Possible impacts of climate change on Mediterranean irrigated farming systems

Gabriele Dono,[T] Raffaele Cortignani,[T] Luca Doro,[S] Luigi Ledda,[S] PierPaolo Roggero,[S] Luca Giraldo,[T] Simone Severini[T]

T: Faculty of Agriculture, Tuscia University, Italy
S: Department of Agronomic Sciences, University of Sassari, Italy

Contact Details: Raffaele Cortignani, faculty of Agriculture, Tuscia University, Via S.C. de Lellis s.n.c., 01100, Viterbo, Italy. E-mail: cortignani@unitus.it, phone: 0039.0761357294, fax: 0039.0761357295

Paper prepared for presentation at the EAAE 2011 Congress
Change and Uncertainty
Challenges for Agriculture,
Food and Natural Resources

August 30 to September 2, 2011
ETH Zurich, Zurich, Switzerland

Abstract:
In the agricultural sector, climate change (CC) affects multiple weather variables at different stages of crop cycles. CC may influence the mean level or affect the distribution of events (e.g., rainfall, temperature). This work evaluates the economic impact of CC-related changes in multiple climatic components, and the resulting uncertainty. For this purpose, a three-stage discrete stochastic programming model is used to represents farm sector of an irrigated area of Italy and to examine the influence of CC on rainfall and on maximum temperature. These variables affect the availability of water for agriculture and the water requirements of irrigated crops. The states of nature, and their change, are defined more broadly than in previous analyses; this allows examining the changes of more climatic variables and crops cultivation.
The effect of CC is obtained by comparing the results of scenarios that represent the climatic conditions in the current situation and in the future. The results show that the agricultural sector would seek to lower costs by modifying patterns of land use, farming practices and increasing the use groundwater. The overall economic impact of these changes is small and due primarily to the reduced availability of water in the future. The temperature increase is, in fact, largely offset by the effects of the increase in CO_2 levels, which boosts the yield of main crops of the irrigated zone. Therefore, availability and water management becomes a crucial factor to offset the increase of evapotranspiration and of water stress resulting from the increase of temperature. However, the costs of CC are very high for some types of farming, which suffer a large reduction in income.

Keywords: discrete stochastic programming model, climate change, water availability, irrigation requirements.

1. Introduction

There is increasing concern about the impact of climatic change on agro-ecosystems, especially on agricultural production. Process-based crop models have been extensively used as tools to simulate crop response to the changing climatic conditions (Niu et al., 2009).
There are various sources of uncertainty in climate change simulations (Raisanen, 2007), and difficulties are associated with establishment of direct relationships between climate variability and water resources, as a consequence of the substantial influence of land cover (Beguería et al., 2003; García-Ruiz et al., 2008) and water management strategies (López-Moreno et al., 2007).
The main problems for irrigation reservoirs in Mediterranean is that they must be filled at the beginning of the irrigation season, whereas the filling season is characterized by a large uncertainty. This means that the management regimen of the reservoir (especially the inflow) must adjust to the variable conditions of the discharge, which in turn depend on the variable occurrence of the seasons of rainfall and snowmelt (López-Moreno et al., 2004).

Climate changes, associated to atmospheric accumulation of greenhouse gases (IPCC, 2007), could alter regional water supplies. Under decreased water availability scenarios, farmer net returns could decrease substantially (Elbakidze, 2006).

This paper evaluates the economic effects of Climate Change (CC) in terms of rainfall and maximum temperature, which are considered the main components of climate (IPCC, 2007; Solomon et al., 2007). In particular, the possible implications on irrigation water use and needs are examined and the impacts are estimated on the use of agricultural land, on inputs (e.g., water, labour), and on the income of the agricultural sector in a Mediterranean Italian area.

In the Mediterranean regions irrigated agriculture is the major water user accounting for more than 60% of total abstractions (OECD, 2006). On the other side, the high water demand of agriculture and population in the Mediterranean are exacerbated by the limited natural availability of water resources and high climatic variability (MGWWG, 2005). Climate change is expected to intensify problems of water scarcity and irrigation requirements in the Mediterranean region (IPCC, 2007; Goubanova and Li, 2006; Rodriguez Diaz et al., 2007). Besides, it is also important to consider that the increasing atmospheric CO_2 can affect agricultural production both directly through the stimulation of photosynthesis, particularly in C3 plants (Cure and Acock, 1986), through improved water use efficiency (Morison and Gifford, 1984), and indirectly as the increased concentration of CO2 and other greenhouse gases in the atmosphere may induce climate change. Maize and alfalfa, which are among the major summer crops requiring irrigation in the Mediterranean regions, are going to be interested by this impact.

