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Simulation of climate change impacts on production and phenology of durum wheat in Mediterranean environments using CERES-Wheat model

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ABSTRACT

The CERES-Wheat crop model was used to simulate grain yields, kernel weights and anthesis dates for three Italian durum wheat varieties (Creso, Duilio and Simeto) under climate change projections at two typical Mediterranean environments (Ussana and Benatzu sites) located in Southern Sardinia (Italy). The model was calibrated and validated in a previous modelling study using long-term weather data from the same experimental sites and agronomic data-sets of the same sites and varieties over the period 1973–2004. To assess the responses of durum wheat varieties to climate changes, 48 synthetic climates based on the combination of increasing temperature and decreasing rainfall were used to represent paths of possible future climate change. The simulated impacts of climate projections on durum wheat varieties at both sites were: grain yield reduction, slightly increasing kernel weight, and earlier anthesis dates. The late variety Creso showed a larger grain yield reduction compared to the early genotypes Duilio and Simeto. Anticipation of time to flowering was larger at Ussana (medium-low fertility soil) than at Benatzu (high fertility soil) with no differences between varieties. Earlier anthesis response was due to temperature increase rather than rainfall reduction, since in the CERES-Wheat model as well as in the majority of crop growth models water availability has no effect on crop development rate. Predictions for kernel weight were more uncertain with a slightly increasing trend in response to increasing temperatures and decreasing rainfall. The CERES-Wheat crop model seems to capture fairly well the greater resilience shown by early genotypes in Mediterranean rainfed conditions. In general, the CERES-Wheat model showed results in line with the findings from real experiments in different pedoclimatic conditions. For these reasons, CERES-Wheat appeared to be reliable when used to evaluate plant responses to projected climate change conditions and can represent a useful tool for developing adaptation strategies and measures such as the choice and selection of adapted genotypes to tackle the negative impact of climate change.

1. Introduction

1.1. Climate change impacts on agricultural crops

The impact of climate change in the 21st century will very likely result in global warming, more frequent heatwaves and droughts, and more erratic precipitation trends (Trenberth et al., 2007). The combination of slight to moderate temperature increase (1–3 °C) with higher CO_2 concentrations should have positive effect on crop yields at global level (Kimball et al., 2002; Ainsworth et al., 2004; Ainsworth and Long, 2005). However, possible risk of fluctuations in yield may overcome the positive effects of temperature increase (Easterling et al., 2007; Hatfield and Prueger, 2015).

Global cereal production is estimated to decrease in the second half of the century under different climate scenarios by 1–11% (Rosenzweig and Parry, 1994; Parry et al., 2004; Fischer et al., 2005; Tubiello and Fischer, 2007). Global and regional impact assessments indicate that increasing heat stress already affects wheat production, and this impact will be exacerbated by future global warming (Semenov and Shewry, 2011; Lobell et al., 2012; Teixeira et al., 2013; Liu et al., 2014; Asseng et al., 2015).

Focusing on the Mediterranean Region, higher temperatures as well as lower rainfall have been projected (Beniston et al., 2007;

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Giannakopoulos et al., 2009) along with more severe aridity (Gao and Giorgi, 2008). Thus, in the next decades the effect of climate change on agriculture in the Mediterranean area will likely lead to increasing plant water stress, decreasing crop yields, and increasing yield variability (Kapetanaki and Rosenzweig, 1997; Maracchi et al., 2005; Giannakopoulos et al., 2009; IPCC, 2014). In particular, the negative impact of climate change on cereal yields will be due to: (i) heat stress; (ii) increased plant water demand with higher transpiration rate; (iii) shortened growing period and anticipated maturity (Porter and Gawith, 1999; Rötter and van de Geijn, 1999; Tubiello et al., 2000; van Ittersum et al., 2003; Parry et al., 2005; Moriondo et al., 2011a; Giannakopoulos et al., 2009).

1.2. Climate change impact on durum wheat

In the Mediterranean Basin durum wheat (*Triticum turgidum* L. subs. durum [Desf.]) is the most widely grown crop. With an average annual production of nearly 18.5 million tonnes (2004–2014), this area accounted for half of the total world production (IGC, 2014). Studies conducted by Ferrise et al. (2011), Tubiello et al. (2000) and Ventrella et al. (2012) indicate that a warmer and drier climate will lead to yield losses of durum wheat in the Mediterranean ranging from −8% to −50%.

Durum wheat is basically used for pasta-making and bread-making. A relevant component of durum wheat production is grain quality to meet the requirements of downstream processing activities such as milling and pasta-making. Several studies reported that grain size progressively decreases with increased temperatures during grain filling both in barley and wheat (Chowdhury and Wardlaw, 1978; Wardlaw and Wrigley, 1994; Gibson and Paulsen, 1999; Passarella et al., 2005). Since grain size of durum wheat is both a yield component and a quality indicator affecting semolina milling properties (Matsuo and Dexter, 1980), climate change might reduce the technological value of durum wheat production, with negative impacts on both the agriculture sector and the food industry of the entire Mediterranean Region.

1.3. Effects of climate change on durum wheat: crop modelling

Assessing the effects of climate change on durum wheat production (i.e. yield and grain quality) is essential for (i) studying the plant responses, (ii) finding adaptation strategies, and (iii) minimizing risks. From this perspective, crop models are powerful tools for assessing the impact of climate change on crop production (Challinor et al., 2014; Rauff and Bello, 2015). Crop models have been widely used to simulate crop growth and development and analyze the responses of major crops to environmental variations (Donatelli et al., 2002; Bindi and Olesen, 2011). However, the number of studies focused on Mediterranean conditions still remains quite limited (Bindi et al., 1996; Guereña et al., 2001; Giannakopoulos et al., 2009; Moriondo et al., 2010; Dettori et al., 2011a; Ferrise et al., 2011; Moriondo et al., 2011b; Toscano et al., 2012; Ventrella et al., 2012; Asseng et al., 2015).

