where $VCV(\pi(x))$ is the variance and covariance matrix of $z_1(x)$ and $VCV(\pi(\bar{x}))$ is the variance and covariance matrix of $z_1(\bar{x})$.

-Total labor avoidance (z_3):

$$z_3(x) = N(\bar{x}) - N(x) \tag{20}$$

Where $N(x) = \sum_i x_i N_i$ is the total labor requirements to produce the crop mix x, $N(\bar{x}) = \sum_i \bar{x}_i N_i$ is the total labor requirements to produce the crop mix $\bar{x}$, and N_i is the total labor per hectare (daily wages) of crop i.

-Hired labor avoidance (z_4):

$$z_4(x) = H(\bar{x}) - H(x) \tag{21}$$

Where $H(x) = \sum_i x_i H_i$ is the hired labor requirements to produce the crop portfolio x, $H(\bar{x}) = \sum_i \bar{x}_i H_i$ is the hired labor requirements used to produce the profit maximizing crop mix $\bar{x}$, and H_i is the hired labor per hectare (daily wages) of crop i.

-Direct costs avoidance (z_5):

$$z_5(x) = D(x) - D(\bar{x}) \tag{22}$$

Where $D(x) = \sum_i x_i D_i$ are the direct costs incurred in the production of the crop mix x, $D(\bar{x}) = \sum_i \bar{x}_i D_i$ are the direct costs incurred in the production of the profit maximizing crop mix $\bar{x}$, and D_i are the direct costs per hectare of crop i.

The model is calibrated using data from ER Statistica (2016) (land use and yields), ISMEA (2016) (market prices), INEA, 2016 (family and hired labor, other costs, subsidies and other revenues), ISTAT, 2013 (water use and irrigation efficiency). Data is available for 55 crops and 89.6% of the case study area during the period 1996-2011. Prices base year is 2000 following the MRIA model and the calibration year (observed crop portfolio) is 2014.

3.4. Simulation

Once the multi-attribute utility function is calibrated, equations [1]-[6] can be used to assess agents' responses to a series of policies or shocks. In this particular exercise, a series of simulations are run in which the irrigation allotments W_g in [6] are reduced from 0 to 50% at 1% intervals ($g = 0, \dots, 50$). For every simulation scenario, agents reassess their decisions and find the optimal crop mix (x^*) and its corresponding attributes (z_p^*; $r = 1, \dots, m$). This information can be used to estimate the Gross Value Added (GVA) of the agricultural sector in the LPRB (Y_g^{RPM}), a function of the gross margin and labor:

$$Y_g^{RPM} = f(z_1^*, z_3^*) \tag{23}$$

This output is transformed to produce the inputs for the macroeconomic simulation. For each simulation run g, a productivity shock σ_g is obtained as a function of the ratio between the estimated GVA and the GVA in the baseline (g = 0):

$$\sigma_g = \gamma \frac{Y_g^{RPM}}{Y_0^{RPM}} \quad [24]$$

Where γ is a fixed coefficient capturing the share of agricultural GVA that the case study area (LPRB) represents in its corresponding region (Emilia Romagna Region).

The productivity shock offers aggregated information at a NUTS 2 level and can be used as an input to conduct simulations in macroeconomic models in general (Carrera et al., 2015; Pérez-Blanco et al., 2016), and the MRIA model in particular (Koks et al., 2015).

4. The MultiRegional Impact Assessment Model

4.1. Model basics

To calculate the regional impacts, in both the affected and surrounding regions, use will be made of the MRIA model. The MRIA model is originally developed for the entire European Union, consisting of 256 NUTS 2 regions, 59 products and 15 sectors (Thissen et al., 2013). For the purpose of this paper, only the 20 Italian regions are considered, and the rest of Europe is aggregated into one. More specifically all import from all other EU regions are aggregated in one row and all export to other EU regions are aggregated in one column.

