

# Agronomic adaptation strategies under climate change for winter durum wheat and tomato in southern Italy: irrigation and nitrogen fertilization

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**Abstract** Agricultural crops are affected by climate change due to the relationship between crop development, growth, yield, CO<sub>2</sub> atmospheric concentration and climate conditions. In particular, the further reduction in existing limited water resources combined with an increase in temperature may result in higher impacts on agricultural crops in the Mediterranean area than in other regions. In this study, the cropping system models CERES-Wheat and CROPGRO-Tomato of the Decision Support System for Agrotechnology Transfer (DSSAT) were used to analyse the response of winter durum wheat (*Triticum aestivum* L.) and tomato (*Lycopersicon esculentum* Mill.) crops to climate change, irrigation and nitrogen fertilizer managements in one of most productive areas of Italy (i.e. Capitanata, Puglia). For this analysis, three climatic datasets were used: (1) a single dataset (50 km × 50 km) provided by the JRC European centre for the period 1975–2005; two datasets from HadCM3 for the IPCC A2 GHG scenario for time slices with +2°C (centred over 2030–2060) and +5°C (centred over 2070–2099), respectively. All three datasets were used to generate synthetic climate series using a weather simulator (model LARS-WG). Adaptation strategies, such as irrigation and N

fertilizer managements, have been investigated to either avoid or at least reduce the negative impacts induced by climate change impacts for both crops. Warmer temperatures were primarily shown to accelerate wheat and tomato phenology, thereby resulting in decreased total dry matter accumulation for both tomato and wheat under the +5°C future climate scenario. Under the +2°C scenario, dry matter accumulation and resulting yield were also reduced for tomato, whereas no negative yield effects were observed for winter durum wheat. In general, limiting the global mean temperature change of 2°C, the application of adaptation strategies (irrigation and nitrogen fertilization) showed a positive effect in minimizing the negative impacts of climate change on productivity of tomato cultivated in southern Italy.

**Keywords** Modelling · Climate change · Agronomic adaptation strategies · Yield · Tomato · Winter durum wheat

## Introduction

The Fourth Assessment IPCC Report (IPCC 2007a) showed that annual global temperatures increased by  $0.74 \pm 0.18^\circ\text{C}$  during the 1906–2005 period and demonstrated that much of this change is due to an increased concentration of Green House Gases (GHGs). Both observed data and simulations of future climate conditions, performed via General Circulation Models (GCMs), indicated that the effect of warming is and will also likely be unequally distributed around the globe, with some areas more prone to climate change than others. In view of these predictions, particular attention should be paid to the Mediterranean region. As supported by both trend analyses

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of the last 50 years (Kostopoulou and Jones 2005) and by GCM simulations for the next decades (Giannakopoulos et al. 2009), the Mediterranean region has been indicated as a possible hotspot for the decades to come. Climate change over this region is shown to be characterized by both increasing temperatures and by relatively large changes in the frequency of extreme climatic events for both temperature and rainfall. Heat stress frequency and dry spell periods are following a positive trend, whereas the number of frost events is decreasing. The amount of rainfall per event has been shown to be increasing, and changes in the distribution of seasonal rainfall have also been recorded. These trends are expected to have a negative impact on many economic sectors of the region including agriculture, forestry, energy consumption and tourism (Hanson et al. 2007). The agricultural and food systems represent one of the most sensitive and vulnerable sectors of the area. Considering the socio-economic importance of these two systems, it is fundamental to assess the effects of future climate change on crop yield (Bindi and Olesen 2011). For this purpose, crop growth simulation models have been widely used (Donatelli et al. 2002). These tools permit the evaluation of crop responses to climate change by combining climate conditions, obtained from observations or General or Regional Circulation Models (GCMs and RCMs, respectively), with the fertilization CO<sub>2</sub> physiological effects, as derived from crop experiments (Ainsworth and Long 2005; Kimball et al. 2002). However, even though many crop simulation studies have been conducted on the major crops (soft wheat, maize, potato, rice, etc.), only a few studies have been focused on typical Mediterranean crops like durum wheat, vegetables, olive, grapevine, etc. (Guereña et al. 2001; Moriondo et al. 2010, 2011b; Ferrise et al. 2011; Bindi et al. 1996, Giannakopoulos et al. 2009). In certain areas, these crops cover a relevant part of the cultivated land (e.g. in Apulia Region “Nuts code: ITF4,” winter durum wheat 337,436 ha, [82% of cereal cultivated area] and tomato 28,409 ha [29% of vegetable cultivated area]) (ISTAT 2009). These studies generally showed that increasing temperatures shorten the growing season of crops (Guereña et al. 2001; Giannakopoulos et al. 2009; Moriondo et al. 2011a), with a subsequent shorter time for biomass accumulation, thereby also resulting in a lower yield (Bindi et al. 1996; Ferrise et al. 2011). However, changes in yields were also dependent on crop distribution (e.g. summer and winter crops), crop type (e.g. C3 and C4 plants) and environmental conditions (water and nutrient availability) (Giannakopoulos et al. 2009).

Among the crop simulation models that have been used for assessing the impact of climate change on agricultural crops, the DSSAT model (Jones et al. 2003) has been most successfully used worldwide over the last 15 years (Dettori

et al. 2011; Lazar and Lazar 2010; Knox et al. 2010; Persson et al. 2009; Jin and Zhu 2008; Meza et al. 2008; Brassard and Singh 2008; Sarkar and Kar 2008; Soltani and Hoogenboom 2007; Kalra et al. 2007; Diagana et al. 2007; Alexandrov and Eitzinger 2005; Eitzinger et al. 2003; Holden et al. 2003; Guereña et al. 2001; Alexandrov and Hoogenboom 2000; Kapetanaki and Rosenzweig 1997).

Building on these premises, this study aims at evaluating the impact of climate change on two typical Mediterranean crops, winter durum wheat (*Triticum turgidum* L., subs. *durum* [Desf.]) and tomato (*Lycopersicon esculentum* L.) using the Decision Support System for Agrotechnology Transfer (DSSAT) v4.0 crop model (Jones et al. 2003). The model was applied in the Apulia region (southern Italy), where both winter durum wheat and tomato represent a large part of the regional agricultural production. The impacts of climate change, as well as the possible beneficial effects of adaptive strategies, such as irrigation and fertilization, were evaluated considering two contrasting climatic change horizons. In the first scenario, mitigation strategies are considered and the global average temperature is restricted to +2°C (above pre-industrial levels). The +2°C is considered to be the critical climatic threshold, beyond which climate change impacts are predicted to become unacceptably negative (IPCC 2007b). In the second scenario, mitigation strategies are not considered and as a result climate can continue to change unchecked up to +5°C.

The results were discussed by considering the possible interactions between the effects of climate, irrigation and fertilization, respectively, on crop yield for winter durum wheat and tomato.

## Materials and methods

### Study area

The impact study was focused on the “Capitanata area” (Lat. 41.76–42.45N, Long. 14.97–15.62E, Fig. 1) of approximately 4000 km<sup>2</sup>, which is located in the northern part of the Apulia Region in southern Italy. The area, with an elevation of 90 m a.s.l., is predominantly cultivated with winter durum wheat, which is grown in a 3–4-year rotation scheme with either tomato or sugar beet. The “Capitanata” is considered one of the most important areas in Italy for the production of winter durum wheat and tomato and, secondarily, for other crops such as cabbage, olive and grapes. Typically, the soils are deep, clay or silty-clay, and vertisol of alluvial origin. The climate is classified as an “accentuated thermomediterranean” (Unesco-FAO classification), with temperatures that may fall below 0°C in winter and exceed 40°C in summer. Rainfall is unevenly

distributed throughout the year and is mostly concentrated in the winter months with a long-term annual average of 550 mm.

#### Weather data and climate scenarios

For the 1975–2005 time period, observed daily data ( $T_{\min}$ ,  $T_{\max}$ , rainfall and global solar radiation) were extracted for the closest grid ( $50 \times 50$  km) from the MARS JRC archive (MARS project <http://mars.jrc.ec.europa.eu/>). For the future, time slices were centred over the 2030–2059 (+2°C) and 2070–2099 (+5°C) time periods, respectively. The daily data ( $T_{\min}$ ,  $T_{\max}$ , rainfall and global solar radiation) were obtained from HadCM3 experiment for the A2 SRES IPCC (New 2005).