Decision Support System for Agrotechnology Transfer (DSSAT) (Godwin et al., 1990; Jones et al., 2003), a software application program that comprises crop simulation models for over 28 crops, has been extensively used worldwide over the last 25 years for many different applications including the evaluation of climate change impacts (Ventrella et al., 2012; Rosenzweig et al., 2014). DSSAT cropping system model is based on a modular structure, which includes also the CERES-Wheat model (Ritchie and Otter, 1985; Ritchie et al., 1988, 1998). CERES-Wheat simulates crop growth, development and yield taking into account the effects of weather, management, genetics, soil water, carbon and nitrogen (Eitzinger et al., 2016). Timsina and Humphreys (2006), using a range of statistical tests to analyze simulated and observed results from several studies across Asia and Australia, proved a good ability of this model to predict phenology (i.e. anthesis and maturity) and, to a slightly lesser extent, grain and biomass yields. Furthermore, they showed that CERES-Wheat performances were in general good under favourable agro-environmental conditions (e.g. high-yielding and/or irrigated environments) and less satisfactory in low-yielding environments. Timsina and Humphreys (2006) emphasized also the importance of long-term data-sets for better evaluating crop model performances.

Since the CERES-Wheat model has been primarily targeted to bread wheat (*Triticum aestivum* L.), only a limited number of studies, basically conducted under Mediterranean conditions, have been performed on durum wheat (Pecetti and Hollington, 1997; Rinaldi, 2004; Rezzoug et al., 2008; Dettori et al., 2011a; Toscano et al., 2012; Ventrella et al., 2012; Dalla Marta et al., 2015). Dettori et al. (2011a) used DSSAT v4.0 (Hoogenboom et al., 2003) to calibrate and validate the CERES-Wheat model and simulate development and yield of three durum wheat varieties in two different agro-ecological sites of Southern Sardinia, Italy. They found that the CERES-Wheat model provides good to fair predictions of grain yield with a tendency to overestimate, and good to very good predictions of anthesis date. However, predictions of grain weight and grain number proved to be less satisfactory.

Crop simulation models are also useful tools to determine the potential impact of climate change on production and to define adaptation strategies. Therefore crop models can be used to predict the responses of crops and varieties to climate change in order to: (i) analyze the most appropriate actions to minimize or reduce potential negative effects; (ii) propose guidelines for plant breeding and agricultural policies.

In this study, CERES-Wheat model was applied with the general purposes (i) to assess the potential impacts of increasing temperatures and decreasing rainfall on grain production and phenology of three hallmark durum wheat varieties grown in two typical Mediterranean environments in Southern Sardinia (Italy), and (ii) to evaluate model responses to changes in climate identifying also possible model deficiencies and searching for their causes. The effect of increasing atmospheric CO_2 concentration was intentionally not included in the analysis with the aim to distinguish differences in model response attributable just to climate variables. Crop model results under climate change projections were also considered comparing simulated outputs with findings from long-term experiments and real-life trials, and discussing the different potential of the three durum wheat varieties to adapt to increasingly harsh growing conditions.

2. Materials and methods

2.1. Study sites and experimental data

This study was carried out at two different sites, Benatzu and Ussana, within the experimental farm of San Michele owned by AGRIS (Agricultural Research Agency of Sardinia) (Lat. 39°24′ N, Long. 9°5′ E). The farm is located in the Campidano plain, an important durum wheat growing area of Southern Sardinia, Italy.

Durum wheat is a major crop in the study area. The climate is Mediterranean, with warm and dry summers and mild winters.

The area shows great soil variability. In particular, the soil of Ussana (114 m a.s.l.), located in a hilly area, is typical of medium- and low-fertility rain-fed durum wheat growing areas of Sardinia and the Mediterranean. It is a sandy clay loam soil, with a percentage of sand greater than 50%. The drainage is moderate, and the stone percentage is about 20%.

The soil of Benatzu (80 m a.s.l.), located in a flat area, is typical of the high-yielding potential rain-fed durum wheat growing areas of

Table 1
Physical and chemical characteristics of soil at Benatzu (*Vertic Epiaquept*)[a] and Ussana (*Petrocalcic Palexeralf*)[a] experimental sites within San Michele farm, Southern Sardinia, Italy.

	Benatzu	Ussana
Sand (%)	26.20	56.40
Silt (%)	34.40	21.50
Clay (%)	39.40	22.10
Stones (%)	30.00	20.00
Textural class	Clay loam	Sandy clay loam
pH in H_2O	8.50	7.90
Organic carbon (%)	1.62	0.83
Organic matter (%)	2.80	1.20
Total nitrogen (%)	0.15	0.07
C.E.C. (cmol kg^{-1})	2.90	2.30

[a] USDA Soil Taxonomy (2002).

Sardinia and the Mediterranean. It is a clay loam soil with a fraction of stones of about 30% and a clay percentage of about 40%.

Daily maximum and minimum air temperatures (°C) and daily rainfall amounts (mm) over the period 1973–2004 were recorded by an automated weather station (SILIDATA AD2, SILIMET s.r.l., Modena, Italy) located in the experimental farm. Daily global solar radiation values (MJ m^2 d^{-1}) were estimated using the software RadEst 3.00 (Donatelli et al., 2003).

Table 1 shows the results concerning the soils classification and the chemical and physical characterization, in order to provide the data required by the model.

Agronomic management and durum wheat experimental data over the period 1973–2004 from both sites came from the Italian Durum Wheat Variety Trials (http://sitoentecra.it/portale/cra_dati_istituto). The experimental design consisted in a triple lattice with 8-rowed plots. Each plot was 5.9 m long and 1.5 m wide with an approximate surface of 10 m^2 and rows spaced 0.18 m apart. Plant density was about 300 plants m^{-2}. The durum wheat varieties Creso, medium-late and short variety, Duilio early-medium and medium-tall variety, and Simeto, early and short variety, well adapted to Mediterranean environmental conditions and grown in rain-fed system, were used to evaluate the potential impact of climate change on durum wheat yield and phenology using CERES-Wheat model simulations. Data were collected in order to initialize the model (i.e. amount and date of fertilizer applications, previous crop, sowing and harvesting dates, sowing depth, plant density), as well as to compare the results from the crop model simulations under climate change projections concerning the harvest and the crop development (i.e. grain yield, kg ha^{-1}; grain weight, g; anthesis date; day after planting-dap) with the observed data from the experimental sites (baseline climate). A summary of the main agronomic management information used to initialize the CERES-Wheat simulations over the three durum wheat varieties are reported in Table 2.