The objective function of the model minimizes total production over all regions (Equation [1]) given that supply should be equal to or larger than demand (Equation [2]). In the MRIA model each industry in each region aims to minimize their costs given the demand for products and the available technologies to make these different products. These technologies describe how industries can make a mix of products out of a specific set of inputs (the Leontief production function). These technologies are ′owned′ by the different industries in the different regions and are therefore only available to them. The mix of inputs that each industry requires to make its specific mix of products represents its production technology and is described by the use table. The mix of products that each industry can make using this technology is described by the supply table. The complete MRIA Model can be described by the following set of equations, with t = time, with p = 1, … , P, with P = number of products, with i and j = 1 , …, I, with I = number of industries, r = 1, …, N, with N = number of NUTS2 regions and with s = 1, ..., N. Appendix I inclueds a full list of all variables and their description.

$$\text{Min } z_t = \sum_{j}^{rs} \mathbf{X}_j^{rs,t} \quad [1]$$

$$\mathbf{S}_p^{r,t} \geq (\mathbf{U}_p^{r,t} + \mathbf{F}_p^{r,t} + \mathbf{R}_p^{r,t})(1-\boldsymbol{\eta}_p^r) - \boldsymbol{\Omega}_p^{r,t} + \mathbf{E}_p^{r,t,EU} + \mathbf{E}_p^{r,t,world} \qquad [2]$$

$$\boldsymbol{\Omega}_p^{r,t} = \mathrm{Max}\left[0, (\mathbf{U}_p^{r,t} + \mathbf{F}_p^{r,t} + \mathbf{R}_p^{r,t})(1-\boldsymbol{\eta}_p^r) + \mathbf{E}_p^{r,t,EU} + \mathbf{E}_p^{r,t,world} - \delta \sum_{ij} \mathbf{A}_{ij,p}^{r,\mathrm{supply}} \mathbf{X}_j^{r,\max}\right] \qquad [3]$$

where:

$$\mathbf{X}_{ij}^{rs,t} \geq 0, \mathbf{X}_{ij}^{rs,t} \leq \mathbf{X}_{ij}^{rs,\max}, \boldsymbol{\Omega}_p^{rs,t} \geq 0, \mathbf{R}_p^{rs,t} \geq 0$$

$$\mathbf{S}_p^{r,t} = \sum_{ij} \mathbf{A}_{ij,p}^{r,\mathrm{supply}} \mathbf{X}_j^{r,t}$$

$$\mathbf{U}_p^{r,t} = \sum_{ij} \mathbf{A}_{ij,p}^{r,use} \mathbf{X}_j^{r,t}$$

$$\boldsymbol{\eta}_p^r = \frac{\mathbf{I}_p^{r,base,EU} + \mathbf{I}_p^{r,base,world}}{\mathbf{U}_p^{r,base} + \mathbf{F}_p^{r,base}}$$

$$\mathbf{E}_p^{r,t,EU} = \sum_p^s \mathbf{T}_p^{rs,t}$$

The MRIA model assumes, in line with standard IO modelling, a demand-determined economy. More specifically, demand from all Italian regions and the rest of the world has to be satisfied by the total supply in all regions and the rest of the world. This implies that if there is a supply restriction in a region (i.e. reduced production as a result of a drought), the model aims to substitute to a non-affected supplier to satisfy demand. The supply of products in all regions should be equal to or larger than demand for these products from all regions. The possibility of supply to be larger than demand is a crucial element in our model that enables us to model inefficiencies in the economy due to limits in the production capacity in the disaster affected area. The production in all regions will take place at the lowest possible costs (industries minimize costs) given demand, the available technologies and the maximum capacity of industries.

4.2. Simulation

A specific event that represents an economic disruption is modeled by reducing the maximum capacity of the affected sector(s). In the case of a drought, the maximum capacity of the agricultural sector is reduced and will become binding for the affected sector in the affected region. This is shown in Equation [4], where Y is Value Added and σ the percent loss in GVA as a result of the drought in the agricultural sector.

$$\mathbf{Y}_j^{r,t,\max} = \mathbf{Y}_j^{r,base,\max}\left(1-\boldsymbol{\sigma}_j^{r,t}\right) \qquad [4]$$

In the MRIA model, there are two ways in which the supply for products can be increased to satisfy the remaining demand. First, the production is increased in sectors in the affected region that are not at their maximum capacity but can produce the demanded product as a by-product. Obviously, this causes inefficiencies in the economy because these products are no longer made by the best possible technology. Second, imports to the region with an excess demand can be increased. The option to increase imports of a certain product is only used when the total of all sectors that can produce this product is away from their combined maximum capacity.

The distribution of imports from other regions is determined by a fixed proportion, which is in line with standard multiregional IO models. Please note that large disasters may result in large additional imports which may cause exporting regions, not directly hit by the disaster, to reach the maximum capacity for certain industries. This is endogenously determined in the model.

