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21st Annual Conference of the European Association of Environmental and Resource Economists

Helsinki, June 24-27, 2015

A stochastic model of irrigation adaptation to climate change in southern Europe

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Abstract

This paper develops a modeling framework that links hydrologic, agronomic, and economic variables within a discrete stochastic programming model. The model is used to analyze climate change adaptation measures in the irrigated agriculture of southern Europe. A wide range of both on-farm and institutional adaptation measures are considered. Results indicate that climate change will have sizable negative impacts on irrigation activities of southern Europe. The severity of these impacts depends on the policy choices and farmers' investment decisions, which are interrelated. Results suggest that adaptation does not necessarily require substantial changes in the current European institutional setting. Rather, the main thrust should be placed on enhancing the adaptive capacity at farm level, and improving farmers' knowledge of climate change impacts for better long-run investment decisions.

Keyword: Climate change, Irrigation, Adaptation, Southern Europe, Stochastic programming, Water policies

1. Introduction

Climate change is an important challenge for sustainable agricultural production in the coming decades. This challenge is specially difficult to harness because global food demand will more than double by 2050, driven by the growth of world population and income. Climate change will increase temperatures and modify the pattern of precipitations, reducing crop yields in both irrigated and rainfed cropland and also livestock productivity because of prolonged or extreme changes in temperature. The biological processes underlying the productivity of plants and animals will be negatively affected by increasing weeds, diseases and pests, along with changes in the development and pollination periods (USDA 2012).

Water resources projections using coupled global hydrological and crop models indicate that crop losses from climate change could be in the range of 20-30% by the end of the century, depending on the CO_2 fertilization effects.[1] Further losses may occur from water resources scarcity in some regions, which will force the reversion of irrigation to rainfed cropland (Elliot et al. 2014).

Changes in precipitation regimes and extreme precipitations will have negative effects on water availability. Precipitations will decrease in mid-latitude and subtropical dry regions, reducing renewable surface water and groundwater resources and escalating the competition for water among sectors (IPCC 2014a). Suitable climate conditions for human activities are expected to move northwards in the northern hemisphere, resulting in higher temperatures, changes in annual and seasonal rainfall patterns, and more frequent and severe extreme events in southern regions.

Climate change projections for the South of Europe and the Mediterranean basin indicate that there would be prolonged droughts and increased water scarcity, excessive heat, spread of pests and diseases, pressures on food production systems, and harmful damages to natural ecosystems. The reductions of water availability in southern Europe would be combined with increased water demand (20-40% increases for irrigation) and with reduced water drainage and runoff resulting from increased evaporation (IPCC 2014b, Jimenez et al. 2014).

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[1] Under representative concentration pathway (RCP) 8.5.

The capacity of irrigated agriculture in southern Europe to adapt to climate change impacts is of particular interest for policy makers and stakeholders. Irrigation adaptation to climate change has become one of the main objectives of the European water and agricultural regulations such as the Water Framework Directive and the 2014-2020 Rural Development policy (EC 2009 and 2013). Understanding the economic and environmental impacts of climate change on irrigation, adaptation possibilities, and cost implications is thus an important step in evaluating the effectiveness of existing policies to address climate change impacts and in providing insights to policy makers for the design of additional adaptation policies.

There is a growing body of economic literature that analyses climate change impacts and adaptation possibilities in irrigation. Two major approaches are widely used. One approach is mathematical programming models (both partial and general equilibrium models) that link biophysical (hydrologic, agronomic, and environmental) and economic components to simulate farmers' choices of crop mix, technologies, and resources use for different climate scenarios, allocation rules, institutional arrangements, and policy interventions (Hurd et al. 2004; Connor et al. 2009; Medellín et al. 2013; Qureshi et al. 2013; Calzadilla et al. 2014). The alternative approach is econometric models that represent observed responses of farmers to past climate conditions under existing policies and institutions. These models are then used to estimate the effects of changes in climatic and policy variables (Zilberman et al. 2002; Mendelsohn and Dinar 2003; Wheeler et al. 2013; Connor et al. 2014). Generally, mathematical programming models are computationally intensive, while econometric models are data intensive.

Both programming and econometric models have provided insights on irrigation adaptation possibilities to climate change. Connor et al. (2009) analyze climate change impacts and adaptation possibilities in the Murray-Darling basin of Australia. They find that relatively low-cost adaptation strategies are available for a moderate climate change scenario and adaptation costs are likely to be relatively small, but costs increase substantially under a more severe climate change scenario. Possible adaptation options include a reduction of irrigated land, change of land use to more opportunistic cropping systems, deficit irrigation, investments in efficient irrigation technologies, and water trading. Wheeler et al. (2013) analyze farmers' willingness to adopt these adaptation strategies in the same basin. They find that farmers convinced that climate change is occurring are more likely to plan accommodating strategies such as improving irrigation efficiency and changing crop mix, but not expansive strategies such as purchasing water or land and increasing irrigated area.

Zilberman et al. (2002) underline the importance of water storage infrastructures and groundwater resources to mitigate climate change-induced drought impacts in the case of California agriculture. They find also that water scarcity and droughts are important incentives to adopt water-conserving technologies and to introduce institutional changes such as water trading and marginal cost pricing of water. Albiac et al. (2013) identify adaptation possibilities in Spain, highlighting the importance of basin planning and stakeholders' cooperation, the availability of alternative sources of water such as treated wastewater and groundwater resources, and investment in conveying facilities and water-conserving technologies.