2.2. CERES-Wheat simulations and climate projections

CERES-Wheat model was used to perform crop growth simulations of durum wheat under future climate conditions only for the baseline CO_2 level (360 ppm) and then assess the potential impact of future climates on yield and phenology of durum wheat. Simulation experiments were based on the same dataset utilized by Dettori et al. (2011a) to derive the so-called genetic coefficients for Creso, Duilio, and Simeto durum wheat varieties (Table A1). Details about the calibration and validation results are provided in Tables A2–A5 and in Supplement 6. In this study, the calibration coefficients were used to perform crop growth simulations under climate projections.

Although simulations were performed using the agronomic and management data observed during the period 1973–2004, the analysis of the simulations was limited to the years when field trial tests were conducted simultaneously on all varieties (i.e. years 1990–2004 for Benatzu and 1989–2004 for Ussana) in order to have a more homogeneous comparison between the durum wheat genotypes. In particular, the simulations were performed on a daily time step, and conducted as a succession of independent growing season, with the moisture content of the top soil set at 75% of field capacity at the beginning of each season. The starting date of all simulations was set on August 1st of each year, considering the growing season from October to June. The planting date was set, for each year, on the observed date, which varied depending on the first useful rainfall occurrences in autumn. The end of the growing season was calculated by taking into account the observed harvest dates for each year. All the agronomic data, such as previous crops and fertilizer management, were set in the experimental file.

Since future climate scenarios cover a wide range of possible future climates and have non-negligible uncertainties, we have adopted an empirical approach to study the different effects of climate change on durum wheat. A set of 48 synthetic climates, based on projections of climate model simulations for the Mediterranean Region, was developed by adjusting the baseline air temperature and precipitation records (actual climate, 1973–2004, at Benatzu and Ussana experimental sites) by between +1 and +6 °C at 1 °C intervals, and by between −5% and −30% at 5% intervals, respectively. The incremental approach is a relatively straightforward and popular procedure for rapid impact assessment (Arnell and Reynard, 1996; Arnell, 1998; Pilling and Jones, 1999; Arnell, 2003; Diaz-Nieto and Wilby, 2005; Pirttioja et al., 2015) with clear advantages (the ease/speed of application and the direct scaling of the scenario in line with changes suggested by the GCM or RCM, the greater capability of resolving many of the regional- and local-scale processes that are often required for impact studies compared to GCMs) and clear disadvantages (several properties of the data, such as the range and variability, remain unchanged). This incremental approach is commonly used to study the sensitivity of an exposure unit to a wide range of variations in climate, facilitating the

Table 2
Main crop management information used to initialize the CERES-Wheat crop growth model. Data derive from the Italian Durum Wheat Variety Trials conducted at the two experimental site of Ussana and Benatzu, Italy, over the period 1973–2004 (http://sito.entecra.it/portale/cra_dati_istituto.php?id=223&lingua=EN).

Trial	Previous crop	Plant density viable seeds m^{-2}	Sowing date	Harvesting date	Fertilizer applications		
					Sowing		End of tillering (Jan-Mar)
					N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	N (kg ha^{-1})
Ussana	Fallow or Faba bean	350	*earliest: Nov 21* **mean: Dec 4** *latest: Dec 20*	*earliest: Jun 5* **mean: Jun 24** *latest: Jul 7*	30	90	60
Benatzu	Fallow or Faba bean	350	*earliest: Nov 21* **mean: Dec 17** *latest: Dec 24*	*earliest: Jun 14* **mean: Jun 30** *latest: Jul 16*	30	90	60

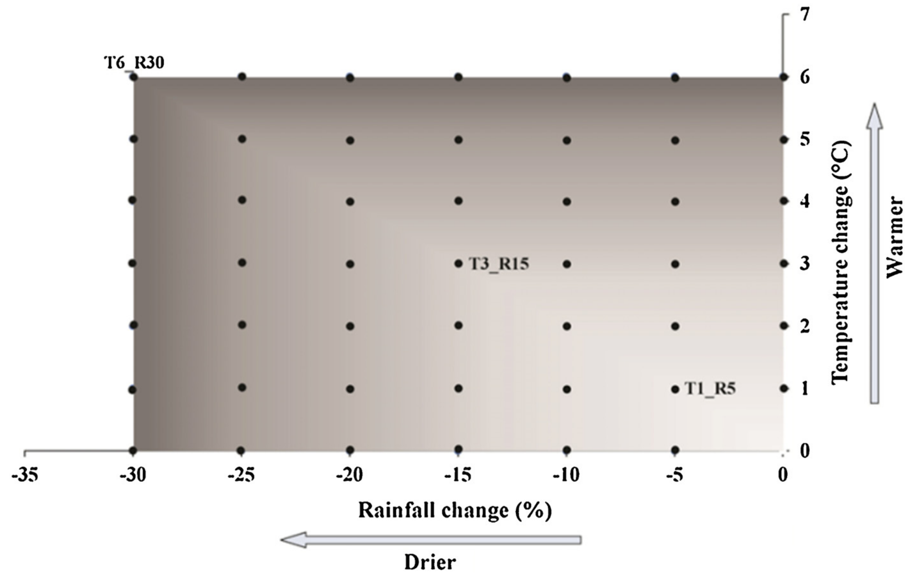

Fig. 1. Synthetic climates developed adjusting the baseline temperature and precipitation records of the experimental sites by between +1 °C and +6 °C at 1 °C intervals, and by between −5% to −30% at 5% intervals, respectively. The 6 climate projections with increasing temperatures (T1, . . ., T6), the 6 climates with decreasing rainfall (R5, . . ., R30), and the 36 climates derived from the combination of increasing temperatures and decreasing rainfall were used in conjunction with the CERES-Wheat crop model to determine the potential impact of climate change on crop production and phenology of three durum wheat varieties.

construction of response surfaces and assisting in identifying critical thresholds or discontinuities of response to a changing climate (Terjung et al., 1984; Rosenzweig et al., 1996; Mearns et al., 2001). In this study, incremental climate projections were developed using constant changes throughout the year and following the scheme reported illustrated in Fig. 1.

