Abstract

The Mediterranean region has always shown a marked inter-annual variability in seasonal weather, creating uncertainty in decisional processes of cultivation and livestock breeding that should not be neglected when modeling farmers' adaptive responses. This is especially relevant when assessing the impact of climate change (CC), which modifies the atmospheric variability and generates new uncertainty conditions, and the possibility of adaptation of agriculture. Our analysis examines this aspect reconstructing the effects of inter-annual climate variability in a diversified farming district that well represents a wide range of rainfed and irrigated agricultural systems in the Mediterranean area. We used a Regional Atmospheric Modelling System and a weather generator to generate 150 stochastic years of the present and near future climate. Then, we implemented calibrated crop and livestock models to estimate the corresponding productive responses in the form of probability distribution functions (PDFs) under the two climatic conditions. We assumed these PDFs able to represent the expectations of farmers in a discrete stochastic programming (DSP) model that reproduced their economic behaviour under uncertainty conditions. The comparison of the results in the two scenarios provided an assessment of the impact of CC, also taking into account the possibility of adjustment allowed by present technologies and price regimes. The DSP model is built in blocks that represent the farm typologies operating in the study area, each one with its own resource endowment, decisional constraints and economic response. Under this latter aspect, major differences emerged among farm typologies and sub-zones of the study area. A crucial element of differentiation was water availability, since only irrigated C3 crops took full advantage from the fertilization effect of increasing atmospheric CO_2 concentration. Rainfed crop production was depressed by the expected reduction of spring rainfall associated to the higher temperatures. So, a dualism emerges between the smaller impact on crop production in the irrigated plain sub-zone, equipped with collective water networks and abundant irrigation resources, and the major negative impact in the hilly area, where these facilities and resources are absent. However intensive dairy farming was also negatively affected in terms of milk production and quality, and cattle mortality because of the increasing summer temperatures. This provides explicit guidance for addressing strategic adaptation policies and for framing farmers' perception of CC, in order to help them to develop an awareness of the phenomena that are already in progress, which is a prerequisite for effective adaptation responses.

Keywords

Adaptation of farms to CC; Mediterranean region; Discrete Stochastic Programming; Regional Atmospheric Modelling System; Crop models; Livestock models

1. Introduction

In analyzing the meteorological conditions of a climatic zone on decennial time periods, it is always found in its sub-areas a significant inter-annual variability that also applies in periods when the climate is perceived as in a stable condition. This variability is generated by the combination of different mechanisms. High frequency mechanisms due to atmospheric dynamics dominate the local climate variability in each month and season. A smaller amount of variability is due to multi-annual and decadal low frequency mechanisms mainly driven by the ocean dynamics. Finally, there is a long term trend induced by global warming: in recent decades this has accelerated, acting both as incremental component, either by modifying the mechanisms of high and low frequency, and the variability that induce. This paper presents the results of an integrated study which assesses the effects of climate variability on crop and livestock production, and farm management of a diversified Mediterranean agricultural district. The results of the analysis are used to assess the economic impact of climate change (CC) at farm typology level, including the effect of changing the variability of atmospheric conditions.

The inherent variability of the Mediterranean climate is mentioned and explained by many studies highlighting the determinants and expressions of climatic variables in the different sections of this region (Navarra and Tubiana, 2013). It was shown that the atmospheric circulation in the Atlantic Ocean determines the variability of rainfall in the autumn period (Delitala et al, 2000; Altava-Ortiz et al, 2011). Similarly, it was shown that heat waves are a frequent feature of the Mediterranean summer (Colacino and Conte, 1995; Matzarakis and Mayer, 1997; Gaetani & Pasqui 2012), and several anomalous warm summers have occurred in the Mediterranean and in southern Europe over the last 60 years, with hot events of different intensities and lengths (Baldi et al., 2006; Segnalini et al., 2011).

The influence of climate variability on crop production and livestock is also extensively treated in the scientific literature. Many researches made use of specific mathematical and statistical models to investigate the relationships between variability in the climatic conditions and livestock production (Johnson, 1987; Hahn, 1999; Vitali et al, 2009; Bertocchi et al, 2014; Bernabucci et al, 2014). Other analyses relied on models providing a rich characterization of optimal growth and represent the response of crops production under different climatic conditions (Brown et al, 2000; Liu and Tao, 2013; Dono et al, 2013a, 2013b). In various studies these models are used to assess the impact of CC by comparing crop yield or the requirement of inputs under conditions of current and future climate (Eckertsen et al., 2001; Semenov and Shewry, 2011; Rötter et al., 2012; Porter et al., 2013; Olesen et al., 2011; Palosuo et al., 2011; Reidsma et al., 2010; Iglesias et al., 2009). There is also growing recognition of the importance of assessing the effects of climate change, and possible adaptation strategies at the agricultural system or farm household level (Claessens et al., 2012), rather than focusing on aggregated results that can conceal large amount of variability.

The estimated relationship between climate variability and agricultural activity can be included in mathematical models simulating economic choices of farms in the context of production risks (Matthews et al., 2013). One of those models, discrete stochastic programming (DSP) (Hardaker et al., 2004), was used to represent the economic impact of many agricultural uncertainties: availability of irrigation water (Calatrava and Garrido, 2005*a*, 2005*b*), productive results of technologies (Coulibaly et al., 2011), weather risks (Mosnier et al., 2009), change in climate variability (Dono and Mazzapicchio, 2010). Dono et al. (2013b) assessed the impact of CC with a three-stage DSP model in which uncertainty is about irrigation water requirements of crops and availability of irrigation water. They compared the results of the model executed with the probability distribution functions (PDF) of those variables under current and future climate: current PDFs were estimated on climate data of the last three decades, future PDFs were estimated by extrapolating data from climate observations of the last decade.

In this paper we propose a significant knowledge step-forward to what was previously proposed in analyzing CC impacts on agricultural systems (Dono et al 2013a, 2013b). Advancements concerns in particular (i) the way present and future climate scenarios were generated; (ii) the choice of combining climate, cropping systems, livestock and economic models to improve the understanding on how CC can generate losers and winners in different farming systems located in the same district, ultimately resulting into changes in the agricultural land use and/or management. This modeling chain provides an integrated assessment of the expected shifts in terms of probability distribution of climate variability and then of crop and livestock system economic performance.

The interdisciplinary approach was applied to the Regional Pilot case study FACCE MACSUR Knowledge hub[1]. It is located in an agricultural district characterized by a variety of farming systems covering a wide range of situations under both irrigated and rainfed Mediterranean conditions. Therefore, a diversity of issues generated by the interaction of CC seasonal impacts on different cropping and livestock systems were deeply explored and analyzed.

Our hypothesis is that the represented farming systems, and the results obtained by the proposed approach can provide a relevant support for the development of contextualized effective and strategic adaptive responses far beyond the analyzed local context, in the transition to future climate in the

[1] http://macsur.eu/index.php/regional-case-studies

Mediterranean region. This also justifies the short-term time horizon chosen for the analysis, which addresses the changes in climate variability that can be immediately relevant for the development of strategic adaptation policies in the context of rural development.