The above-mentioned studies underline two main institutional adaptation interventions to address climate change impacts: water markets and investments in water-conserving technologies (irrigation modernization). Water markets are considered a good option to smooth the economic impacts of climate change. Estimations of potential water market benefits during drought both in Australia and California are close to 1 billion US dollars per year (Connor and Kaczan 2013; Medellín et al. 2013). A challenge to water markets is the third party effects such as the environmental impacts, which would reduce the benefits of trading and increase adaptation costs. Water markets reduce streamflows because previously unused water allocations are traded, and also because gains in irrigation efficiency at parcel level reduce return flows to the environment (Howe et al. 1986; Qureshi et al. 2010). Another worrying effect is the large surge in groundwater extractions, as shown in the Millennium drought in the Murray-Darling.[2]

Policies that promote investments in irrigation modernization are considered also important options for climate change adaptation given that modernization reduces land abandonment, facilitates the adoption of diversified and high-value cropping pattern, and increases crop yields, leading to an increase in the value of agricultural production and a reduction of adaptation costs (Perry et al. 2014). In addition, modernization

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[2] Blewett (2012) indicates that extractions between 2002 and 2007 were seven times above the allowed limits placed on groundwater users.

supports rural development and improves water quality. However, contrary to widespread expectations, modernization increases water depletion through crop evapotransipiration and reduction of return flows that could be beneficially used downstream, or contribute to in-stream flows and groundwater replenishment (Perry et al. 2014; Huffaker 2008).

Along the same lines, this paper presents a modeling framework that could be used to evaluate the impacts of climate change and variability, and adaptation possibilities in irrigated agriculture in Southern Europe. We chose a representative basin in southern Europe, the lower Jucar basin in Spain, as our case study. This basin is a good experimental field for studying irrigation adaptation possibilities to confront water scarcity and drought impacts from the impending impacts of climate change. The Jucar River is under severe stress with acute water scarcity, near zero outflows and escalating degradation of ecosystems.

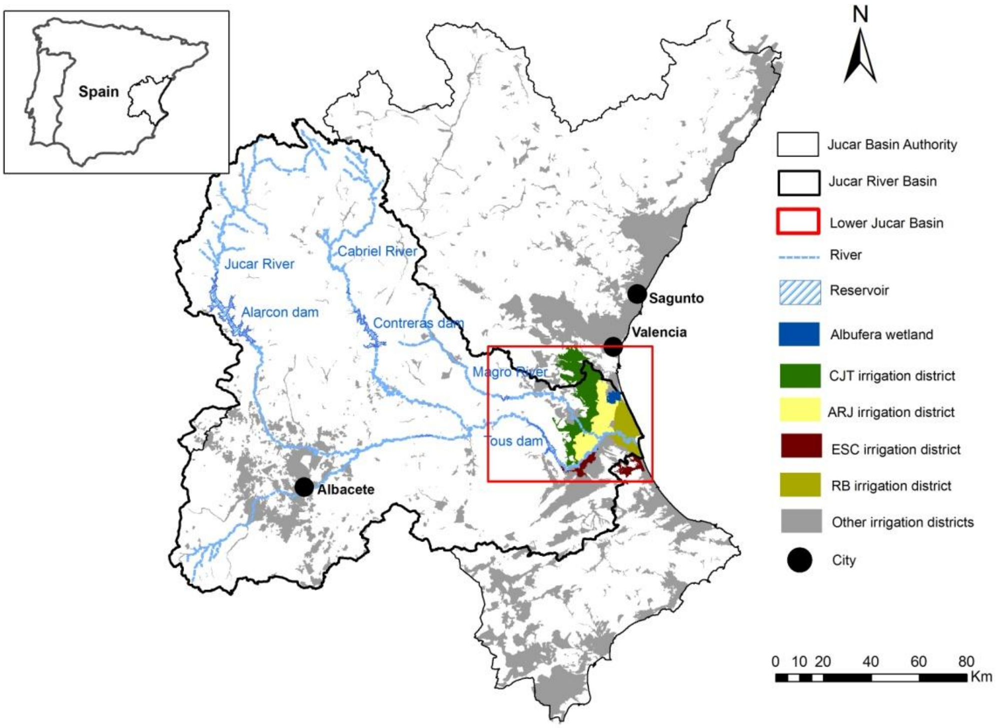
The contributions of this paper relative to prior literature are both methodological and empirical. The modeling framework links hydrologic, agronomic, and economic variables within a discrete stochastic programming model that simultaneously estimates short and long-term adaptation possibilities to climate change. Empirically, the model accounts for a wide range of on-farm and institutional adaptation possibilities and provides information on the relative contribution of each one to overall adaptation, and the tradeoff and interaction between them. The results could contribute to the design of efficient climate change adaptation responses in the irrigated agriculture of southern Europe.

The paper is organized as follows. First, the lower Jucar Basin is presented in section 2. Section 3 describes the modeling framework. Climate change and adaptation scenarios are presented in section 4. Section 5 presents the simulation results. Section 6 concludes with the summary and policy implications.