The selection of these synthetic climates was guided by information and data from recent global and regional climate simulations over the Mediterranean Region. Therefore, they are in line with global and regional projections, representative of the potential range of future climate changes in the Mediterranean, and physically plausible and consistent. Despite their somewhat arbitrary nature and the use of constant changes throughout the year, they capture a wide range of possible changes in Mediterranean climate and offer a simple and useful tool for evaluating both the potential impacts of climate change on durum wheat production and the response to climate change of the CERES-Wheat model.

The model was run using the 48 synthetic climates, for the three varieties grown in two sites. The simulation results concerning the grain yield, the seed weight, and the anthesis date were analyzed to assess the impacts of climate change projections on the crop.

3. Results

The responses of the CERES-Wheat model to the simulated climates at the two experimental sites – Benatzu and Ussana – for annual values of grain yield, anthesis date and average seed weight, and for three durum wheat varieties, were analyzed by comparing observed (under baseline climate) and simulated (under future climate) values.

Fig. 2 shows an example of the effects of the climate change simulations on the mean grain yield of Creso, Duilio, and Simeto varieties at both experimental sites for 2 of the 48 synthetic climates.

The mildest simulated climate projection is characterized by an increase in air temperature equal to +1 °C and a reduction in rainfall of −5% compared to the actual mean temperatures and total rainfall amount, respectively.

The worst-case climate implies an increase in temperature equal to +6 °C and a large reduction of annual rainfall (−30%). Simulations show a clear detrimental effect on yield determined by increasing temperatures and decreasing rainfall for all varieties and sites, with the largest decrease observed at the medium-low-fertility site of Ussana (−4% and −32% on average for the mildest and worst-case climate projections, respectively) and on the early variety Simeto (−5% and −30% on average for the mildest and worst-case climate projections, respectively).

Fig. 3 illustrates the percentage changes in grain yield of all varieties compared to the mean values observed at Benatzu and Ussana, and resulting from simulations of the 48 synthetic climates with increasing temperatures and decreasing rainfall.

In general, the relative yield response to climate change shows clear similarities for all the combinations of site and variety, with all simulations indicating decreases in yield for increased temperature and decreased rainfall. For combinations of temperature and rainfall change across the ranges defined by this study, the temperature was the dominant constraint on yield at both sites and for all the varieties for warming above about 4 °C. Contour lines were almost vertical under these warming conditions, indicating that rainfall changes had little effect on yield in these regions of the impact surface response. Under conditions of less warming (below 4 °C), rainfall had an increasing influence. Also, the sensitivity of yield response to rising temperatures is higher under dry conditions than under moderate or severe dry conditions. For example, in Fig. 3 for an increase of temperature equal to 1–2 °C, contour lines were almost vertical under rainfall reduction less than −15%. In other words, simulations indicate that durum wheat is more responsive to heat stress when there is no competing water stress.

However, while the pattern of these impact responses are quite similar for all the combinations of sites and varieties, the relative strength of these relationships displays variation between varieties and between sites.

Comparing the different responses of the three varieties to the simulated climates at both sites, Creso (medium-late cycle) proved to be the most sensitive, with the greatest yield reduction (greater than −32%) observed at Ussana site when a large rainfall reduction was combined with a large temperature increase.

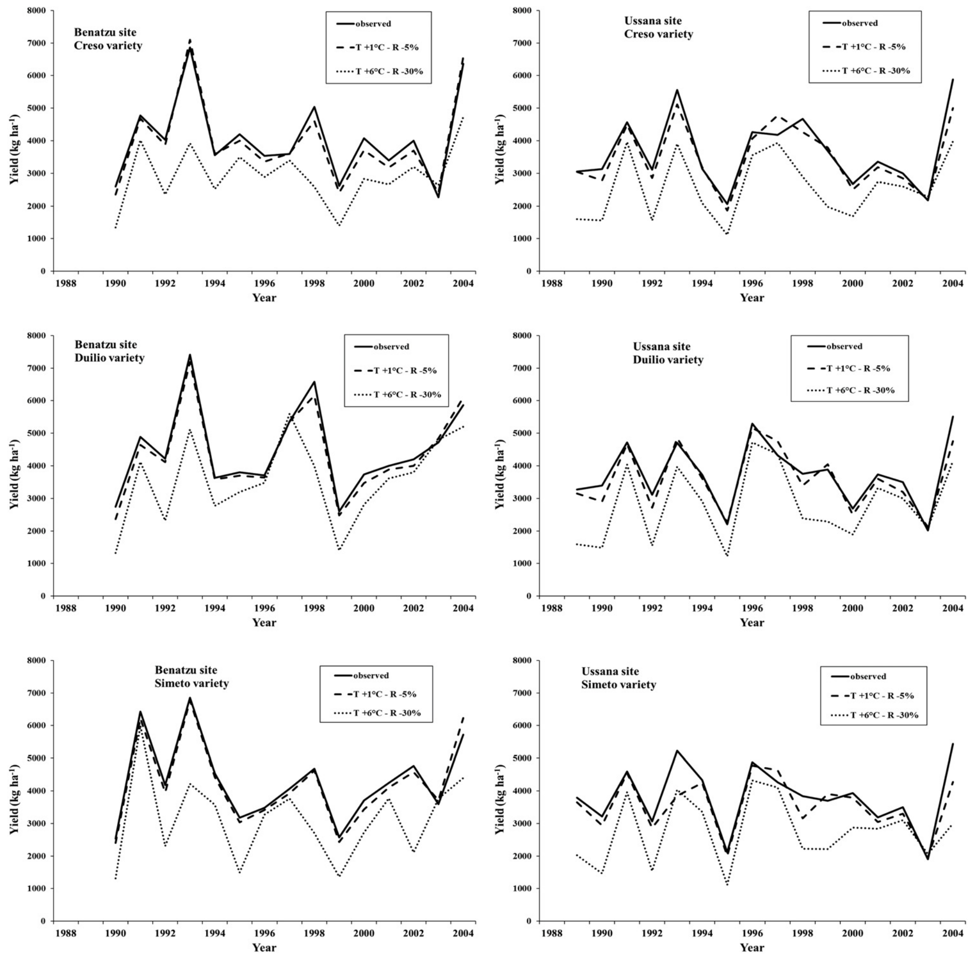

Fig. 2. Grain yield under current and future climates for durum wheat varieties Creso (top), Duilio (middle), and Simeto (bottom) at Benatzu (left) and Ussana (right) experimental sites. Simulations are based on 2 climate projections: T1_R5 (temperature increase: +1 °C; rainfall reduction: −5%) and T6_R30 (temperature increase: +6 °C; rainfall reduction: −30%).