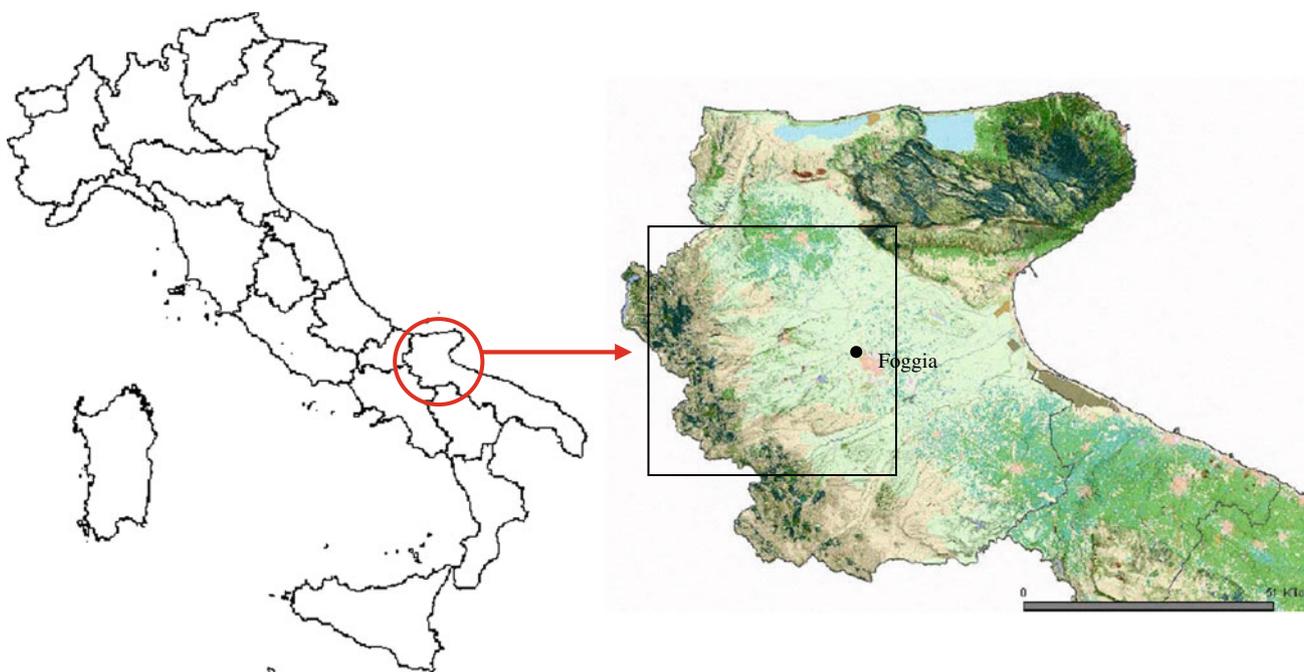
In order to overcome the problem of the coarse original HadCM3 GCM resolution, a statistical downscaling procedure, based on the LARS Weather Generator (Semenov and Barrow 1997; Semenov 2007), was adopted. In particular, for the present time, observed daily data, extracted from MARS JRC archive, were used for the local calibration of the LARS weather generator and for producing synthetic daily weather data representing the Baseline scenario. For the two future time slices, daily data HadCM3 were used to calculate the perturbing variables of LARS-WG (monthly precipitation, temperature and solar radiation changes, as well as changes in both the length of the wet and dry series and changes in the standard

deviation of temperature) and were also used for producing synthetic daily weather data representing +2°C (Anomaly\_2) and +5°C (Anomaly\_5) future scenarios.

Mean monthly maximum and minimum temperatures, solar radiation and rainfall of Baseline (1975–2005) and future climate scenarios (Anomaly\_2 and Anomaly\_5) are shown in the Fig. 2. Compared to the Baseline scenario, mean annual  $T_{\max}$  was projected to increase by 2.3 and 5.5°C in Anomaly\_2 and Anomaly\_5, respectively. A similar trend was also observed for the mean annual  $T_{\min}$ , with rising values about 1.7 and 4.2°C in Anomaly\_2 and Anomaly\_5, respectively. Instead, for rainfall, a 10.4 and 20.9% mean reduction in annual rainfall was predicted for Anomaly\_2 and Anomaly\_5 scenarios.

#### Crop simulation models

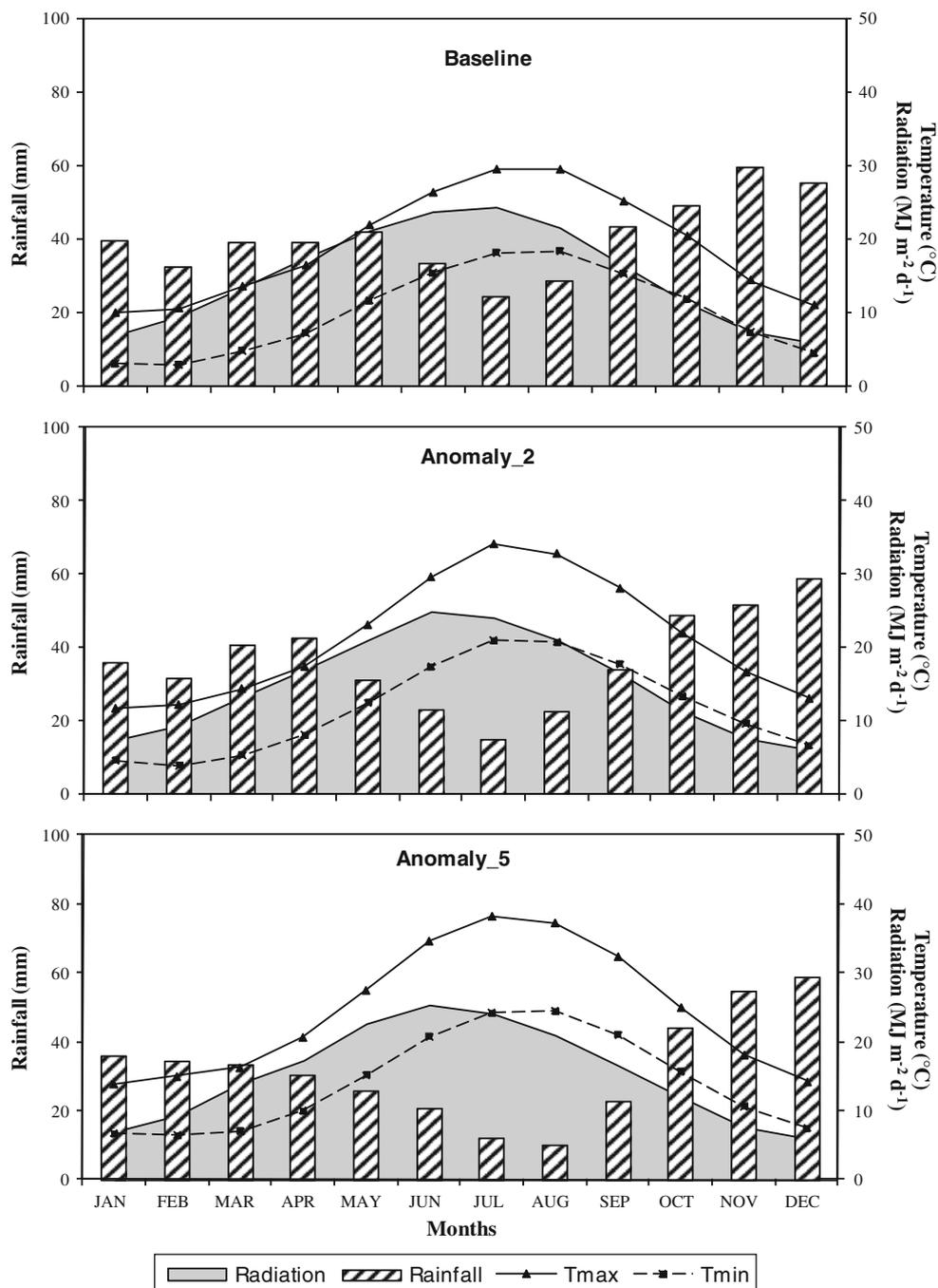
The CERES-Wheat and CROPGRO models, both included in the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.0 software program (Jones et al. 2003), were used in this study to perform crop yield simulations of winter durum wheat and tomato, respectively. The two cropping system models were previously calibrated and validated in the test area for winter durum wheat (cv. Simeto; Rinaldi 2001) and tomato (cv. PS 1296; Rinaldi et al. 2007). The calibration and validation of the models were carried out in a CRA-SCA Experimental Farm in Foggia, Italy (41°26'N, 15°30'E, 90 m above sea