2. Materials and methods

2.1. Study area, data sources and agricultural uncertainties from climate variability

The study area is a 54,000 ha farming district located in the center-west of Sardinia (Italy). The agricultural system was reconstructed with reference to the situation of the year 2010, using the data of the Italian 6th General Agricultural Census, of the Farm Accountancy Data Network (FADN), and of a Water User Association (WUA), Consorzio di Bonifica e Irrigazione dell'Oristanese, that supplies irrigation water to part of the area. The productive conditions of crops and livestock in this area were derived from interviews to farmers, agronomists, leaders of the Regional administration and of the local agricultural cooperatives. The requirements of labor, chemicals, and water were defined for the various stages of production of the crops, including yields. Similarly, the feed requirements of the various categories of livestock were specified, with the actual food rations and the products obtained. The prices of the production factors were also collected.

The agricultural district under study can be divided in two sub-zones depending on the avarilability of irrigation water. In the irrigated sub-zone, the WUA supplies water from the Eleonora d'Arborea dam, with a reservoir of some 450 Mm^3, of which 120 Mm^3 are yearly made available to potentially irrigate 36,000 ha. The main irrigated cropping systems are based on cereals, mainly silage maize and rice, and other forage crops, mainly alfalfa and Italian ryegrass, but includes also horticultural crops such as artichokes, watermelon and tomatoes, citrus orchards, olive trees, vineyards, durum wheat and barley. The breeding of dairy cattle of Sardinia is largely concentrated in the WUA sub-zone (Arborea district), with a well-organized cooperative system for production, processing and marketing of cow milk. The rain-fed sub-zone covers some 18,000 ha where occasionally a limited amount of water is available, taken from wells in some farms. In this sub-zone 55% of the agricultural land is made of pastures, tares, woods or set-aside fields; durum wheat and barley predominate on the rest of land. The dairy sheep industry is largely present in this sub-zone and involves some 372,000 sheep and a number of small sheep milk processing plants.

Structural and economic features of the farms of this area were represented in the economic model by 13 farm typologies, identified on the basis of data from the FADN and the Agricultural Census.

Climate variability generates uncertainty for the various crop and livestock activities in the study area. Sheep farming in the rain-fed zone is constrained by the inter-annual instability of pasture and hay-crop yields, which is closely dependent on climatic factors particularly in the autumn and spring. The pasture growing season starts with season's rainfall break in the autumn, is constrained by low temperature and radiation in the winter and reaches its maximum in the spring, to decrease sharply in quantity and quality at the onset of the summer, soil humidity reaches a minimum. The dairy sheep farming system is adjusted to concentrate lambing in October-November and February, in order to extend the flock milking season from December-January until July. Low Autumn pasture yields would result in increased purchases of feed and forage or the early depletion of hay stocks. Hay stocks are produced in May from a single cut of annual hay-crops (e.g. annual ryegrass, oats sometimes mixed with legumes) or less frequently meadow grasslands. Dairy cattle irrigated forage systems are also affected by climate in terms of variable irrigation needs but also in terms of forage yield, which can also result into higher external feed input demand on bad years.

These effects of climatic variability generate uncertainty on the crop allocation in arable lands. The purchase of feed or hay or the increased well water extraction are the most common adaptive responses to bad years in rainfed and irrigated lands respectively. However, there are other effects of climate variability that are instead difficult to mitigate with corrective actions. This is the case of heat waves with high air humidity levels in the summer, which cause the losses of production of cow's milk, the worsening of its quality levels which results into reduced price, and the increased mortality of cows. This distinction in the possibility of mitigating the effects of climate variability will be reflected in our analysis on how the choices of farm management will be simulated.

In the following sections, the relationships between climate variability and the various productions under present and near future climatic conditions are explored by modeling the impact of the uncertainty of production on the management of the farms and on their economic results.

2.2. Climate and model scenarios

The potential climatic forcing acting on the study area, and the changes due to CO_2 in the A1B scenario, were evaluated with a downscaling strategy to produce calibrated time series of rainfall and temperature over the study region. This strategy builds a modeling chain describing with a high level of reliability the main atmospheric variability that acts on the area, from large scale to local scale; and considering the change in the concentration of greenhouse gases. It applies a coupled model of general circulation to estimate large scale atmospheric and ocean response to future A1B emission scenario as described in Scoccimarro et al. (2010). In this regard, we selected two periods of 11 years: 2000–2010 representing current climate conditions, and 2020–2030 as conditions of near future. These global simulations belong to a specific set developed by the Euro-Mediterranean Center on Climate Change (www.cmcc.it) in the EU project Circe (http://www.circeproject.eu). The general circulation model drives the Regional Atmospheric Modelling System (RAMS) applied on the study area to increase the physical description of acting mechanism at local scale, and to better represent local variability (Pielke et al., 1992). The proposed RAMS model configuration follows settings as other studies on numerical weather forecast (Meneguzzo et al., 2004).

Due to limitations in the geo-morphological representation of numerical models (mountain chains or land cover), significant systematic errors may affect direct outputs of modeling chain atmospheric fields reducing the potential usage for agricultural applications. Such systematic errors were reduced by applying a post-processing procedure based on observed data. To this end the RAMS was also forced with reanalysis dataset: the Reanalysis-2 for the atmospheric component (Kanamitsu et al., 2002), and the reconstructed sea surface temperature from Hadley Centre (Rayner et al., 2003), with the same configuration for current and future scenarios. The direct RAMS model outputs, only forced by reanalysis datasets were compared to surface observed data of the study area for the period 2000-2010. Bias corrections were then computed using a linear regression at daily scale for temperature values, and a quantile-quantile correction for rainfall to reduce typical modeling bias as described in Pasqui et al. (2013). Those corrections were then applied to the outputs of RAMS simulations to calibrate current and future climate scenarios, assuming that the geo-morphological source of errors will act independently, since stationary by nature. Finally, the statistical representativeness of the calibrated 11 years of each scenario created with RAMS was improve were extended to 150 years of daily data by means of the weather generator WXGEN (Nicks et al., 1990) hereinafter called *150 synthetic years*.

2.3. Crop models and agronomic data

Two crop models were used to estimate the influence of temperature, rainfall and atmospheric CO_2 concentration on the main crops of the study area in the two climate scenarios: the EPIC model (Environmental Policy Integrated Climate, v 0810; Williams, 1995) and the DSSAT model (Decision Support System for Agrotechnology Transfer v 4.6; Jones et al., 2003; Hoogenboom et al., 2012). EPIC was widely validated and used for several purposes ranging from the simulation of crops yields (Balkovic et al., 2013; Wang et al., 2005; Cabelguenne et al., 1990) to more complex uses like the assessment of the impact of climate change (Strauss et al., 2012; Niu et al., 2009). DSSAT is used to determine optimum crop management practices (including cultivar, fertilizer, water and tillage), precision agriculture, climate change and variability, long-term sustainability, environmental pollution, and genomics (Jones et al., 2003; Hoogenboom et al., 2012).