The contribution of this analysis is twofold. The first is methodological, because a three-stage Discrete Stochastic Programming (DSP) model is proposed for representing the impact of uncertainty regarding rainfall and maximum temperatures at different stages of the cropping season. In this way two climate components and therefore two elements of uncertainty are represented, which yields an improved analysis of the economic impact of CC, given that previous studies generally only considered the effect of change in a single climatic component (Bazzani and Scardigno, 2009; Dono and Mazzapicchio, 2009, 2010a and 2010b). In literature, other studies utilized a 2-stages DSP model to evaluate the effect of variation of two climatic components on availability of water for irrigation and on crop yields (Connor et al., 2009). Another recent study used a 3-DSP model to analyze the impact of the CC in an area of local agriculture (Dono et al., 2010). However, its approach raises technical problems in the use of 3-stages DSP model when the analysis is extended to more crops. The analysis of the next few pages adopts a broader approach and represents the farmer's choice process as directly related to the change in the probability of various temperature levels.

A second contribution concerns the interdisciplinary nature of the work, in which an economic analysis is linked to an agronomic analysis performed by the Environmental Policy Integrated Climate (EPIC) model, which is simulates how changes in weather variables affect the irrigation requirements and the crop production. The analysis was designed by an interdisciplinary research team.

The remainder of this paper is organized as follows. Section 2 describes the main characteristics of the study, the climatic components, data used and output of the EPIC model, and characteristics of the 3-stages DSP model. Section 3 describes the results regarding trends in rainfall, maximum temperature and CO_2, the results of the EPIC model in terms of crop water requirements and yields, the probabilities associated with each state of nature, and the results of the DSP model. This analysis reveals the effects of CC on the farm income, in relation to various farm typologies in the study area. the effects on patterns of land use and of various productive inputs. The discussion is developed by separating the combined effect of changes in precipitation (i.e. in water availability and irrigation requirements) from the influence only due to changes in temperature and CO_2 concentration.

2. Material and methods

The analysis covers an irrigated agricultural area in the north-west of Sardinia, where the uncertainties associated with climate change concern the irrigation water available in a reservoir, managed by a consortium of local farmers, and the irrigation requirements of crops, particularly corn and alfalfa. The first uncertainty depends on the abundance of autumn-winter rains; the second depends on maximum temperatures and on level of evapotranspiration in the spring and summer.

The uncertainty on rainfall and maximum temperatures acts at two different times of the seasonal farm activity: the actual availability of water is only known at the beginning of the irrigation season; the irrigation requirements remain uncertain until summer. From the farmers' perspective, choices are made at different times with different elements of uncertainty. In particular, a choice must be made in early autumn on land use by crops in the dry winter-spring season, compared to irrigated crops in the spring and summer. Among other factors, the choice depends on expectations about the availability of water in the dam next summer, and the water needs of summer crops.

2.1. Study area

In the study area, located in northwestern Sardinia (Italy), irrigation water is administered by the Nurra water board (Consorzio di Bonifica della Nurra), which utilizes water from the dam reservoir at Cuga Lake (total capacity, 84 million m^3) that can be used to provide water for domestic consumption in the years of water shortage.

The water board provides water to around 2,900 farms for an area of 21,043 ha of which about 4,000 ha are annually irrigated. Since 2002, a charge has been applied based on actual consumption (€ 0.03/m^3). In some farms an additional source of irrigation water is groundwater extracted from their own wells. In years of water scarcity (e.g., 1995, 2000, and 2002), the Regional Commissioner for Water Emergencies gave priority to water distribution for domestic consumption at the expense of agriculture, which resulted in reduced water availability for this sector.

The main components of the climate (rainfall and maximum temperature) were analysed using 516 successive monthly observations, from 1961 to 2009, provided by the Italian Research Unit for Meteorology and Climatology Applied to the agricultural sector (CRA-CMA), as measured at a meteorological station at Alghero Airport, which is located within the irrigated area. These time series are evaluated for the long-term trend and the probability distribution of various climatic factors (e.g., rainfall and temperature) which are likely the most relevant in influencing farmers' choices. Linear trends were estimated using the least squares method.

2.2. The EPIC model for estimating the link between temperature and the irrigation requirements

Crop simulation models are valuable tools for irrigation management and to determine irrigation requirements at the farm level (Nijbroek et al., 2003) as well as at the regional or national level (Heinemann et al., 2002). The Erosion Productivity Impact Calculator (EPIC) is a simulation model designed to assess the influence of weather and management strategies on agricultural production, and on soil and water resources (Williams et al., 1989). The model is able to simulate a variety of management strategies, including crop rotation, tillage operations, the scheduling of irrigation, and the rates at which nutrients and pesticides are applied, as well as the timing of their application. EPIC has been extensively evaluated against observations under various environmental conditions. (Niu et al., 2009) to simulate the growth and development of several crops all over the world.

Simulations employing the EPIC model were performed using daily maximum and minimum temperature and precipitation and using soil information derived from a typical soil profile in the study area (Madrau *et al.*, 1981). To simulate climate change, the atmospheric CO_2 concentration was also considered, as obtained from the NOAA (2010), which increased from 318 ppm in 1961 to 358 ppm in 2003. Finally, information on typical cropping system management of grain and silage corn and alfalfa was obtained by direct interviews with farmers.

