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Risk of water scarcity and water policy implications for crop production in the Ebro Basin in Spain

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Abstract

The increasing pressure on water systems in the Mediterranean enhances existing water conflicts and threatens water supply for agriculture. In this context, one of the main priorities for agricultural research and public policy is the adaptation of crop yields to water pressures. This paper focuses on the evaluation of hydrological risk and water policy implications for food production. Our methodological approach includes four steps. For the first step, we estimate the impacts of rainfall and irrigation water on crop yields. However, this study is not limited to general crop production functions since it also considers the linkages between those economic and biophysical aspects which may have an important effect on crop productivity. We use statistical models of yield response to address how hydrological variables affect the yield of the main Mediterranean crops in the Ebro River Basin. In the second step, this study takes into consideration the effects of those interactions and analyzes gross value added sensitivity to crop production changes. We then use Montecarlo simulations to characterize crop yield risk to water variability. Finally we evaluate some policy scenarios with irrigated area adjustments that could cope in a context of increased water scarcity. A substantial decrease in irrigated land, of up to 30% of total, results in only moderate losses of crop productivity. The response is crop and region specific and may serve to prioritise adaptation strategies.

1 Introduction

Water conflicts in the Mediterranean have been extensively reported, and many of the studies have analysed the costs for governments to maintain or even increase water supply (Smith, 2002). In the past, studies have focused on the supply side through cost-benefit analyses. However, with the new water-related problems, such as climate change, droughts and floods, focus on the demand side is needed. For this kind of analysis physical, political and socioeconomic components must be integrated for an

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optimal management of activities to increase the basin's output.

It is crucial for the Mediterranean region, where irrigation represents as much as 90% of total water consumption (Gómez-Limón and Riesgo, 2004), to measure the risks associated with climate variability in agriculture and to implement water demand policies that promote an efficient allocation and use of resources in the region's farms.

According to the OECD, agriculture is the major user of water in most countries, since about 70% of total available water is used for irrigation. It also faces the enormous challenge of producing almost 50% more food by 2030 and doubling production by 2050. This will likely need to be achieved with less water, mainly because of growing pressures from urbanisation, industrialisation and climate change (OECD, 2010). Agriculture is also the main user of other environmental and natural resources and therefore has an important role to play in global ecosystem sustainability. Therefore, small changes in agricultural water use (in planting, crop management or crop production) can have significant economic and hydrological impacts.

In Spain, irrigated agriculture accounts for 80% of national consumption of water (Gómez-Limón and Riesgo, 2004) and only 40% of the land area is suitable for cultivation (Iglesias et al., 2000). This paper focuses on the Ebro Basin, where agriculture can reach up to 90% or more of water demand. In fact, more than 354 245 ha of irrigated land are projected to be added according to the National Irrigation Plan (2001) for the nine regions in the Ebro Basin. This represents an increase of 21 10 hm³/yr of water demand and an expected increase of 44% in the irrigated area, raising the total mean to 1 128 653 ha. This increase imposes significant additional pressure on aquatic ecosystems and has serious environmental implications, such as the maintenance of environmental flows and water quality in rivers.

The Ebro Basin is located in the Northeast of the Iberian Peninsula with a total area of 85 362 km². This watershed is the largest in Spain, accounting for 17.3% of the total national area. It is made up of 347 major rivers, including the Ebro River, which drains the basin. It rises in the Cantabrian Mountains and ends in the Mediterranean and has a total length of 910 km and 12 000 km of main river network (CHEBRO, 2009).

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The climate in the Ebro Basin is primarily Continental Mediterranean, with hot, dry summers, cold, wet winters and short, unstable autumns and springs. In the middle of the basin, the climate is semi-arid and in the northwest corner it is oceanic. Consequently, there is a wide heterogeneity in temperature. In 2007, for example, the province of Tarragona reached a maximum temperature of 43 °C, while Burgos had a minimum of -22 °C. Our methodological approach deals with these differences since links bio-physical and socio-economic factors.

2 Methods

2.1 Steps on methodology

The methodology developed in this study is applied to selected crops in Ebro Basin. Models are obtained for each of 8 crops in order to estimate the risk of water variability and policy scenarios. The methodology includes the following 4 steps: (1) we estimate linear regression models by ordinary least squares (OLS). Statistical models of yield response have proven useful to estimate the water requirements at different locations for selected crops and have also proven useful to evaluate the effects of extreme contingencies and other socioeconomic variables (Al-Jamal, 2000; Griliches, 1964; Lobell et al., 2005; Lobell et al., 2006). We introduce environmental, hydrological, technological, geographical and economic variables to characterize crop yield for these main Mediterranean crops in the Ebro River Basin. The goal was to analyse social capital (labour and technology components of the production function) and natural resources capital (water for irrigation and irrigated area components of the production function) together. Literature on this specific area includes Acharya and Barbier (2000), Alcalá and Sancho-Portero (2002), Echevarría (1998) and Hussain and Muddasser (2007). (2) In a second step, we try to understand the interactions between agricultural production and profit functions focusing on water demand. To do so, we analyze the total agricultural gross added value (GAV) of the region and its interaction

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with the aggregate crop yield. (3) We use the Montecarlo method to characterize statistical properties of crop yield in response to water patterns or policy adjustments. This method is a powerful and commonly used technique for analyzing complex problems and conducting experiments to evaluate probabilistic risk (Rubinstein, 1981). In agriculture, this method is used to characterize statistical properties of crop yield in response to climatic variables and other inputs (Lobell and Ortiz-Monasterio, 2006; Iglesias and Quiroga, 2007). (4) Finally, we simulate the structural adjustments, in this case a decrease in irrigated area (ha) that could allow the agricultural sector, to cope with increased water restrictions for the agricultural sector. See Fig. 1.