The reduction in grain yield of Simeto (early cycle) and Duilio (early medium cycle) was relatively lower compared to Creso genotype, with maximum yield losses greater than −28 to 30%, again at Ussana site.

In general, the CERES-Wheat model predicted greater percentage decrease of grain yield at the low-yielding site of Ussana than in the fertile soil of Benatzu. In particular, the overall average grain yield reduction for the three varieties (Creso, Simeto and Duilio) calculated using the simulations from all 48 climate projections was equal to 16.2% and 19.0% at Benatzu and Ussana, respectively.

In summary, the overall simulated effect of climate change projections characterized by increasing temperature and decreasing rainfall is a gradual reduction in grain yield for all varieties and sites compared to the actual climate conditions, with the most relevant effects determined by temperature for warming above about 4 °C. Under these warming conditions, rainfall reduction had little effect on yield, but under conditions of less warming (below 4 °C), rainfall had an increasing influence.

Fig. 4 shows that kernel weight tends to increase slightly when temperature increases, and this response is greater when annual rainfall does not decline or the decrease is small (−5%).

On average, the increase in kernel weight ranged from 3% to 5% at both sites and for all the varieties. Rising temperatures combined with small decrease of rainfall determined an increment of kernel weight ranging from 2% to 8% compared to the observed values, again at both experimental sites. In general, the effect of water scarcity led to a reduction in the kernel weight increase. The increment in kernel weight was particularly evident for the Simeto and Duilio varieties at Benatzu under the warmest synthetic climates.

The effects of the synthetic climates on the phenological behaviour of durum wheat were determined by comparing predicted and observed anthesis dates by site and variety. However, since in the CERES-Wheat model as well as in the majority of crop growth models water availability has no effect on crop development rate (Asseng et al., 2013), the analysis is restricted to the impact of temperature on the time to anthesis. In general, the shortening effect of temperature on cycle length of durum wheat is evident, with progressive temperature increases leading to earlier flowering dates. In the range of temperature changes investigated, simulations showed anticipation of flowering time of 3 to 13 days, for temperature increase ranging from 1 °C to 6 °C, respectively (Fig. 4).

Simulations showed also that the overall shortening effect was larger at Ussana site (medium-low fertility soil) than at Benatzu site (high fertility soil): indeed flowering dates were up to 13 and 11.5 days earlier on average than the observed means at Ussana and Benatzu sites, respectively. This suggests that soil fertility can play a crucial role in reducing the time to flowering of durum wheat.

Examining this shortening effect by variety, simulations performed using Creso, Duilio and Simeto data did not show different responses to temperature for time to flowering between the three genotypes.