The EPIC simulation was performed according to a watering strategy which reduces the number of days of water stress and that replicates the irrigation technique used in the studied area.

The outputs of the simulation model for each of the considered cropping activities are: water demand, yield, water use efficiency.

2.3. A 3-stages DSP Model for evaluating the economic impact of CC.

Many studies have investigated the economic effects of CC on the agricultural sector (CEDEX, 2000; Christensen and Christensen, 2002; Giupponi and Shechter, 2003) based on long-term analyses at the aggregate level, i.e., continental or national scales (Xiong et al., 2010). In contrast, few studies have performed short-term analyses at a sub-regional level (Dono and Mazzapicchio, 2010(a) and 2010(b)). In the case of agriculture and water management, models based on DSP have been used to estimate the effects on agriculture of changes in water availability due to CC (Dono and Mazzapicchio, 2010a and 2010b). DSP models allow the representation of a sequence of choices that are made under conditions of uncertainty (McCarl and Spreen, 1997). In particular, it allows the representation of decision-making concerned with production activities conducted at certain times (stages), which are influenced by certain conditions (states of nature) that are not known with certainty. Only probability values can be attributed to the occurrence of the different states of nature. The decision maker does not know which state of nature will occur, and can only give them a certain probability of happening.

The DSP model presented in this study is based on three stages, and considers three states of nature regarding the abundance of autumn-winter rains and two states regarding maximum temperatures and level of evapotranspiration in the spring and summer. The states of nature on the rainfall pattern influence the availability of water in a dam; the states on maximum temperatures and on level of evapotranspiration, influence the production conditions of major crops, in particular their irrigation requirements and yields.

A different approach is used in a recent study which employs a 3-stages DSP model to analyze the impact of the CC in the same agricultural area (Dono et al., 2010). In that case, the climatic impact was directly expressed by the change in the probability of water requirement and yield of corn. These parameters and their probability distribution are directly affected by temperature, and besides, the farmer has direct knowledge of them. This supported using a 3-stage DSP for modelling a choice process of the farmer based on the expectation of possible scenarios for these variables. Yet, this approach raises technical problems when the analysis is extended to more crops. The various species have, in fact, different reactions to the CC, with different changes in the probability levels of their productive states: this complicates the management of the 3-stages DSP model, by dramatically increasing the number of states of nature to be considered.

The following analysis adopts a broader approach which represents choice process of the farmer as directly related to the change in the probability of temperature levels. EPIC is used to simulate the farmer's judgment on water requirements and yield of various crops in the various temperature conditions. This allows expanding the 3-stage DSP model to more crops, because restricts to the single temperature parameter, which is observed by the farmer, the states of nature, and their variation, to be represented. The following analysis focuses on corn and alfalfa, because they are used to feed livestock, which are an important part of the local economy, and because they utilize more than 50% of irrigation water used in the area1. However, based on this procedure, and after a proper local calibration of EPIC, the analysis can be extended to a large number of crops and changes in climatic variables.

2.3.1. Conceptual structure of the 3-stages DSP Model.

The first stage of the model corresponds to the phase of autumn sowing, when the farmer decides how much land to allocate to each autumn–winter crop and how much is to be reserved for crops to be sown in spring. At this stage, the farmer does not know how much dam water will be available during the irrigation season, or the water requirements of the summer crops. Consequently, the farmers are assumed to make decisions based on expectations, attributing probability values to the scenarios of water availability, which mature in the second stage, and of temperature (and hence of the water requirements of summer crops), which mature in the third stage.

The second stage of the model corresponds to the period when water has finished accumulating in the reservoir (March–April), and has thereby materialised into one of the states of nature that were uncertain at the time of fall programming. At this stage, the farmers are sowing the summer crops and the consortium’s irrigation season begins (April–October). The farmers remain subjected to certain constraints and still suffer a degree of uncertainty. One constraint is that the farmer can sow the summer crops only on the land that had been set aside for this purpose at the first decision stage. Uncertainty still exists at the second stage regarding the irrigation requirements of these crops, which depend on the temperatures during the third stage.

The third stage of the model corresponds to the period in which the temperature influences the requirements of irrigated summer crops (June–July). Therefore, the last of the states of nature occurs, which was uncertain at the time of the autumn programming. The farmer now has full

1. [1] The remainder of the water is applied to vineyards and to a lesser degree to a wide range of different tree crops and vegetables, whose irrigation requirements are difficult to simulate using EPIC.

knowledge of water supply and irrigation requirements, yet is subjected to the constraint of having already sown the summer crops, and can only adapt by changing the watering intensity.