We applied EPIC to simulate alfalfa, a silage corn-Italian ryegrass double cropping system based on two corn hybrids with different earliness, widely used in the irrigated sub-area served by the WUA, and rainfed hay crops and grasslands, very common in the rainfed sub-area. We calibrated EPIC based on local crops datasets, soil and weather from field trials, or from interviews with farmers in the study area. Table 1 reports the parameters for EPIC calibration.

Table 1 – Parameters for EPIC calibration[2]

	Original values				Calibrated values			
	Maize Silage	Ryegrass / Hay-crop	Alfalfa	Pasture	Maize Silage	Ryegrass / Hay-crop	Alfalfa	Pasture
DLAI	0.8			0.7	0.9			0.8
DLAP1	15.05	20.32			10.15	10.05		
DLAP2		45.95		50.95		70.95		30.95
DMLA	6.0	5.0	5.0		6.25	4.5	2.6	
HMX	2.0	0.8			3.1	1.0		
PPLP2	7.77				6.90			
RDMX		1.3				2.0		
RLAD	1.0	0.5			0.9	1.0		
TBS		0.0		0.0		4.0*		5.0

* Abraha and Savage, 2008.

Italian ryegrass is cultivated from mid-October to mid-May to produce hay and is occasionally irrigated in case of drought, while the growing season of silage maize is from the end of May till September and is always irrigated. Both crops were simulated using constant sowing dates, while harvest was scheduled based on accumulation of heat units: harvests of silage maize and ryegrass hay were respectively set to 90% and 60% of the units of the total heat required for maturity. Alfalfa was simulated as a 4-year continuous cultivation, and 4-5 mowing from May to September. The irrigated crops were simulated without water and nitrogen stresses, by setting automatic irrigation based on soil water content and automatic fertilization based on plant N stress. In the rainfed area, grasslands are mainly composed of annual grasses and legumes and grazing occurs all year round. Rainfed hay crops are based on oats and/or Italian ryegrass annual species, sown in October-November, grazed until mid-February and mowed in

[2] DLAI is the part of growing season when leaf area declines due to senescence. DLAP1 and DLAP2 are two points on a *development curve of the leaf surface* for an *unstressed* plant: before the decimal point is the fraction (%) of the growing season, after it there is the fraction of the potential maximum leaf area index. DMLA is maximum potential leaf area index. HMX is maximum crop height. PPLP2 is the second of two points on the plant population curve, where the value before the decimal point is the number of plants per square meter, after the decimal point is the proportion of maximum leaf area achieved at that plants density. RDMX is maximum root depth. RLAD is leaf area index decline rate parameter. TBS is minimum temperature for plant growth.

May. The hay-crops were simulated with automatic N fertilization, while grasslands were unfertilized. The static soil option was adopted to avoid changes in soil properties that could affect the simulated crop production in the continuous 150 years simulation.

We applied DSSAT to simulate the systems of irrigated rice paddy, and rainfed winter cereals. We obtained datasets for rice and winter cereals from surveys, interviews, observations, sample analysis, and from data systematically collected by private farms. The cultivar coefficients of the crops were estimated with the Genetic Coefficient Estimator (Hunt et al., 1993) based on long-term data obtained from private farms. The coefficients of species and ecotype where left unchanged. Table 1.bis reports parameters for DSSAT calibration.

Table 1.bis – Parameters for DSSAT calibration[3]

	Original values			Calibrated values		
	Rice	Durum wheat	Barley	Rice	Durum wheat	Barley
P1	400			400		
P20	12			13		
P2R	100			165		
P1V		60	10		5	5
P1D		75	30		75	30
P5	580	500	220	550	450	350
G1	76	26	16	66	30	20
G2	.0230	35	40	.280	35	45
G3	1.0	2.0	2.7	1.0	1.0	1.5
G4	1.0			1.0		
PHINT	83	95	89	83	60	74

Rice is sown in the second half of April and harvested at the end of September, while winter cereals are grown from November to late June. Rice was simulated without water stress by setting automatic irrigation based on soil water content, and using the local business as usual fertilization schedule. Rainfed winter cereals were simulated with automatic N fertilization option. Constant sowing dates were simulated for both, rice and winter cereals, while harvests were scheduled when physiological maturity occurred. Other model inputs such as soil properties were kept constant over time.

[3] Rice cultivar coefficients: P1 thermal units to complete the juvenile stage; P20 critical photoperiods; P2R Delay in the development phasic leading to the panicle initiation, for each hour increase in photoperiod above P20; P5 thermal units for the grain filling period; G1 number of spikelet per unit dry matter of the main culm; G2 single grain weight under ideal growing conditions; G3 relative tillering potential; G4 tolerance coefficient for the thermal environment. Winter cereals cultivar coefficients: P1V Optimum temperature required for vernalization; P1D Photoperiod response; P5 Grain filling phase duration; G1 Kernel number per unit canopy weight at anthesis; G2 Standard kernel size under optimum conditions; G3 Standard, non-stressed mature tiller weight (including grain); PHINT Interval between successive leaf tip appearances.

2.4. *Livestock analysis and data*

The relationships between climate and animal production in the current and future scenarios were estimated on the basis of the results of studies carried out in Holstein breed, which is widely prevalent in the local dairy district. Attention was focused on the relationships between temperature and humidity, condensed in the temperature humidity index (THI), and the mortality of cattle, the quantity and quality of milk produced.

The links between THI and mortality were studied using the Bovine Spongiform Encephalopathy database provided by the Italian Reference Centre for Animal Encephalopathies (Vitali et al., 2009). The database contained records from 2002-2007 on 51,240 cows older than 24 months, died in 2,291 dairy farms. THI data were related with deaths by associating each farm was to the nearest of 73 weather stations, whose data on temperature and relative humidity were used to calculate THI using the formula of Kelly and Bond (1971). The relationship between THI and milk yield were studied on 596,515 test-day records from 484 dairy farms located throughout Italy and dated from 2001 through 2007 (Bernabucci et al., 2014). Milk yield data were associated to daily THI calculated from data of 35 meteorological stations located within a maximum of 5 km from each farm. The THI-somatic cells relationship study (Bertocchi et al., 2014) was conducted on 508,613 bulk milk tests recorded monthly during the period 2003-2009 in 3,328 dairy farms located in the Po valley. The somatic cells count, expressed as cells/ml, was converted into the somatic cells score (SCS). The SCS values of 5.00 and 4.58, corresponding to 400,000 and 300,000 cells/ml, are the limits for commercialization of *milk cow* and *high quality milk cow*, respectively. Each farm was associated to the nearest weather station and SCS values were associated to daily THI data from 40 weather stations. The relationships between THI, cow mortality, milk yield and SCS were established by a 2-phase linear regression procedure (Nickerson et al., 1989) to detect an inflection point, if one exists, in the relationship between the independent variable (THI) and the dependent variable (mortality, milk yield and SCS).

