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Impact of climate change on water and nitrogen use efficiencies of processing tomato cultivated in Italy

D. Cammarano [a,*], D. Ronga [b,**], I. Di Mola [c], M. Mori [c], M. Parisi [d]

[a] Department of Agronomy, Purdue University, USA
[b] Department of Life Science, University of Modena and Reggio Emilia, Via Amendola, n. 2, 42122, Reggio Emilia, Italy
[c] Department of Agricultural Sciences, University of Naples Federico II, Via Università, n. 100, 80055, Portici, Italy
[d] CREA Research Centre for Vegetable and Ornamental Crops, Via Cavalleggeri, 25, 84098, Pontecagnano Faiano, Italy

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ABSTRACT

Tomato (Solanum *lycopersicum* L.) is a globally important vegetable recognized for its positive health benefits. As most of the vegetable production, tomato require significant amount of agronomic inputs. However, recent shifts in climate patterns in terms of timing and amount in rainfall, patterns in air temperature, and the associated extreme events have caused harm and disruption to the agricultural sector worldwide. The objective of this study was to: i) evaluate the ability of a crop simulation model to simulate yield and growth parameter of a processing tomato in South west Italy; ii) quantify the impacts of projected climate on business as usual agronomic practices; iii) understand the role of projected changes and increased CO_2 on the water and nutrient efficiency. Field trials from an open field at Sele Valley (40°35′03.8″ N, 14°58′48.6″ E) (Salerno, South east Italy) during a two-year period (2004–2005) were used. Baseline climate data (1984–2018) were available and four contrasting projections were selected as function of their spread in terms of changes in growing season rainfall and temperature respect to the baseline. The crop model DSSAT (Decision Support System of Agrotechnology Transfer) was used for this study. The model was able to simulate tomato response to N fertilization with acceptable error levels respect to the ones reported in literature. The projected increase in air temperature and changes in rainfall caused a shortening ranging from 1.5 to 3 days in tomato phenology causing an overall 15 % reduction in tomato yield. To offset the negative impact of rainfall and temperature changes, additional irrigation water (from 85 to 110 mm) and nitrogen rate (from 20 to 30 kg N ha^{-1}) is needed. However, the increase in irrigation water does not translate in significant yield increase and caused an increase in water and nitrogen use efficiency of less than 10 %.

1. Introduction

Tomato (Solanum *lycopersicum* L.) is a globally important vegetable that has been recognized for his positive health benefits being rich in antioxidants and low in cholesterol, saturated fats and sodium (Capanoglu et al., 2010; Friedman et al., 2000; Di Cesare et al., 2012, 2010). There are two types of cultivated tomato, the one for fresh consumption and the one used for industrial transformation (processing) which is usually grown under field conditions. The global production of processing tomato, in 2019, was about 3.7 million metric tons (FAOstat, 2020; WPTC, 2019). Italy is the biggest EU producer of processing tomato contributing by 13 % of the global processing tomato (WPTC, 2019).

As most of the vegetable production, tomato require significant amount of agronomic inputs. Ronga et al. (2019a, b) stated that the amount of irrigation water needed by the crop ranges between 400 and 600 mm. The requirement for nitrogen (N) fertilization varies during the growing season, with the highest demand during the vegetative phase and an overall uptake of about 300 kg N ha^{-1} (Ronga et al., 2017). While past research has focused in optimizing the amount of water and N that maximize yield and quality, recent studies have shown how deficit irrigation and partial root-zone irrigation can produce similar yield levels and better nutritional qualities respect to the full irrigation (Wei et al., 2018). N management is a factor impacting plant growth, photosynthesis and quality of the fruits and is generally applied at small doses during the growing season for avoiding exces-

* Corresponding author.
** Corresponding author. Present address: Centro Ricerche Produzioni Animali - CRPA S.p.A, viale Timavo 43/2, 42122, Reggio Emilia, Italy.
E-mail addresses: dcammar@purdue.edu (D. Cammarano); domenico.ronga@unimore.it (D. Ronga)

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sive N losses and often in fertigation with irrigated water (Wang et al., 2010; Ronga et al., 2015).

However, recent shifts in climate patterns in terms of timing and amount in rainfall, patterns in air temperature, and the associated extreme events have caused harm and disruption to the agricultural sector worldwide. This will also cause problems to the processing tomato industry for optimizing water and N managements. In addition, atmospheric carbon dioxide (aCO_2) has been increasing over the years reaching the present value of 413 ppm (Tans and Keeling, 2020). The aCO_2 plays an important role in leaf photosynthesis, crop growth and yield (Ainsworth and Long, 2005). The interaction of increased aCO_2, changes in air temperature, rainfall and their impacts on the processing tomato has been quantified in few modelling studies in the Mediterranean basin (Giuliani et al., 2020; Rinaldi et al., 2007; Ventrella et al., 2011).

Crop growth models are computerized representations of the dynamic interaction between the soil-plant-atmosphere continuums and have been extensively used in climate change impact studies (Cammarano et al., 2019; Asseng et al., 2014). The application of crop growth models for impact studies on tomato is limited. Rinaldi et al. (2007) found that a combination of deficit irrigation in the amount of 400 mm for a growing season along with N fertilization of 200 kg N ha^{-1} optimizes tomato production in the Foggia growing area (South east Italy). In addition, the impact of climate change in the same area causes an acceleration in phenology, decreasing dry matter (DM) production and reducing crop yield. However, the optimization of irrigation and fertilization strategies would offset some of the negative impacts of climate (Ventrella et al., 2011).

In most climate change impact studies, researchers chose one or few global climate models (GCM) and made climate impacts assumptions based on that climate outputs. Ruane and McDermid (2017) showed how among the GCMs, their response in terms of temperature and rainfall interactions is rather diverse, with some having peculiar behavior. Picking few or the ensemble of them without considering the uncertainty around the projections can lead to inconsistencies (Ruane and McDermid, 2017). Comparing the obtained results against other studies from different geographical areas is often biased because of the chosen GCM. In fact, the approach suggested by Ruane and McDermid (2017) can be used to subset a number of GCMs into a smaller subset in relation to the information that are important to maintain. Such information can be decided *a-priori* and can help to quantify the climate change impacts in a uniform way across different geographical regions (Cammarano et al., 2020, 2019; Ruane et al., 2015). Therefore, in order to make an informed assessment of climate change impacts on agricultural crop, the abovementioned approach would be the optimal solution.