**Fig. 1** The Capitanata area (from <http://www.cartografico.puglia.it>) with the *box* showing the grid cell utilized in this study. The *point* indicates the experimental farm where the models were calibrated and

validated. The area around Foggia represents irrigated or nor irrigated arable lands mostly cultivated with winter wheat and vegetables

**Fig. 2** Monthly averages of air temperature (maximum and minimum), solar radiation and rainfall of the three scenarios: Baseline, Anomaly\_2 and Anomaly\_5



level), on a representative soil of the study area, which has a clay-loam texture with an alluvial origin, as classified by the Soil Taxonomy-USDA as a fine, mesic, Typic Chromoxerert (Soil Survey Staff 1992). Soil properties, used as input for the models, are provided in Table 1.

CERES and CROPGRO are considered the two primary crop models in the DSSAT software package and represent the most physiologically based agronomic models available in recent times. Above all, they represent dynamic simulation models that simulate the impacts of weather,

soil properties, genotype and management on daily crop phenological development and growth, as well as on the dynamics of soil water and nitrogen. Both models calculate potential biomass accumulation as the product of radiation use efficiency and intercepted photosynthetically active radiation (PAR). The percentage of incoming PAR intercepted by the canopy is an exponential function of leaf area index (LAI).

To run CERES and CROPGRO models, minimum inputs are required and these include weather, soil

**Table 1** Soil properties used as input for DSSAT models

Soil layer (cm)	SLLL	SDUL	SSAT	SRGF	SBDM	SLOC	SLCL	SLSI	SLNI	SLHW
0–20	0.24	0.42	0.55	1.00	1.04	1.50	48.5	38.7	0.13	8.4
21–40	0.24	0.42	0.55	0.80	1.17	1.50	48.5	38.7	0.13	8.4
41–60	0.24	0.42	0.56	0.20	1.27	1.04	54.4	34.5	0.10	8.5
61–80	0.20	0.36	0.56	0.10	1.30	0.93	54.4	37.1	0.07	8.5
81–130	0.20	0.36	0.56	0.05	1.30	0.93	54.4	37.1	0.07	8.5

*SLLL* soil water at lower limit ( $\text{cm}^3/\text{cm}^3$ ), *SDUL* soil water at drained upper limit ( $\text{cm}^3/\text{cm}^3$ ), *SSAT* soil water at saturated upper limit ( $\text{cm}^3/\text{cm}^3$ ), *SRGF* root growth factor (–), *SBDM* soil bulk density, moist ( $\text{g}/\text{cm}^3$ ), *SLOC* soil organic carbon (%), *SLCL* clay (%), *SLSI* silt (%), *SLNI* total soil nitrogen (%), *SLHW* soil pH in water

properties, plant characteristics and experimental data. The minimum daily weather dataset requirements of the model are solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ), rainfall (mm) and  $T_{\min}$  and  $T_{\max}$  ( $^{\circ}\text{C}$ ).

In our study, the 50 km  $\times$  50 km daily weather data obtained from the LARS Weather Generator ( $T_{\min}$ ,  $T_{\max}$ , rainfall and solar radiation) were used as input variables for the crop models (DSSAT) for the three different climate scenarios (Baseline, Anomaly\_2 and Anomaly\_5). In order to consider the  $\text{CO}_2$  fertilization effect, three increasing atmospheric concentrations were selected: 360, 550 and 700 ppm for the 1975–2005 period (Baseline), Anomaly\_2 and Anomaly\_5, respectively.

#### Adaptation strategies

To evaluate the effect of agronomical adaptation strategies (irrigation in interaction with nitrogen fertilization) under future climate change, different management scenarios were compared for the two crops. For winter durum wheat (cv. Simeto), the following treatments were applied: (1) rainfed; (2) automatic irrigation using a sprinkler method, programmed to operate when 10% of the available crop water (CAW) in the upper 0.5 m of the soil depth is depleted (IRR10); (3) 60 kg of  $\text{N ha}^{-1}$  (Low N), and (4) 120 kg of  $\text{N ha}^{-1}$  (High N). For both nitrogen treatments, N fertilization was scheduled in two equal applications, before sowing with ammonium phosphate and as a top dressing with ammonium nitrate.

For tomato (hybrid PS 1,296, globe-shaped fruits), four irrigation scenarios in interaction with two N fertilization treatments were applied. To start the automatic irrigation, as a drip method, the thresholds of CAW were fixed to 20 (IRR20), 40 (IRR40), 60 (IRR60) and 80% (IRR80). Similarly, for winter durum wheat, “Low N” and “High N” fertilization regimes were considered, with 100 and 200  $\text{kg ha}^{-1}$ , distributed in two applications, at pre-transplanting and top dressing using ammonium phosphate and ammonium nitrate, respectively.

In both crop simulations, identical initial soil moisture conditions (60% of crop available soil water) were used.

The harvest date was also simulated by the model at crop maturity. In addition, the simulation option was set for using the Priestley and Taylor method in order to estimate potential evapotranspiration. Fixed sowing dates for both crops and the three climate scenarios were imposed (26th November [330 DOY] for winter durum wheat, 30th April [120 DOY] for planting tomato). Crop management options adopted in this study were relative to those generally practiced by the local farmers in the study area.

#### Assessment of uncertainties

As regards the climate change scenarios inferred from GCMs, uncertainties are associated with imperfect knowledge and/or representation of physical processes, limitations due to the numerical approximation of the model's equations, simplifications and assumptions in the models and/or approaches, internal model variability, and inter-model or inter-method differences in the simulation of climate response to given forcing. Reducing the wide range of uncertainty inherent in projections of global and regional climate change will require major advances in our scientific understanding on the subject in the years to come. Projections about the probability, frequency and severity of extreme weather events should be carefully evaluated (Mall et al. 2006).

In this paper, uncertainties in model estimates, attributable to different climate scenarios and agronomic practices related to nitrogen fertilization and irrigation, were assessed by analysis of variance using the GLM procedure of the Statistical Analysis System, SAS Institute (1996).

## Results

### Winter durum wheat responses

#### Phenology

Under the two future climate scenarios, higher temperatures induced a reduction in the phenological cycle of

winter durum wheat. This reduction was higher in the vegetative cycle (i.e. sowing-anthesis phase: up to -30 days under Anomaly\_5 scenario), whereas in the reproductive cycle (i.e. anthesis-maturity phase) reductions were negligible (up to 3–4 days). Consequently, the seasonal length reduction determined a decrease in seasonal evapotranspiration (-8 and -21% under Anomaly\_2 and Anomaly\_5, respectively), which, however, was a very small effect of daily water requirement (Table 2).

### Crop biomass

The effects of climate change, irrigation and N fertilization on the principle crop biomass parameters were reported in Table 3. The statistical analysis showed that the three effects, and their respective interactions, were highly significant, with the exception of those for “Climate × Nitrogen” and “Climate × Nitrogen × Irrigation.”

**Climate change** Changes in temperature, precipitation and CO<sub>2</sub> atmospheric concentration were predicted to increase in grain yield of about 10% under Anomaly\_2 scenario and a reduction of about 8% under Anomaly\_5 scenario. The same trends were observed for the other biomass parameters (total dry matter, grain number, LAI) (Table 3).