In our approach, the estimation of the crop production function plays a fundamental role, since it is then used to evaluate the added value as well as the risk and policy implications. Estimation of production functions is always controversial and each approach has strengths and limitations. Here we have followed the Solow-Stiglitz perspective (Solow, 1974; Stiglitz 1979, 1997), as specified below. According to Solow (1956), there are two factors of production to obtain output, capital (K) and labour (L). Where its technological possibilities are represented by a production function:

$$Y = F(K, L) \quad (1)$$

It is assumed that production shows constant returns to scale. Therefore the production function is homogeneous to the first degree. This is equivalent to assuming no scarcity of non-augmentable resources such as land. If we assume scarce-land, this would lead us to decreasing returns to scale in capital and labor and the model would become more Ricardian. Nowadays, it is well known that natural resources are very important to economic growth and environmental sustainability. In this context we find an extended production function named the Solow-Stiglitz model (Solow, 1974; Stiglitz 1979), which includes natural resources (R).

$$Y = K^{\alpha_1} L^{\alpha_2} R^{\alpha_3} \quad \text{with } \alpha_1 + \alpha_2 + \alpha_3 = 1 \text{ and } \alpha_i > 0 \quad (2)$$

This function was criticized because of the assumption that R and K are substitutes, so that for example, the use of R tends to zero as K tends to infinity. But this is not

true, since, if K tends to infinity, R will be exhausted. This would indicate that they are complementary (Daly, 1997; Stiglitz, 1997). There are empirical studies that have shown that in agriculture, statistical models of yield response have been proven useful to estimate input requirements at different locations for selected crops (Griliches, 1964; Lobell et al., 2005, 2007).

2.2 Data

To characterize our model we use regional, national and international sources of data. Table 1 describes the variables included in this study and the source of data. We have included information about crop yield and water requirements of eight representative crops in the 18 regions in the Ebro Basin from 1976 to 2002. Crop yield is defined as the ratio between production (T) and agricultural total area (ha) and data were obtained from the Spanish Ministry of Environment (MARM). Economic and geographic variables were mainly obtained from the Spanish Institute of Statistics (INE) while technological variables were taken from FAOSTAT and Food and Agriculture Organization (FAO).

To build a proxy variable for irrigation, we used Ebro Basin management authority local data (CHEBRO, 2004) about net water needs of crops. Finally, climatic data such as total precipitation, maximum and mean temperatures, and number of days below 0°C were taken from the Spanish Meteorological Agency (AEMET) to characterize the impact of climate.

2.3 Crop-water production function

We have estimated a crop-water production function that establishes the relationship between crop yield and water applied for a range of crops that represent irrigated agriculture in the Ebro Basin. The crop-water production function is linear in the deficit irrigation section because all the applied water is used for evapotranspiration, and the production function is equal to the evapotranspiration production function. Neverthe-

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less, non-linear responses indicate that not all water is used by the crop, since some goes to deep drainage and the evapotranspiration production function is really a production function. The function becomes curvilinear as more of the applied water goes to deep drainage. Generally, a curvilinear function is expressed as a second order polynomial (Al-Jamal, 2000). This function is not unique and varies among crops and zones.

The specified model is:

$$\ln Y_t = \alpha \ln Y_{t-1} + \beta_0 + \beta_1 L_t + \beta_2 \text{Mac}_t + \beta_3 \text{Mac}_{t-n} + \beta_4 \text{Altitude}_t + \beta_5 \text{Area_ebro}_t + \beta_6 \text{Irrig_area}_t + \beta_7 \text{Irrig}_t + \beta_8 \text{Irrig}_t^2 + \beta_9 \text{Prec}_{it} + \beta_{10} T_Max_{it} + \beta_{11} T_Mean_{it} + \beta_{12} Fr_{it} + \beta_{13} Dro_t + \varepsilon_t$$

Where the dependent variable ($\ln Y_t$) is the natural logarithm of the crop yield for a site in year t . The explanatory variables were described on Table 1. The subscript i on climate and some water variables refers to the three months periods (i =def (Dec, Jan, Feb), mam (Mar, Apr, May), jja (Jun, Jul, Aug) and son (Sep, Oct, Nov)).

We used OLS to estimate the coefficients. To facilitate the improvement of particular model estimation for each crop, 95% confidence intervals were estimated assuming normality of the residuals, and significant relations were considered into the estimated model. White's general test (White, 1980) was used to check conditional heteroscedasticity under null hypothesis (H_0) of homoscedasticity (Johnston and Dinardo, 2001). Durbin-Watson statistics are used to check autocorrelation existence (Durbin and Watson, 1950).

When the parameters α_i are estimated, the marginal effect of a change in the explanatory variables is given by:

$$\frac{\partial E[\ln Y | X_i]}{\partial X_i} = \alpha_i$$

The signs and magnitude of the marginal effects indicate the effect of a particular input variable X_i over the crop yield. In this case, the coefficients of the model have

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to be interpreted as semi-elasticities because the model presents a semi-logarithmic transformation. The interpretation is that semi-elasticity is responsible for the percent increase of yields produced by a unit change in the input variable.