The South west of Italy is an important area of tomato production (Ronga et al., 2015), with a different climate than the eastern zone and no impact studies in this area exist. The objective of this study was to: i) evaluate the ability of a crop simulation model to simulate yield and growth parameter of a processing tomato produced in South east Italy; ii) quantify the impacts of projected climate on business as usual agronomic practices; iii) understand the role of projected changes and increased CO_2 on the water and nutrient efficiency.

2. Materials and methods

2.1. Study site and experimental design

Field trials were carried out in an open field at Sele Valley (40°35′03.8″ N, 14°58′48.6″ E) (Salerno, South west Italy) during a two-year period (2004–2005) in a typical Haploxerepts soil (Soil Survey Staff, 2014). The soil had the following characteristics: sand 26.8 %, silt 40.8 %, clay 32.4 %, limestone 2.4 %, pH 7.8, organic matter 1.6 %, total nitrogen 1.3‰, P_2O_5 126 mg kg^{-1}, and K_2O 324 mg kg^{-1}.

2.1.1. Crop production

The cultivar "*Messapico*" (Nunhems, S'Agata Bolognese (BO), Italy) with elongated fruit was transplanted with a density of 3 seedlings m^{-2}. Plants were transplanted the 5th of May 2004 and 9th of May 2005 using twin rows with of 0.35 m between each row of the twin and 0.35 m between plants in the row, while the distance between the twin rows was 1.7 m.

The total P_2O_5 and K_2O rates were calculated according to the soil analysis and administered at ploughing. Regarding N fertilization, six rates were considered (0, 50, 100, 150, 200, and 250 kg of N ha^{-1}), with the 250 kg N ha^{-1} lower than the rate used by farmers (290 kg N ha^{-1}). A randomized complete block design was used using four replicates, each of 4.0 m × 5.1 m.

Irrigation scheduling was based on crop evapotranspiration (ETc) and calculated as ETc = ETo × Kc, where ETo (reference evapotranspiration) was determined as suggested by Hargreaves and Samani (1985), and Kc (crop coefficient) for tomato crop was adjusted considering the environmental conditions and the crop growth stage (Allen et al., 1998). In each plot, 100 % ETc was restored when 40 % of the total available water was depleted, in accordance to Doorenbos and Pruitt (1977). Totals of 255 and 294 mm of water were applied in 2004 and 2005, respectively, by drip irrigation. Weed control and plant protection were done according to the cultivation protocols of the Campania Region (Italy). A single harvest was done the 9th of Aug 2004 and 5th of Aug 2005 when the ripe fruits accounted for approximately 85 % of the total.

2.1.2. Parameters recorded in open field

The main physiological and morphological parameters were biweekly assessed in five (in 2004) and four (in 2005) sampling times on two plants *per* plot. In the first growing season (2004), the sampling corresponded to the following physiological stages: (1) beginning of flowering (stage 6.1; Meier, 2001); (2) full flowering (stage 6.3); (3) beginning of fruit development (stage 7.1); (4) fruit and seed ripening (stage 8.1); (5) fully ripe (stage 8.9) (Meier, 2001). While in the second growing season (2005), sampling started at full flowering stage until fully ripe stage. For the destructive parameters, two plants were collected at each time-point (leaving at least another two neighboring plants on each side) by digging plants to a soil depth of 40 cm, then washing away the soil from the roots. The leaf, fruit (ripe and un-ripe), and total biomass dry weights were recorded. In addition, leaf area index (LAI) was measured using a subsample of fresh leaves that was run through an LI-3000A leaf area meter (LI−COR, Lincoln, NE, USA), and this was linked to the leaf dry weight.

The mean values and the standard deviation of the parameters recorded in the open field were used in the manuscript when referring to the observed data (Table 1).

2.2. Climate data

The baseline climate data was obtained from the weather station located directly in the experimental farm where the open filed study was carried out and included daily weather data from 1984 to 2018. Daily incoming solar radiation (MJ d^{-1} m^{-2}), maximum and minimum air temperature (°C), and rainfall (mm).

The climate projections to near-future (2010–2040) were computed. Forty global climate models (GCMs) were used to compute the changes in monthly temperatures and monthly rainfalls resulting in 40 future weather scenarios *per* baseline. The climate model projections were from the global Couple Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). For this study, RCP 4.5 was used, where the RCPs are a greenhouse gas concentration trajectory which are consistent with the ranges of possible changes of greenhouse

Table 1
Mean values of the leaf area index (LAI), the leaf weight (LWAD), aboveground biomass (CWAD), and tomato yield (PWAD) for the growing season 2004 and 2005 at six nitrogen rates. The numbers in parenthesis represent the standard deviation of the mean, with n = 8.

TREATMENT	Date	LAI [a]	LWAD [b]	CWAD [c]	PWAD [d]
(-)	*(dd-mm-yyyy)*	*(-)*	*(kg DM ha^{-1})*	*(kg DM ha^{-1})*	*(kg DM ha^{-1})*
2004–0 N	11-Jun-04	0.8 (0.15)	534 (42)	771 (107)	5 (1)
2004–0 N	20-Jun-04	1.8 (0.45)	1128 (153)	2535 (186)	858 (96)
2004–0 N	15-Jul-04	1.4 (0.05)	1148 (51)	4192 (188)	2450 (121)
2004–0 N	22-Jul-04	0.8 (0.10)	766 (111)	5868 (237)	4338 (272)
2004–0 N	9-Aug-04	0.9 (0.07)	1615 (95)	7120 (496)	4715 (446)
2004–50 N	11-Jun-04	1.2 (0.08)	683 (67)	905 (912)	19 (3)
2004–50 N	20-Jun-04	2.5 (0.16)	1382 (106)	2947 (280)	994 (218)
2004–50 N	15-Jul-04	1.8 (0.23)	1238 (179)	5264 (309)	3264 (175)
2004–50 N	22-Jul-04	1.5 (0.19)	1036 (83)	7416 (243)	5607 (201)
2004–50 N	9-Aug-04	1.2 (0.16)	1526 (244)	7557 (465)	5143 (376)
2004–100 N	11-Jun-04	1.2 (0.11)	606 (49)	874 (85)	21 (4)
2004–100 N	20-Jun-04	3.0 (0.24)	1576 (41)	3301 (206)	1166 (183)
2004–100 N	15-Jul-04	2.1 (0.32)	1502 (92)	6279 (199)	3923 (139)
2004–100 N	22-Jul-04	2.0 (0.08)	1465 (101)	8382 (180)	6105 (336)
2004–100 N	9-Aug-04	1.3 (0.31)	1486 (133)	8711 (419)	6097 (263)
2004–150 N	11-Jun-04	1.7 (0.20)	838 (45)	1106 (97)	13 (3)
2004–150 N	20-Jun-04	3.6 (0.69)	1755 (163)	3474 (347.12)	1167 (156)
2004–150 N	15-Jul-04	2.7 (0.27)	1779 (131)	6704 (438)	3994 (320)
2004–150 N	22-Jul-04	2.0 (0.11)	1464 (107)	8429 (488)	6054 (431)
2004–150 N	9-Aug-04	1.6 (0.25)	1624 (180)	9245 (230)	6664 (136)
2004–200 N	11-Jun-04	1.6 (0.16)	816 (23)	1144 (63)	19 (8)
2004–200 N	20-Jun-04	3.8 (0.44)	2052 (222)	3889 (219)	1195 (137)
2004–200 N	15-Jul-04	2.7 (0.41)	1633 (68)	6538 (282)	3922 (257)
2004–200 N	22-Jul-04	2.6 (0.24)	1889 (163)	10905 (1101)	7908 (921)
2004–200 N	9-Aug-04	2.1 (0.43)	1989 (239)	10175 (399)	6959 (430)
2004–250 N	11-Jun-04	1.4 (0.10)	716 (76)	1029 (86)	14 (3)
2004–250 N	20-Jun-04	3.6 (0.56)	1847 (307)	3909 (480)	1451 (239)
2004–250 N	15-Jul-04	3.1 (0.27)	1911 (231)	6552 (91)	3553 (271)
2004–250 N	22-Jul-04	2.8 (0.15)	2058 (124)	10109 (733)	6951 (517)
2004–250 N	9-Aug-04	2.2 (0.16)	2388 (167)	10983 (654)	7313 (461)