2.5. *The economic model of farm management*

The effects of climate variability on farmers' choices are represented by a DSP model of supply (Cocks, 1968; Rae, 1971; Mccarl and Spreen, 1997; Hardaker et al., 2004; Connor et al., 2009). In this decision-making process, some variables are uncertain when farmer plans the seasonal activity: they occur in succeeding months (*stages*), when can take different values (*states of nature*) that affect differently the next steps, and the productive results. So, when planning, farmer can only assign a probability to each *state*, and define corrective actions to continue at best the production activity in the various cases. According to the DSP, farmer plans the activity based on the *state* with the highest expected income, calculated on its optimal and suboptimal results. The optimal result is achieved if planning is based on a *state* of nature, and it really occurs; suboptimal results happen when other *states* occur. To plan considering the chance of suboptimal results leads to precautionary choices, resulting in an lower income than that would have occurred in a context of certainty, that considers only the optimal solution. This *cost of uncertainty* may increase if the CC modifies the probability, or the representative values of the various *states*: so, the impacts of CC can be evaluated by comparing the results of the DSP model under present *vs.* future climate. A general representation of a DSP model under the agro-climatic uncertainty may be as follows:

$$\max_{x_{n_s}, cr_{n_s}, ca_{n_s}} z = \sum_s P_s * (GI_s * x_{n_s} - C_{cr} * cr_{n_s} - C_{ca} * ca_{n_s}) + Pm * Qm \qquad (1)$$

subject to

$$A_s * x_{n_s} \leq B_s + cr_{n_s} \qquad \forall s \qquad (2)$$

$$x_{n_s} = x_{n+1_s} \qquad \forall s \qquad (3)$$

$$N_s * Y_s * x_{n_s} + ca_{n_s} \geq R_s \qquad \forall s \qquad (4)$$

$$x_{n_s} \geq 0, cr_{n_s} \geq 0 \; and \; ca_{n_s} \geq 0 \qquad \forall s \qquad (5)$$

The decision-making is modeled in (n) *stages*, with (s) *states of nature* for uncertain variables. The variables relate to land allocation (x_{n_s}), and possible corrective actions (cr_{n_s}, ca_{n_s}). Equation (1) is the objective function, with expected gross income (*z*) that weights the values in the *states of nature* for their probabilities (P_s). Uncertainty involves gross margins (GI_s), allocation of land among crops (x_{n_s}), and corrective actions (cr_{n_s}, ca_{n_s}). Pm and Qm are the price and quantity of the milk. Constraint (2) shows that uncertainty can affect A_s and B_s, ie matrix of technology and availability of resources, and that choices can involve land allocation, x_{n_s}, and corrective actions, cr_{n_s}, in *stages* (*n*) and *states* (s). Constraint (3) ensures that choices of previous stages affect subsequent. Constraint (4) affects animal feeding: N_s, Y_s e R_s are the unitary contributions of nutritional elements, crop yields, and nutritional needs of cattle categories. Corrective actions ca_{n_s} can be done at *stage* (*n*) for *state* (*s*). The number of *stages*, parameters and variables depends on the case study. For instance, modeling uncertainty on water available in a dam at the beginning of the irrigation season, Calatrava and Garrido (2005b) divided allocation of the land in two *stages*, with *states* involving diverse levels of water availability. Dono et al. (2013b) consider three *stages* with uncertainty also concerning irrigation needs.

This study considers uncertainty on the watering needs of irrigated crops and on the yields of forage crops cultivated in the irrigated and rainfed zones. Therefore, the corrective actions modify the use of groundwater and the purchase of feeds and fodder. Representative values and probabilities of *states of nature* for the different crop variables (yields and water requirements) were estimated by executing EPIC, DSSAT, and the livestock models on climate data of the *synthetic 150 years*. The outcomes were used to estimate the PDFs of the yields, current and future, of pastures and grasslands in the rainfed zone, and of irrigation needs, and relative yields, of maize, ryegrass and alfalfa in the irrigated zone. The PDF of net evapotranspiration (ET_N) was used to evaluate the change in irrigation needs of other crops when moving from present to future climate. All PDFs were obtained with a maximum likelihood estimator. Chi-square tests were applied to identify the function that best approximates the data set. Finally, the range of each PDF was arbitrarily divided into three *states*, with 25% probability for low and high states, and 50% for intermediate. The arithmetic mean obtained from those *synthetic years* lying within each *state* was used as its representative value. The DSP procedure was not used to model the effects of climate on livestock mortality, yields and quality of cow's milk, and yield of sale crops as rice, durum wheat and barley. This because farmers have no chance to correct those effects once occurred, or is still difficult to assess results and costs of the mitigation actions. In such cases, the model considers only the average effect under present and future climate.

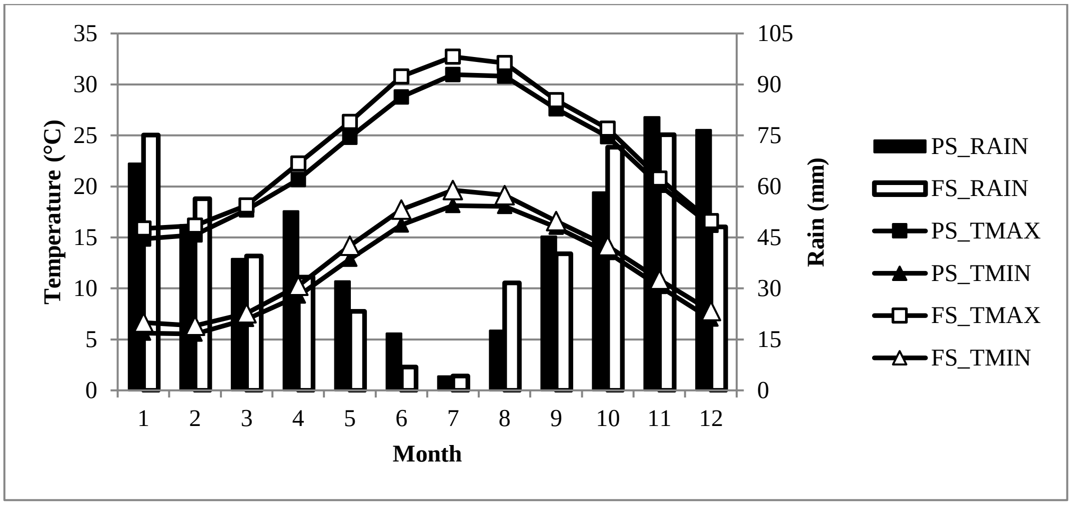
The DSP model was calibrated to base year 2010 with PMP approach of Röhm and Dabbert (2003): it better represents the choices among technically similar crops, with substitution elasticity higher that among different crops, and was useful to model the choice between cultivars of maize.