**Nitrogen applications** Nitrogen fertilization showed that High N treatment (120 kg ha<sup>-1</sup>) significantly increased all biomass parameters (from +33% for biomass to +44% for LAI) (Table 3). However, High N also resulted in a concomitant increase in the variability of inter-annual yield.

**Irrigation treatment** Irrigation significantly increased all biomass parameters (from +12% for LAI to +75% for total biomass). In addition, irrigation had a strong effect not only on the mean grain yields, but also on the inter-annual variability of grain yields with reductions ranging from 40 to 10% (Table 3).

**Interaction “Nitrogen × Climate”** To better understand the importance of irrigation, the irrigation efficiency (IE) was calculated according to the following equations:

$$IE = 100 \frac{Y_{\text{irrigated}} - Y_{\text{rainfed}}}{Y_{\text{rainfed}}} \quad (1)$$

IE significantly decreased from Baseline to the future scenarios, regardless of nitrogen levels (Table 4).

**Interaction “Nitrogen × Irrigation × Climate”** When all effects (interaction “Nitrogen × Irrigation × Climate”) were considered, the highest grain yield was obtained under non-limiting conditions for water and nitrogen (High N level and IRR10) under both present and future climate scenarios (Fig. 3). Grain yields under Anomaly\_2 scenario were similar or slightly higher (but not significantly) than those obtained when compared to the Baseline one. On the contrary, at higher input levels, the Anomaly\_5 scenario showed a significant yield reduction of more than 20%. These trends in grain yields for the different scenarios, irrigation levels and N treatments were explained by the very similar trends of the number of kernels per m<sup>2</sup> (Fig. 4). This demonstrated that the expected increase in temperature and reduction in precipitation during flowering and grain development (i.e. from the end of April to middle May, Fig. 2) had strong negative effects on durum wheat yields.

### Tomato responses

#### Phenology

The length of both vegetative and reproductive tomato phenological cycles was rather strongly affected by climate change. The Anomaly\_5 scenario was characterized by a greater shortening of the cycle than the Anomaly\_2 scenario with reduction of about 14 versus 5 days and 10 versus 8 days in the vegetative and reproductive cycles, respectively (Table 5). These reductions in the length of the phenological cycles counterbalanced the increase in evaporative demand of the atmosphere due to the warmer conditions, thus the seasonal evapotranspiration was very similar in all the three climate scenarios. Daily water requirement, however, showed an increment of approximately 10 and 30% under the Anomaly\_2 and Anomaly\_5 scenarios, respectively (Table 5).

**Table 2** Averages of cycle length, seasonal and daily evapotranspiration of durum wheat simulated by CERES-Wheat model as a function of climate scenarios

Climate scenarios	Season length (day)		Seasonal ETp (mm)	Daily ETp (mm d <sup>-1</sup> )
	Sowing-anthesis	Anthesis-maturity		
Baseline	152.8	45.1	484.7	2.40
Anomaly_2	140.7	47.0	446.1	2.33
Anomaly_5	122.3	48.5	391.3	2.24

**Table 3** Averages and standard deviations of durum wheat yield simulated by CERES-Wheat model as a function of climate scenarios, nitrogen fertilization and irrigation management

	Grain yield (t ha <sup>-1</sup> )	Total dry matter (t ha <sup>-1</sup> )	Grain number 10 <sup>3</sup> (N° m <sup>-2</sup> )	LAI (cm <sup>2</sup> cm <sup>-2</sup> )
<i>Climate effect</i>				
Baseline	4.32 ± 1.09	11.81 ± 2.92	9.93 ± 2.55	2.15 ± 0.54
Anomaly_2	4.79 ± 0.98	13.42 ± 2.61	11.11 ± 2.26	2.12 ± 0.41
Anomaly_5	3.99 ± 0.95	11.79 ± 2.50	9.31 ± 2.18	1.78 ± 0.26
<i>Nitrogen effect</i>				
N_Low	3.73 ± 0.82	10.60 ± 2.29	8.61 ± 1.89	1.61 ± 0.29
N_High	5.01 ± 1.20	14.09 ± 3.06	11.63 ± 2.77	2.31 ± 0.52
<i>Irrigation effect</i>				
Rainfed	3.66 ± 1.53	8.97 ± 4.21	8.55 ± 3.57	1.90 ± 0.61
IRR10	5.08 ± 0.49	15.71 ± 1.15	11.69 ± 1.09	2.13 ± 0.20
Climate (C)	***	***	***	***
Nitrogen (N)	***	***	***	***
Irrigation (I)	***	***	***	***
C × N	n.s.	n.s.	n.s.	n.s.
C × I	***	***	***	***
N × I	***	***	***	***
C × N × I	n.s.	n.s.	n.s.	n.s.

Significance of main effects and their interactions are reported

n.s. not significant

\*\*\*  $P \leq 0.001$

**Table 4** Irrigation efficiency of durum wheat simulated by CERES-Wheat model under climate scenarios

Climate scenarios	Low N	High N
Baseline	52	65
Anomaly_2	30	37
Anomaly_5	24	27

### Crop biomass

All the biomass parameters analysed revealed that the effects of climate change, irrigation and N application, as well as their respective interactions, were highly significant (Table 6).

**Climate change** Under the future climate scenarios, the model simulated negative effects on tomato yield (a decrease in fruit dry matter of approximately 10 and 26% in the Anomaly\_2 and Anomaly\_5 scenarios, respectively). Similar trends were also observed for the harvest index (HI) and total dry matter. However, this latter parameter was much less reduced compared to the Baseline (−2 and −5% under Anomaly\_2 and Anomaly\_5, respectively). Moreover, due to rising temperature that determined more favourable conditions for vegetative growth than fruit growth, the maximum leaf area index (LAI<sub>max</sub>) was

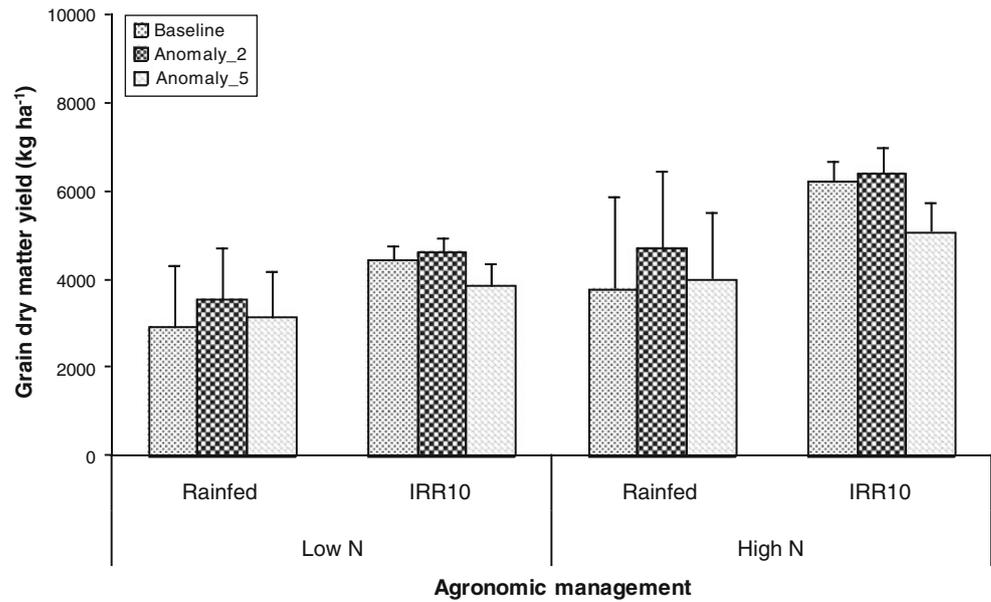
predicted to increase from 3.4 (Baseline) to 3.7 (Anomaly\_5) under future scenarios.

**Nitrogen applications** As predicted, increasing N fertilizer levels significantly improved tomato yields. In particular, the High N level (200 kg ha<sup>-1</sup>) significantly increased fruit yield, total dry matter, HI and LAI<sub>max</sub> values (+48, +32, +10 and +31%, respectively), in comparison with the values obtained with the low N level (Table 6).