5. Results

5.1. Calibration

Table 1 presents the calibration results and the corresponding calibration residuals for the ADs of the LPRB using the RPM and a multi-attribute utility function.

Table 1: RPM calibration results and residuals

	Parameter			Calibration residuals		
Agricultural District	α_1	α_2	α_3	e_τ	e_x	e
Pianura di Reggio Emilia	68.3%	6.2%	25.4%	2.6%	10.4%	6.5%
Pianura di Modena	84.5%	15.5%	0.0%	1.2%	5.4%	3.3%
Pianura di Ferrara	80.7%	2.8%	16.5%	1.3%	1.4%	1.4%
Pianura di Carpi	82.6%	10.6%	6.8%	1.3%	6.6%	4.0%
Pianura di Busseto	86.3%	1.0%	12.7%	0.1%	3.8%	2.0%
Pianura a sinistra del Reno	80.8%	7.1%	12.1%	1.1%	7.4%	4.3%
Bonifica Ferrarese Occidentale	82.9%	9.4%	7.7%	2.0%	11.4%	6.7%
Bonifica Ferrarese Orientale	85.8%	3.6%	10.6%	2.7%	14.0%	8.4%
Basso Arda	75.1%	0.7%	24.2%	1.8%	4.7%	3.3%
Bassa Reggiana	76.3%	1.4%	22.3%	2.1%	7.0%	4.6%
Bassa Modenese	80.7%	4.8%	14.5%	0.5%	2.7%	1.6%
Pianura di Parma	86.1%	1.3%	12.6%	0.9%	6.0%	3.5%
Pianura di Piacenza	87.5%	1.9%	10.6%	0.9%	0.0%	0.5%
Colline del Nure e dell'Arda	84.5%	3.7%	11.7%	4.3%	3.9%	4.1%
Colline di Bologna	98.9%	1.1%	0.0%	4.2%	9.9%	7.1%

Colline di Salsomaggiore	75.4%	8.7%	15.9%	0.3%	0.1%	0.2%
Colline Modenesi	88.9%	11.1%	0.0%	3.7%	8.3%	6.0%
Colline tra Enza e Secchia	99.5%	0.5%	0.0%	0.2%	0.1%	0.2%
Medio Parma	98.9%	1.1%	0.0%	2.9%	4.0%	3.5%
Colline del Trebbia e del Tidone	81.3%	4.9%	13.8%	4.5%	2.0%	3.3%
Colline del Reno	99.0%	1.0%	0.0%	5.7%	7.0%	6.4%
Valli del Dragone e del Rossenna	79.6%	0.5%	19.9%	3.6%	2.0%	2.8%
Alto Taro	97.6%	2.4%	0.0%	0.5%	0.1%	0.3%
Alto Reno	83.5%	16.5%	0.0%	2.3%	0.1%	1.2%
Alto Parma	98.8%	0.7%	0.5%	0.6%	0.1%	0.4%
Alto Panaro	86.3%	13.7%	0.0%	3.3%	9.6%	6.5%
Montagna del Medio Trebbia	99.9%	0.1%	0.0%	3.5%	0.1%	1.8%
Montagna del Medio Reno	97.2%	2.8%	0.0%	3.3%	9.0%	6.2%
Montagna tra l'Alto Enza e Alto Dolo	99.2%	0.8%	0.0%	0.1%	0.1%	0.1%
Alto Nure	94.0%	1.0%	4.7%	1.4%	7.0%	4.2%

Source: Own elaboration from (ER Statistica, 2014; INEA, 2015; ISMEA, 2014; ISTAT, 2013)

Of the five attributes explored, only three are found relevant in explaining farmers' decisions, namely profit (α_1 parameter), risk avoidance (α_2) and total labor avoidance (α_3). Profit and risk avoidance are relevant in all 30 ADs, while total labor avoidance is relevant in explaining the behavior of 18 ADs. Variability in the values of the parameters reflects the heterogeneity of the LPRB. For example, the representative farmer of Colline di Bolgona is close to profit maximizing ($\alpha_1 = .989$), with risk avoidance ($\alpha_2 = .011$) having a minor yet significant role in explaining its behavior. On the other hand, the behavior of the representative farmer of Pianura di Reggio Emilia is largely explained by the avoidance of management complexities ($\alpha_3 = .254$), which typically relates to ADs with a traditional agriculture. Larger risk aversion coefficients such as those observed in Alto Reno ($\alpha_2 = .165$) and Pianura di Modena ($\alpha_3 = .155$) show a higher willingness to sacrifice the provision of other attributes if this contributes to limit risk. *Ceteris paribus* (i.e. same domain), agents with a higher α_1, α_2 and α_3 will display crop portfolios with a higher profit, risk avoidance and management complexities than others, respectively.