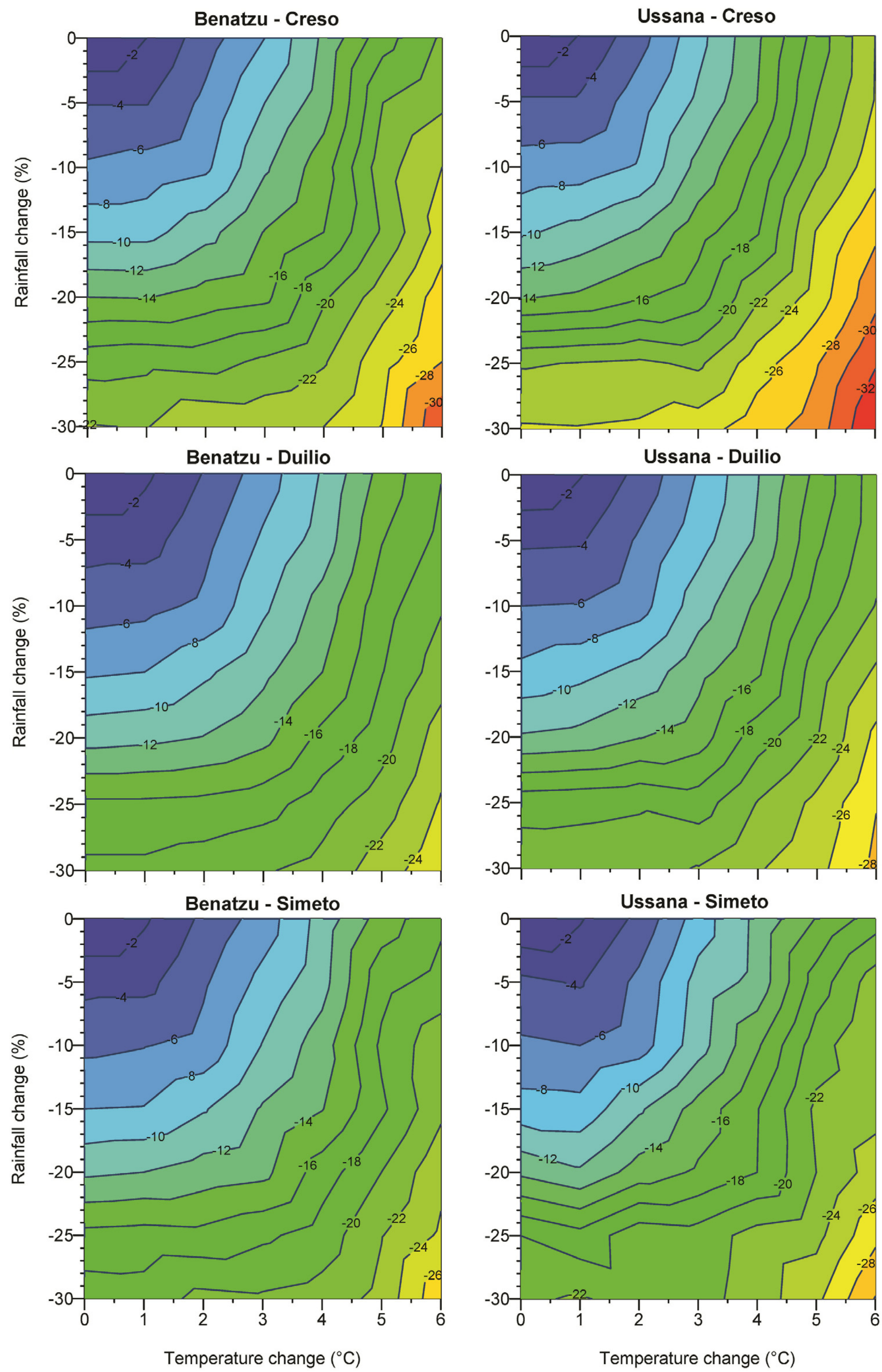

Fig. 3. Percentage decline of grain yield of Creso, Duilio and Simeto varieties for changes in temperature and rainfall (48 climate change projections) relative to the baseline climate (1973–2004) at the experimental sites of Benatzu and Ussana (Sardinia, Italy).

4. Discussion

Fig. 2 shows the evident negative effect of increasing temperatures and decreasing rainfall on simulated grain yields at the two experimental sites. CERES-Wheat simulations under future climate projections indicated that the more relevant yield reductions occurred at Ussana site, where soil is less fertile and more prone to the negative impact of rainfall reduction and water scarcity (Fig. 3).

It is interesting to analyze these locally scaled results in light of the existing literature at both global and Mediterranean area level. Our results obtained by simulating rain-fed wheat production under future climate projections are mostly consistent with several studies at both global level for developing countries (Rosenzweig et al., 1993; Rosenzweig and Parry, 1994; Parry et al., 2004; Fischer et al., 2005; Tubiello and Fischer, 2007) and regional level for the Mediterranean Basin including

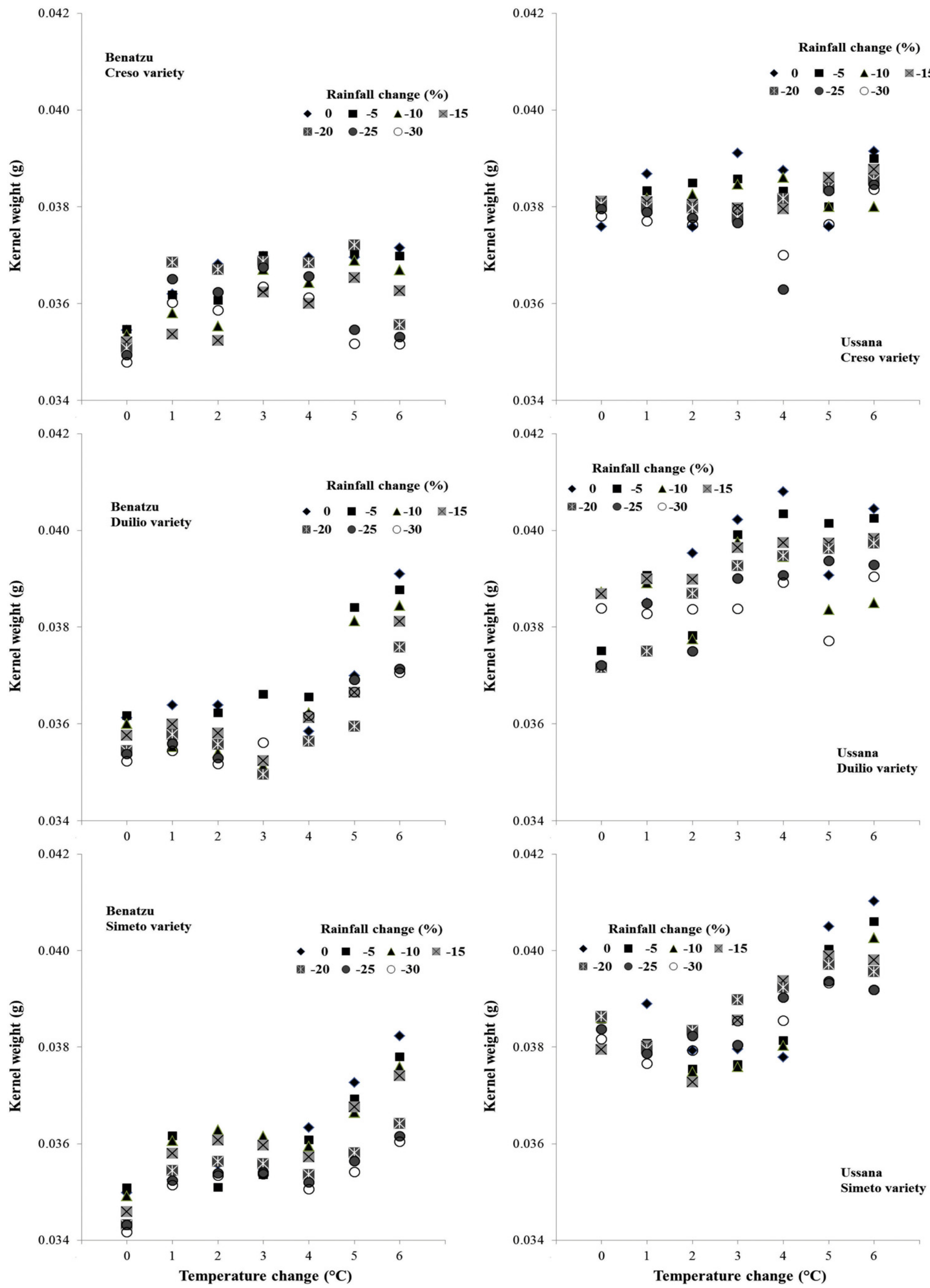

Fig. 4. Average seed weight of durum wheat at the experimental sites of Benatzu and Ussana (Sardinia, Italy) under 48 climate change projections characterized by rainfall reduction and rising temperatures relative to the baseline climate (1973–2004).