Table 1 (*Continued*)

TREATMENT	Date	LAI [a]	LWAD [b]	CWAD [c]	PWAD [d]
(-)	*(dd-mm-yyyy)*	*(-)*	*(kg DM ha^{-1})*	*(kg DM ha^{-1})*	*(kg DM ha^{-1})*
2005–0 N	1-Jul-05	1.1 (0.10)	413 (56)	1171 (90)	533 (25)
2005–0 N	14-Jul-05	0.7 (0.21)	372 (99)	1878 (263)	1275 (166)
2005–0 N	26-Jul-05	0.7 (0.06)	354 (17)	1973 (288)	1331 (256)
2005–0 N	5-Aug-05	0.7 (0.27)	493 (176)	2361 (367)	1520 (172)
2005–50 N	1-Jul-05	1.7 (0.27)	541 (111)	1718 (208)	817 (232)
2005–50 N	14-Jul-05	1.2 (0.59)	634 (75)	3000 (336)	1935 (237)
2005–50 N	26-Jul-05	0.9 (0.08)	438 (18)	2653 (257)	1859 (226)
2005–50 N	5-Aug-05	0.8 (0.13)	555 (147)	3199 (864)	2189 (556)
2005–100 N	1-Jul-05	2.4 (0.56)	667 (173)	2273 (485)	1138 (331)
2005–100 N	14-Jul-05	1.7 (0.11)	788 (120)	4010 (464)	2709 (336)
2005–100 N	26-Jul-05	1.4 (0.20)	657 (887)	4258 (282)	3068 (239)
2005–100 N	5-Aug-05	1.2 (0.47)	813 (315)	5689 (1643)	4178 (1123)
2005–150 N	1-Jul-05	3.6 (0.28)	928 (63)	2989 (229)	1548 (299)
2005–150 N	14-Jul-05	2.4 (0.58)	929 (159)	4829 (534)	3334 (324)
2005–150 N	26-Jul-05	1.7 (0.26)	963 (138)	5416 (763)	3834 (528)
2005–150 N	5-Aug-05	1.6 (0.62)	982 (354)	7914 (1921)	6112 (1536)
2005–200 N	1-Jul-05	4.0 (0.71)	1139 (252)	3710 (459)	1991 (285)
2005–200 N	14-Jul-05	3.4 (0.82)	1262 (156)	5979 (802)	4007 (557)
2005–200 N	26-Jul-05	2.4 (0.34)	1252 (252)	6581 (611)	4620 (280)
2005–200 N	5-Aug-05	1.8 (0.33)	978 (104)	6525 (1435)	4854 (1238)
2005–250 N	1-Jul-05	5.1 (0.46)	1308 (113)	4395 (539)	2340 (419)
2005–250 N	14-Jul-05	3.6 (0.36)	1233 (155)	6298 (337)	4393 (157)
2005–250 N	26-Jul-05	3.7 (0.71)	1534 (238)	7886 (556)	5311 (333)
2005–250 N	5-Aug-05	1.8 (0.50)	958 (413)	6334 (1216)	4669 (1081)
Sources of variation		***p-value***			
Treatment (T)		< .001	< .001	0.097	0.306
Year (Y)		0.942	< .001	0.106	0.436
T*Y		0.388	0.999	0.958	0.956

[a] Leaf Area Index.
[b] Leaf weight.
[c] Aboveground biomass.
[d] Yield.

gas emissions. For example, the RCP 4.5 assumed that the greenhouse gas emission peaks around 2040 and then decline. Further details of the RCPs and methodology can be found on the IPCC website (IPCC, 2019). A corresponding elevated CO_2 (eCO_2) level of 538 ppm was used when simulating crop response for the mid-century. The baseline level of CO_2 380 ppm was used when simulating the baseline period (1980–2010).

The baseline weather data was perturbed using the DSSAT perturb software (www.climsystems.com). The software used the baseline weather data of the weather station available in the experimental farm where the open field study was performed and the CMIP5 GCM projections to generate 40 daily weather files using the algorithms and approaches described in details in Yin et al. (2013).

Following the approach of Ruane and McDermid (2017) the percent change in growing season rainfall (April to August) and the absolute changes in air temperature (April to August) respect to the baseline were calculated and resulting data plotted using the same methodology described in Ruane and McDermid (2017). However, in this study, it was decided to select 4 GCMs representing the different position in the rain-temperature change spaces. The aim was to select 4 GCMs (GCM1, GCM2, GCM3, and GCM4) with contrasting combinations of rain and temperature changes respect to the spread of the GCMs (Table 2).

2.3. Crop simulation model

The crop model DSSAT (Decision Support System of Agrotechnology Transfer) version 4.7 was used for this study (Jones et al., 2003; Hoogenboom et al., 2012). The crop model has many different modules that communicate with each other to simulate the daily interactions of soil-plant-climate-agronomic management. The main crop growth models within the DSSAT framework are the CERES-based models, used often to simulate cereals, and the CROPGRO-based models, originally developed for legume crops (Boote et al., 1998). The CROPGRO was a generic crop model that has been adapted to a variety of crops, along with tomato (Koo, 2002).