Average calibration residuals display satisfactory metrics for performance evaluation below 10% (Gómez-Limón et al., 2016; Pérez-Blanco et al., 2016).

5.2. Simulation

5.2.1. Microeconomic simulation

The microeconomic simulation reduces irrigation allotments from 0 to 50% at 1% intervals ($g = 0, \dots ,50$) and assesses agents' responses resolving the optimization problem in equations [1]-[6] using the objective functions calibrated in the previous section. Irrigation restrictions constrain farmers to rely on less water intensive and/or rainfed crops, which are typically characterized by lower gross margin, labor intensity and GVA. Figure 3 presents, for selected irrigation restriction scenarios, GVA losses measured as a percentage of the initial GVA of each AD in the LPRB.

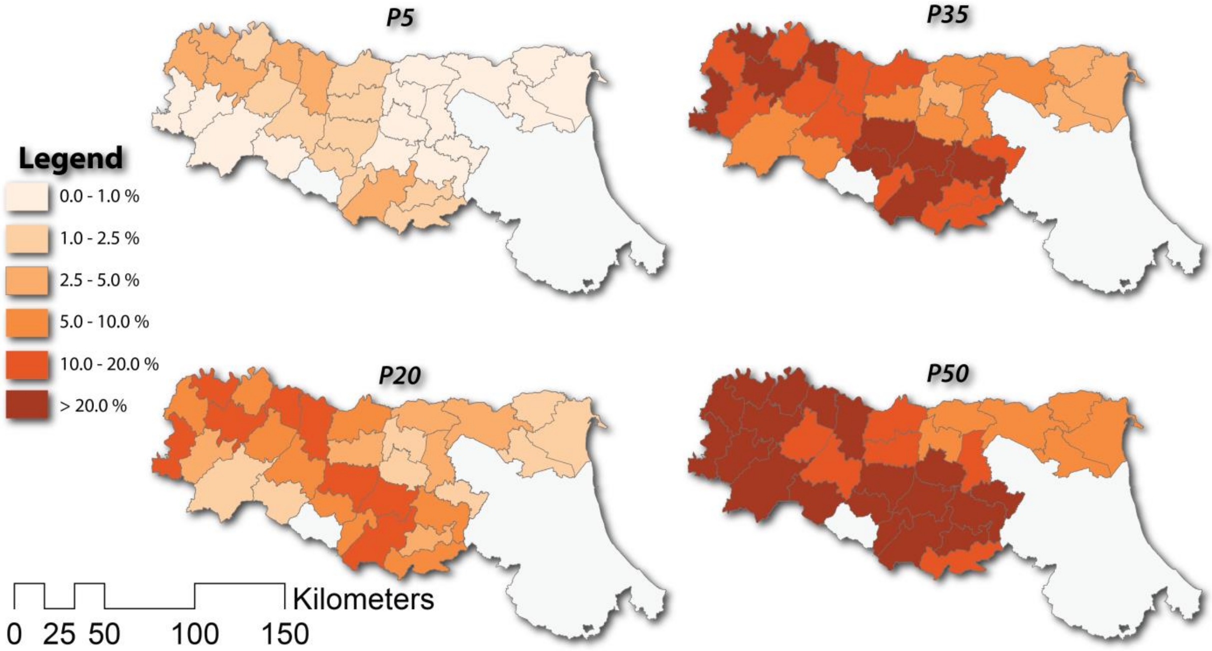

Figure 3: GVA losses (%, 2000 prices) for selected irrigation restrictions. *Source: Own elaboration from* (ER Statistica, 2014; INEA, 2015; ISMEA, 2014; ISTAT, 2013)