3. Results

3.1. RAMS-WXGEN simulation of current AND future Oristano climate scenarios

The present and future climate scenarios computed with RAMS and WXGEN models represent the basic forcing to drive the productive impact assessment and the economic evaluation. Temperature and precipitation anomalies expected in the near future showed a high seasonal heterogeneity. Both minimum and maximum seasonal mean temperature are expected to increase in all seasons with a stronger signal in the summer. Expected precipitation seasonal mean values changes are negative and weaker in winter and stronger in spring (-33%), while weak positive or absent anomalies are expected respectively for summer and fall. All these future climate change features are aligned with the already observed long term trends during the past 30 years.

Figure 1. ***Synthetic 150 years*****: average values of maximum and minimum temperatures (TMAX, TMIN) and precipitations (RAIN) for current and future scenarios (PS, FS).**



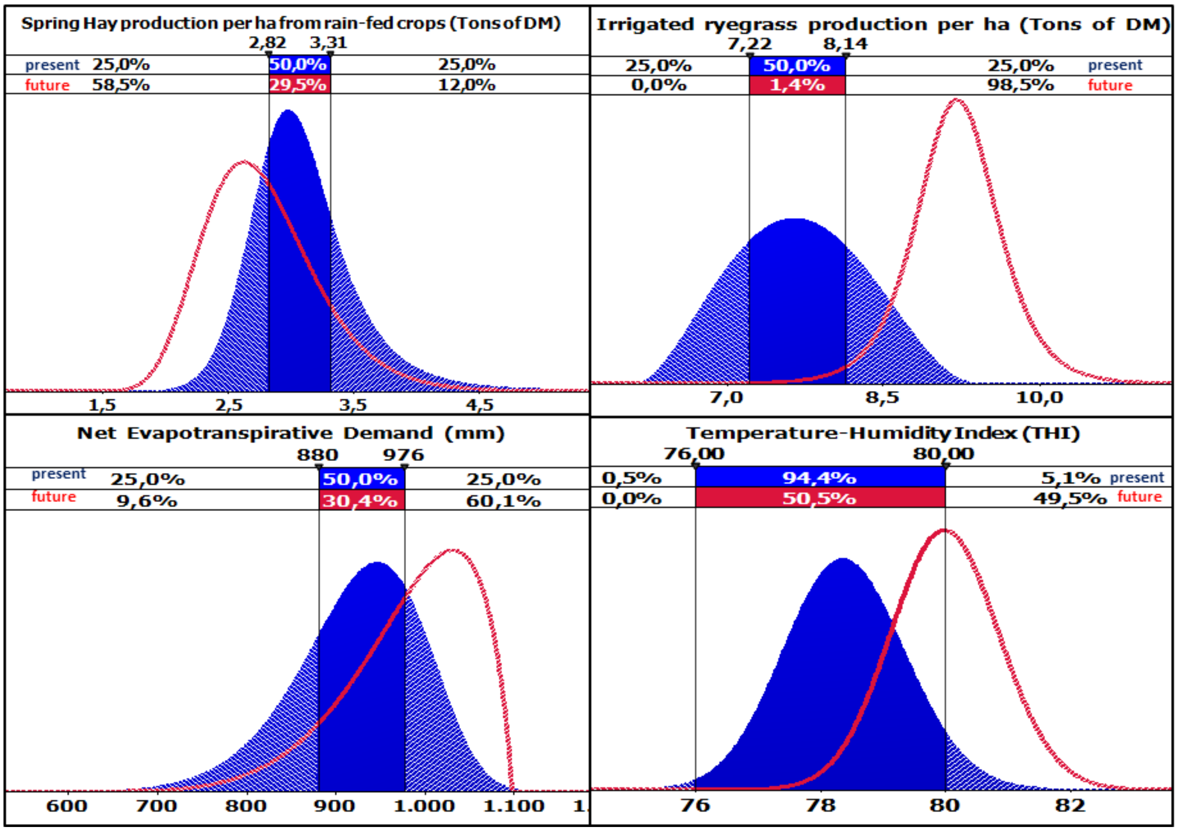
3.2. Impact of CCV on crop yields, irrigation needs and livestock performance

Crop yields, irrigation needs, and productive performances of the cattle in both climate scenarios were estimated with the EPIC, DSSAT, and the livestock models, based on the daily weather data of the *synthetic 150 years*. The outcomes were then used to estimate corresponding PDFs. Figure 1 shows as example some of these PDFs, with the solid blue representing the function of the present, and the red line that of the future. In the first three graphs the *states of nature* are separated by thresholds delimiting, in the present climate, a probability of 25% for the *low state*, of 50% for the *intermediate*, and of 25% for the *high*.

The first graph reports the PDFs of the dry matter per hectare (DM/Ha) of spring hay from rain-fed crops. The probability of harvesting less than 2.8 t DM ha^{-1} rises from 25.0% under present climate to 58.5% under future climate. Conversely, the probability of intermediate yields drops from 50.0% to 29.5%, and that of abundant yields drops from 25.0% to 12.0%. This result is the consequence of the expected reduced rainfall and increased temperatures in spring, when the grass growth rate is at its maximum potential, but is constrained by the increased water stress under future climate and rainfed conditions. These losses occur despite the simulations of the future climate were run under higher atmospheric CO_2 concentration. The second graph shows that removing the water stress by imposing automatic irrigation, this impact of climate change was reversed and the probability of high DM yields for Italian ryegrass increased from 25.0% under present climate to 98.5% under the future climate.

The third graph shows the impact of rising temperatures and reduced rainfall on ET_N from the end of spring to early summer, which corresponds to the irrigation season. Note that the increased probability of high irrigation needs shifts from 25.0% to 60.1% when moving from the present to future climate scenario. The opposite happens for the *states* with lower irrigation needs. The shift of ET_N is supposed to proportionally affect irrigation needs of fruit, vegetables and other sale crops. However, this trend is also found for ryegrass, silage maize and alfalfa, whose irrigation needs, and the corresponding PDFs, were directly estimated.

Figure 1. Current and Future PDFs for *a)* Spring hay yield of rainfed crops, *b)* Irrigated ryegrass yield, *c)* ETN from April to August, *d)* THI (July-August).



The fourth graph shows the PDFs of THI in July-August, highlighting states of nature that do not depend on the probability of the present, as the other three, but from specific threshold values. In particular, we consider values of THI greater than 76, in which the quantity of milk per head begins to shrink (Bernabucci et al., 2014), and values greater than 80 in which a livestock mortality is generated (Vitali et al., 2009). The graph shows that as early as the present there is a very high probability, 99.5%, that the yield of milk per cow in July-August is less than in the rest of the year. This probability persists in the future: 100.0%. Instead, the probability of livestock mortality dramatically increases, going from 5.1% of the present, to 49.5% of the future. Our study also estimated the effect of climate on productive performances of livestock in April-June and in all the other months. It was found that in April-June will increase the chances of having values of THI associated with an appreciable deterioration of the fat content, protein and somatic cell count of milk (the graph is not shown).

Table 2 provides further details on the representative values entered in the model for the *states of nature* derived from the PDFs of the variables under present and future climate. These results are to be read from a different perspective from that used for graphs in Figure 1. Here the probabilities remain constant and the change is reported as +/- % shift of the representative values.