The soil water is simulated with a tipping bucket approach, in which precipitation and/or irrigation is the run-off, infiltrated, evaporated, uptake by crop or lost by drainage as described in detail in Ritchie (1998). The crop was subjected to water stress when the ratio between potential crop transpiration (demand) and potential root water uptake (uptake) fell below a certain threshold (Ritchie, 1998). Water stress impacts different processes, from expansive growth to photosynthesis. Any of these processes have a threshold value of the demand/uptake ratio. For this study we considered the impact of water stress on expansive growth processes because they are the ones most sensitive to water deficit, the index ranges between 0 (no stress) to 1 (maximum stress) (Boote et al., 2008).

The soil N module simulated the mineralization/immobilization processes, N leaching, nitrification, denitrification, volatilization and all the different crop N uptake and redistribution of N in the crop (Jones et al., 2003). Crop N uptake was simulated matching the potential supply of soil N with crop N demand. The crop N demand was made of a "deficiency" demand that is the quantity of N required to restore the actual N concentration to the critical N concentration. In addition, the crop N demand was also made of a component that is needed for new growth (Godwin and Singh, 1998).

The input data consisted in the daily weather data, soil data, agronomic management in terms of timing and input amount, and the amount of soil water and soil mineral N prior sowing (initial conditions). The model was calibrated using the highest fertilized treatment (250 N) of both 2004 and 2005 growing seasons and evaluated on the other treatments.

The amount of irrigation and fertilization for the baseline simulations was chosen in order to minimize the water stress on expansive growth. It was aimed at keeping the water stress index somewhere below 0.5 but not to 0 because with deficit-irrigation techniques a small amount of stress, that would not negatively affect growth is allowed. The N fertilization was applied at key stages when also water was applied. The amounts found in this way were referred to "Baseline". Next, the crop model was run with the selected GCMs but with the same irrigation/fertilization amount and aCO_2 concentration as the baseline (BCO2-Birr), then with elevated atmospheric CO_2 concentration (eCO_2) and baseline irrigation/fertilization amount (ECO2-Birr), and finally with the elevated atmospheric CO_2 concentration and adjusted irrigation/fertilization amount to keep the water stress factor below the 0.5 threshold (ECO2-Eirr) (Table 2).

2.4. Data analysis

The simulated and observed values were evaluated using the Root Mean Square Error that is calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}(O_i - S_i)^2}{n}} \quad (1)$$

Where O_i were the observations, S_i the simulations, and n was the number of comparisons. A second index used to evaluate the crop model respect to the observation was the Wilmott index of agreement (D-Index), with values ranging between 0 (poor fit) and 1 (indicating a good fit). Usually, D-index values above 0.5 are to be considered acceptable. The D-Index expressed the measure of the goodness of fit and has been used as cross-comparison method between models (Wilmott, 1982; Martre et al., 2015; Cammarano et al., 2019).

Table 2
The simulated interactions of atmospheric CO_2 concentration, water and fertilizer amounts, and the projected growing season (April to August) rainfall and temperature changes respect to the baseline climate for the 2050.

ID	Weather	GCM-ID	CO_2	Irrigation	Fertilization	Rain Change [a]	T Change [b]
–	–	–	(ppm)	(mm)	(kg N ha $^{-1}$)	(%)	(°C)
BCO2-Birr	Baseline	–	380	435	290	0	0
ECO2-Birr	GCM1	MIROC4H	538	435	290	−42.6	1.3
ECO2-Birr	GCM2	MRI-CGCM3	538	435	290	−22.7	2.4
ECO2-Birr	GCM3	INMCM4	538	435	290	−2.70	0.8
ECO2-Birr	GCM4	GFDL-ESM2M	538	435	290	−7.40	1.5
ECO2-Eirr	GCM1	MIROC4H	538	545	310	−42.6	1.3
ECO2-Eirr	GCM2	MRI-CGCM3	538	528	320	−22.7	2.4
ECO2-Eirr	GCM3	INMCM4	538	520	320	−2.70	0.8
ECO2-Eirr	GCM4	GFDL-ESM2M	538	520	320	−7.40	1.5

[a] The rainfall change is % change respect the growing season rainfall.
[b] The temperature change is the delta difference between the projected and baseline growing season temperature; BCO2-Birr: Baseline CO_2 concentration and baseline irrigation; ECO2-Birr: Elevated CO_2 concentration and baseline irrigation; ECO2-Eirr: Elevated CO_2 concentration and adjusted irrigation.

$$D = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(\left|O_i - \bar{O}\right| + \left|S_i - \bar{O}\right|\right)^2} \quad (2)$$

Where $\bar{O}$ is the mean of the observed values.

The relative change in terms of yield, water, nitrogen and transpiration use efficiencies respect to the baseline was calculated as follows.

$$RC = \frac{S_{f,g,i} - S_{b,i}}{S_{b,i}} * 100 \quad (3)$$

Where $S_{f,g,i}$ was the simulated (S) value as predicted by the GCM g, for a given growing season I, and $S_{b,g,i}$ was the baseline (b) value simulated for the growing season i. The box and whiskers plots were used to plot the relative changes and the horizontal line in the box represented the median, the box was the 25th and the 75th percentiles, the whiskers the 10th and 90th percentiles. All the Figures were made using GGPLOT2 (Wickham, 2016).

3. Results

3.1. Observed data

The observed LAI values ranged between 0.7 and 5.1 across the years and treatments for which there were statistical significant differences (Table 1). There was a difference in the values between the growing season 2004 and 2005 at different N levels, with the 0 N showing overall high values in 2004 than 2005 and the 250 N showing higher values in 2005 (Table 1). Overall, the leaf weight values statistically significant and were higher for the growing season 2004 with values ranging between 534 and 2328 kg DM ha^{-1}, while in 2005 they ranged between 354 and 1534 kg DM ha^{-1} (Table 1). Aboveground biomass and tomato yield showed similar patterns with values higher for the growing season 2004 among all the treatments. Both parameters were not statistically different among treatments and years (Table 1). The standard deviations of the measured parameters increased at higher N fertilization levels for both years when comparing the same sampling date. For example, the standard deviation of the tomato yield at harvest in 2005 was 172.6 kg DM ha^{-1} for the N0 and 1081 kg DM ha^{-1} for the 250 N (Table 1). From the observed patterns, the tomato dry yield in 2005 was lower than in 2004 but with higher standard deviation (Table 1). This also resulted in different yield peaks to N inputs, with the maximum yield in 2004 and 2005 achieved at 250 and 150 kg N ha^{-1}, respectively.