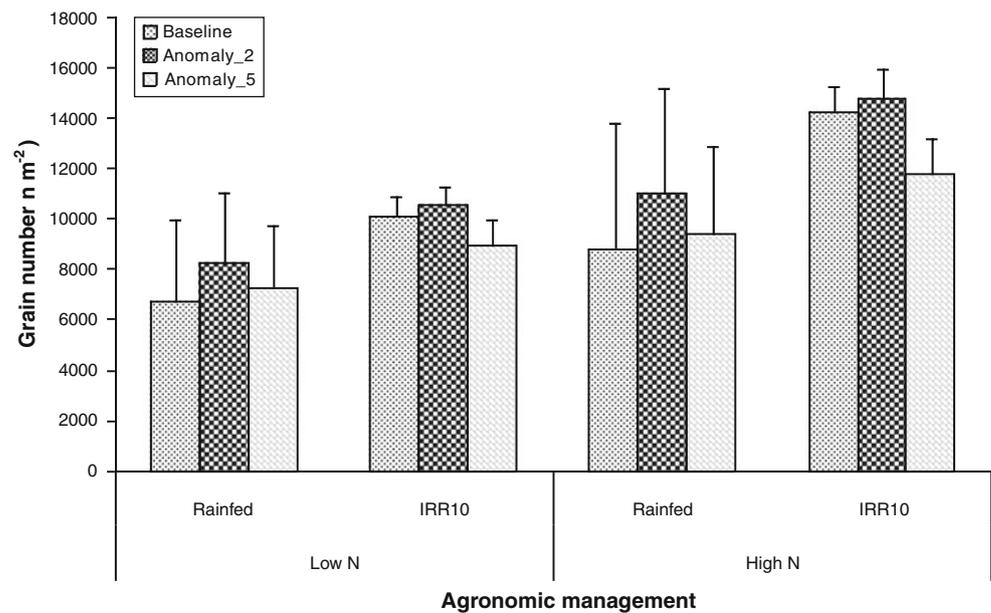
**Irrigation treatment** The maximum effect of irrigation treatments was obtained with IRR40 and IRR60 with yields of around 7 t ha<sup>-1</sup> and total dry biomass around 16 t ha<sup>-1</sup>. A further increase in the amount of added water did not produce any increase in yields, but actually resulted in a decrease (fruit yield of 6.6 t ha<sup>-1</sup>) (Table 6).

**Interaction “Climate × Nitrogen × Irrigation”** Figure 5 showed the effects of the interaction “Climate × Nitrogen × Irrigation” on tomato fruit yield. The response functions with increasing irrigation volumes were different in the three scenarios. In the Baseline scenario, the yield response to increasing water supply was almost linear and become curvilinear in the two future scenarios. A curvilinear trend in the yield response curves for future scenarios, more evident for Anomaly\_5, can be attributed to a

**Fig. 3** Effects of irrigation and N fertilization on simulated grain dry matter yield of winter durum wheat under climate change scenarios. The bars represent the standard deviations



**Fig. 4** Effects of irrigation and N fertilization on simulated grain number yield of wheat under climate change scenarios. The bars represent the standard deviations



**Table 5** Averages of cycle length, seasonal and daily evapotranspiration of tomato simulated by CROPGRO model as a function of climate scenarios

Climate scenarios	Season length (day)		Seasonal ETp (mm)	Daily ETp (mm d <sup>-1</sup> )
	Planting-flowering	Flowering-maturity		
Baseline	43.5	78.0	710.4	5.85
Anomaly_2	38.4	69.5	697.4	6.46
Anomaly_5	29.6	68.0	741.8	7.60

lowering of the threshold, compared to the Baseline scenario. The lowering of a threshold beyond a certain point means that other factors became the main limiting factor of crop growth (e.g. high temperature shortening of crop cycle

and photosynthetic activity). Moreover, the negative yield trend for CAW higher than 60%, under future scenarios can be explained by the reduction of crop water uptake that determined conditions of wet soil and losses of water by

**Table 6** Averages and standard deviations of tomato production simulated by CROPGRO model as a function of climate scenarios, nitrogen fertilization and irrigation management

Climate scenarios	Fruit dry matter (t ha <sup>-1</sup> )	Total dry matter (t ha <sup>-1</sup> )	HI	LAI (m <sup>2</sup> m <sup>-2</sup> )
<i>Climate effect</i>				
Baseline	7.65 ± 0.40	16.75 ± 0.76	0.45 ± 0.02	3.45 ± 0.52
Anomaly_2	6.93 ± 0.49	16.41 ± 0.78	0.42 ± 0.02	3.53 ± 0.59
Anomaly_5	5.63 ± 0.87	15.94 ± 0.83	0.35 ± 0.06	3.71 ± 0.58
<i>Nitrogen effect</i>				
N_Low	5.44 ± 0.48	14.12 ± 0.70	0.39 ± 0.03	3.09 ± 0.47
N_High	8.04 ± 0.70	18.62 ± 0.88	0.43 ± 0.04	4.04 ± 0.66
<i>Irrigation effect</i>				
IRR20	6.09 ± 0.81	15.61 ± 1.30	0.39 ± 0.06	3.28 ± 0.95
IRR40	7.08 ± 0.44	16.30 ± 0.65	0.43 ± 0.02	2.60 ± 0.46
IRR60	7.13 ± 0.43	16.57 ± 0.54	0.43 ± 0.02	3.18 ± 0.28
IRR80	6.65 ± 0.67	16.99 ± 0.67	0.39 ± 0.04	5.19 ± 0.55
Climate (C)	***	***	***	***
Nitrogen (N)	***	***	***	***
Irrigation (I)	***	***	***	***
C × N	***	***	***	***
C × I	***	***	***	***
N × I	***	***	***	***
C × N × I	***	***	***	***

Significance of main effects and their interactions are reported

*n.s.* not significant

\*\*\*  $P \leq 0.001$

drainage. The linear component of the equations, reported in Fig. 5, increased significantly from the scenario in the Baseline to the Anomaly\_2 and Anomaly\_5 scenarios, respectively (for High Nitrogen condition 14.1, 123.7 and 240.6 kg ha<sup>-1</sup>%<sup>-1</sup>, respectively). This increase was attributable to the response to increased potential evapotranspiration characterizing the three scenarios. Similar HI relationships, in function of irrigation scheduling, were obtained (data not shown), indicating that both heat and water stresses influenced the translocation of assimilates to the tomato fruit.

As regards the irrigation quantity in relation to the irrigation scheduling, the seasonal irrigation depth increased linearly with increasing irrigation threshold, reaching values between 400 and 600 mm (Fig. 6). Meanwhile, the relationship between water use efficiency of the fruit dry matter (WUE) and irrigation scheduling indicated that there was a significant deviation of linearity between WUE and irrigation supplies. This was particularly evident for Anomaly\_5, followed by Anomaly\_2 (Fig. 7). Even in this case, 40 and 60% of CAW were respectively demonstrated to be the best irrigation treatments in order to achieve the maximum values of WUE under different climate scenarios.