Italy (Tubiello et al., 2000; Ferrise et al., 2011; Ventrella et al., 2012).

Different studies (Attri and Rathore, 2003; Xiao et al., 2005; Ventrella et al., 2012) explored the projected positive effect of slight temperature increase on wheat grain yield, presumably determined by the positive response of crops to elevated CO_2 concentration in the atmosphere. However, the present study did not take into account the physiological effect of projected high levels of CO_2, focusing the analysis on the impacts of changes in climate variables. Rosenzweig and Tubiello (1997) pointed out the difficulty of estimating the combined effects of climate change and elevated CO_2, and other studies emphasized our incomplete knowledge on the field-level interactions between CO_2 and biotic and abiotic factors (Ainsworth and Long, 2005; Tubiello et al., 2007). Despite this limitation, our simulations showed levels of grain yield reduction that seem to be realistic for most Mediterranean environments when compared, for example, with experimental data from Multi-Environment-Trials.

The slight positive effect of increasing temperature and decreasing rainfall on kernel weight (Fig. 4) is difficult to interpret, also because little research has been conducted over rain-fed durum wheat to date on this topic. In addition, our simulated kernel weight responses seem to contradict research findings on bread wheat indicating that high temperatures (Gibson and Paulsen, 1999), heat shocks (Wardlaw et al., 2002) and water stress (Khanna-Chopra et al., 1994) during grain filling cause a reduction of kernel weight at maturity. Based on our previous work (Dettori et al., 2011a) and on findings reported by some authors

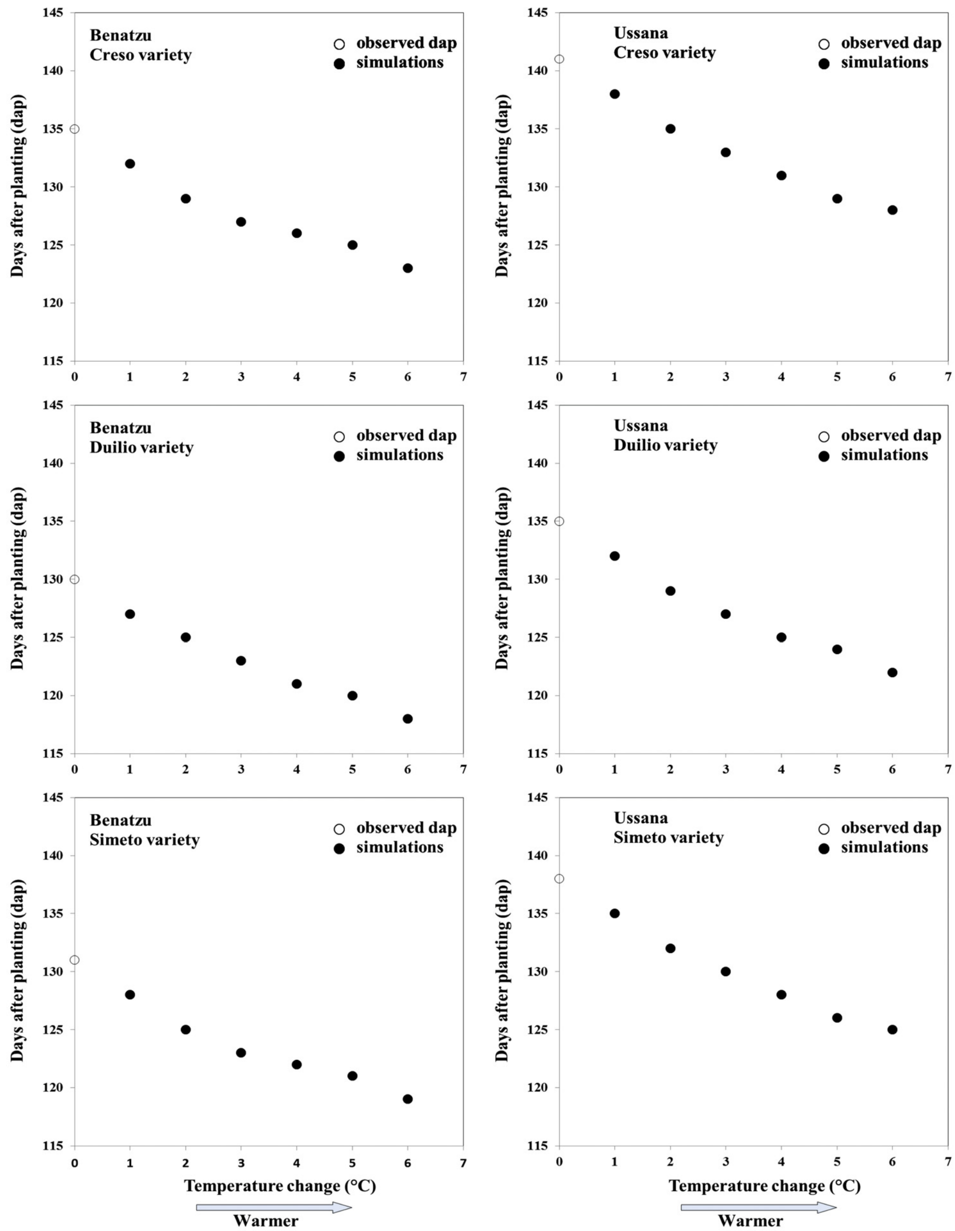

Fig. 5. Anthesis dates (days after planting) at the experimental sites of Benatzu and Ussana (Sardinia, Italy) under climate change projections relative to the baseline climate characterized by increasing temperature. Simulation results are compared with observed data (observed dap).

(Moreno-Sotomayor and Weiss, 2004; Langensiepen et al., 2008), limitations in calibrating and validating CERES-Wheat model for this trait depend on both lack of process simulation and need for a specific durum wheat calibration. For example, Langensiepen et al. (2008) reported that inaccuracies in estimating yield components depend on modelling inaccuracies in simulating underlying physiological processes under stressed and non-stressed conditions. This is particularly relevant for crops grown in rain-fed system, and this indicates the need to improve our knowledge on the accuracy of CERES-Wheat crop model in predicting kernel weight.