2. Case study area: the lower Jucar basin

The lower part of the Jucar basin is located in the region of Valencia in Spain (Figure 1). This basin has an irregular Mediterranean hydrology, characterized by recurrent drought spells and normal years with dry summers. Irrigated area in the lower Jucar basin expands over 102,000 ha, representing 49 percent of irrigated area in the whole

Figure 1. Map of the lower Jucar basin.



Jucar basin. The main crops grown are rice, corn, tomato, watermelon, peach, and citrus. Extractions for irrigation are about 980 Mm^3 per year, of which 770 are surface water and 210 are groundwater resources (CHJ 2014). The analysis undertaken in this paper focuses on irrigation activities in the four major irrigation districts in the lower Jucar basin: Acequia Real del Jucar (ARJ), Escalona-Carcagente (ESC), Ribera Baja (RB), and Canal Jucar-Turia (CJT). These districts use almost 80 percent of total extractions in the lower Jucar basin.

The lower Jucar basin includes the Albufera wetland, which is one of the most important aquatic ecosystems in southern Europe. The Albufera is catalogued in the RAMSAR list, and declared a special protected area for birds. It receives water mainly from the return flows of the ARJ and RB districts. Other flows originate from the neighboring Turia basin, and from the discharge of untreated and treated urban and industrial wastewaters in the adjacent municipalities.

The growth of water extractions in the upper Jucar and the severe drought spells in recent decades have triggered considerable negative environmental and economic impacts in the basin. For instance, the water available to ARJ district has been reduced from 700 to 200 Mm^3 in the last 40 years. Consequently, the dwindling irrigation return flows have caused serious environmental problems to the Albufera wetland. In addition, outflows to the Mediterranean Sea are below 1 m^3/s, which is very low compared with the other two major rivers in the region, the Ebro and Segura Rivers (Garcia-Molla et al., 2013).

One key issue for water management in the lower Jucar basin is adaptation of irrigation to the upcoming effects of climate change, which would exacerbate water scarcity and the intensity and frequency of droughts. Estimations of climate change impacts in the Jucar basin for a range of climate and socioeconomic scenarios for 2100 indicate a reduction of rainfall by up to 25 percent, an increase of temperature by up to 5 ºC, an increase of evapotranspiration by up to 22 percent, and a reduction of runoff by up to 45 percent (CEDEX 2010).

3. Modeling framework

The modeling approach used in this paper is discrete stochastic programming (DSP). The advantage of using DSP models compared to other programming techniques is their ability to capture sources of risk that influence the objective function and the constraint set, and also allowing for a multi-stage decision process in which the decision makers' knowledge about random events changes through time as economic choices are made (Rae 1971). DSP has been used previously in many studies in the literature to analyze different water management problems. Some examples are the measurement of forgone irrigation benefits derived from rural to urban water transfers under uncertain water supplies (Taylor and Young 1995), the impacts of reducing pumping in the Edwards aquifer in Texas (McCarl et al. 1999), and the assessment of water market outcomes under uncertain water supply in Spain (Calatrava and Garrido 2005). DSP models seem to be a suitable approach to investigate irrigation adaptation to climate change because they can incorporate the production decisions in agriculture and the uncertainty linked to climate change impacts (Connor et al. 2009).

This paper develops a two-stage DSP framework that could be used to analyze the impacts of climate change and variability on irrigated agriculture. The first stage represents farmers' choice of long-run capital investment in cropping and irrigation systems as a response to the expected climate change scenario made prior to knowledge of the annual water inflows to the basin, which is a stochastic variable. The long-run horizon is equivalent to the economic life of the capital investment which is in the range of 20 to 30 years. The second stage represents the short-run (annual) decisions regarding variable input levels, including irrigated and fallowed land, and irrigation water applied to crops after stochastic annual water inflows to the basin are known. These short-run decisions are conditional on the fixed capital investment level chosen in the first stage.

The objective of the model is to maximize farmers' profits in each irrigation district subject to technical and resource constraints. The objective function is given by the following formulation:

$$Max\, \pi_k = \left[-\sum_i fcc_{i,k} - \sum_{i,j} fic_{i,j,k}\right] \cdot A1_{i,j,k} \tag{1a}$$

$$+\sum_s pr_s \cdot \sum_{i,j} p_i \cdot Y_{i,j,k,s}\left(W_{i,j,k,s}\right) \cdot A2_{i,j,k,s} \tag{1b}$$

$$-\sum_s pr_s \cdot \sum_{i,j} pw_k \cdot IW_{i,j,k,s} \cdot A2_{i,j,k,s} \tag{1c}$$

$$-\sum_s pr_s \cdot \sum_{i,j} vc_{i,k} \cdot A2_{i,j,k,s} \tag{1d}$$

$$-\sum_s pr_s \cdot \sum_{per,j} yp_{per,j,k} \cdot AF_{per,j,k,s} \tag{1e}$$

where decision variables are presented by capital letters. π_k is farmers' profits in irrigation district k; $A1_{i,j,k}$ is the area of crop i equipped with irrigation system j in district k in the first stage; $A2_{i,j,k,s}$ is the irrigated area of crop i equipped with irrigation system j in district k and state of nature s in the second stage. $Y_{i,j,k,s}$ is yield of crop i equipped with irrigation system j in district k and state of nature s, which depends on the water applied to the crop, $W_{i,j,k,s}$. $IW_{i,j,k,s}$ is gross irrigation requirement of crop i equipped with irrigation system j in district k and state of nature s. $AF_{per,k,s}$ is the fallowed area of perennial crop, per ($per \subset i$), in district k and state of nature s.