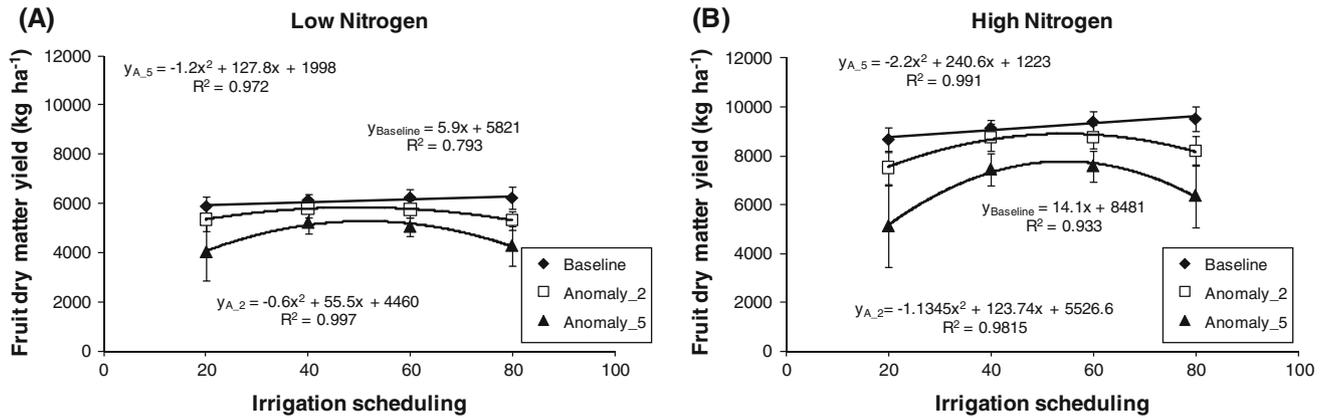
Finally, the relationship between fruit yield and total applied water (precipitation and irrigation) and then between fruit yield and irrigation water are shown in Figs. 8 and 9, respectively. In the first case, the response functions were demonstrated to move progressively

downwards from the Baseline scenario to Anomaly\_5, indicating a progressive yield reduction due to expected climate change. Analysing the tomato yield in function of irrigation (Fig. 9), it is evident that the response functions moved, not only downwards, but also to the right, thereby indicating both yield reductions and a significant increase in irrigation requirement. In particular, in Anomaly\_2, with irrigation depths of 450–500 mm, it was possible to obtain the same fruit yield as that shown for the Baseline. However, under Anomaly\_5, the fruit yield was significantly lower than that obtained in the Baseline, even at 550 mm.

## Discussion

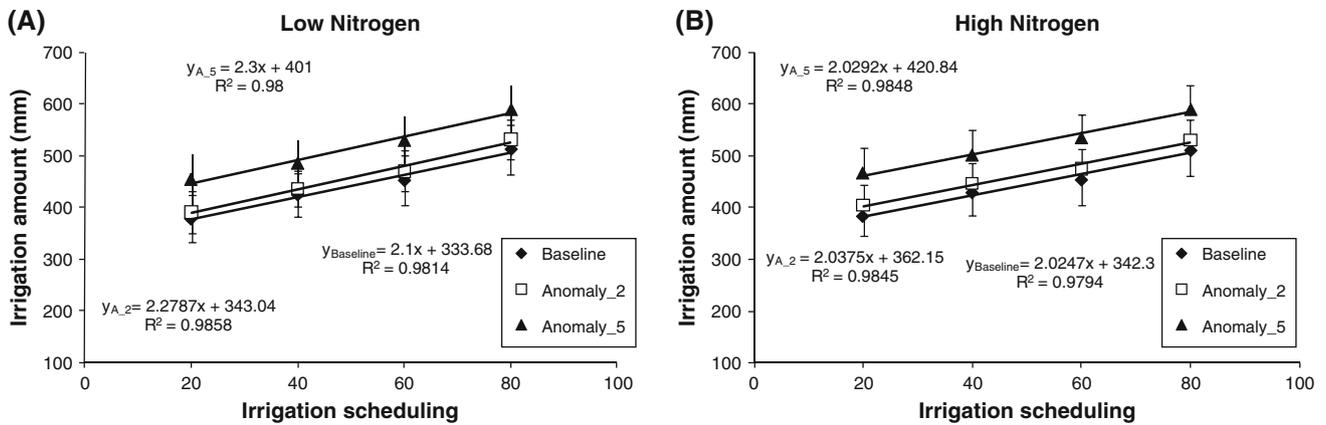
### Winter durum wheat

The simulations for winter durum wheat showed that, for an increase of +2°C, the positive fertilization effect of increasing CO<sub>2</sub> concentration on durum wheat yields was greater than the negative effects due to rising temperature and declining rainfall. These results were in agreement with those reported in the FAR-IPCC report (IPCC 2007b). The latter report indicated how +2°C may represent a threshold level, up to which the effects of climate change will be minimal in many areas of the globe for many agricultural crops. Similar results were also obtained in many other studies. Attri and Rathore (2003) reported different wheat genotype responses under climate change



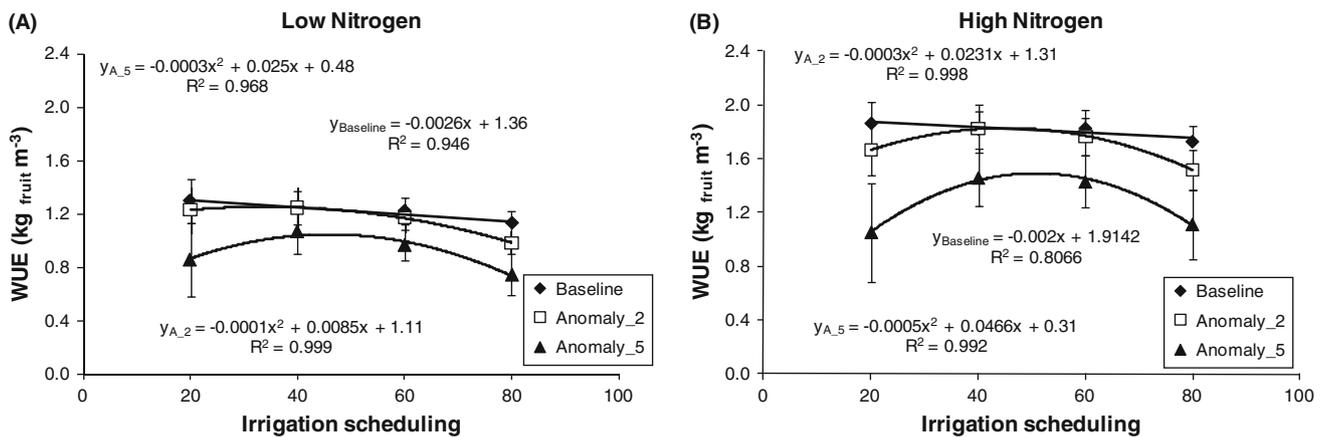
**Fig. 5** Relationship between fruit dry matter yield of tomato and irrigation scheduling (% of soil water content to trigger automatic irrigation), when low (a) and high (b) N fertilizers were applied under

the three climate change scenarios. The lines represent the linear or curvilinear regressions fitted to simulated values. The equations are also reported with the respective regression coefficients



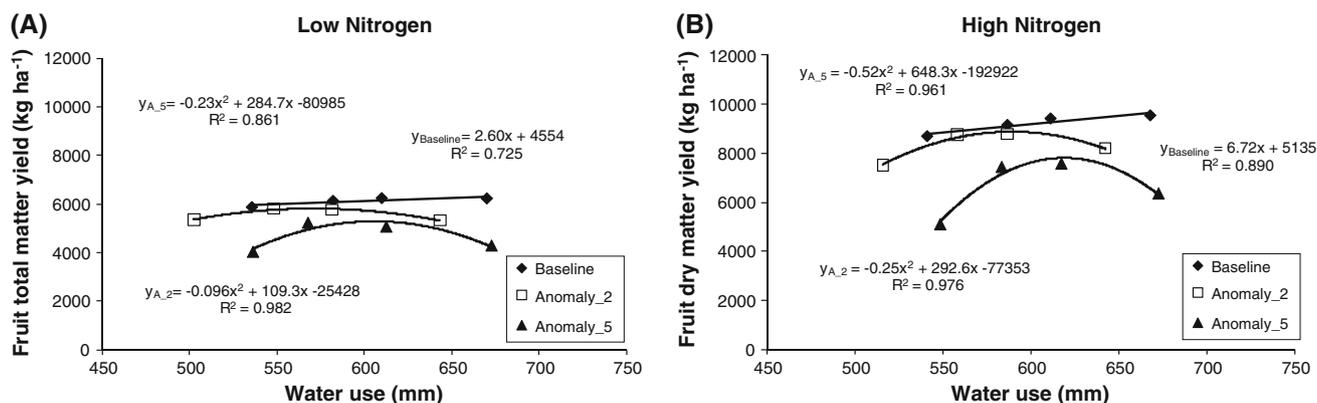
**Fig. 6** Relationship between irrigation amount and irrigation scheduling (% of soil water content to trigger automatic irrigation), when low (a) and high (b) N fertilizers were applied under the three climate

change scenarios. The lines represent the linear or curvilinear regressions fitted to simulated values. The equations are also reported with the respective regression coefficients