The DSP model then describes a condition in which the farmer is aware that he could achieve non-optimal outcomes when deciding how much area to cultivate with autumn crops and, conversely, how much to keep for summer crops. Therefore, the model assumes that the farmer adopts a precautionary approach, without focusing on an individual state of nature. Instead, the farmer considers technical and economic data, and probability data, in computing the expected outcome of each choice[2].

2.3.2. *Mathematical structure of the DSP Model.*

The DSP model can be formalized as follows:

(1) $$\max_{x_1, x_{3_{k,r}}} Z = GI * x_1 + P_k * P_r * GI_r * x_{3_{k,r}}$$

subjected to

(2) $$A * x_1 + A * x_{2_k} \le b_k \qquad \forall k$$

(3) $$A * x_1 + A_r * x_{3_{k,r}} \le b_{k,r} \qquad \forall k, r$$

(4) $$x_{3_{jsp,k,r}} = x_{2_{jsp,k,r}} \qquad \forall jsp, k, r$$

where ***Z*** is the total gross income; ***x1***, ***x2*** and ***x3*** are vectors of cropping activities (expressed in hectares) respectively influenced by the conditions of the first, second and third stages; P_k are the probabilities of the *k* states of rainfall (hence water availability in dam); P_r are the probabilities of the *r* states of temperature (hence irrigation requirements and yields); ***GI*** is the gross income unitary of each activity; ***A*** is the matrix of technical coefficients; and ***b*** are the quantities of available resources. Constraint (2) refers to choices made in the first and second stages (e.g., regarding the allocation of land), and constraint (3) is concerned with choices made during the third stage (e.g., regarding the allocation of water and irrigation requirements during summer). Constraint (4) maintains the area of spring–summer crops (jsp) in passing from the second to third stages.

This model considers six possibilities, given that the assumption regarding the states of nature is a combination of three conditions of rainfall levels (water availability) and two maximum temperatures (irrigation requirements and yields). These six combinations generate one optimal result and five sub-optimal results. The DSP selects the combination with the highest expected income and indicates the corresponding use of resources. The model is solved using the General Algebraic Modelling System (GAMS), which generates a wide range of results, of which the main ones are discussed below.

2.4. *States of nature and their probabilities of occurrence in the DSP model*

In specifying the DSP model, the weather conditions during the period 1984–2003 were first reconstructed and their respective probabilities of occurring were calculated to obtain the present-day (current) scenario. Once included in the DSP model, these data yielded the outcomes regarding income and the use of resources for this scenario. Next, the trends that emerged in the period 1961–2009 for rainfall, temperature and CO_2 concentration levels were projected to 2015 to obtain a future scenario, with the related conditions of water accumulation in the dam reservoir and the irrigation requirements and yields of corn and alfalfa. The relative probabilities of these conditions were included in the DSP model, which generated the expected value for income and use of

---

2. [2] In other words, for each state of nature, the farmer considers the optimal and suboptimal results, and calculates the average of their income, weighted by the probabilities of the respective states of nature. The farmer then compares these averages of all possible states of nature, and adopts the solution with the highest value. This choice is associated with a use of resources which is the weighted average of the possible outcomes, both optimal and sub-optimal.

resources in this future scenario. This outcome was compared with the result for the current situation. The analysis also considered a second future scenario that includes only the effect of changes in temperatures and CO_2 (and in irrigation requirements and yields), in order to distinguish the effect of this change from the impact of changes in rainfall patterns (and water availability). Comparisons of the results of these future scenarios with the current situation indicate how variations in the use of resources and income are attributable to single elements of CC and to the combination of multiple elements.

2.4.1. States of nature and probabilities for water availability

Dono and Mazzapicchio (2010b) described the specification of the states of nature for rain regimes, and hence for water availability in the area’s dam, for the current and future scenarios. An examination of historical data on water accumulation in the reservoir of the Cuga dam indicates that related to the area’s rainfall regime, three states of availability should be considered: abundant, intermediate, and low. Abundant availability represents the accumulation level in years when the amount of water in the dam was so great that no limits were placed on irrigation or other uses. The state of intermediate availability represents the level of accumulation in years when relative scarcity arose, meaning that irrigation was limited by the consortium, although rationing was not imposed by public authorities. The state of low availability represents years when the public authorities rationed the availability of water for agriculture, in order to ensure adequate drinking water.

2.4.2. States of nature and probabilities for corn and alfalfa irrigation and yields

The states of nature for current temperature and for CO_2 concentration level were defined based on climate data of the area for the period 1961–2003. To this end, the statistical report was first estimated between temperature and CO_2, in order to ascertain if significant contributions of this second parameter are lost when the analysis focuses only on the first one. A close statistical relationship was verified between these two parameters; based on 1984–2003 data a probability distribution was hence estimated for the maximum temperatures in June and considered as significant in generating total irrigation water needs and yields of corn and alfalfa. The resulting estimated function was used to represent farmers’ expectations on temperatures that influence irrigation needs and yields of corn and alfalfa in 2004, which is the baseline of this study.