3.2. Climate data

The historical long-term (1984–2018) maximum and minimum air temperatures, and rainfall were shown in Fig. 1. The maximum air temperature showed an increasing trend for the month of April, which was usually the tomato transplanting time, with an annual increase of 0.07 °C, while for the other months the increase was much smaller (Fig. 1a). The minimum air temperature showed a similar pattern of the maximum air temperature with April begin the month of the higher annual increase with a 0.054 °C (Fig. 1b). The cumulative rainfall, for the month of April to August, showed an increase for each month, except for April where the cumulative rainfall from 1984 to 2018 decreased (Fig. 1c).

The 40 GCMs and their growing season precipitation and temperature changes were reported in Fig. 2, while the full list is shown in Supplemental Table 1. The range of rainfall change varied between -43 % and +5% respect to the baseline growing season rainfall (Fig. 2), while the growing season temperature was higher between +0.8 and +2.4 °C than the baseline (Fig. 2).

The selection of the 4 GCM used in this study were shown with the circle in Fig. 2, and where defined respect to the general spread of the GCMs. Their range of temperature and rainfall changes respect to the baseline was reported in Table 2. They were identified: i) GCM1 with -42.6 % rain and +1.3 °C (Table 1 and blue circle in Fig. 2); ii) GCM2 with -22.7 % rain and +2.4 °C (Table 1 and red circle in Fig. 2); iii) GCM3 with -2.7 % rain and +0.8 °C (Table 1 and green circle in Fig. 2); and iv) GCM4 with -7.4 % rain and +1.5 °C (Table 1 and black circle in Fig. 2).

3.3. Crop model calibration and evaluation

The results of the calibration were shown in Fig. 3 and the crop parameters in Supplemental Table 2. The simulated LAI showed a RMSE of 0.95 and a D-Index of 0.69; while the simulated leaf weight showed a RMSE of 449 kg DM ha^{-1} and a D-index of 0.67 (Fig. 3a, b). Aboveground biomass and tomato yield showed good agreement between observed and simulated results with a RMSE of 1584 kg DM ha^{-1} and 1039 kg DM ha^{-1} and a D-Index of 0.93 and 0.95, respectively (

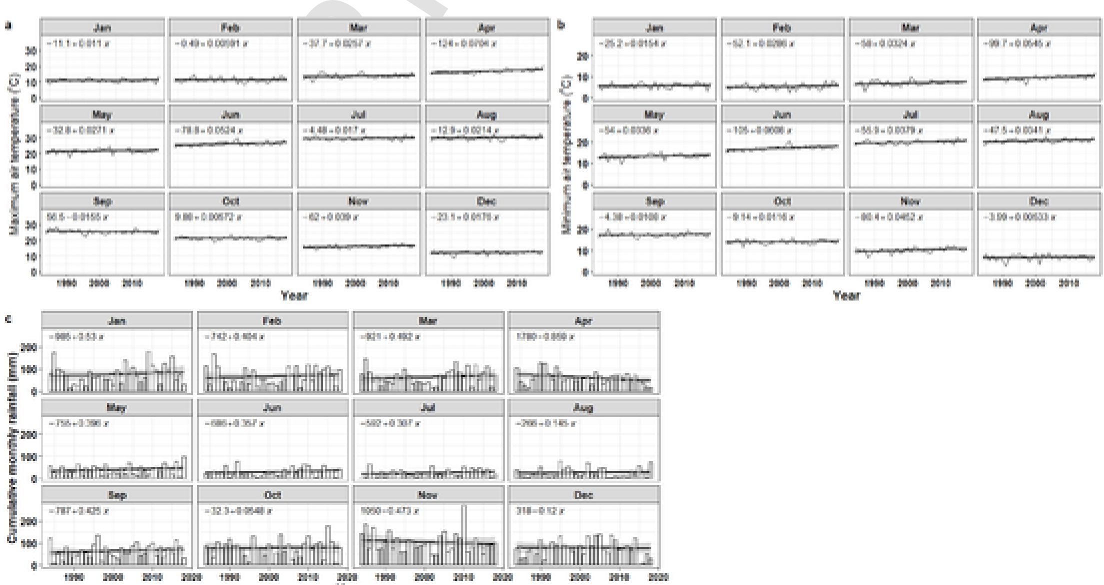

Fig. 1. Historical daily climate patterns from 1984-2017 (o 2018) of (***a***) maximum air temperature; (***b***) minimum air temperature; and (***c***) cumulative monthly rainfall.

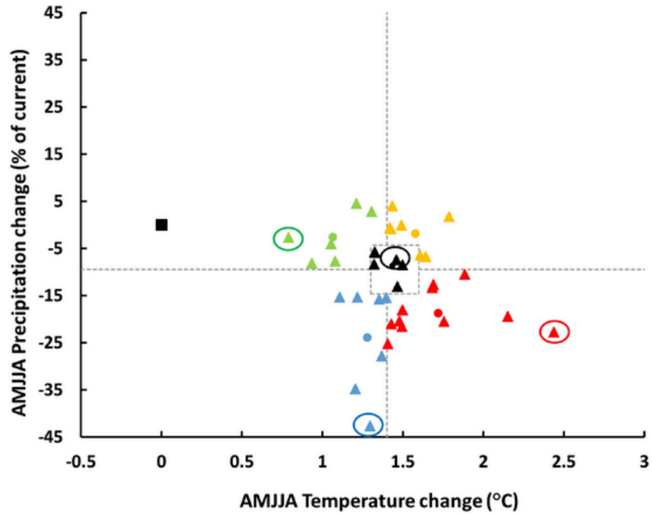

Fig. 2. Spread of the 40 Global Climate Models (GCMs) for RCP 4.5 respect to the baseline (black square) in terms of relative changes in growing season (AMJJA, Apr-May-Jun-Jul-Aug) rainfall and temperature. Each triangle is colored by a quadrant, which is defined in Ruane and McDermid (2017). The dots in each quadrant represent the mean of the GCMs within each quadrant and the selected GCMs are reported with the colored circle for the GCM1 (blue circle), GCM2 (red circle), GCM3 (green circle), GCM4 (black circle) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Fig. 3c, d). Overall, these RMSE values correspond to 14 % of the maximum yield and biomass values. The evaluation of the DSSAT-tomato on the remaining experiments was shown in Fig. 4. Overall the RMSEs were 0.68, 415 kg DM ha^{-1}, 1648 kg DM ha^{-1} and 1008 kg DM ha^{-1} for LAI, leaf weight, aboveground biomass and yield, respectively. While the D-index was 0.85 for LAI, 0.72 for leaf weight, 0.91 for aboveground biomass, and 0.94 for yield (Fig. 4). Similarly, the RMSE values for yield and biomass correspond to 13 % and 15 % of their maximum values, respectively.