Table 2: Representative (i.e. mean) values for *states of nature* of crop yields, irrigation needs, ET_N and summer THI under present climate, and percentage changes pf future climate vs present (%Δ)

	Crop system		Present climate			Future climate (%Δ)		
			Low	Intermediate	High	Low	Intermediate	High
Yield ($t\ ha^{-1}$ d.m.)	Grassland (autumn)		0.6	1.1	1.5	-17.1	-5.5	8.1
	Grassland (spring)		0.8	1.0	1.3	-19.3	-11.4	-8.2
	Hay crop	Autumn-winter grazing	0.3	0.7	1.0	22.5	5.1	5.3
		Spring hay cut	2.7	3.4	3.5	-14.7	-20.7	-7.1
	Italian ryegrass (irrigated)		7.8	7.7	7.5	16.4	19.7	23.6
	Alfalfa		14.0	14.1	14.1	-2.1	-1.1	-1.6
	Silage maize (a)		22.1	22.3	22.3	-5.8	-6.9	-7.2
	Silage maize (b)		21.4	21.6	21.6	4.5	2.6	2.8
Irrigation needs (mm)	Italian ryegrass		101	126	139	44.2	38.1	40.3
	Alfalfa		621	657	660	3.9	3.6	5.7
	Silage maize (a)		384	415	428	-7.0	-4.2	-1.4
	Silage maize (b)		391	421	436	1.4	4.2	7.1
ET_N (mm/ha)			599	650	688	0.0	4.2	4.1

Source: our elaborations and analyses

In this perspective, notice the forecasted increase in the *high state* of the autumn pasture yield, due to increased temperature and increased rainfall occurrence in October, which expresses the expected increased occurrence of earlier season's break than under present climate, and hence a longer growing season. The situation of rainfed grasslands and of hay-crops under rainfed conditions is opposite in spring, when representative values decrease sharply because of water constraints. On the contrary, Italian ryegrass yields without water constraints responded very positively to the CO_2 and temperature rise under future climate but at the cost of much more than proportional increases of irrigation volumes, resulting into a drop in irrigation water use efficiency. Alfalfa irrigation needs also increased because of the increased summer temperatures. The same applies to fruits and vegetables, whose irrigation needs of the future increase in proportion to the increase of the ET_N. The crop cycle duration under future climate was reduced for silage maize. However, maize yields and irrigation needs were reduced for the hybrid currently in use and increased for the hybrid with longer cycle.

As regards crops and productive performances of livestock that are not modeled with DSP, higher temperatures and atmospheric CO_2 concentrations of the future increase average yields of rice, 7.7%, reduce yields of barley, -0.8%, maintain constant yields of durum wheat, +0.1%[4]. The estimates on milk production indicate an annual reduction of 2%. This is due to decreases in July-August ranging from 9.1% to 10.3%, depending on the composition of the herd of the two farm types representing the dairy cattle sector. In addition, there is an average annual reduction of 0.3% in the price of milk that is due to the deteriorating quality in April-June, which reduces 3.8% the related payments.

3.3. Results of the DSP model: land use

The values of the three *states of nature*, and the respective probabilities were included in the DSP model that generated the use of resources and the related economic results under the present and future scenarios. Table 4 reports the results on the hectares of the main crops in the current scenario, and their percentage changes in the future for the total study area and its two subzones.

Table 4 – Land use under present and future climatic scenarios [percentage changes of future over current (%Δ)]: total area, zone irrigated by the *WUA* and *rainfed* zone.

	Present climate (Ha)			Future climate (%Δ)		
	Total	*WUA*	*Rainfed*	*Total*	*WUA*	*Rainfed*
Grain cereals	13,533	10,440	3,093	20.8	1.5	86.0
Durum wheat	*8,335*	*6,426*	*1,909*	*2.2*	*1.0*	*6.2*
Rice	*2,300*	*2,300*	*0*	*1.6*	*1.6*	*-*
Barley	*1,958*	*1,160*	*798*	*-4.6*	*-5.3*	*-3.6*
Maize	*100*	*86*	*14*	*116*	*136*	*-6*
Forage crops	32,488	13,437	19,051	-7.3	2.0	-13.9
Grasslands	*11,394*	*0*	*11,394*	*-7.2*	*-*	*-7.2*
Hay crops	*9,523*	*2,408*	*7,115*	*-18.3*	*3.9*	*-25.8*
Silage maize	*5,711*	*5,711*	*0*	*6.1*	*6.1*	*-*
Italian ryegrass	*3,580*	*3,555*	*25*	*12.4*	*11.9*	*89.6*
Alfalfa	*1,990*	*1,533*	*457*	*-29.9*	*-38.0*	*-2.8*
Triticale	*290*	*230*	*60*	*-3.2*	*-4.0*	*-0.2*
Field horticultural crops	6,021	5,703	318	0.1	0.1	-0.1
Processing tomato	*1,935*	*1,902*	*33*	*-0.3*	*-0.3*	*-0.2*
Melon and watermelon	*1,485*	*1,368*	*117*	*-0.6*	*-0.7*	*-0.02*
Potato	*516*	*509*	*7*	*2.7*	*2.8*	*-0.8*
Carrot	*256*	*256*	*0*	*6.2*	*6.2*	*-*
Early potato	*114*	*92*	*22*	*-8.2*	*-10.2*	*0*
Greenhouse crops	434	385	49	-1	-2	0
Tree crops	1,702	1,351	351	0	0	0

Source: our elaborations and analyses

[4] The fertilization effect of increased atmospheric CO_2 counteracts the reduction in wheat yields and barley due to higher temperatures.

Major changes in the rainfed zone affect cereals and fodder crops, with significant reductions of the main forage crops that, due to the decrease in rainfall in the spring, suffer from a reduction in productivity in the rainfed conditions. In contrast, the increased production of Italian ryegrass with irrigation in the future climate, resulted to an increased cultivated area in the dairy cow farms, and in one of the dairy sheep farms that manages some land located in the irrigated sub-zone. The area planted to corn silage increases: this is due to the notable expansion of the late hybrid at shorter circle, which compensates the considerable drop of the variety that is currently widely cultivated, -19.9%. Minor changes affected vegetable crops: the appreciable contraction of early potatoes is also caused by the choices of dairy farms that expanded the irrigated late hybrid of silage maize and Italian ryegrass that became more productive due to increased temperature and atmospheric CO_2.

3.4. Results of the DSP model: use of main inputs

The changes in farming systems are associated with changes in the use of inputs, Table 5.

Table 5 – Use of main inputs in the current (absolute values) and future scenario [percentage changes of future over current (%Δ)]: total area, area served by *WUA facilities* and *rainfed* area.