The RPM provides valuable information on the magnitude and distribution of impacts below the regional level. For example, a 50% reduction of irrigation allotments reduces GVA by EUR 78/ha in the ADs of *Bonifica Ferrarese Orientale* and the *Montagna del Medio Trebbia*; nonetheless, in *Bonifica Ferrarese Orientale* this figure represents less than 6% of the GVA in the baseline ($g = 0$), and almost 33% in the *Montagna del Medio Trebbia*. In the *Bonifica Ferrarese Orientale* there is a significant surface of water intensive and low value added crops (mostly rice), and farmers relinquish these marginal water uses to irrigate crops with a higher value added. On the other hand, crops in the *Montagna del Medio Trebbia* have a lower value added, and there is not a similar pool of water resources allotted to water intensive and low value added crops farmers can draw upon. This divergence between absolute loss and its relative impact is also observable basin-wide: while *relative* GVA losses are more significant in the southern and western areas of the LPRB, *absolute* losses are larger in the profitable ADs downstream. This information can serve to balance cost-effectiveness and equity issues across ADs in the implementation of irrigation restrictions.

Irrigation restrictions in the Po River Basin District are based on a proportional rule that relinquishes the same percentage of the water allotment from farmers, independently of the economic losses involved. Revising this allotment rule can enhance cost-effectiveness and equity, but it can also be contested by some parties, incur in large transaction costs and be unfeasible in the short to medium term. The macroeconomic simulation that follows aims to illustrate the economic repercussions of current drought management and follows a proportional rule. This information can be used as a benchmark to assess other reallocation rules eventually explored by policy-makers, which could be tested using the methods presented in this work. Figure 4 shows the tradeoffs between water conservation and GVA losses in the LPRB for all simulation runs, following a proportional rule for irrigation restrictions.