In the Ebro Basin there exists a very high variability in precipitation and it is common to observe that recurrent drought periods affect agricultural production. To date, it is difficult to characterize droughts because of their spatial and temporal properties and the range of indicators required (Hayes 2002; Keyantash and Dracup 2002; Bradford 2000). In this work, we use the frequently used Standardized Precipitation Index (SPI, McKee et al., 1993). This index, based on the probability of precipitation for any time scale, calculates the difference in accumulated precipitation between a selected aggregation period and the average precipitation for that same period, it is an index. The calculation of the SPI for any location is based on the long-term precipitation record for a desired time. This long-term record is fitted to a probability distribution, and is then transformed into a normal distribution, implying values that vary around 0. This allows areas with different climates to be relatively compared (McKee et al., 1993; Steinmann et al., 2005). We have selected 12 months as the aggregated period for calculation. To define the criteria for a drought event we follow McKee et al.'s (1993) table where a drought event occurs when SPI values are -1.0 or less (see Table 2). This criterion was followed in previous detailed works in Spain (Iglesias et al., 2007; Garrote et al., 2007). We, then, construct a dummy variable that equals 1 if the year t is a drought year (with SPI smaller than -1) and 0 in other cases.

Due to the large number of correlated variables the selection of explanatory variables for model specification is important. Greene (2003) shows two alternatives to follow: (a) an inductive approach, which consists in starting with a reduced model and amplifying it by including more variables to a general model. The main problem associated with this approach is that the computed statistics can be biased and inconsistent if the hypothesis is incorrect. (b) A deductive approach, which consists in starting with a given general model to set up a correct fitted model. This approach is frequent in recent analyses since, although inefficient, the estimates and test statistics computed

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from this over-fitted model are not systematically biased. We therefore, we use the second approach in this paper. Finally, to help in the choice of appropriate models, we have used Akaike (1973) and Schwarz (1978) and adjusted R squared criteria. To complete this process of variable selection, we observe a strong relationship between some of the explanatory variables which might be a source of collinearity problems. Given this possible problem, we calculated the variance inflation factor (VIF) for each of the explanatory variables:

$$\text{VIF}(x_k) = \frac{1}{1 - R_k^2}$$

VIF represents the squared standard error (or sampling variance) of $\hat{\beta}_k$ in the estimated model divided by the squared standard error that would be obtained if x_k were uncorrelated with the remaining variables (Chatterjee and Hadi, 2006). Thus, we follow the following criteria: (i) values larger than 10 give evidence of collinearity and, (ii) a mean of the VIF factor considerably larger than one suggests collinearity. We then proceed to eliminate variables which have a VIF value larger than 10. We proceed in an iterative way when collinearity persists.

2.4 Agricultural added value

Agricultural added value variations are characterized as a function of crop yields as follows:

$$\ln\text{GAV}_t = \beta_0 + \beta_i \ln Y_{it} + \varepsilon_t$$

Where the dependent variable ($\ln\text{GAV}_t$) is the natural logarithm of agricultural gross added value for a site in year t and the subscript i refers to the different crops considered.

In this case, the coefficients of the model can be understood as elasticities because the model presents a logarithmic transformation. The interpretation is that elasticity is

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responsible for the percent increase of yields produced by a one percent increase in the input variable.

Diagnostic tests were conducted as in the crop-water production function estimation process.

5 2.5 Montecarlo risk analysis

According to Iglesias and Quiroga (2007), risk analysis bridges the gap between impact evaluation and policy formulation by focusing policy's interest on consequences (i.e. crop yield) rather than agents (i.e. rainfall or irrigation). There are many definitions of risk but, in a wide sense, risk can be defined as the capacity of a system to suffer losses when it is exposed to an external stressor.

In this paper, we use the Montecarlo method, which is a key component of uncertainty and probabilistic risk evaluation, since it allows us to generate random samples of statistical distributions to measure risk (Robert and Casella, 2004; cited in Iglesias and Quiroga, 2007; Hammersley and Handscomb, 1975). In agriculture, Montecarlo simulation offers a flexible and accurate approach for investigating and understanding statistical properties of crop yield in response to inputs like irrigation and rainfall (Lobell and Ortiz-Monasterio, 2006). In terms of to water policy, we analyze marginal effects on the statistical model to calculate how a reduction in irrigated area could affect crop yield (Iglesias and Quiroga, 2009; Llop, 2008). Using Montecarlo simulations we obtain 10 000 random values of statistical distributions of every crop yield and then analyze the distribution of probabilities to obtain a certain yield (risk level).

2.6 Water policy scenarios

We have evaluated three policy scenarios considering a reduction of agricultural irrigated land of 10%, 20% and 30%. These scenarios are consistent with a perspective of increased water scarcity and reflect the policy implications of environmental concerns. The European Water Framework Directive states that it is necessary to restore

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and conserve the ecological health of rivers, thus the Hydrological Plan of the Ebro Basin must accommodate the irrigated land area, review current concessions and seriously consider the removal of salinised irrigated areas as well as those that consume too many resources due to their low profitability.

5 On the other hand, the establishment of environmental flows in some sections of the Ebro Basin Rivers means that current irrigation areas will have to be reduced. Currently, there is a provisional minimum flow of between 5% and 10% of current annual average flow which is made by sections. It is important to observe that the minimum ecological flow in the Ebro river mouth has been set at $100\text{ m}^3\text{ s}^{-1}$. This amount is
10 practically arbitrary, due to the absence of more detailed studies. At this moment, some complementary actions are being taken in order to improve the systems' basin efficiency. For instance, existing or future infrastructure needs to respect the minimum ecological flow required downstream (Herranz, 2008; CHEBRO 2004).