	Present climate			Future climate (%Δ)		
	Total	*WUA*	*Rainfed*	*Total*	*WUA*	*Rainfed*
Total water (Mmc)	121,665	116,429	5,237	1.8	1.8	1.3
WUA water (Mmc)	*114,669*	*112,587*	*2,082*	*1.9*	*1.8*	*2.5*
Water pumping (Mmc)	*6,996*	*3,842*	*3,155*	*0.1*	*-0.2*	*0.5*
Total labor (000 hours)	5,235	3,972	1,264	-0.5	-0.2	-1.3
Family labor (000 hours)	*4,325*	*3,300*	*1,025*	*-0.1*	*-0.1*	*0.0*
Temporary labor (000 hours	*910*	*671*	*239*	*-2.3*	*-0.6*	*-7.0*
Nitrogen	9,828	7,724	2,104	1.2	3.3	-6.7
Phosphorus	4,993	3,677	1,316	2.6	2.9	1.6
Potassium	6,564	4,763	1,800	-4.8	1.8	-22.3
Feeds	113,598	83,253	30,345	0.5	-5.2	16.3

Source: our elaborations and analyses

The use of water provided by the WUA increased, which is also true for the watering of the land managed by one dairy sheep farm type in the irrigated area. Also, use of groundwater increased in the rainfed zone, even if limited by the small number and capacity of the farm wells. Total employment of labor reduced, especially for temporary workers in the rainfed hilly areas. Use of chemicals differently changed, though in the most intensive zone all the considered elements increased. However, the main economic impact due to the change in climatic scenarios concerns the purchase of feed in the sheep farms of the rainfed zone. Feed includes hay and concentrates that are purchased to offset the expected grassland and hay-crop yield decline, caused by the reduction of spring rains.

3.5. Results of the DSP model: income of the area and of the farm types

With regard to the total area, under the *Future* scenario a limited reduction of net income, -2.6%, is expected (Table 6 and 7). However, major differences arose between the CC impact in the irrigated area (WUA) and in the rainfed zone where the net income dropped by -5.4%.

Table 6 - Economic results for the present climatic scenario, absolute values (000 €), and future climatic scenario, [percentage changes of future over present (%Δ)] for the total case study area, the irrigated sub-zone served by *WUA facilities* and the *rainfed* sub-zone.

	Present climate (000 €)			Future climate (%Δ)		
	Total	*WUA*	*Rainfed*	*Total*	*WUA*	*Rainfed*
Total revenues	202,124	176,979	25,146	-0.4	-0.5	0.3
Animal	*89,806*	*75,278*	*14,528*	*-1.1*	*-1.3*	*0.0*
Variable costs	127,744	111,795	15,949	1.1	0.5	4.8
Technical means	*65,889*	*59,757*	*6,132*	*2.2*	*0.9*	*15.0*
Feed	*22,953*	*19,008*	*3,945*	*-1.7*	*-5.4*	*16.3*
Extra-farm labor	*7,738*	*5,707*	*2,031*	*-2.3*	*-0.6*	*-7.0*
Payments to the WUA	*2,144*	*2,107*	*37*	*1.1*	*1.1*	*0.0*
Water pumping from farm wells	*278*	*121*	*156*	*0.2*	*-0.2*	*0.5*
Gross margin	106,025	89,253	16,772	-1.9	-1.5	-4.0
Net income	**77,738**	**66,102**	**11,636**	**-2.6**	**-2.1**	**-5.8**

Source: our elaborations and analyses

The decline of NI in the irrigated sub-zone was due to a small percentage reduction in revenues and to an analogous percentage increase in variable costs. The decrease of revenues was due to the reduction of cow's milk production. This is partly offset by the decrease in the purchase of livestock feed due to the expected increase in farm fodder yields; however, this is achieved by increasing the use of chemical inputs and expanding the irrigated area, which increases their respective cost components. Table 7 identifies the farm types that suffer or benefit from these changes, with the NI in the present climate for each entire type and its representative farm; the percentage change of NI in the future; and the value of the similarity FK Index (Finger and Kreinin, 1979). FKI declines from 1 to 0 when land use and cultivation technologies of the future are changed respect to the present, showing an adaptation effort based on the current technologies. Data show that the negative impacts in the WUA sub-zone almost affect exclusively the two cattle types that suffered a -5 to -6% drop of NI. The value of FKI of these types is the lowest in the area, indicating that they change more intensely the use of soil and the cultivation techniques, including the adoption of the other hybrid of maize. Without these changes, the simulation would have produced a higher impact of the CC. Other types in this sub-zone benefited by increases of NI, due to the increased cereal yields from the CO_2 fertilization effect. In the rice-growing farms, the effect on the rice crop yield is notable, and the same applies to the NI of these farms.

Table 7 – Net Income per typology and representative farm in the present climate [absolute values (000 €)]; percentage changes of Net Income in future climate scenario respect the present (%Δ); similarity index of Finger and Kreinin (FKI).

	Present climate (000 €)		Future climate (%Δ)	FKI
	Typology	Representative farm		
Rice	4,317	179.9	9.3	0.99
Citrus	2,670	39.3	0.0	1.00
Cattle A	26,355	202.7	-5.1	0.81
Cattle B	6,825	170.6	-5.9	0.80
Greenhouse	1,231	26.8	0.4	0.94
Vegetables - Cereals	18,761	33.4	-0.8	0.98
Cereals – Forages	4,739	86.2	2.3	0.98
Tree and arable crops	1,204	12.0	0.0	0.99
Vegetables – Fruit	1,014	10.1	0.0	1.00
Cereals - Forages	2,719	28.9	-0.1	0.98
Sheep A	2,235	49.7	-6.3	0.87
Sheep B	1,869	9.9	-12.6	0.89
Sheep C	3,799	29.5	-7.8	0.85
Irrigated zone	66,102	64.5	-2.1	0.93
Rain-fed zone	11,636	20.9	-5.8	0.88
Total area	77,738	49.1	-2.6	0.91

Source: our elaborations and analyses

A larger NI decline occurs in the rainfed zone, table 6, caused by an increase of variable costs that more than offset the slight expected increase in revenues generated by the increase in the cereal yields and in the net sales of the arable crops. In particular, there are significant consequences of the reduction in the fodder production from grasslands and hay-crops for sheep, which notably increased the purchases of feed and hay, greatly compressing the income of the ovine types, and hence of the entire zone (Table 7). The sheep farm type with some land with water provided by the WUA suffered a less dramatic reduction of N, as irrigation allowed to fully exploit the higher winter temperature and CO_2 fertilization effects. All these impacts led to a further widening of the gap between the profitability of the rainfed vs irrigated sub-zones. In the future climate scenarios, the net income per unit of family labor in the rainfed zone is expected to be barely half of that obtainable in the WUA zone (€ 23.534 against € 43.197, not reported in the table), while it is 87% of the latter in the present climate scenario. This result comes despite the efforts to adapt of these farm types, with changes in land use and currently available techniques, as indicated by the low values for the FKI similarity index.

4. Discussion

In this research, we provided a detailed analysis of how climate change will affect a wide range of

Mediterranean farming systems located in the same agricultural district, in contrast to other kind of analyses based on regional averages (Calzadilla et al., 2014).