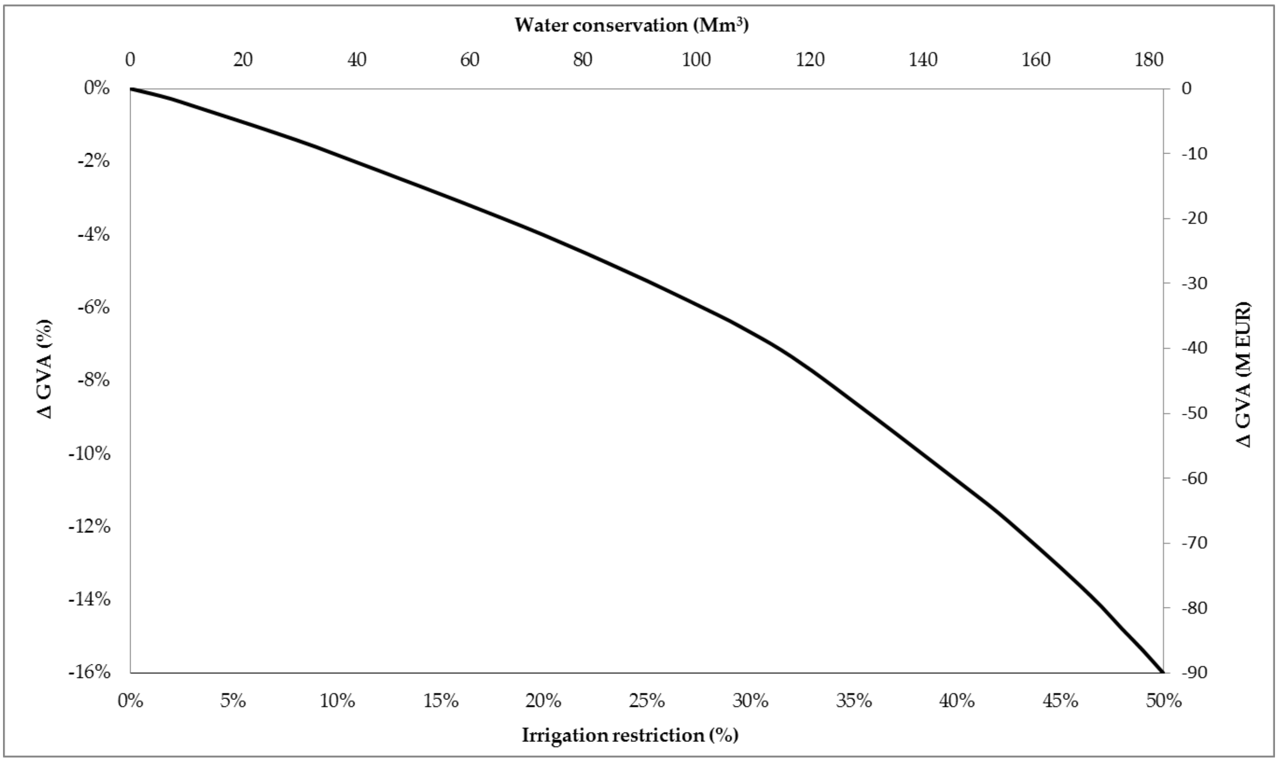

Figure 4: Tradeoffs in irrigation restrictions: water conservation vs. GVA losses (2000 prices) in the LPRB. *Source: Own elaboration from* (ER Statistica, 2014; INEA, 2015; ISMEA, 2014; ISTAT, 2013)

As the water availability constraint is strengthened, trading GVA off for water conservation becomes costlier. A hypothetical water conservation/irrigation restriction target of 25 Mm^3 would cost EUR 0.26/m^3; 50 Mm^3, EUR 0.29/m^3; 100 Mm^3, EUR 0.33/m^3; and 150 Mm^3, EUR 0.41/m^3.

5.2.2. Macroeconomic simulation

GVA estimations in Figure 4 (Y_g^{RPM}) provide the necessary information to calculate the productivity shock that feeds macroeconomic simulations (σ_g). The productivity shock first reproduces the GVA losses forecasted by the RPM, only this time in a macroeconomic context. The MRIA model then looks for a new equilibrium and estimates, for every irrigation restriction scenario, the impacts on sectorial and regional GVA. Figure 5 presents the sectorial disaggregation of the impacts of irrigation restrictions in the Emilia Romagna Region, where the LPRB is located. For the sake of simplicity, the results produced by the model for the 15 economic sectors considered are aggregated and presented in Figure 5 for five groups, namely: S1 (Agriculture); S3 (Food, beverages and tobacco), S5 (Coke, refined petroleum, nuclear fuel and chemicals); S2, S4, S6 and S8 (Mining ,quarrying and energy supply; Textiles and leather; Electrical and optical equipment; Other manufacturing); and S9 to S15 (Construction; Distribution; Hotels and restaurants; Transport, storage and communications; Financial intermediation; Real estate, renting and business activities; Non-Market Services). Figure 6 displays, for selected scenarios, the impact irrigation restrictions have on the GVA of the 20 Italian regions.