The maximum temperature was identified as a suitable parameter for this analysis for two reasons: the easy measurement and perception by the farmers and the fact that it can be considered as a reliable proxy for water requirements of all crops. The use of temperature instead of the specific water requirements of each crop is a limitation imposed by the need of identifying a unique probability distribution of climatic anomalies for all crops. However, the estimate the expected impact on actual evapotranspiration of each crop was estimated with EPIC.

The parameters of this function and the data for 1984–2003 enabled the identification of two states of nature, as well as related probabilities. The threshold between these two states was defined by observing that the temperature in 2002 is outlier of the full set of data, with 30.6°C, and 28.9°C in 1998 is the temperature that immediately precedes in the series. For this reason it was decided to set at 29.0°C the threshold between *normal* and *exceptional* condition. This division made it possible to calculate the probabilities for the two states of nature for *normal* and *exceptional* condition. The average values of those intervals were considered representative of these two states. It was found that the average value of the *normal* state is close to that observed in 1989, while the average of the *exceptional* state is much closer to that of 1998. Data from these two years were hence considered as representative of the two states of nature in the current period, and were included in EPIC to obtain the corresponding water requirements and yields of corn and alfalfa.

A future scenario of this probability distribution was constructed by projecting to 2015 the linear trend of the maximum temperatures in June using the EPIC weather generator. In this way, a data series was obtained for the period 1996–2015, for which the probability distribution was calculated. Finally, using the threshold between the two states, as identified for the period 1984–2003, the respective average temperature values and probability levels were calculated for the future scenario.

Even in this case, the average value of the *normal* state was found as close to that observed in 2000, while the average of the *exceptional* state is closer to 2006. Data from these two years were considered as representative of the two states of nature in the future period, and were included in EPIC to obtain the corresponding water requirements and yields of corn and alfalfa.

3. Results and discussion

3.1. States of nature and their probabilities of occurrence

The density function estimated for the accumulation levels of water in the reservoir, based on rainfall data for the period 1984–2003, indicated probabilities for the low, intermediate and abundant states of water accumulation of 27.3%, 40.7% and 32.0%, respectively. The probability values for the future period (1996–2015) were 38.8%, 13.7% and 47.5%, respectively.
The estimated functions of the maximum temperature of June are represented by a normal distribution with $\chi^2 = 0.4$ and P value = 0.9402 for the current period and a normal distribution with $\chi^2 = 4.4$ and P value = 0.2214 for the future period.
The probability values in the current period are 94.1% for the normal state and 5.9% for the exceptional state. In the future period the probabilities change respectively in 84.9% and 15.1%.
The table 1 shows also the yields and the water use of the considered crops in the various reference years.

Table 1. Scenarios description and parameters regarding the states of nature and probabilities for corn and alfalfa irrigation requirements and yields

	Current				**Future**			
State of nature	Normal		Exceptional		Normal		Exceptional	
Reference year	1989		1998		2000		2006	
Temperature °C	26.39		29.51		27.07		29.64	
Probabilities	94.1%		5.9%		84.9%		15.1%	
	Yield (t/ha d.m.)	Water use (m^3/ha)	Yield (t/ha d.m.)	Water use (m^3/ha)	Yield (t/ha d.m.)	Water use (m^3/ha)	Yield (t/ha d.m.)	Water use (m^3/ha)
Alfalfa IRR	11	5757	11.3	6097	11.3	5696	13	6671
Alfalfa DRY	7	2142	7.15	2742	5.8	2576	4.85	2336
Corn silage								
long cycle	131	4200	149	4200	180	4000	151	4600
short cycle	125	4200	122	4200	147	4000	149	4400
Corn grain	74	5200	87	5800	101	5400	80	5600

3.2. Results of the DSP model

The DSP model was subjected to a validation process based on a comparison of cropping systems drawn from field observations in 2004 with those identified by the current-period version. The Finger–Kreinin index[3] yielded a value of 91.1% indicating that the model adequately reproduces the observed production systems. This finding suggests that the model could provide useful information on the possible adjustment of farms to changing economic, structural and environmental conditions.

The effect of CC was assessed by comparing the results of the scenario representing the current situation and the future scenarios. In particular in the future are considered three scenarios: CC regarding the water availability, the water requirements and yields (*Total CC*); CC regarding only

3. [3] This index is defined as the sum of the minimum values of the shares of each crop group in the two series: observed and simulated by the model.

the water availability (*Only-Water CC*); CC regarding only the water requirements and yields (*Non-Water CC*).

Below, the results of DSP models are presented for the area served by the consortium. The model also represents the farm sector in the area outside it, where farmers practice rainfed agriculture. However, because changes in the accumulation of water in the reservoir do not influence the choices made by farmers and corn is not grown in this area, the results for these farms are not presented here.