The results showed that already in the next in the 2020-30 decade, CC can generate different alterations of atmospheric conditions that are all relevant for the annual planning of agricultural activities under Mediterranean conditions, and this is in line to previous findings of these same Authors in a study conducted in a different area of the same region (Dono et al., 2013a). Those changes can be beneficial for some of the agricultural activities but unfavorable for others, thus leading to winners and losers under the same area and climatic pressures. For example, the increase in temperatures and change in rainfall in some autumn months increase the yields of the pastures of that period, and with them the self-sufficiency of sheep farms for feed. The expected increase in yield of grass meadows and pastures under irrigation, and the beneficial economic consequences for the supply of forage in the irrigated livestock farms, is consistent with the results of other studies in Europe (Schönhart et al., 2014). However, sign and magnitude of changes in yield of those cases depend on specific trends in temperature and in rainfall. For other changes, the magnitude and the sign of the productive and economic impacts depend on the resource endowment of farms in the specific context, and the way access to them is regulated. For example, in rainfed areas the increased probability of high temperatures and low rainfall in the spring, has a negative impact on the fodder production and, therefore, increases the costs for purchasing fodder. On the contrary, the current non limiting availability of water resources in the WUA zone, allows irrigated farms to escape the negative effects of spring drought on fodder production, and to take full advantage of the potential yield increase of C3 crop species due to the expected increased concentration of atmospheric CO_2, which result into lower cost for fodder supply. This is important in dairy farms because this advantage at least partially compensates for other negative economic impacts of CC due to the reduction of production and quality of milk in the summer months and increased mortality of livestock, thus confirming the close relationship between the capability of adaptation of farms to CC and their resource endowment, as evidenced by Antle et al. (2004) for northern USA farming systems. Similarly, Reidsma et al. (2010) conclude that the heterogeneity of the income impacts of the CC on EU agriculture, at both regional level and farm, and the adaptation capacity largely depend on the characteristics of the farms (size, intensity and kind of land use) in the same region. Consequently, the intra-regional diversity degree of the farm types can result into complementarities that can contribute to reduce the overall regional impact; while on inter-regional base, climatic conditions are the major determinants of productive and income variability. We found this evidence particularly true for the Mediterranean context.

The model results show that in some cases, the available technologies provide appreciable opportunities for adaptation, as already found in other studies (Shrestha et al, 2013): for example, in producing silage maize, the availability of a wide range of hybrids with different degree of earliness, ~~it~~ can effectively contribute to mitigate the impact of higher temperatures on the duration of the crop production cycle, thus maintaining substantially the current crop yield. This flexibility is influenced by the criteria used to manage resources. For example, in the case of water, the peculiar system of payments per hectare-crop (i.e. the cost of water depends on the crop type and not by effective water consumption) implies that the increased usage increases the cost of use of the resource (and payments to WUA) only for the expansion of the irrigated area and not for the increased amount of water consumed, as already remarked by Dono and Giraldo (2012). Finally, the spontaneous adaptation simulated in this study is associated with an increased environmental pressure in zones that already have more intensive use of chemical inputs.

5. Conclusions

The interdisciplinary modelling approach adopted for this study allowed the integrated assessment of the expected impacts of CC over a wide range of farming systems under Mediterranean conditions. The chosen approach was not a cascade, i.e. by identifying first the climate alterations, and proceeding along the agricultural-livestock-economic chain. Instead, the crucial phases of the cropping systems were identified, and farm management understood from the farmers' perspective, to test their sensitivity to climate change. Under Mediterranean rainfed conditions, the expected increase in summer temperatures is unimportant to those production systems that had been designed according to the certainty that in this period crop growth is near to zero due to the characteristic summer drought. This is the case of the rainfed dairy sheep farming system, that is managed to minimize the flock feed requirements in summer. Instead, other changes, perhaps less considered, can be particularly relevant, namely the increased temperatures and reduced rainfall in spring, which result into lower hay-crop yields and hence higher vulnerability of rainfed livestock farming systems. The need to focus on specific aspects of climate change that are most worth to consider as they may reveal gaps in the adaptive capacity of the different farming systems, is an important conclusion of this study. In contrast, a limitation of this study is that it was not focused on the role of extreme weather events, disasters, which impede or destroy the production cycles, rather than altering them.

Also, this *agricultural perspective* focused the study on the influence of climate variability on the production performance of crops and livestock, which are relevant for farm management. Thus, the impacts of CC on the production and on the agricultural economy were assessed by simulating the actual possibilities of adaptation of farmers to a new climatic scenario.

The main results showed different impacts on irrigated and rainfed sub-zones. Livestock systems relying on rainfed sub-zones proved to be most vulnerable to a reduction of the net farm income that could hamper their ability to continue their business: family farm income per unit of labor was reduced to less than half of that achieved in the irrigated sub-zone. The main weakness of those activities, especially the forage production in the sheep farms, is in the lack of flexibility in the access to water in the rainfed sub-zone, mainly because of a lack of irrigation infrastructures, given the abundant reservoir water availability managed by the WUA. Therefore, it may be vital either extend to those zones the irrigation infrastructure, or to facilitate the vertical integration of rainfed and irrigated districts to supply forage production at sustainable price in dry years.

The results of the analysis also indicate that the impact in the more intensively irrigated area is concentrated on dairy cattle farms and is mainly generated by the reduction of quantity and quality of milk production. This suggest to better explore, and model the effects of increased temperature on milk production, including the adaptation options related to management aspects. In the specific case under study, the irrigated area is not particularly prone to scarcity condition of water resources. Therefore it can easily respond to the water requirements and not to suffer for quantity constraints. However, this is also related to the peculiar criteria of water pricing in the district, which is based on a per crop and per area basis, which were not changed in our simulation of future scenarios. Instead, a water pricing based on volumetric criteria could generate relevant cost impacts associated to the increased water use: this could further reduce the income of other farm types which currently are not significantly affected by CC, such as rice crop systems. This should not be ignored because the EU Water Framework Directive calls for such kind of pricing systems.

A final evidence regards some environmental impacts of the simulated changes. First, it should not be overlooked that the greater adaptability come at the cost of more intensive use of chemical inputs and can therefore increase the environmental pressure in areas already intensively exploited. Furthermore, the increase in the groundwater use for irrigation may lead to further environmental concerns in the rainfed zone. This kind of issues must be considered particularly worrying in the Mediterranean region where the salinization of groundwater is increasingly determined by overexploitation and threatened by sea level rise generated by global warming. This calls for interventions and further research efforts towards the increase the efficiency of the WUA in providing their services and possibly enhancing synergies between the areas supplied by the WUA and the rainfed areas, which may offer potential complementarities in the local context.

Overall, the outcomes of this study suggest that the challenges posed by climate change in the near future require more than just a more efficient management of resources at local scales. Effective adaptation pathways may emerge from a strategic long-term contextualized visionary perspective of the future of agriculture, emerging from the integration of scientific and lay knowledge (Nguyen et al, 2014). This is particularly important in the vulnerable areas of the world such as the Mediterranean basin.

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