Our simulations indicated a reduction of the period from sowing to anthesis ranging from 3 to 14 days according to climate change projections, variety and site (Fig. 5). This shortening effect was due to the warming climates rather than to the water shortage, since the primary effect of rainfall change and water availability on grain yield simulated by CERES-Wheat, and by the majority of crop growth models, is through limitations on growth, with no effect on crop development rate and, therefore, on anthesis date. Our result are in agreement with the widely accepted evidence that shortening of the growing period is one of the main impacts of climate change on crops, and it is also one of the primary causes of projected decreases in yield (Parry et al., 2005). The results of our study are also consistent with those of Moriondo and Bindi (2007), who found a general reduction of the crop growing cycle of winter cereals (i.e. barley and wheat) in the entire Mediterranean Region in response to a 2 °C increase in temperature, with a decrease of the duration of the growing season ranging from 1.2 days in Tunisia to 12.2 days in Serbia.

Our results showed also that the overall shortening effect of temperature was larger at Ussana site (medium-low fertility soil) than at Benatzu site (high fertility soil) and that the early cultivars Duilio and Simeto did not show differences in the anticipation of the time to flowering when compared to the late cultivar Creso (Fig. 5).

However, under drought conditions, early genotypes are able to complete their development phases more rapidly thereby avoiding water shortage during grain filling. In general, the productive value of earliness as a drought escaping mechanism was quantified in 30 kg ha^{-1} day^{-1} by Fischer and Maurer (1978). In addition, the key-role of earliness as an adaptive trait in the Mediterranean rain-fed areas in conditioning yield potential was confirmed by studies comparing different species such as durum wheat and triticale (Giunta et al., 1993; Gouache et al., 2012) as well as different cultivars of durum wheat (Annicchiarico and Pecetti, 1993). In the current study, the early genotypes had larger yield performance than the late genotype on the basis of both observed and simulated data (Figs. 2 and 3). Therefore, the CERES-Wheat crop model seems to capture fairly well the greater resilience shown by early genotypes to rain-fed Mediterranean conditions. Cultivar choice is one of the main farm-level adaptation measures to reduce the negative impacts of climate change on crop production (Parry et al., 2005). Easterling et al. (2007) estimated an avoidance of 10–15% yield reduction due to cropping adaptations such as changing varieties and planting times. Various authors have been using crop growth simulation models to explore the agronomic adaptation strategies under climate change and analyze the simulated effects on grain yields of fertilization and irrigation (Ventrella et al., 2012) as well as planting dates (Pecetti and Hollington, 1997) in some major durum wheat growing areas of the Mediterranean Region. However, little effort has been made to improve our understanding on the effect of variety choice. From this perspective, targeting varieties onto different environments and climatic conditions is one of the main adaptation strategies for coping with climate change (Tubiello et al., 2000; Annicchiarico, 2009). Our results, based on observed data and simulated grain yield responses to climate change projections, indicated that the late genotype Creso proved to be the most sensitive to increasing temperatures and decreasing rainfall and that Duilio and Simeto cultivars appeared to be more climate-resilient to the simulated changes (Figs. 3 and 4). In addition, our findings show that the negative impact of the synthetic climates was more relevant in the less fertile and more drought prone soil of Ussana site. Since these simulation outputs are confirmed by observations, the results from CERES-Wheat simulations showed that the model predicts well both yields and anthesis dates. However, the response of CERES-Wheat model at the low-yielding site of Ussana may somewhat be affected by the poorer performance of this model in low fertility soils as pointed out by Staggenborg and Vanderlip (2005) and Timsina and Humphreys (2006).

Simulation results reported in this study should be interpreted in light of the combination of yield, cycle duration and adaptation to dry conditions where earliness proves to play a major role in the Mediterranean areas. From this point of view, Multi-Environment-Trials (METs), i.e. field experiments carried out over years and across different locations, may represent a key mean to assess the agreement between crop models simulations and experimental data. For example, METs performed in irrigated and rain-fed conditions across Mediterranean and other environments (Dettori et al., 2011b) showed that Simeto and Duilio proved to be significantly higher-yielding than Creso variety. Moreover, most of the earliest genotypes ranked among the top-yielding and stable materials especially in rain-fed environments, thereby confirming the simulation results obtained in this study. The comparison between early and late genotypes did not show any particular relationship between time to flowering and kernel weight. However, although this result might explain, to some extent, the performance of the CERES-Wheat model when predicting kernel weight values, further research studies are needed to improve our knowledge about the relationships between environment, physiological responses and genotype adaptation.

5. Conclusions

This study showed the responses of the CERES-Wheat crop model to a range of 48 climate change projections, examined the existing literature on projected climate change impacts on wheat crop and discussed simulation results over three durum wheat varieties in light of the observations from yield trials carried out in various environmental conditions. The impact of climate change projections on grain yield is more negative moving from mild to severe climates for all genotypes, but reductions are to some extent mitigated for Simeto and Duilio (early genotypes) in comparison with Creso (late genotype). In the range of temperature and rainfall changes investigated in this study, the temperature was the dominant constraint on yield for warming level above about 4 °C. Under these warming conditions, water shortage had little effect on yield. However, rainfall showed to have an increasing influence when warming intensity is lower. In addition, the sensitivity of yield response to rising temperatures is higher under dry conditions than under moderate or severe dry conditions. This indicates that durum wheat is more responsive to heat stress when there is no competing water stress.

On the other hand, kernel weight tends to increase slightly in response to increasing temperatures, in particular when annual rainfall does not decline or the decrease is small. All genotypes showed earlier flowering dates as a consequence of increasing temperatures, with no differences among cultivars. The detrimental joint effect of simulated increasing temperatures and decreasing rainfall on durum wheat yield is also influenced by soil fertility, with stronger impact in low-yielding potential soils.

Furthermore, our analysis indicates that CERES-Wheat crop model responses are highly consistent with observations from most rain-fed durum wheat growing areas of the Mediterranean Region. Therefore, CERES-Wheat model proves to be a reliable tool to determine the impact of climate change on crops and can be successfully used to support adaptation strategies such as targeting cultivars onto specific environments or to guide selection decisions in crop breeding programmes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2017.02.013.

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