Parameters are represented by lower case letters, where $fcc_{i,k}$ is fixed crop establishment costs; $fic_{i,j,k}$ is fixed irrigation equipment costs; p_i is crop prices; pw_k is water cost; $vc_{i,k}$ is variable cost other than water; $yp_{per,k}$ is perennial land fallowing penalty; and pr_s is the probability of each state of nature s.

The crops i which are included in the model are the main crops cultivated in the study area: rice, cereals, vegetables, citrus, and other fruit trees. The irrigation systems j are flood, sprinkler and drip. Surface water inflows to the basin in the period 1990-2011 are classified into four states of nature (s). The states are low, moderately low, moderately high, and high inflow levels, with probabilities of 10%, 40%, 40%, and 10%, respectively.

Expression (1a) represents long-run (first-stage) choices of capital investment in cropping and irrigation systems. Expression (1b), (1c), and (1d) represent short-run (second-stage) crop revenues, water costs, and variable costs, respectively. Expression (1e) represents a perennial land fallowing penalty, indicating possible future yield losses if farmers decide to fallow perennial crop lands.

The yields, $Y_{i,j,k,s}$, are determined using crop-water production functions. These functions represent crop yield as an increasing function of water available for the crop up to a point beyond which additional water reduces yield. These quadratic production functions take the following form:

$$Y_{i,j,k,s}\left(W_{i,j,k,s}\right) = a_{i,j,k,s} + b_{i,j,k,s} \cdot W_{i,j,k,s} + c_{i,j,k,s} W_{i,j,k,s}^{2} \quad (2)$$

where the parameters a, b, and c are the intercept, linear and quadratic coefficients, respectively. These functions are estimated following the procedure developed by Warrick and Yates (1987) that relates crop yield to maximum and minimum crop water requirements and application uniformity. The production functions are calibrated based on local yield, water requirement, and economic data from Kahil et al. (2014).

The variable applied water, $W_{i,j,k,s}$, is defined as the quantity of water available for each crop i equipped with irrigation system j in district k and state of nature s, which is the sum of net irrigation water and effective rainfall. This relationship is defined as follows:

$$W_{i,j,k,s} = IW_{i,j,k,s} \cdot ef_{j,k} + ER_{i,k,s} \quad (3)$$

where $ef_{j,k}$ is the efficiency of each irrigation system j in district k, and $ER_{i,k,s}$ is effective rainfall for each crop i in district k and state of nature s.

The objective function (1a-e) is maximized subject to the following constraints:

$$\textstyle\sum_{i,j} A1_{i,j,k} \leq landavail_{k} \quad \forall\, k \quad (4)$$

$$A2_{i,j,k,s} \leq A1_{i,j,k} \quad \forall\, i,j,k,s \quad (5)$$

$$AF_{i,j,k,s} = A1_{i,j,k,s} - A2_{i,j,k,s} \quad \forall\, i,j,k,s \quad (6)$$

$$\textstyle\sum_{i,j} IW_{i,j,k,s} \cdot A2_{i,j,k,s} \leq wateralloc_{k,s} \quad \forall\, k,s \quad (7)$$

$$\Phi_{k,s} = \left[wateralloc_{k,s} - \textstyle\sum_{i,j} IW_{i,j,k,s} \cdot A2_{i,j,k,s}\right] \quad (8a)$$

$$+\left[\sum_{i,j} IW_{i,j,k,s} \cdot A2_{i,j,k,s} \cdot \left(1 - ef_{j,k}\right)\right] \quad \forall\, k, s \tag{8b}$$

$$\Psi_s = \alpha \cdot \Phi_{ARJ,s} + \beta \cdot \Phi_{RB,s} \quad \forall s \tag{9}$$