3.2.1. Land and water use

CC results in a small reduction of the cropped area. However, the impact is negative and strong on irrigated crops given that total water use decreases by around 6%. In particular, there are not negligible reductions in cereals, vegetables and alfalfa. Note that the area planted with corn does not change (Table 2).

Table 2. Land and water use in current and future scenarios for the whole area.

	Current	**Future**		
	Baseline	**Total CC**	**Only-Water CC**	**Non-Water CC**
	ha	*% change respect to Current Baseline*		
Cereal	1,017	-3.5	-12.6	4.0
corn	965	0.0	-10.0	7.0
Vegetable	1,431	-24.0	-13.9	-9.2
Forage crops	13,456	2.6	0.1	-0.4
alfalfa	609	-9.7	2.8	7.0
Grassland	3,405	-3.0	6.4	2.3
Tree crops	2,677	0.0	0.0	0.0
Total	21,986	-0.6	-0.4	-0.3
	000 m^3	*% change respect to Current Baseline*		
Total water	18,373	-5.8	-5.3	1.3
consortium	15,578	-8.4	-7.3	1.6
private wells	2,795	8.6	5.8	-0.6

Note that because of the decrease in the amount of alfalfa produced on farm, livestock farmers resort to purchasing feed, which led to increased costs.

In the *Only-Water CC* scenarios, there is a reduction of the area planted with vegetables and with corn. In contrast, the harvested areas of alfalfa and grassland increases in order to replace, in part, the corn produced to feed the cattle.

In the *Non-Water CC* scenarios has a very different impact on cropping patterns. While this negatively affects the land devoted to vegetables, the land in which corn and alfalfa are grown increases by around 7%. Note that this happens thanks to a increase of water use mostly supported by the water provided by the irrigation consortium (Table 2).

The comparison of the results of applying the two CC sub-scenarios (*Only-Water CC* and *Non-Water CC*) shows that the components of CC act in a very different way on the relative profitability of corn. While the impact of CC is positive for corn when the instable and reduced availability of water are not considered, this latter phenomenon has a very negative impact on corn production.

3.2.2. Economic results

The application of the *Total CC* scenario has a limited negative impact on total farm revenue that is fully compensated by a decline in variable costs (Table 3). Thus it results in no change of the overall farm gross margin. Also in this case, the main elements of the CC scenario have a different impact. When only the change in water availability is accounted for (*Only-Water CC*) the whole gross margin of the considered farms declines by around 1%: this is due to a decline of total revenues that is not compensated by the limited reduction of variable costs (Table 3). Note that the variable costs do not decline as much as in the previous case because the cost for animal feed increases drastically and the cost for pumping water from private wells increases under the considered conditions. As already explained, this is motivated by the reduction of the land devoted to crops producing feed on farm and the need for contrasting the decline in surface water availability. Applying the CC scenario that does not account for the change in water availability (*Non-Water CC*), it has a positive impact on farm gross margin (Table 3). This is due to a limited increase of farm revenues and to a decline of variable costs. In this case feed costs do not increase very much and pumping costs even decline.

Table 3. Economic results in the whole area and gross margins for the farm typologies for current and future scenarios.

	Current	**Future**		
	Baseline	**Total CC**	**Only-Water CC**	**Non-Water CC**
	000 €	*% change respect to Current Baseline*		
Total revenue	66,858	-0.8	-0.9	0.2
crop sales	58,664	-0.9	-1.0	0.3
Variable costs	19,456	-3.2	-0.8	-2.0
animal feed	285	103.0	114.6	9.4
Gross margin	47,402	0.1	-0.9	1.1
	000 €	*% change respect to Current Baseline*		
Dairy cattle	3,090	-1.7	-3.8	1.9
Mixed	4,549	7.5	-1.2	8.9
Sheep	11,645	0.6	-2.8	3.2
Olive groves	13,762	-2.4	-2.1	-0.2
Vineyards	6,532	-1.2	-0.7	-0.2
Vegetable	982	-2.9	-2.9	-1.5

While the implications of applying the simulation scenarios on the overall economic performances of the whole set of farms are not very large, this is not the case when considering the gross margins of various types of farms (Table 3). Considering the application of the Total CC scenario, the worst effects are found in farms specialized in vegetable, in olive and in dairy productions. The simulated conditions have also a positive impact on mixed farms. When the scenario considering the only change in water availability is applied, this has a very negative impact on the economic performances of dairy farms, mainly due to the need to reduce the corn production and to increase the purchase of feed. Gross margins also decrease in sheep, vegetable and olive farming. Here all farm typologies experience a negative impact of CC.

Completely different is the case when the available water is unchanged. Here the impact remain negative for vegetable farms, negligible for two farms and positive for mixed, olive and dairy farms (Table 3).