The observed crop flowering date was 7 Jun for both years, while the simulated was 9 Jun 2004 and 6 Jun 2004 (data not shown).

The crop coefficients calibrated for the CROPGRO-Tomato were shown in Supplemental Material Table 2.

3.4. Climate change impacts

The relationship between simulated days to flowering and mean air temperature for the different GCMs was shown in Fig. 5. Overall, the increase in temperature caused a shortening in phenology of 1.5 days for the GCM3 and of 3 days for the GCM2 (Fig. 5a). The impact of the different GCMs and irrigation/CO_2 combinations are shown in Fig. 5b. Overall, the baseline processing tomato yield varied between 7000–9000 kg DM ha^{-1} depending on mean air temperature values. There was a statistically significant difference among the simulated yields under different GCM and management combination ($p < 0.001$). The impact of the changes in rainfall and temperature given the same aCO_2 and irrigation caused a decrease in tomato yield for the all the four different GCMs (Fig. 5b).The impact of elevated CO_2 caused an increase of simulated yield for the GCM3, GCM1, and GCM4, but the GCM2 scenario showed a statistical significant decrease in simulated yield, especially when the mean air temperature was above 25 °C, in this condition both the BCO2-Birr and ECO2-Birr showed a drastic decrease in simulated yield to values ranging between 2900 and 3200 kg DM ha^{-1} (Fig. 5b). When the irrigation and the fertilization were adjusted there was a positive impact on the simulated yield (black dots in Fig. 5b) which was evident for the GCM3, GCM1 and GCM4. The GCM2 showed that at mean air temperatures between 23 and 25 °C the yields might increase, but above that threshold, even the new irrigation amount was not able to offset the shortening of the phenology (Fig. 5a and b).

The baseline irrigation amount was 435 mm and the fertilization was 299 kg N ha^{-1}; under the 4 projected climate the additional amount of irrigation water would be 110, 93, 85, and 85 mm for the GCM1, GCM2, GCM3, and GCM4, respectively (Fig. 6a). Furthermore, the additional amount of N fertilizer was 20 kg N ha^{-1} for the GCM1 scenario, and 30 kg N ha^{-1} for the others (Fig. 6b). Most of the additional water and N inputs were given between transplanting to flowering (about 30 days after transplanting; data not shown).

The relative changes of simulated yield, nitrogen use efficiency (NUE), water use efficiency (WUE), and transpiration use efficiency (Teff) were shown in Fig. 7. The impact of rainfall and temperature changes without considering changing in aCO_2 and irrigation water and fertilization (BCO2-Birr) showed a negative yield change between across the 4 GCMs ranging between -5 and -25 % (Fig. 7). In addition, the NUE, WUE and Teff showed reductions from -5 to -30 % in efficiency under the BCO2-Birr.

The impact of elevated CO_2 on baseline irrigation and fertilization (ECO2-Birr) showed a mean 10 % increase in yield under the GCM1, GCM3 and GCM4 (Fig. 7). However, the “GCM2” showed contrasting results with a mean change of 0 and a response from -20 to +20 % in yield (Fig. 7). The NUE was increased under the GCM1, GCM3 and GCM4 scenarios by about 12 %; but it showed a similar pattern of the yield changes for the GCM2 (Fig. 7). The WUE for the GCM2 showed negative results for the ECO2-Birr with a mean decrease of about -13 % (Fig. 7). The relative transpiration efficiency change was negative for GCM1, GCM3 and GCM4 with mean values ranging between -10 and -25 % (Fig. 7).

When the agronomic management was adjusted (irrigation and fertilization; ECO2-Eirr) the relative yield showed some minimal but statistically significant ($p < 0.001$) increase respect to the ECO2-Birr with some positive impact on the GCM4. However, the NUE decreased under all the 4 GCMs and WUE and Teff did not show significant increases (Fig. 7).

4. Discussions

Projected changes in growing season show a reduction of rainfall and an increase of the temperatures indicating a considerable increase in irrigation water and N fertilization, impacting on the processing tomato sustainability.

4.1. Observed data

The observed treatments showed a positive response to the highest N fertilization (250 N) where the highest LAI and aboveground biomass were observed for both growing seasons (Table 1). These results agree with findings of Scholberg et al. (2000) and Farneselli et al. (2013), and for different crop in similar environments by Tedone et al. (2014) and Conversa et al. (2019). Ronga et al. (2019a) demonstrated how the increase in N rates will affect aboveground biomass accumulation without impacting the allocation to the different organs.

4.2. Climate data

The use of historical weather data showed that during the tomato growing season (April to August) the transplanting month (April) is getting hotter and drier. This means that the current climate variability is already impacting the amount of water that needs to be provided after transplanting. Previous studies have reported the impacts of agronomic management on tomato yield but neglecting the climate impacts (Higashide and Heuvelink, 2009; Di Cesare et al., 2012). Rinaldi et al. (2007) using 53 years of historical weather data from Fog-