Also, it is well known that irrigated area is a crucial element when talking about
15 agricultural water demand. In Table 3, we can observe a summary of irrigated areas by Community. These are grouped by large and small irrigation systems for each of the nine Autonomous Communities contained within the basin. According to the CHEBRO, the existing concessional irrigated areas' demand, in the current situation of distribution by crop, is $6310\text{ hm}^3\text{ yr}^{-1}$ while the current concessional irrigable area is 783 948 ha.
20 Here, Aragón and Cataluña account for more than 77% of this area. It is important to say that this demand does not coincide with the annual supplied volume, which depends on the actually irrigated area, and the actual of annual crops among other factors (CHEBRO normative).

25 Under a hydrologic-hydraulics point of view and according to the regulation and concessional guidelines' adaptations, the maximum possible irrigation area in the future will reach 985 999 ha, corresponding to a demand of 8213 hm^3 . Under the same assumptions, it would expand to a maximum irrigated area of 1 271 306 ha with a demand of 9879 hm^3 . This represents a partial increases of 202 051 ha and 285 307 ha for each of the two horizons. However, the effective development of these areas will de-

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pend on agricultural policy decisions taken by competent institutions. Nevertheless, the COAGRET Report (2007) says that the establishment of future environmental flows on some river sections will imply cuts in current irrigation extensions in order to follow the statements of the Water Framework Directive. It is therefore difficult to think about an increase in those ha.

Relative to the total agricultural area in the Ebro Basin, alfalfa, wheat, grapevine, olive, potato, maize and barley are the seven most representative crops in the Ebro Basin since they account for almost 60% of the total agricultural area in this region. Rice does not represent a large percentage of the total cultivated area in the overall basin, but it is the most important crop in the Ebro Delta area and it is an intensively irrigated crop. Alfalfa, maize, potato and rice are mainly irrigated while wheat, barley, grapevine and olive are primarily rainfed crops (Table 4).

3 Results

3.1 Crop-water production functions and agricultural added value

The relationship between crop yields and amount of water for irrigation in the six representative crops varies with crop and location (Fig. 2). The relationship between crop yield and irrigation is obviously positive in an initial phase but the marginal decrease to scale. For alfalfa, potato and maize, the most irrigated crops considered, the decreasing phase is not observed within the range of irrigated values considered in this study. For wheat, barley and grapes, optimization of the amount of water is essential. In these crops, additional water beyond a threshold results in reduced output. Rice is not shown since it is always irrigated nor are olives since the amount of irrigated land in this region is relatively small compared to the irrigated land of the other crops.

Irrigated land has evolved differently for each crop and area considered (Fig. 3). In the upper basin (Burgos province) the proportion of irrigated area for the cereals crops increases during the period of analysis. This increase is a result of the lack of water

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scarcity problems in this part of the basin during the period of analysis. In contrast, in the middle basin (Zaragoza province) and the lower basin (Tarragona province) the trend is clearly downward, except in the case of maize in Zaragoza, where the tendency is almost constant. This reflects an increased limitation of irrigation due to prioritization of water for the environment.

We estimated crop-water production functions that explain the influence of water on crop productivity and also incorporate a wide range of variables (Table 5). The increasing trend in crop productivity is explained largely by technological and management variables. We assume that yield increases due to improved varieties are linked to more intensified management. We tested the adequacy of the functions to represent crop-water production functions as outlined in the methods section; in the cases where regressions present heteroskedasticity the regressions are estimated with the White method (1980) to obtain robust estimates (following Wooldridge, 2003).

As already mentioned, the coefficients of the crop-water production functions can be interpreted as semi-elasticities. This means that when a unit change is produced in the explanatory variable, the dependent variable experiments proportional changes.

In general the eight crop-water production functions present the expected signs according to the agricultural processes. Irrigation for alfalfa, wheat, rice, potato, maize and barley present a positive impact on the crop yield but this decreases after a given amount of water. Irrigation is not statistically significant for grapevine and olive yield. This may be due to the small area of these crops under irrigation and to the fact that irrigation in these crops is “deficit irrigation” used only to maintain yield during drought periods. Irrigation area also has an important impact on alfalfa, wheat, grapevine, potato, maize and olive. For this last crop, the effect of irrigation area is the largest. In contrast, drought does not show significant impacts for all crops. Only wheat, barley, and grapevine have negative significant impacts in this variable probably because these crops are rainfed. In other words, except for olives, irrigated crops do not show evidence of significant impact of drought on their yield.

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Table 6 shows the estimated profit function for each crop yield. The estimation of this function has been considered for all crops; however, we only took into account those that are significant. In other words the effects may be poorly specified for crops that are not represented in the entire geographic area. We note that when yields of alfalfa, maize, potatoes and wheat increase by 1 unit, the agricultural gross added value increases. A strictly economic analysis might suggest the desirability of a stronger orientation of production towards wheat and maize, because an increase in the yield of these crops has a major impact on the region's agricultural GAV. However, this does not take into account the cost of virtual water. Even though today the Ebro Delta does not present problems of availability of water the problems associated with the necessity of large amounts of irrigation water that are caused due to factors such as the crop's characteristics, natural ground permeability and capillary rise of salt water should not be ignored. Therefore, an analysis of water risk management is necessary. In the next section, we analyze the water risk of the selected crops and the impacts of potential changes in water policy.

It is important to note that the contribution to the gross added value includes direct payments linked to crop productivity during the period of analysis (before 1986 from the agricultural policy in Spain and since 1986 from the EU Common Agricultural Policy). The recent decoupling of productivity and payments, since 2008, may change the relative contribution of each crop to the gross added value.