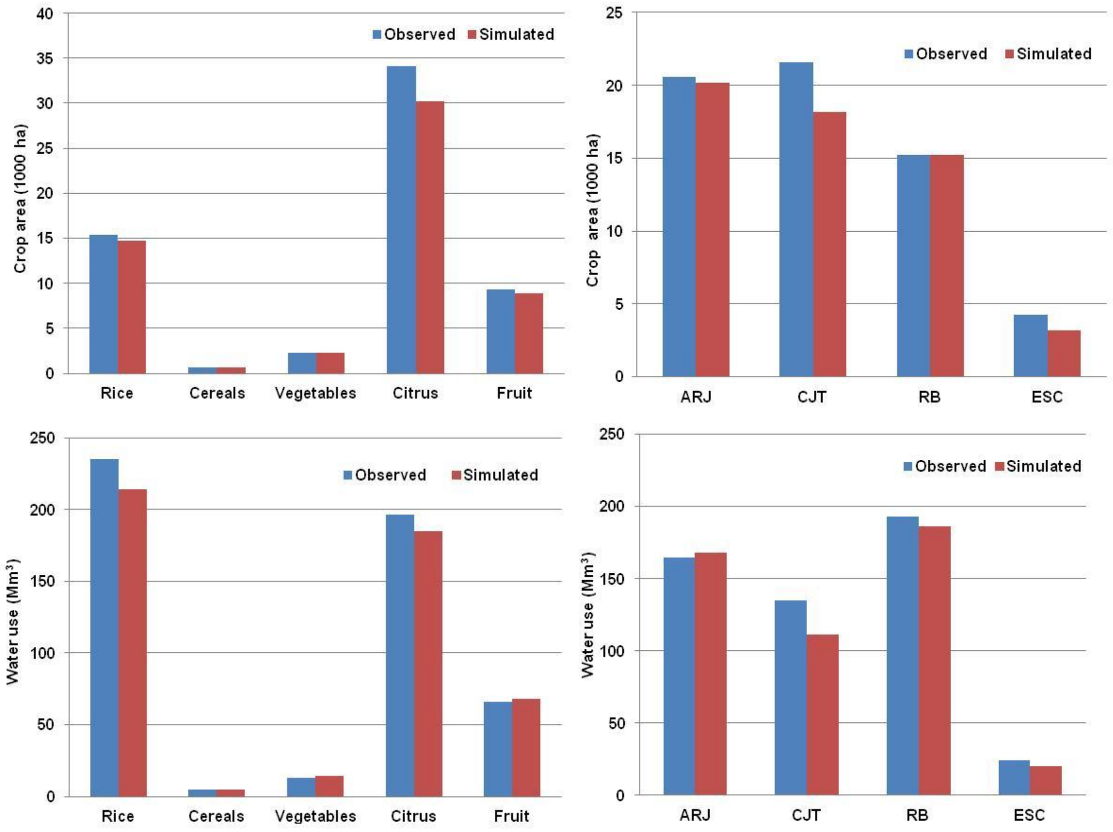
Expression (4) represents land available in each irrigation district, $landavail_k$, for capital investments in cropping and irrigation systems (first-stage decision). Expressions (5) and (6) represent the possibility that a share of area with capital investments, $A1_{i,j,k}$, can be irrigated, $A2_{i,j,k,s}$, or fallowed, $AF_{i,j,k,s}$, in each state of nature (second-stage decision). Expression (7) states that the water used in an irrigation district under each state of nature does not exceed the water allocated to that district, $wateralloc_{k,s}$. Expression (8a-b) calculates irrigation water left for environmental flows in each irrigation district and state of nature, $\Phi_{k,s}$, which is the sum of unused irrigation water (8a), and irrigation return flows (8b). Irrigation return flows are calculated as a function of water use and efficiency.

Expression (9) determines the quantity of water flowing to the Albufera wetland from environmental flows in each state of nature,Ψ_s. Parameters α and β represent the shares of environmental flows that feed the wetland from the ARJ and RB irrigation districts, respectively. $\Phi_{k,s}$ and Ψ_s are proxy variables for environmental impacts of climate change.

Detailed information on the technical coefficients and parameters of the model have been collected from field surveys, expert consultation, statistical reports, and reviewing the literature. This information covers crop yields and prices, water and production costs, crop water requirements, irrigation efficiencies, and land availability (GV 2009; GCLM 2009; INE 2009; MARM 2010).

The use of mathematical programming models to analyze agricultural production at regional level faces the problem of aggregation and overspecialization because farms in a region are different in terms of resources availability, and technological and management ability. Ideally, a regional model should include a component for every individual farm, but this is unfeasible because of the complexity of such a model (Hazell and Norton 1986). Many approaches have been developed to solve this problem and to calibrate regional models to observed conditions such as the representative farm approach (Day 1963), the convex combination approach (Önal and McCarl 1991), and

Figure 2. Observed and simulated area and water use by crop and irrigation district.



the positive mathematical programming (PMP) approach (Howitt 1995; Röhm and Dabbert 2003).

The model is calibrated for the year 2009 (a moderately high state of nature year), with observed crop area, and water use by crop and irrigation district using the PMP approach. The Röhm and Dabbert‘s procedure is applied, in which there is a larger elasticity of substitution among crop variants than among completely different crops. Crop variants include the same crop grown under different irrigation systems. The outcomes of the model are broadly consistent, indicating that the model reproduces reliably the observed situation (Figure 2).

4. Climate change and adaptation scenarios

The modeling framework is used to analyze climate change impacts and adaptation possibilities in the Jucar basin. We evaluate the impacts of an average climate change scenario with a reduction of water inflows to the basin by 32%, and an increase of crop irrigation requirements by 15% compared to the baseline scenario (current climate conditions), following the climate change projections in the Jucar basin by CEDEX

Table 1. Water allocation to irrigation districts by climate scenario and state of nature.

Climate scenario	State of nature	P value (%)	Water allocations (Mm^3)			
			ARJ	ESC	RB	CJT
Baseline	Low	10	61	12	119	17
	Moderately low	40	111	22	217	34
	Moderately high	40	168	38	274	54
	High	10	222	66	336	80
Climate change	Low	10	49	9	91	8
	Moderately low	40	89	16	166	16
	Moderately high	40	134	28	210	25
	High	10	178	49	257	37

(2010) and Rodriguez et al. (2007). Eight combinations or experiments of several on-farm and institutional adaptation measures are analyzed. Adaptation measures at farm-level are crop mix changes, land fallowing, irrigation system modernization, and deficit irrigation. Adaptation measures at institutional-level are public subsidies for irrigation modernization, and introduction of water trading. These experiments show the contribution of each adaptation measure to overall adaptation, and the tradeoff and interaction between the different possibilities. The objective function (1a-e) and the water availability constraint (7) are relaxed depending on the adaptation experiment.