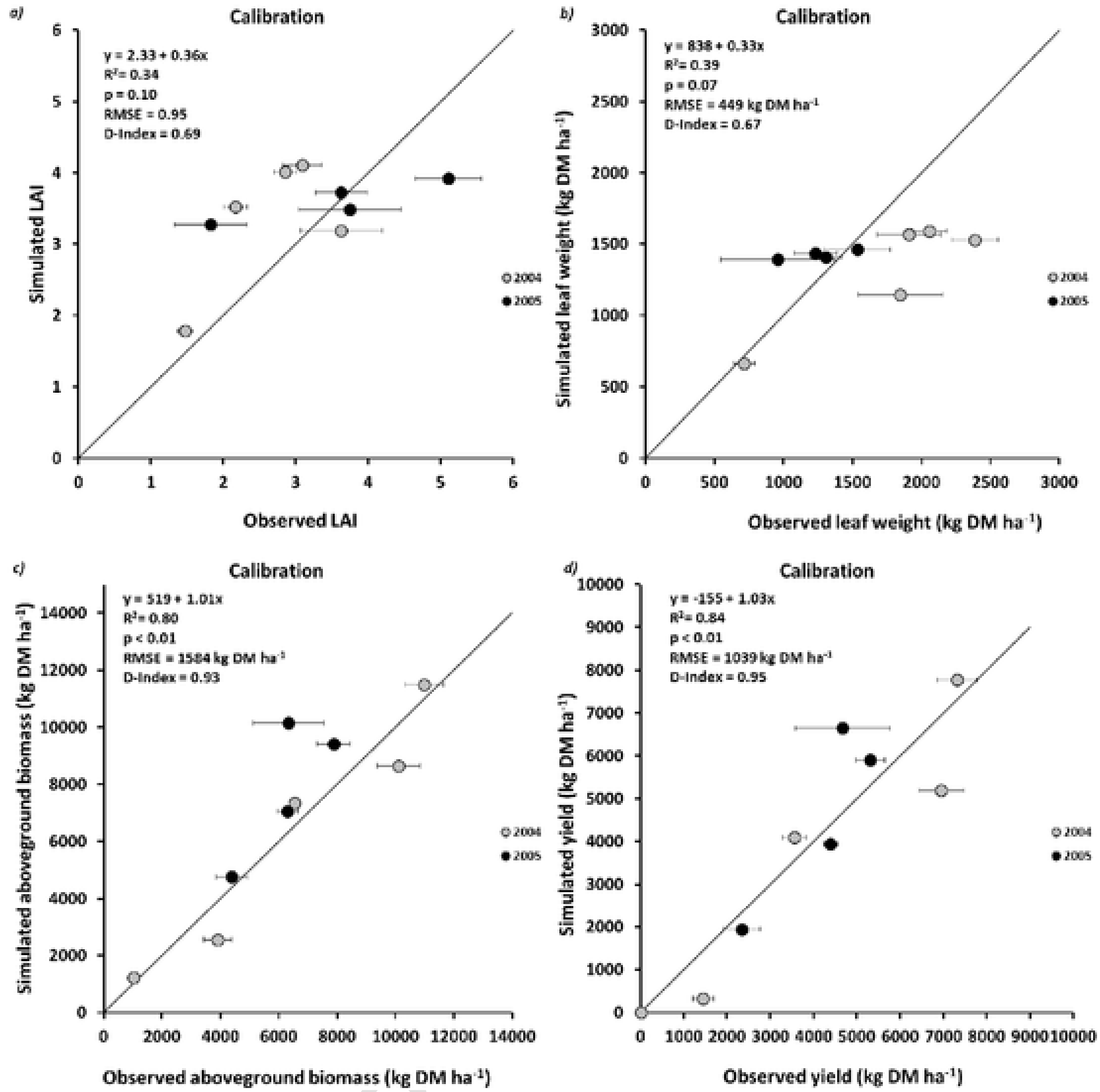

Fig. 3. Calibration of the DSSAT-GROPGRO-Tomato for the growing season 2004 (grey dots) and 2005 (black dots) for the high fertilized treatment (250 N), for the (**a**) leaf area index; (**b**) leaf weight; (**c**) aboveground biomass; and (**d**) tomato yield. The error bars represent the standard deviation of the mean values with n = 4.

gia (South east Italy) found the total amount of water that would optimize environmental and economic tomato productivity. The results of that study showed a seasonal water amount of about 400 mm while in this study it was found that 435 mm as the optimal amount. The main difference is driven by the drier April in South east Italy meaning more water was needed during the vegetative stage.

The generated GCMs showed a spread respect to the baseline as also shown in Ruane and McDermid (2017) and Cammarano et al. (2019, 2020). The way of displaying and choosing GCMs makes impact studies comparable across countries and cropping systems as showed in Rosenzweig and Hillel (2015) and in the updated version of that project (https://agmip.org/regional-integrated-assessments-2/). Ventrella et al. (2011) used projected climate to quantify the impacts of climate change on tomato water and fertilization, but they used the A2-SRES scenarios and only one GCM. The same authors used this GCM to produce two anomalies in terms of temperature changes. In the present study the CMIP5 with four contrasting GCMs was used. The main difference is that the previous study, one GCM outputs were changed only in terms of their temperature anomaly while in the present study the selected GCMs had interactive impacts of rainfall and temperature changes. The selection of the different extremes produced a set of 4 GCMs with contrasting rain and temperature behaviors.

4.3. Crop model calibration and evaluation

The calibration and evaluation indices of the DSSAT-Tomato model were in line to the ones published elsewhere. Boote et al. (2012); Rinaldi et al. (2007), and Elsayed et al. (2017) reported, for tomato grown in different environmental conditions and treatments values of RMSE and D-index in line to the ones reported here. The poor matching of LAI values for one growing season and not for the other was also reported in Boote et al. (2012). The authors concluded that this might be due to not reproducing accurately the decline in LAI associated with both senescence and N remobilization.

4.4. Climate impacts

The different GCMs, which represent different combinations of temperature and rainfall, caused a different crop response in terms of phenology and crop production. The results of the present study agree with the findings of Ventrella et al. (2011) that an increase in temperature caused a shortening of the phenology. However, the authors modified the weather data to obtain a temperature anomaly of both +2 and +5 °C. In our study, the range of temperature changes respect to