3.2 Montecarlo risk analysis

Statistical properties of crop yield in response to water patterns were derived using Montecarlo simulations in order to asses risk levels. Figure 4 shows the cumulative density probability functions where significant differences in risk levels between crops can be observed. According to these cumulative distribution functions, the probability of having low yields is higher for olive, barley and wheat and lower for alfalfa and potato.

Table 7 provides the detailed statistical properties from Fig. 4. Rice and alfalfa present a low variation coefficient (CV) while olive and grapevine have a high variability.

On the other hand, we observed that the skewness coefficient is above +1 in potato, olive, alfalfa and barley, indicating that they have an elevated probability of obtaining results above the mean. Also, the skewness coefficient is greater than 0, indicating that there is no large probability of having a low yield. The kurtosis coefficient for every crop yield is lower than 3, and we have a platykurtic distribution that indicates that the probability distribution functions of the crop yields have a wide peak (a lower probability than a normally distributed variable of values near the mean) and thin tails (a lower probability than a normally distributed variable of extreme values). Figure 5 presents the distribution function for rice, which is practically normal.

3.3 Water policy scenarios

Although irrigation contributes to social welfare in many regions, it cannot be rural development's the sole concern. As we mentioned before, nowadays there are no explicit restrictions on the irrigation area in the Ebro Basin. However, within the context of increases of water demands and policy developments such as the Water Framework Directive restrictions context, it is necessary that the Basin Plan consider adaptation measures such as changes in irrigated land to cope with environmental and sustainability constraints. Thus, we propose three possible scenarios, in which we assume a reduction of the irrigated area by 10%, 20% and 30%. Table 8 shows the yield changes responding to these scenarios.

A substantial decrease in irrigated land, of up to 30% of total, results in only moderate losses of crop productivity. The response is crop specific, wheat is the least affected and alfalfa is the most affected. These results contrast with the relative importance of the crop as measured by the gross added value (Table 6). Both indicators, the gross added value and the changes in crop productivity, are useful to choose adaptation strategies. For example, the contribution of maize to the gross added value is large and the yield is highly reduced as result of irrigated land reduction. Therefore the economic losses of irrigated land reduction in a maize producing area are significant. In contrast, although the yield reduction of alfalfa is comparable to that of maize, the

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resulting economic loss due to limitation in irrigated land is smaller because alfalfa's contribution to the gross added value is low.

The reductions are consistent given the uncertainty of future policy and our purpose is to show the implications in terms of production risk. Using the models presented in Table 8, we note that these scenarios imply yield losses, ranging from 1% to more than 15%. Regardless of the extent of the reduction in irrigated land imposed by the policy, we see that wheat and grapevine do not suffer major losses in yield performance, whereas alfalfa, potato and maize would be affected considerably given that they are mostly irrigated crops. Since the irrigation area was not significant for rice (which is 100% irrigated), we cannot observe, using this technique, the amount of decrease in its yield would most likely decline. One important factor to consider is the fact that the losses are not proportional. Therefore, the loss is larger when the irrigation area is reduced from 10–20% scenarios than when it is reduced from 20–30% scenario. Finally, the reductions in crop yields can be used to estimate the necessary incentives for the implementation of environmental goals (Iglesias and Quiroga, 2009).

4 Conclusions

Given the pressure, mainly from agriculture, on water in the Mediterranean, this paper presents an analysis of the factors that affect eight major crops in the Ebro River Basin including latent risks as well as policies that could be implemented. We analyzed the marginal effects on the statistical model to calculate the effect of a potential reduction in irrigated area on crop yield. This study was based on an analysis of demand.

Extended water production functions by crop were estimated. These show the expected signs for most of the variables. Focusing on the hydrological variables, our results show that an increase in irrigation and in the irrigated area has a positive impact on crop yields. However, the impact of irrigation is not always positive given that after a certain quantity of water supplied to the crop, yield begins to decrease (negative sign in irrigation elevated to square). The precipitation also shows a positive impact on

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crop yields, except for maize in the *son* quarter (Sep, Oct, Nov), which might be due to excessive water from irrigation, given the usual humidity of this time of the year.

A strictly economic analysis might suggest that production could be oriented to wheat and maize, given their impact on agricultural gross value added of the area. However, this does not consider the cost of virtual water. Maize is a major crop in the Ebro Delta, in the low basin, that could suffer a reduction on water availability. An analysis of water risk management is needed. Rice and potatoes show a low variation coefficient, implying low variability. Olive shows low yield and high variability in this area, although under a reduction in irrigated area scenario, this crop is not severely affected. Potato, maize and alfalfa are the ones most affected by a reduction in irrigated area, because they are mainly irrigated crops.

Finally, the methodology presented here can be extended to examine additional factors that affect crop yield and interact with water demand, such as climate change, irrigation systems, and fertilizer application.

Acknowledgement. This research has been supported by the European Commission CIRCE project and the ARCO project of the Spanish Ministry of Environment, Rural, and Marine Affairs (MARM). We also acknowledge the data support of Agencia Estatal de Meteorología (AEMET).

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Table 1. Description of variables.