4. Conclusions

This study assessed the economic impact of climate change (CC) on irrigated agriculture under Mediterranean conditions. In particular, CC is expected to bring about modifications in rainfall and in various climatic parameters including temperature and CO_2 concentration. In the study area, this is expected to increase the variability of the water accumulation level of reservoir used for irrigation. It would also request changes in the crop production techniques including irrigation requirements and yields. The changes in production techniques have been evaluated by means of an agronomic model considering two of the most important irrigated crops: corn and alfalfa.

A Discrete Stochastic Programming (DSP) model was developed and used to simulate the responses of farmers to CC in an irrigated area of Sardinia. This has been done comparing current and future scenarios.

The model produced contrasting results indicating a different degree of sensitivity of agriculture to rainfall and other climatic parameters. Indeed, while the first element of CC has clearly a negative impact on the whole area gross margin, the opposite occurs when only the other elements are considered, mainly for the role of CO_2 in increasing the production of corn and alfalfa. Thus the overall impact of CC is very mixed and it is unevenly distributed among different farm typologies according to their production orientation. In particular, farms growing irrigated crops such as vegetables, olive grows and vineyards as well as dairy farms were predicted to experience a reduction in income. This would mainly happen because these farm typologies are negatively affected by the decline in surface water availability. In particular, the situation of the largest dairy farms is of interest. In fact, dairy farms across most of Sardinia, as well as those in the rest of Italy, are similar to those represented by the present model, whose results have therefore a more general valence.

Also, the simulation results indicate that CC influences the use of natural resources. In particular, the expected increase in the variability of reservoir water levels and rising temperatures and crop water requirements resulted in increased exploitation of groundwater extracted from privately own wells.

These findings would help to guide agricultural policies designed to support adaptation in the agricultural sector, and pose some fundamental issues regarding which strategies to pursue. In particular, the modelling results represent a useful case study of production conversion in response to near-future CC. As a general result, the conclusion can be drawn that, in the studied system, water availability is crucial because it lessens the susceptibility of the agricultural sector to temperature change. This is an important finding because it suggests that, if it will be possible to ensure an adequate amount of surface water resources, the agricultural sector could adapt relatively well to the expected CC. This also suggests that more emphasis should be given to improve the quality of the infrastructures used to accumulate water and the management of water resources. This strategy can also have positive environmental implications because it could prevent farmers to further increase the use of ground-water that may have negative environmental consequences.

5. Acknowledgments

This analysis was funded by the AGROSCENARI Research Project (www.agroscenari.it), financed by the Italian Ministry of Agriculture.

References

Bazzani G.M., Scardigno A., 2009: *Un modello di simulazione territoriale per l'analisi economica dell'uso dell'acqua in agricoltura in presenza di cambiamento climatico*, paper presented to XLVI Convegno SIDEA "Cambiamenti nel sistema alimentare: nuovi problemi, strategie, politiche". Piacenza, 16-19 settembre 2009.

Beguería, S., López-Moreno, J.I., Lorente, A., Seeger, M., García-Ruiz, J.M., 2003: *Assessing the effects of climate oscillations and land-use changes on streamflow in the central Spanish Pyrenees,* Ambio n.32: 283–286.

CEDEX (Centro de Estudios y Experimentacion de Obras Publicas), 2000: Continental *Waters in the Mediterranean Countries of the European Union,* Spanish Ministry of the Environment, http://hispagua.cedex.es/Grupo1/documentos/documen/htm

Christensen J.H., Christensen O.B., 2002*: Severe summertime flooding in Europe*, Nature, n. 421, pp. 805-806.

Connor J., Schwabe K., King D., Kaczan D., Kirby M., 2009: *Impacts of climate change on lower Murray irrigation.*The Australian Journal of Agricultural and Resource Economics, 53, pp 437-456.

Cure, J.D. and Acock, B., 1986: *Crop responses to carbon dioxide doubling: a literature survey*. Agric. For. Meteorol., 38: 127-145.

Dono G., Mazzapicchio G., 2009: *Effetti della Riforma Fischler e influenze dei Cambiamenti Climatici sull'attività di irrigazione in un'area del Mediterraneo*, paper presented to XLVI Convegno SIDEA "Cambiamenti nel sistema alimentare: nuovi problemi, strategie, politiche", Piacenza, 16-19 settembre 2009.

Dono G., Mazzapicchio G., 2010 (a): *L'impatto economico dei Cambiamenti Climatici sulla disponibilità di acqua irrigua in un'area del Mediterraneo*, Economia delle Fonti di Energia e dell'Ambiente, n.1/2010.

Dono G., Mazzapicchio G., 2010 (b): *Uncertain water supply in an irrigated Mediterranean area: an analisys of the possible economic impact of Climate Change on the farm sector*, Agricultural Systems, Vol. 103, Issue 6.