Table 1 shows water allocations to irrigation districts under each climate scenario and state of nature. These allocations are estimated using the reduced form hydrological model of the Jucar basin developed in Kahil et al. (2014). This model includes several demand nodes from upstream to downstream river reaches, and allocates water to those nodes subject to water mass balance and continuity of river flow, and various institutional and environmental constraints. We maintain the probability distribution of states of nature for the baseline scenario into the climate change scenario, because of the lack of information on the possible alteration of the probability distribution under climate change. Table 2 shows the eight adaptation experiments, representing the different combinations of on-farm and institutional adaptation possibilities.

5. Results and discussion

Results of the different climate and adaptation experiments are presented in terms of economic impacts, land use changes and irrigation systems distribution, and water use and environmental flows. Table 3 presents the economic outcomes of the experiments.

Table 2. Climate change adaptation experiments.

Adaptation possibilities	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
On-farm adaptation								
Crop mix change	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Land fallowing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Irrigation modernization	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Deficit irrigation	No	No	No	No	Yes	Yes	Yes	Yes
Institutional adaptation								
Subsidy for irrigation modernization	No	Yes	No	Yes	No	Yes	No	Yes
Water trading	No	No	Yes	Yes	No	No	Yes	Yes

Results show that climate change will likely have negative effects on irrigation activities in the Jucar basin for the scenarios considered. However, the severity of those effects depends on the adaptation possibilities available for irrigation. Farmers' profits are reduced by 38% under the most restrictive experiment (Exp 1), and only by 5% under the most flexible experiment (Exp 8).

The comparison between the different experiments with and without each adaptation possibility allows identifying the contribution of each option to overall adaptation, and the tradeoff and interaction between them. Results of these comparisons indicate that introducing water trading is the best individual adaptation option, improving famers' profits between 19 and 26% (8 to 11 million €/year). The second-best option is deficit irrigation, which improves farmers' profits between 10 and 16% (4 to 8 million €/year). Subsidizing irrigation modernization contributes less to overall adaptation, compared to the other two options. This option improves farmers' profits between 9 and 12% (4 to 5 million €/year), but at a high cost for society in terms of public subsidies (4 to 5 million €/year). The analysis of the interactions between adaptation possibilities indicates that a policy supporting water trading together with full on-farm adaptation (Exp 7) results in lower costs to farmers compared to other adaptation combinations (trade and subsidies (Exp 4) or full on-farm adaptation and subsidies (Exp 6)).

Crop revenues and production costs (long and short-run) decrease under climate change for all experiments compared to the baseline scenario. However, they increase progressively as more adaptation possibilities are included because more area is equipped with crop and irrigation systems, and the shift towards more high-value crops

Table 3. Economic outcomes of the climate and adaptation experiments (10^6 €).

Economic indicators	Baseline	Climate change							
		Exp 1	**Exp 2**	**Exp 3**	**Exp 4**	**Exp 5**	**Exp 6**	**Exp 7**	**Exp 8**
Long-run fixed costs	120.1	86.7	88.6	88.8	88.2	87.9	96.9	100.7	108.7
Short-run production costs*	93.2	63.4	67.3	70.6	72.2	65.8	73.3	82.9	87.8
Fallow penalty	1.6	2.6	2.8	1.6	1.6	0.5	0.5	0.0	0.0
Crop revenues	278.2	192.2	202.2	208.6	213.7	197.7	219.6	238.4	256.8
Public Subsidy	5.5	0.0	4.2	0.0	4.3	0.0	4.6	0.0	4.9
Farmers' Profits	63.3	39.5	43.5	47.7	51.8	43.4	48.8	54.8	60.2

* Short-run production costs include variable and water costs.

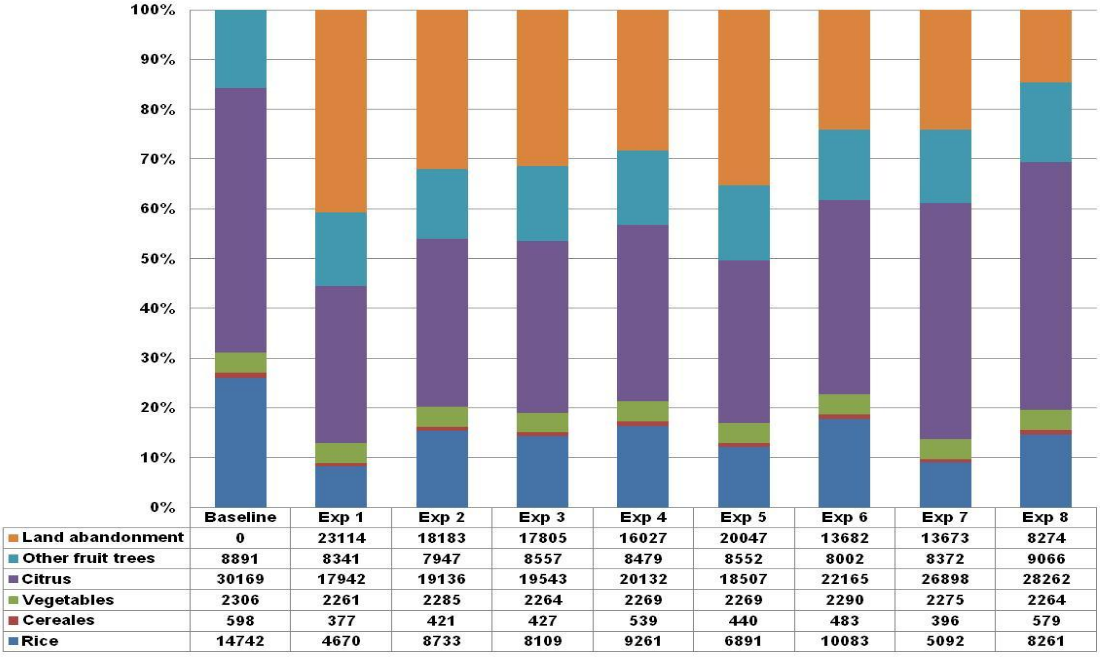
and costly equipments. The perennial land fallowing penalty increases under climate change for the most restrictive experiment (Exp 1) compared to the baseline scenario because of the lack of enough water in some years to avoid future yield losses and the limited adaptation options. The penalty is reduced when more adaptation options are included, especially with the adoption of deficit irrigation and water trading.