Type of variable	Name	Definition	Unit	Source of Data
Economic	Y_t	Crop yield at a site in year t	t/ha	MARM
	GAV_t	Gross added value of agriculture a site in year t	K€ current prices	MARM and INE
	L_t	Total employment of agricultural sector at a site in year t	People (thousands)	Labour Force Survey (LFS). INE
Water	$Irrig_{it}$	Net water needs of crops in the i th month in year t	m/month	Planning Hydrographic Office – CHEBRO
	$Prec_{it}$	Total precipitation in the i th month/3 month period in year t	mm/month	AEMET
Management	Mac_t	Machinery in year t	No (thousands)	FAO
	I_t	Irrigated area by crop type	ha	MARM
Geographic	$Altitude_t$	Variables indicating 0–600, 601–1000 and more than 1000 m		INE
	$Area_ebro_t$	Dummy variables indicating the 3 main areas of the basin: Northern, Central and Low Ebro		Own elaboration
Climate	T_Max_{it}	Maximum temperature in the i th month/3 month period in year t	°C	AEMET
	T_Mean_{it}	Average temperature in the i th month/3 month period in year t	°C	AEMET
	Fr_{it}	No. of days with temperatures below 0°C in the i th month/3 month period in year t		AEMET
	Dro_t	Dummy variable indicating drought years	1 or 0 as a function of SPI critical value	SPI calculated from AEMET precipitation data

Table 2. SPI values and drought intensities.

SPI values	
2.0 or more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2 and less	Extremely dry

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Table 3. Irrigated area by irrigation systems.

Region	Irrigation area and percentages					
	Large systems		Small systems		Total	
	ha	%	ha	%	ha	%
Aragón	237 813	52.2	161 721	49.1	399 045	50.9
Cantabria	0	0.0	553	0.2	553	0.1
Cataluña	160 625	35.3	46 316	14.1	207 036	26.4
Castilla – La Mancha	0	0.0	241	0.1	241	0.0
La rioja	17 584	3.9	34 864	10.6	52 448	6.7
Castilla – León	0	0.0	8913	2.7	8 913	1.1
Navarra	39 359	8.6	48 407	14.7	87 766	11.2
Valencia	0	0.0	275	0.1	275	0.0
País Vasco	0	0.0	27 277	8.3	27 277	3.5
Total land area	455 381	100.0	328 568	100.0	783 948.69	100.0

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Table 5. Estimated coefficients of crop-water functions, robust t-statistics and R^2 .

	Alfalfa	Wheat	Rice	Grapevine	Olive	Potato	Maize	Barley
$\ln(Y_{t-1})$				0.4441 [4.73] ^f				
L							-0.0116 [3.66] ^f	-0.0118 [3.66] ^f
Mac	-0.0067 [2.05] ^b	-0.0103 [3.19] ^f			0.0022 [4.74] ^c	0.0013 [9.62] ^f	0.0010 [5.61] ^f	0.0007 [3.25] ^f
Mac_{t-1}	0.0069 [2.16] ^b	0.0109 [3.39] ^f		0.0010 [3.39] ^f				
Mac_{t-2}			0.0005 [1.73] ^a					
$Altitude_{(p-600)}$		-4.80E-05 [4.24] ^f		-6.20E-05 [4.41] ^f				
$Altitude_{(601-1000)}$	-2.06E-05 [4.05] ^f	2.58E-05 [1.69] ^a						2.66E-05 [1.86] ^a
$Altitude_{(1-1000)}$	-1.49E-05 [3.36] ^f	-8.94E-05 [6.54] ^f		-6.57E-05 [4.01] ^f			-1.38E-05 [2.16] ^b	-6.53E-05 [4.89] ^f
Cent_ebro	-0.0412 [1.28]	-0.1006 [1.69] ^a		-0.0781 [1.56]			-0.2954 [6.32] ^f	-0.2646 [4.15] ^f
Northern_ebro	0.2226 [4.53] ^f	-0.4780 [2.97] ^f		-0.3589 [3.08] ^f			-0.3249 [5.22] ^f	-0.6043 [4.07] ^f
Irrig_area	0.8531 [9.65] ^f	0.5964 [3.75] ^f		0.9993 [4.53] ^f	1.6479 [4.22] ^f	0.5693 [11.41] ^f	0.7691 [9.00] ^f	
Irrig	0.0963 [7.10] ^f	0.2024 [4.73] ^f	0.1543 [2.08] ^b			0.0355 [2.08] ^b	0.0766 [3.35] ^f	0.2496 [5.19] ^f
$Irrig^{-2}$	-0.0083 [5.69] ^f	-0.0447 [6.59] ^f	-0.0213 [1.89] ^a			-0.0002 [0.08]	-0.0027 [1.38] ^a	-0.0649 [6.24] ^f
$Prec_{def}$					0.0015 [2.41] ^b		0.0006 [3.49] ^f	
$Prec_{mam}$	0.0010 [6.52] ^f							
$Prec_{jia}$					0.0017 [2.58] ^b		0.0006 [2.88] ^f	
$Prec_{son}$		0.0005 [3.30] ^f					0.0000 [0.20]	0.0004 [2.33] ^b
$Prec_{year}$						0.0001 [1.80] ^a		
$T_{Max_{def}}$							0.0059 [2.17] ^b	
$T_{Max_{mam}}$		-0.0098 [3.39] ^f						-0.0133 [4.33] ^f
$T_{Max_{jia}}$				-0.0099 [3.10] ^f	-0.0273 [3.34] ^c			
$T_{Max_{son}}$		0.0092 [2.35] ^b					0.0069 [1.88] ^a	0.0187 [5.03] ^f
$T_{Mean_{year}}$	0.0474 [4.12] ^c	-0.0879 [3.00] ^f	0.0377 [2.24] ^b			-0.0685 [10.02] ^c	-0.0602 [2.95] ^f	-0.1394 [5.40] ^f
F_{def}		-0.0022 [1.67] ^a						-0.0019 [1.41]
F_{mam}		-0.0090 [1.66] ^a			-0.0297 [2.80] ^f			-0.0117 [2.53] ^b
F_{son}					0.0303 [2.79] ^c	-0.0120 [4.06] ^f	-0.0069 [2.11] ^b	
Dro		-0.1281 [2.22] ^b		-0.1328 [1.97] ^a				-0.1737 [3.75] ^f
Adj R -squared	0.65	0.63	0.17	0.84	0.41	0.62	0.77	0.55
White test: p -value	0.0008	0.4362	0.3695	0.038	0.6504	0	0.0154	0.5003

t-statistics and robust t-statistics in brackets, ^a significant at 10%; ^b significant at 5%; ^c significant at 1%

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Table 6. Estimated coefficients of profit function (logarithm of the gross added value), robust t-statistics (in brackets) and R^2 .