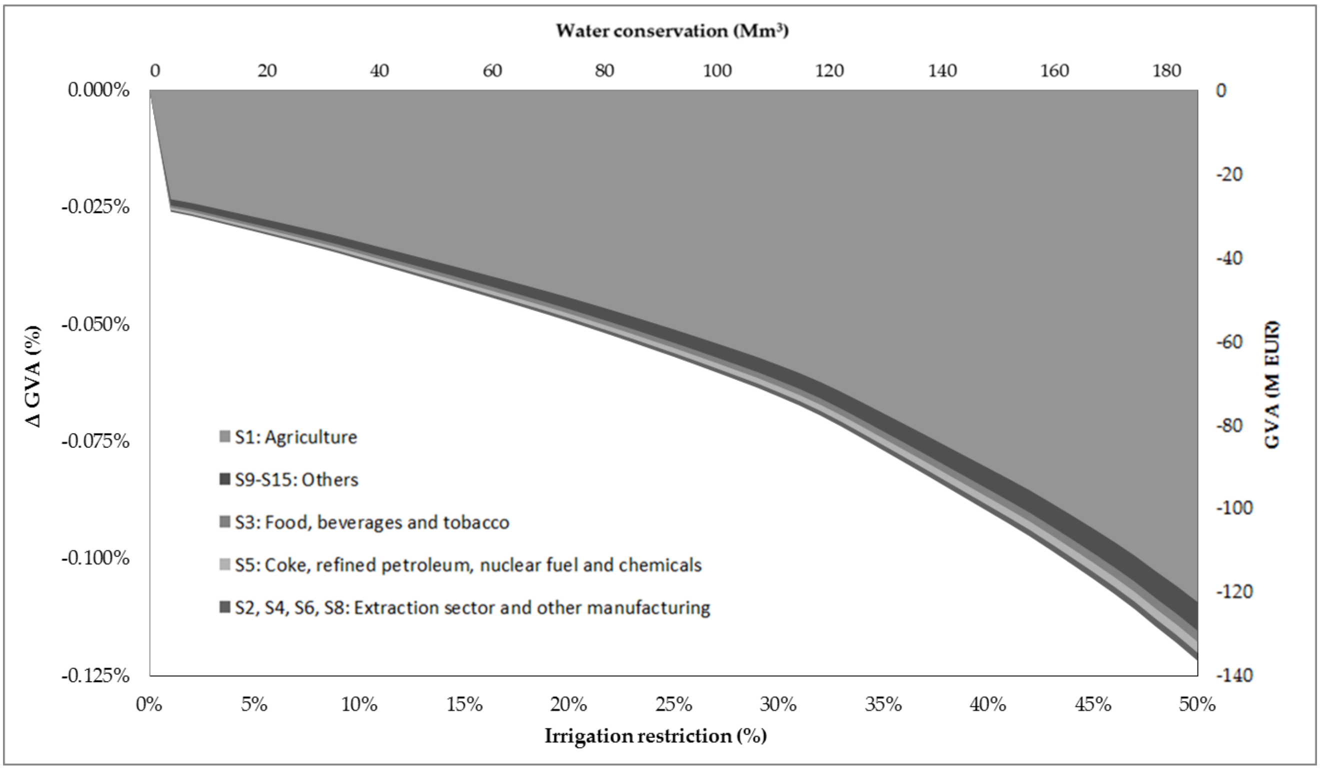

Figure 5: Tradeoffs in irrigation restrictions: water conservation vs. GVA losses (2000 prices) in the Emilia Romagna Region. *Source: Own elaboration from* (ER Statistica, 2014; INEA, 2015; ISMEA, 2014; ISTAT, 2013)

The Emilia Romagna Region where the LPRB is located is the most affected region. GVA losses in the agricultural sector (S1) lead to significant disruptions in the food industry (S3) through forward linkages, and in the chemicals and refinery industry (S5) through backward linkages. To a lesser extent, the remaining economic sectors are also negatively impacted, with the exception of Electrical and optical equipment (S6) and Non-market services (S15), which experience marginal increases in the GVA. Negative feedbacks amplify the initial shock and inflate GVA losses as compared to the microeconomic simulation. The aggregation of sectorial impacts results in an overall reduction of the GVA of the Emilia Romagna Region that ranges between -0.03% (g = 1) and -0.12% (g = 50).

The linkages that economic sectors from other Italian regions have with those in Emilia Romagna, both as customers of outputs and/or supplier of inputs, are affected by the production contraction, which results in inefficiencies that may negatively affect the GVA. On the other hand, the production contraction in Emilia Romagna Region results in a demand excess in the region that propels the production of substitute goods elsewhere in Italy. The latter effect prevails in the macroeconomic assessment conducted in this paper, which shows that irrigation restrictions in Emilia Romagna have a positive impact on the GVA of other Italian regions. Most benefited regions are Molise, Basilicata, Sardinia, Calabria and Sicily, due to the relevance of agriculture in their economy and the significant trade relationships with Emilia Romagna. GVA growth in other Italian regions compensates nearly 26.4% of GVA losses in the Emilia Romagna in every scenario, although the aggregation of regional impacts still results in an overall reduction of the Italian GVA that ranges between -0.002% (g = 1) and -0.009% (g = 50). This outcome highlights the capacity of the Italian economy to absorb a significant part of damages caused to the agricultural output of a major region, and underpins the rationale of solidarity policies in face of natural disasters such as droughts.

On average, the GVA losses estimated for the LPRB using the microeconomic simulation represent 58.6% (Emilia Romagna) and 79.7% (Italy) of the GVA losses estimated using the macroeconomic simulation. This highlights the relevance of the inter-sectorial linkages within and among the Italian regions, suggesting that microeconomic models need to be complemented with macroeconomic models in water policy appraisals.