The economic outcomes described above are explained by farmers' choices of capital investments in cropping and irrigation systems. Long-run choices of land use indicate that under climate change farmers reduce irrigated land between 15 and 41% compared to baseline scenario (Figure 3). Introducing water trading (Exp 3) results in the highest increase of irrigated area (or the lowest rate of irrigation abandonment, 16%) compared to the most restrictive experiment (Exp 1), followed by subsidizing irrigation modernization (15%), and deficit irrigation (9%). However, the contribution of deficit irrigation to the increase of irrigated area is more important when combined with the other adaptation options (11 to 19%), than the contribution of water trading (6 to 17%) or subsidizing irrigation modernization (5 to 17%).

The crop mix changes considerably, with a decline in the relative importance of water-intensive and low-value crops such as rice and cereals, and an increase in high-value crops such as vegetables and fruit trees. Irrigated area falls by 32 to 68% for rice, 3 to 37% for cereals, and 6 to 41% for citrus, while the area of vegetables and other fruit trees remains almost unchanged.

The large reduction in the area of citrus in some experiments is explained by the fact that farmers do not have enough adaptation options to confront reduced water availability, especially in dry years (low water state of nature). Thus, the efficient

Figure 3. Long-run land use choice by climate and adaptation experiment.



	Baseline	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Land abandonment	0	23114	18183	17805	16027	20047	13682	13673	8274
Other fruit trees	8891	8341	7947	8557	8479	8552	8002	8372	9066
Citrus	30169	17942	19136	19543	20132	18507	22165	26898	28262
Vegetables	2306	2261	2285	2264	2269	2269	2290	2275	2264
Cereales	598	377	421	427	539	440	483	396	579
Rice	14742	4670	8733	8109	9261	6891	10083	5092	8261

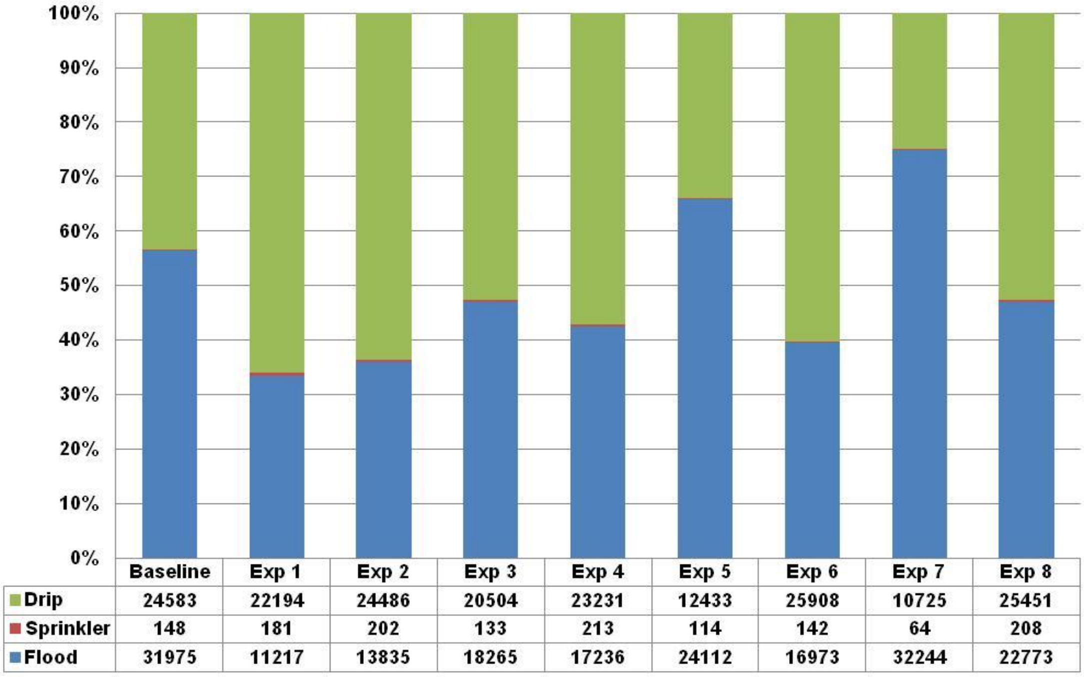
Note. Land use is presented in percentage term in the graph and in hectares in the table.

response in the presence of substantial cultivated area of citrus is to reduce long-run capital investments to minimize both current and future yield losses. These future losses (perennial land fallowing penalty) arise from the failure to meet a minimum threshold of applied water that ensures full productivity in future years.