	Coefficients
Yield_Alfa	0.04 [4.58] ^b
Yield_Maize	0.11 [3.56] ^b
Yield_Potato	0.02 [2.49] ^a
Yield_Wheat	0.20 [2.80] ^b
Constant	9.31 [22.08] ^b
Observations	133
R -squared	0.31

Robust t-statistics in brackets;
^a significant at 5%; ^b significant at 1%

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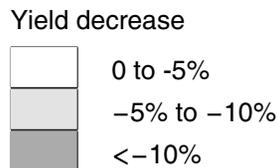
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Table 8. Yield changes for irrigated area policy scenarios.

Decrease in irrigated land	Changes in crop productivity					
	Alfalfa	Wheat	Grapevine	Olives	Potatoes	Maize
–10%	–4.8	–0.7	–1.5	–2.2	–4.3	–4.8
–20%	–11.2	–1.4	–2.9	–4.4	–8.4	–9.4
–30%	–15.5	–2.0	–4.3	–6.6	–12.3	–13.7



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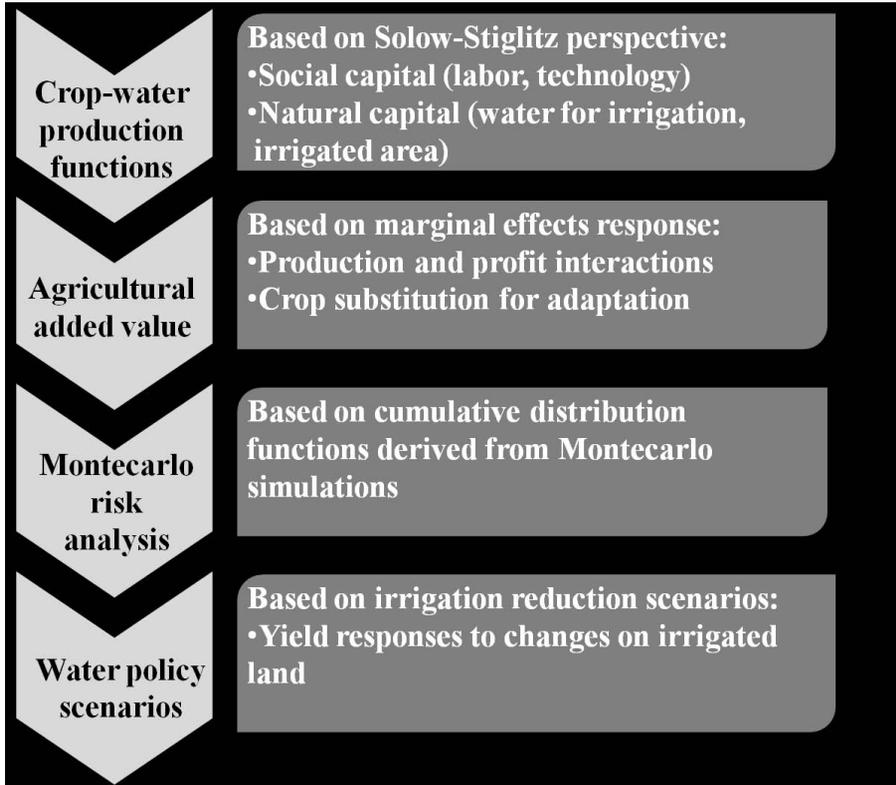


Fig. 1. Steps on methodology.

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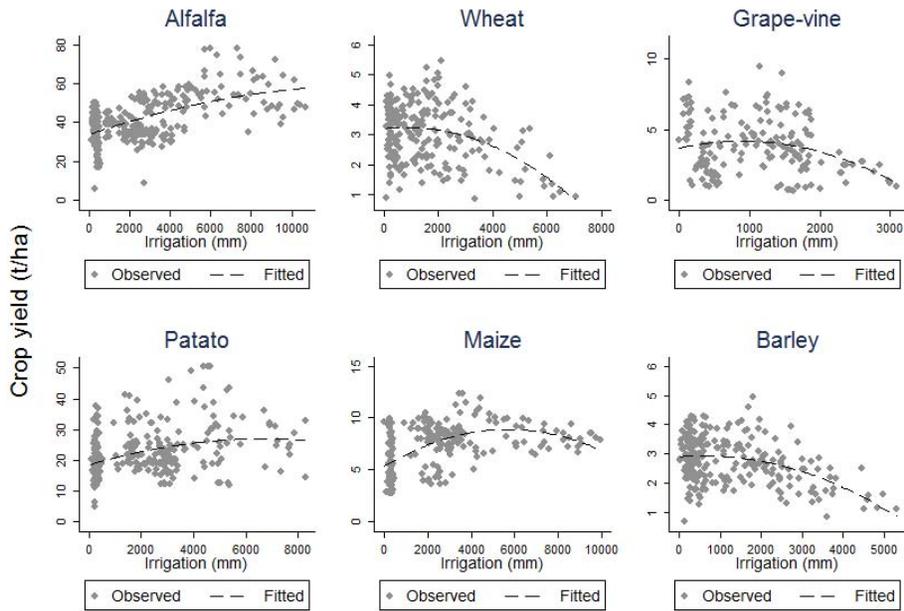
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Source: MARM and CHEBRO databases

Fig. 2. Observed crop response to irrigation water applied.