Dono G., Cortignani R., Mazzapicchio G., Doro L., Ledda L., 2010: *An evaluation of the economic impact of climate change through a three-stages discrete stochastic programming model*,. paper prepared for the 120th EAAE Seminar "External Cost of Farming Activities: Economic Evaluation, Risk Considerations, Environmental Repercussions and Regulatory Framework", Chania, Crete, Greece, 02 - 04 September, 2010

Elbakidze L., 2006. *Potential economic impacts of changes in water availability on agriculture in the Truckee and Carson River basins, Nevada, USA*, Journal of the American Water Resources Association, n.42(4):841-849.

García-Ruiz, J.M., Regüés, D., Alvera, B., Lana-Renault, N., Serrano-Muela, P., Nadal-Romero, E., Navas, A., Latron, J., Martí-Bono, C., Arnáez, J., 2008. *Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees*, Journal of Hydrology n.356: 245–260.

Giupponi C., Shechter M.,2003: *Climate Change in the Mediterranean,* Socio-economic Perspectives of Impacts, Vulnerability and Adaptation, Edward Elgar Publishing, 2003.

Goubanova, K., Li, L., 2006, *Extremes in temperature and precipitation around the Mediterranean in an ensemble of future climate scenario simulations*, Global and Planetary Change, doi:10.1016/j.globaplacha.2006.11.012.

Heinemann A.B., Hoogenboom G., Faria R.T. de, 2002: *Determination of spatial water requirements at county and regional levels using crop models and GIS. An example for the State of Parana, Brazil*, Agric Water Manage 52: 177–196.

IPCC (2007). *Historical Overview of Climate Change Science*.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis – Summary for Policymakers*, Contribution of WGI to the 4th Assessment Report of the IPCC, Geneva.

López-Moreno, J.I., Beguería, S., Vicente-Serrano, S.M. y García-Ruiz, J.M., 2007. *The influence of the nao on water resources in central Iberia: precipitation, streamflow anomalies and reservoir management strategies,* Water Resources Research W09411. doi: 10.1029/2007WR005864.

Madrau S. et al., 1981. *Rilievo integrale dell'area di Tottubella (Sardegna nord-occidentale),* Atti dell'Istituto di Mineralogia e geologia, vol. 2. University of Sassari.

McCarl B.A., Spreen T.H., 1997: *Applied mathematical Programming using algebraic systems*, available at: http://agecon2.tamu.edu/people/faculty/mccarl-bruce/mccspr/thebook.pdf.

MGWWG – Mediterranean Groundwater Working Group of the Mediterranean Joint Process WFD/EUWI Process, 2005. Mediterranean Groundwater Report, Draft Version 17.10.2005. <http://www.emwis.org/GroundWaterHome.htm>.

Morrison, J.I.L., R.M. Gifford. 1984: *Plant growth and water use with limited water supply in high CO2 concentrations. 1. Leaf Area, water use and transpiration*. Australian Journal of Plant Physiology 11:361-374.

Nijbroek, R., Jones, J.W., Hoogenboom, G., 2003: *Optimal irrigation strategy for a spatially variable soybean field: a modeling approach*, Agricultural Systems, 76: 359–377.

Niu Xianzeng, Easterling William, Hays Cynthia J., Jacobs Allyson, Mearns Linda (2009). Reliability and input-data indiced uncertainty of EPIC model to estimate climate change impact on sorghum yields in the U.S. Great Plains, Agriculture, Ecosystem and Environment, Vol. 129,n.1-3: 268-276.

NOAA (National Oceanic and Atmospheric Administration), 2010: *Mauna Loa CO2 annual mean data*, Earth System Research Laboratory (ESRL), available at: http://www.esrl.noaa.gov/gmd/ccgg/trends/.

OECD, 2006, *Report on the OECD Workshop on Agriculture and Water: Sustainability, Markets and Policies*, Adelaide, Australia, 14–18 November 2005, COM/AGR/CA/ENV/EPOC/RD (2005) 71.

OECD/Eurostat, 2000. *OECD/Eurostat Joint Questionnaire on Inland Waters 2000*, Statistical Office of the European Communities, Eurostat, Luxemburg.

Raisanen, J., 2007, *How reliable are climate models?*, Tellus Series A: Dynamic Meteorology and Oceanography, n.59: 2–29.

Rinaldi, M., 2001: *Application of EPIC Model for Irrigation Scheduling of Sunflower in Southern Italy*, Agric. Water Manage. 49: 185-96.

Rodriguez Diaz, J.A., Weatherhead, E.K., Knox, J.W., Camacho, E., 2007, *Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain*, Regional Environmental Change n.7: 149–159.

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M. M. B., LeRoy, Miller H. Jr., Chen, Z., 2007: *Climate Change 2007 – The Physical Science Basis*. Cambridge University Press.

Xiong W., Holman I., Lin E., Conway D., Jiang J., Xu Y. and Li Y., 2010: *Climate change, water availability and future cereal production in China,* Agriculture, Ecosystems & Environment, Vol.135, Issues 1-2.