Long-run choices of capital investments in irrigation systems suggest that farmers mostly choose to move away from less-efficient flood system towards more-efficient sprinkler and drip systems (Figure 4). Subsidizing irrigation modernization provides a good incentive to farmers for such a change. However, in some experiments farmers reduce the area under sprinkler and drip systems. The reason is the possibility of adopting deficit irrigation and/or purchasing water in the market, instead of investing in costly irrigation systems that may not be needed in wet years (high water state of nature), with lower crop water requirements and higher water availability.

Table 4 presents the water use indicators of the eight climate and adaptation experiments. Water use under climate change decreases between 17 and 28% compared to the baseline scenario, but water use increases progressively as more adaptation options are included compared to the most restrictive experiment (Exp 1).

Figure 4. Long-run irrigation system choice by climate and adaptation experiment.



	Baseline	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
🟩 Drip	24583	22194	24486	20504	23231	12433	25908	10725	25451
🟥 Sprinkler	148	181	202	133	213	114	142	64	208
🟦 Flood	31975	11217	13835	18265	17236	24112	16973	32244	22773

Note. See not to Figure 3.

Water use expands by 15% (or 49 Mm^3) under the most flexible experiment (Exp 8) compared to the most restrictive experiment (Exp 1). The contribution of the adaptation options to the increase in water use is different. Water use increases between 2 and 9% (8 to 29 Mm^3) when subsidizing irrigation modernization, between 2 and 8% (6 to 27 Mm^3) for water trading, and between 2 and 7% (7 to 23 Mm^3) with the adoption of deficit irrigation. The introduction of these on-farm and institutional adaptation possibilities provides significant incentives for farmers to expand water extractions that are left in-stream in wet years under the most restrictive experiment (Exp 1). These water extractions become activated to expand the irrigated area of flexible annual crops in wet years under the experiments 2 to 8. The in-stream unused water is reduced between 22 and 47% compared to the most restrictive experiment (Exp 1).

The decrease of both the volume of water left in-stream and the irrigation return flows leads to a reduction of environmental flows between 21 and 37% (45 to 81 Mm^3). The consequence is a fall of the inflows to the Albufera wetland between 24 and 40% (11 to 18 Mm^3) compared to the baseline scenario. Subsidizing irrigation modernization contributes more to the reduction of environmental flows and inflows to the Albufera wetland, followed by the introduction of water trading, and the adoption of deficit irrigation.

Table 4. Water outcomes of the climate and adaptation experiments (Mm^3).

Water indicators[*]	**Baseline**	**Climate change**							
		Exp 1	**Exp 2**	**Exp 3**	**Exp 4**	**Exp 5**	**Exp 6**	**Exp 7**	**Exp 8**
Water use	449	324	353	351	359	347	367	358	373
Unused water	94	100	70	73	65	78	58	67	53
Environmental flows	217	172	152	157	148	174	146	164	136
Inflows to Albufera	45	34	31	33	31	33	29	28	27

[*] Results of the water indicators are average values across probability weighted states of nature.

6. Conclusions and policy implications

Irrigated agriculture in southern Europe faces many challenges similar to most arid and semiarid regions. These challenges are how to manage growing water demand from urban and industrial uses, how to address the social claims for greater environmental flows and better water quality, and how to meet the rising world food demand. Furthermore, the foreseeable impacts of climate change in this region suggest large reductions of water availability, increased needs for irrigation, and more frequent extreme drought events.

This paper presents a modeling framework that links hydrologic, agronomic, and economic variables within a discrete stochastic programming model. The model is used to analyze the contribution of several on-farm and institutional adaptation measures for overall adaptation taking into account the interaction and tradeoff between them. The results could be used to inform policy makers and stakeholders about the efficiency of the adaptation responses to climate change in the irrigated agriculture of southern Europe.

Modeling results in the lower Jucar basin of Spain suggest that climate change will likely have negative impacts on the irrigated agriculture in southern Europe. However, the severity of these impacts depends on the policy choices at farm and institutional levels, and the linked investment decisions in cropping and irrigation systems. Results highlight that introducing water trading is the best option in terms of farmers' private benefits. However, full on-farm adaptation may achieve better results than those of water markets when taking into account the environmental concerns. Water markets based on consumptive water use rather than on water extractions, could be an interesting policy to reap the private benefits of free market while protecting ecosystems. However, its implementation is a complex task which requires a clear definition of water rights (as the consumptively used portion of diversions), well-functioning water institutions (for measurement, monitoring and enforcement), and stakeholders’ cooperation.

Providing public subsidies to farmers for investing in irrigation modernization is the worst policy options in terms of private and social benefits, even if combined with other on-farm or institutional adaptation possibilities. The results indicate that programs subsidizing irrigation modernization are likely to exacerbate water scarcity problems, and reduce water available for downstream consumptive and environmental uses.

These findings suggest that irrigation adaptation to climate change does not necessarily require substantial changes in the current institutional setting in Europe, and highlight the value of on-farm adaptation measures. Hence, adaptation policies in Europe could be more effective if they are oriented towards enhancing the adaptive capacity at farm level, and farmers’ knowledge of climate change impacts for better long-run investment decisions.

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