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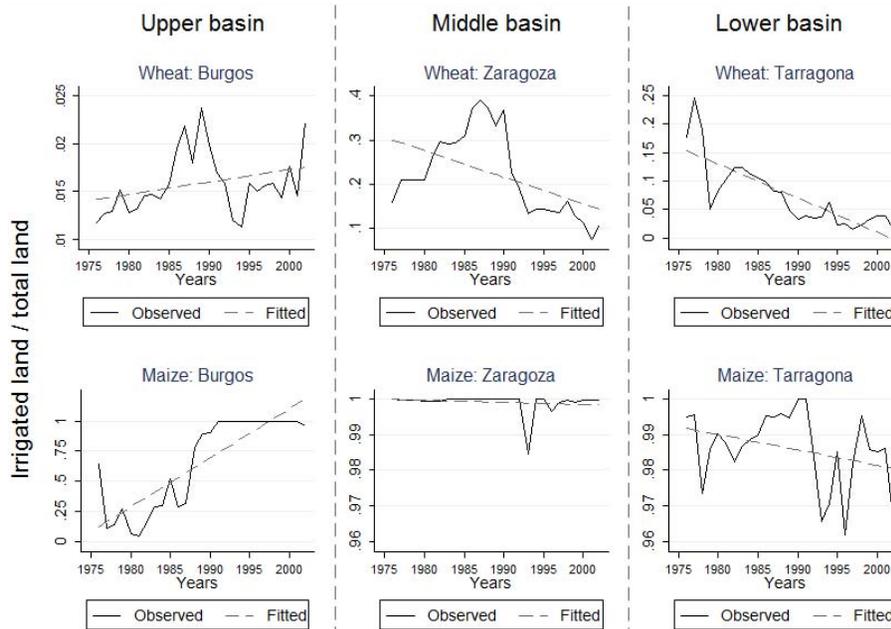
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Source: MARM and CHEBRO databases

Fig. 3. Irrigated land for wheat and maize at representative areas of Upper (Northern, Central and Low) Ebro: Burgos, Zaragoza and Tarragona.

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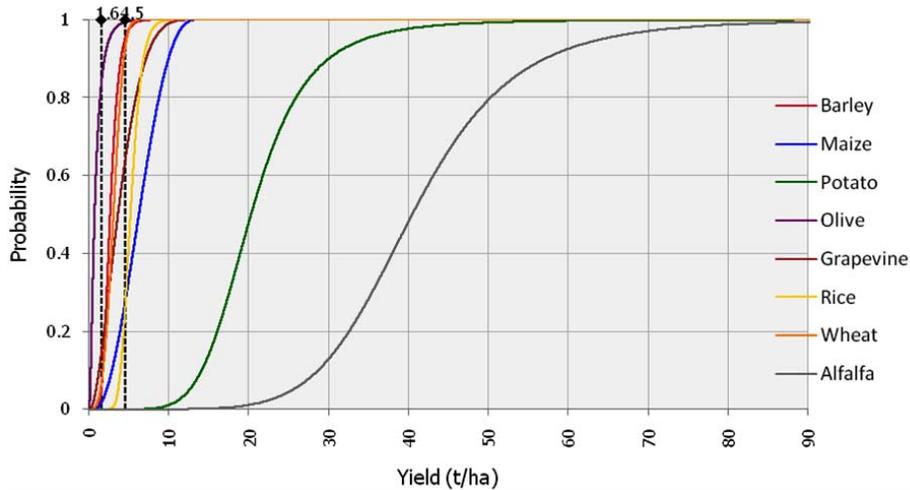


Fig. 4. Cumulative density probability function of crop yield.

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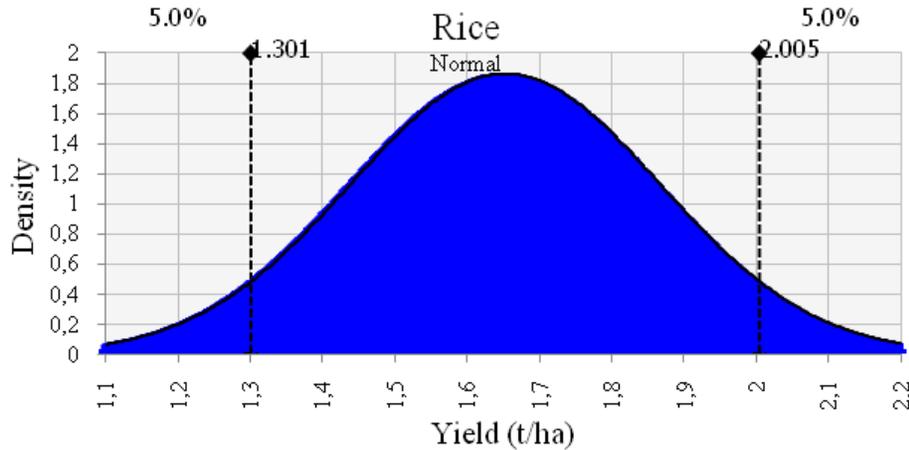


Fig. 5. Distribution function of simulated rice yield in the low Ebro. Normal distribution with mean=1.62 and SD=0.21.

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