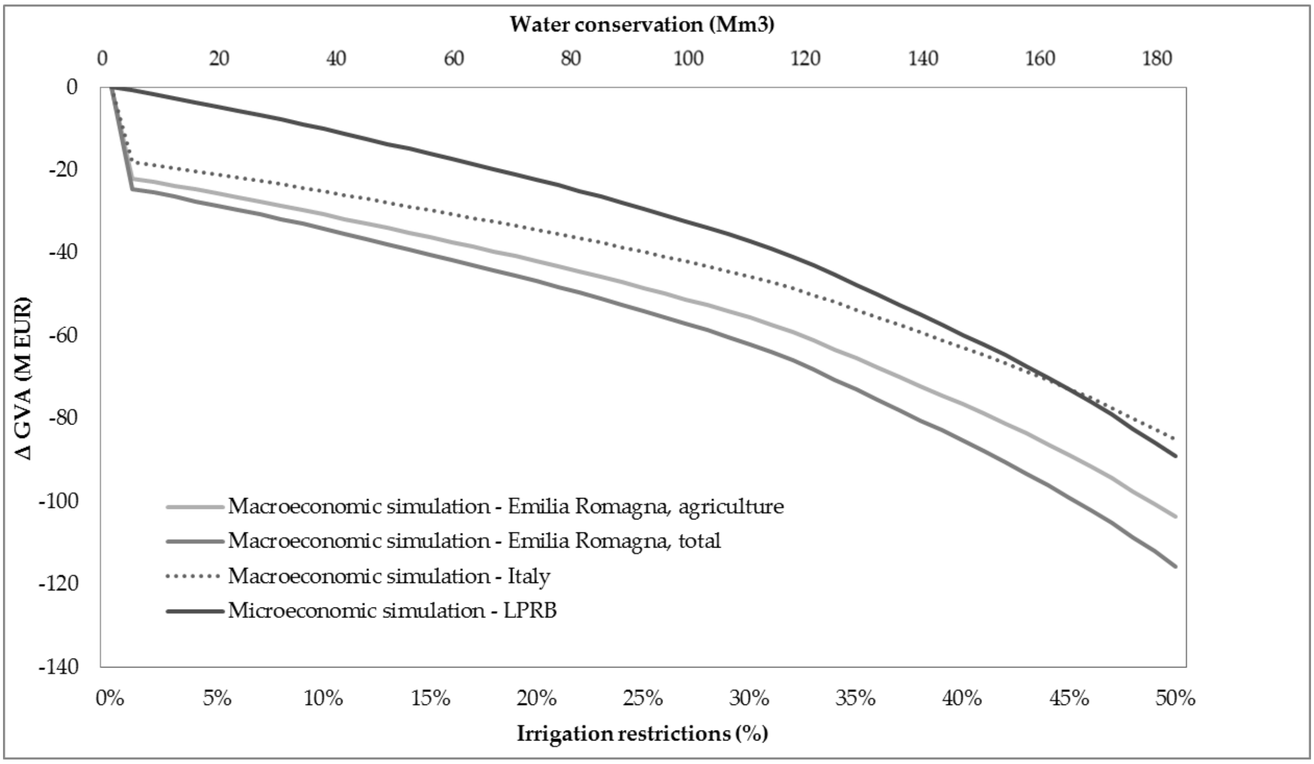

Figure 6: Tradeoffs in irrigation restrictions: water conservation vs. GVA losses (2000 prices), micro- and macroeconomic simulations. *Source: Own elaboration from* (ER Statistica, 2014; INEA, 2015; ISMEA, 2014; ISTAT, 2013)

6. Conclusions

While Europe and Southern Europe are considered as having adequate water resources on the whole, imbalances occurring when water demand exceeds available resources in the short (drought) and long term (scarcity) are no longer uncommon. Droughts have increased in frequency and intensity in areas like the LPRB, where they were a rare phenomenon only a few decades ago, and so have done water restrictions, particularly in the agricultural sector. This paper presents a method to assess the micro- and macroeconomic economic impacts of irrigation restrictions by means of connecting a multi-attribute RPM working at an AD level with a regionally-calibrated MRIA model using a modular approach. To the best of our knowledge, this is the first time both models are combined. The multi-attribute RPM is used to elicit the utility function of agents (ADs) in the area affected by the drought, and then assesses their response to a series of incremental irrigation restrictions. Resultant impacts on the GVA of the area are elaborated and used as inputs in the macroecnonomic simulation, which estimates the economy-wide repercussions of irrigation restrictions on Italy's economic sectors and regions. Methods are general and replicable in other geographical contexts. The development of alternative simulation modules can be also explored to assess the economic impact of other water policies.

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