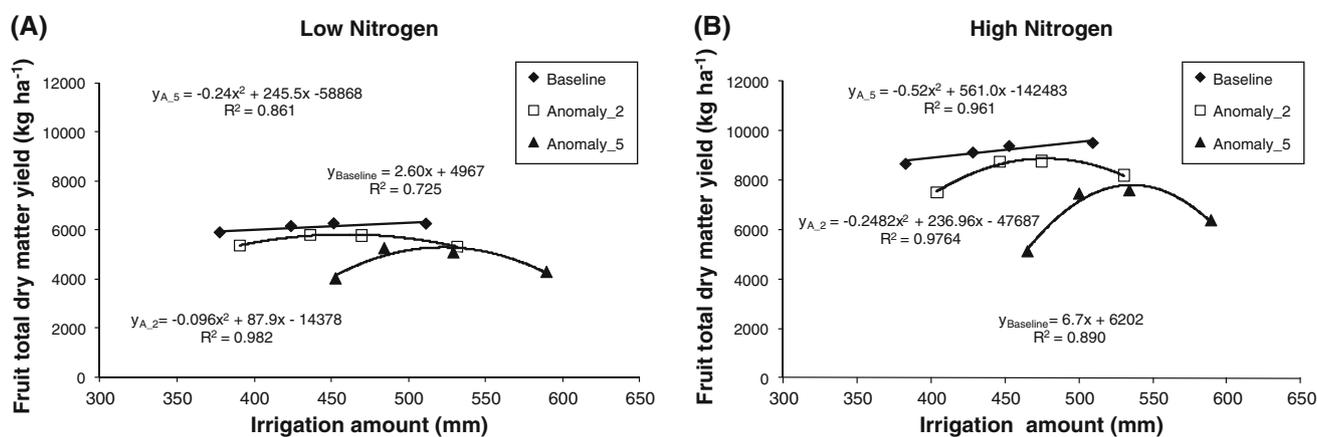
**Fig. 7** Relationship between WUE in fruit yield and irrigation scheduling (% of soil water content to trigger automatic irrigation), when low (a) and high (b) N fertilizers were applied under the three

climate change scenarios. The lines represent the linear or curvilinear regressions fitted to simulated values. The equations are also reported with the respective regression coefficients



**Fig. 8** Fruit total dry matter yield as a function of water use (irrigation + precipitation), when low (a) and high (b) N fertilizers were applied under the three climate change scenarios. The lines

represent the linear or curvilinear regressions fitted to simulated values. The equations are also reported with the respective regression coefficients



**Fig. 9** Fruit total dry matter yield as a function of irrigation amount, when low (a) and high (b) N fertilizers were applied under the three climate change scenarios. The lines represent the linear or curvilinear

regressions fitted to simulated values. The equations are also reported with the respective regression coefficients

in rainfed and irrigated conditions. In that study, it was shown that for temperature increases up to +2.0–2.5°C, the yield responses were still positive, whereas for increases of 3°C or the more positive effects of elevated CO<sub>2</sub>, the wheat yield was completely overcome by the negative climate effects. Tubiello et al. (2000) showed that for the same study area (i.e. Foggia Province), wheat yields decreased by 30–50% as a result of a 4°C increase in temperature. Additionally, in a study carried out by Ferrise et al. (2011) for the entire Mediterranean basin, the projected warmer and drier climate is predicted to increase the risk of yield losses especially for temperature increases exceeding 2°C.

However, such findings were focused on the effect on wheat yields, mostly determined by temperature, rainfall and CO<sub>2</sub> concentration without considering the importance of taking into account the interactions with agronomical practices, such as nitrogen fertilization and irrigation, that can modify the crop response to climate change. This behaviour was in agreement with that reported by El

Afandi et al. (2010), for the middle Egypt area under A2-B2 climate change scenarios, in which the adoption of correct irrigation scheduling may be used to reduce the negative impact on heat yields due to higher temperature and lower rainfall.

#### Tomato

The simulations for tomato showed that for both future climate scenarios (i.e. +2°C and +5°C), the positive fertilization effect of increasing CO<sub>2</sub> concentration was not sufficient to overcome the negative effects determined by increasing temperature and reducing rainfall. These results also highlighted that summer crops, including tomato, may be strongly affected by climate change that in this very important agricultural area of Italy. Unfortunately, studies on the response of tomato to climate change are very limited. However, the studies carried out by Dane et al. (1991) and Tshiala and Olwoch (2010) showed how high

temperature may be considered the primary cause of significant losses in tomato yield and quality (Dane et al. 1991). In particular, Tshiala and Olwoch (2010) reported that temperatures exceeding 25°C were likely to reduce tomato yield. Assuming a non-linear yield response to air temperature, for a ~1°C rise in temperature above 25°C, tomato yields may decline by about 10%.

This trend, with an higher impact of climate change on summer crops than on winter crops, was also found in studies conducted on other crops in Mediterranean countries, such as legumes, sunflower (Giannakopoulos et al. 2009; Moriondo et al. 2010, 2011a) and soybean (Moriondo et al. 2010).

The modification of present management strategies (e.g. irrigation scheduling) showed that an increase in the frequency of irrigation treatments (i.e. start the automatic irrigation when soil reached 40 and 60% of crop available water) may reduce the negative effect of climate change on tomato yields. At the same time, however, the results showed that under future climate scenarios tomato yields will be limited more by high temperature than by water availability. In particular, under both future climate scenarios it was predicted that any further addition of water above that provided by the irrigation treatment IRR40 would not produce any increase in tomato yields since high temperature was the limiting factor shortening both crop cycle and photosynthetic activity.

## Conclusions

This simulation study has provided details relating to the responses of crops under climate change and also how management practices may be used to maximize the crop yield optimizing the application quantities and the time of application during the crop cycle.

The simulation results of the CERES-Wheat and CROPGRO models in one of the most important agricultural areas of Italy (i.e. Capitanata, Apulia Region) led to the conclusion that climate change could negatively affect yields of winter durum wheat and especially those of tomato. The differences in crop responses between the two crops depend on the interaction between crop phenology and climate conditions. In particular, in autumn–winter crops, such as durum wheat, a shorting in phenology would restrict the crop-growing cycle to the wet seasons in order to avoid the extremely high temperatures predicted in the future scenarios for the summer months. Moreover, in the future scenarios, the phenological cycle of spring crops would occur in a period of the year (from April until August) that will be characterized by higher variability in minimum and maximum temperatures compared to Baseline scenario (data not shown).

These negative effects of climate change could be attenuated by the application of adaptation strategies, such as the management techniques of irrigation and nitrogen fertilization. However, the climatic conditions of the most pessimistic scenario, Anomaly\_5, dramatically reduced the possibilities of adaptation for the cultivation of tomato more markedly than those observed for winter durum wheat.

Limiting the global mean temperature change of 2°C (above pre-industrial levels) may permit the application of appropriate adaptation strategies in order to reduce the negative effects of climate change on crop productivity to acceptable levels, particularly for the spring–summer crops, such as tomato that appears to be more sensitive to climate change than the winter durum wheat in southern Italy. For a temperature change of around 5°C, environmental conditions are likely to exceed the adaptation capacity of the investigated crop cultivars and, at least for tomato cultivation in southern Italy, it would not be possible to restore the yield level of the Baseline. However, this conclusion does not take into account the possible and wished-for genetic progress that could expand the plasticity of the plants by increasing their ability to adapt to high temperatures and CO<sub>2</sub> concentrations.

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## References

- Ainsworth EA, Long SP (2005) What have we learned from 15 years of free-air CO<sub>2</sub> enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO<sub>2</sub>. *New Phytol* 165:351–372
- Alexandrov VA, Eitzinger J (2005) The potential effect of climate change and elevated air carbon dioxide on agricultural crop production in central and south-eastern. *J Crop Improv* 13:291–331
- Alexandrov VA, Hoogenboom G (2000) The impact of climate variability and change on crop yield in Bulgaria. *Agr For Meteorol* 104:315–327
- Attri SD, Rathore LS (2003) Simulation of impact of projected climate change on wheat in India. *Int J Climatol* 23:693–705
- Bindi M, Olesen JE (2011) The responses of agriculture in Europe to climate change. *Reg Environ Change* 11:151–158
- Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F (1996) Modelling the impact of climate scenarios on yield and yield variability of grapevine. *Clim Res* 7:213–224
- Brassard JP, Singh B (2008) Impacts of climate change and CO<sub>2</sub> increase on agriculture production and adaptation options for southern Québec, Canada. *Mitig Adapt Strateg Glob Change* 13:241–265
- Dane F, Hunter AG, Chambliss OL (1991) Fruit set, pollen fertility and combining ability of selected tomato genotypes under high temperature field conditions. *J Am Soc Hort Sci* 116(5):906–910
- Dettori M, Cesaraccio C, Motroni A, Spano D, Duce P (2011) Using CERES-Wheat to simulate durum wheat production and phenology in Southern Sardinia, Italy. *Field Crop Res* 120:179–188

- Diagana B, Antle J, Stoorvogel J, Gray K (2007) Economic potential for soil carbon sequestration in the Niore region of Senegal's Peanut Basin. *Agr Syst* 94:26–37
- Donatelli M, van Ittersum MK, Bindi M, Porter RJ (2002) Modelling cropping systems—highlights of the symposium and preface to the special issues. *Eur J Agron* 18:1–11
- Eitzinger J, Stastna M, Zalud Z, Dubrsky M (2003) A simulation study of the effect of soil water balance and water stress on wheat production under different climate change scenarios. *Agr Water Manag* 61:195–217
- El Afandi G, Khalil FA, Ouda SA (2010) Using irrigation scheduling to increase water productivity of wheat-maize rotation under climate change conditions. *Chil J Agric Res* 70(3):474–484
- Ferrise R, Moriondo M, Bindi M (2011) Probabilistic assessments of climate change impacts on durum wheat in the Mediterranean region. *Nat Hazards Earth Syst Sci* 11:1293–1302
- Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from global warming. *Global Planet Change* 68:209–224
- Guereña A, Ruiz-Ramos M, Diaz-Ambrona CH, Conde J, Mínguez MI (2001) Assessment of climate change and agriculture in Spain using climate models. *Agron J* 93:237–249
- Hanson CE, Palutikof JP, Livermore MTJ, Barring L, Bindi M, Corte-Real J, Durao R, Giannakopoulos C, Good P, Holt T, Kundzewicz Z, Leckebusch G, Moriondo M, Radziejewski M, Santos J, Schlyter P, Schwarb M, Stjernquist I, Ulbrich U (2007) Modelling the impact of climate extremes: an overview of the MICE project. *Clim Change* 81:163–177
- Holden NM, Brereton AJ, Fealy R, Sweeney J (2003) Possible change in Irish climate and its impact on barley and potato yields. *Agr For Meteorol* 116:181–196
- IPCC, 2007a: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, UK, 996 pp.
- IPCC, 2007b: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976 pp.
- ISTAT (2009) Data warehouse dell'Istituto Nazionale di Statistica Italiano
- Jin ZQ, Zhu DW (2008) Impacts of changes in climate and its variability on food production in Northeast China. *Acta Agron Sinica* 34:1588–1597
- Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2003) The DSSAT cropping system model. *Eur J Agron* 18:235–265
- Kalra N, Chander S, Pathak H, Aggarwal PK, Gupta NC, Sehgal M, Chakraborty D (2007) Impacts of climate change on agriculture. *Outlook Agr* 36:109–118
- Kapetanaki G, Rosenzweig C (1997) Impact of climate change on maize yield in Central and Northern Greece: a simulation study with Ceres-Maize. *Mitig Adapt Strateg Glob Change* 1:251–271
- Kimball BA, Kobayashi K, Bindi M (2002) Responses of agricultural crops to free-air CO<sub>2</sub> enrichment. *Adv Agron* 77:293–368
- Knox JW, Rodríguez Díaz JA, Nixon DJ, Mkhwanazi M (2010) A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agr Syst* 103:63–72
- Kostopoulou E, Jones PD (2005) Assessment of climate extremes in the Eastern Mediterranean. *Meteorol Atmos Phys* 89:69–85. doi: [10.1007/s00703-005-0122-2](https://doi.org/10.1007/s00703-005-0122-2)
- Lazar C, Lazar DA (2010) Simulation of temperature increase influence on winter wheat yields and development in South-Eastern Romania. *Roman Agric Res* 27:7–15
- Mall RK, Singh R, Gupta A, Srinivasan G, Rathore LS (2006) Impact of climate change on Indian agriculture: a review. *Clim Change* 78:445–478
- Meza FJ, Silva D, Vigil H (2008) Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. *Agr Syst* 98:21–30
- Moriondo M, Bindi M, Kundzewicz ZW, Szwed M, Chorynski A, Matczak P, Radziejewski M, McEvoy D, Wreford A (2010) Impact and adaptation opportunities for European agriculture in response to climatic change and variability. *Mitig Adapt Strateg Glob Change* 15:657–679
- Moriondo M, Giannakopoulos C, Bindi M (2011a) Climate change impact assessment: the role of climate extremes in crop yield simulation. *Clim Change* 104:679–701
- Moriondo M, Bindi M, Fagarazzi C, Ferrise R, Trombi G (2011b) Framework for high-resolution climate change impact assessment on grapevines at a regional scale. *Reg. Environ Change*. doi: [10.1007/s10113-010-0171-z](https://doi.org/10.1007/s10113-010-0171-z)
- New M (2005) Arctic climate change with a 2°C global warming. In: Rosentrater LD, New M, Kaplan JO, Comiso JC, Watt-Cloutier S et al (eds) Evidence and implications of dangerous climate change in the arctic. WWF International Arctic Program, Oslo, pp 1–15
- Persson T, Garcia y Garcia A, Paz J, Jones J, Hoogenboom G (2009) Maize ethanol feedstock production and net energy value as affected by climate variability and crop management practices. *Agr Syst* 100:11–21
- Rinaldi M (2001) Durum wheat simulation in southern Italy using CERES-Wheat model. I. Calibration and validation. In: Proceedings of the 2nd international symposium on modelling cropping systems, Florence, Italy, July 16–18, pp 81–82
- Rinaldi M, Ventrella D, Gagliano C (2007) Comparison of nitrogen and irrigation strategies in tomato using CROPGRO model. A case study from Southern Italy. *Agr Water Manag* 87:91–105
- Sarkar R, Kar S (2008) Sequence analysis of DSSAT to select optimum strategy of crop residue and nitrogen for sustainable rice-wheat rotation. *Agron J* 100:87–97
- SAS Institute (1996) SAS/STAT software: changes and enhancements through release 6.11. Cary, NC
- Semenov MA (2007) Development of high resolution UKCIP02-based climate change scenarios in the UK. *Agr For Meteorol* 144:127–138
- Semenov MA, Barrow EM (1997) Use of a stochastic weather generator in the development of climate change scenarios. *Clim Change* 35:397–414
- Soil Survey Staff (1992) Keys of soil taxonomy. Tech. Monogr. 19, 5th edn. Blacksburg, Virginia, SMSS
- Soltani A, Hoogenboom G (2007) Assessing crop management options with crop simulation models based on generated weather data. *Field Crop Res* 103:198–207
- Tshiala MF, Olwoch JM (2010) Impact of climate variability on tomato production in Limpopo Province, South Africa. *Afr J Agric Res* 5(21):2945–2951
- Tubiello FN, Donatelli M, Rosenzweig C, Stockle CO (2000) Effects of climate change and elevated CO<sub>2</sub> on cropping systems: model predictions at two Italian locations. *Eur J Agron* 13:179–189