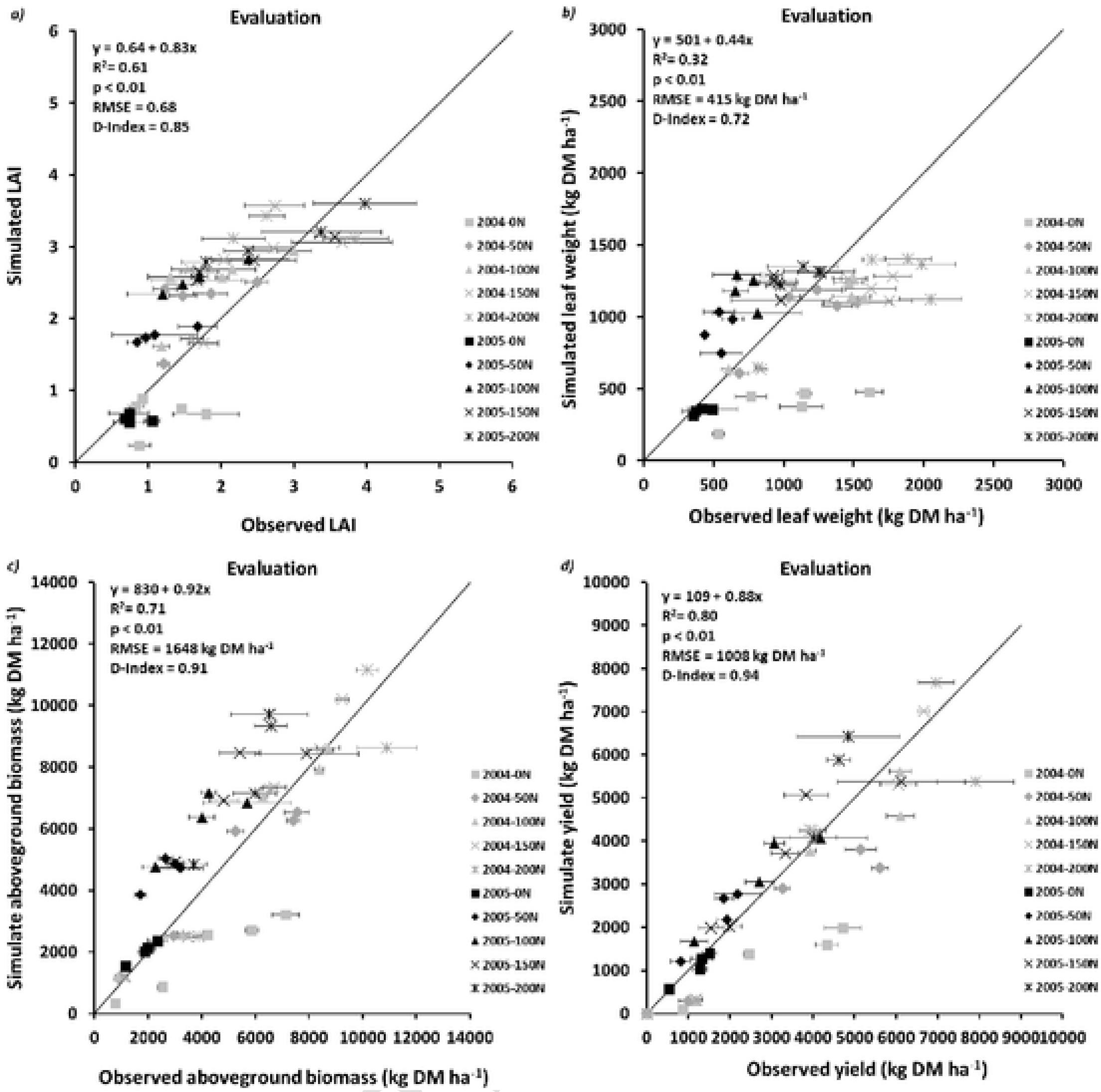

Fig. 4. Evaluation of the DSSAT-GROPGRO-Tomato for the growing season 2004 (grey dots) and 2005 (black dots) for five fertilized treatment (0 N, 50 N, 100 N, 150 N, 200 N), for the (**a**) leaf area index; (**b**) leaf weight; (**c**) aboveground biomass; and (**d**) tomato yield. The error bars represent the standard deviation of the mean values with n = 4.

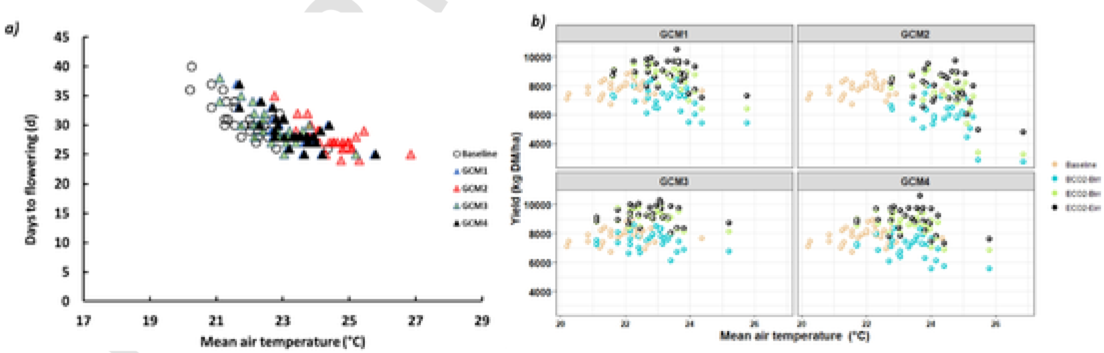

Fig. 5. Relationship between mean air temperature and (***a***) days to flowering for the baseline (grey dots), GCM1 (blue triangle), GCM2 (red triangle), GCM3 (green triangle), GCM4 (black triangle); and (***b***) tomato yield under baseline weather and management conditions (orange dots, similar in all quadrants), baseline CO_2 concentration (BCO2) and baseline irrigation and fertilization (Birr) (BCO2-Birr; blue dots), elevated CO_2 concentration (ECO2) and Birr (ECO2-Birr; green dots), and ECO2 and adjusted irrigation and fertilization (ECO2-Eirr; black dots) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

the baseline were between +0.8 and +2.4 °C, which means the most extreme temperature change in the GCM2 was not as high as the one reported by Ventrella et al. (2011). In that study, Ventrella et al. (2011) used a longer time frame (2099) and therefore higher absolute temperature increase respect to this study. In addition, Boote et al. (2012) have subsequent adjusted the cardinal temperature of the crop model to different thresholds, meaning that the comparison of the simulated impacts with older studies will be less relevant. The overall reduction of future tomato yield and the amount of water required is in line with the ones reported by Giuliani et al. (2020).

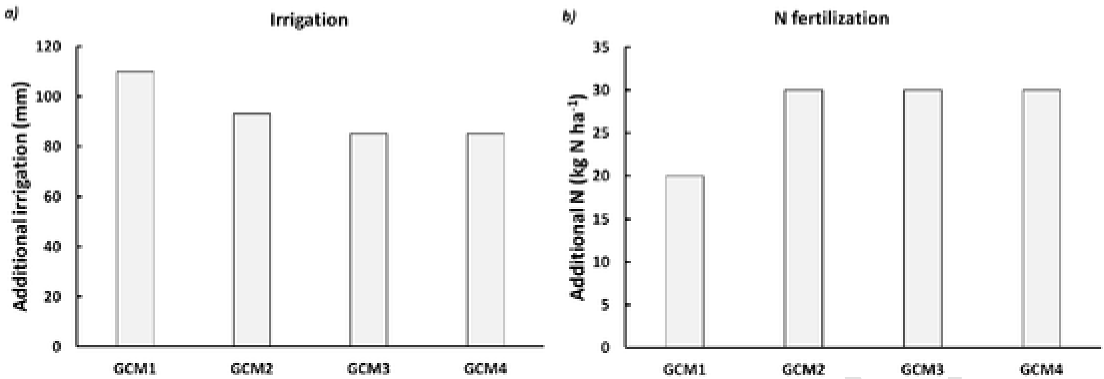

Fig. 6. Additional agronomic inputs in terms of (***a***) irrigation (baseline irrigation = 435 mm); and (***b***) fertilization (baseline fertilization = 290 kg N ha^{-1}) for the four GCMs belonging to the RCP4.5 and with an atmospheric CO_2 concentration of 538 ppm.

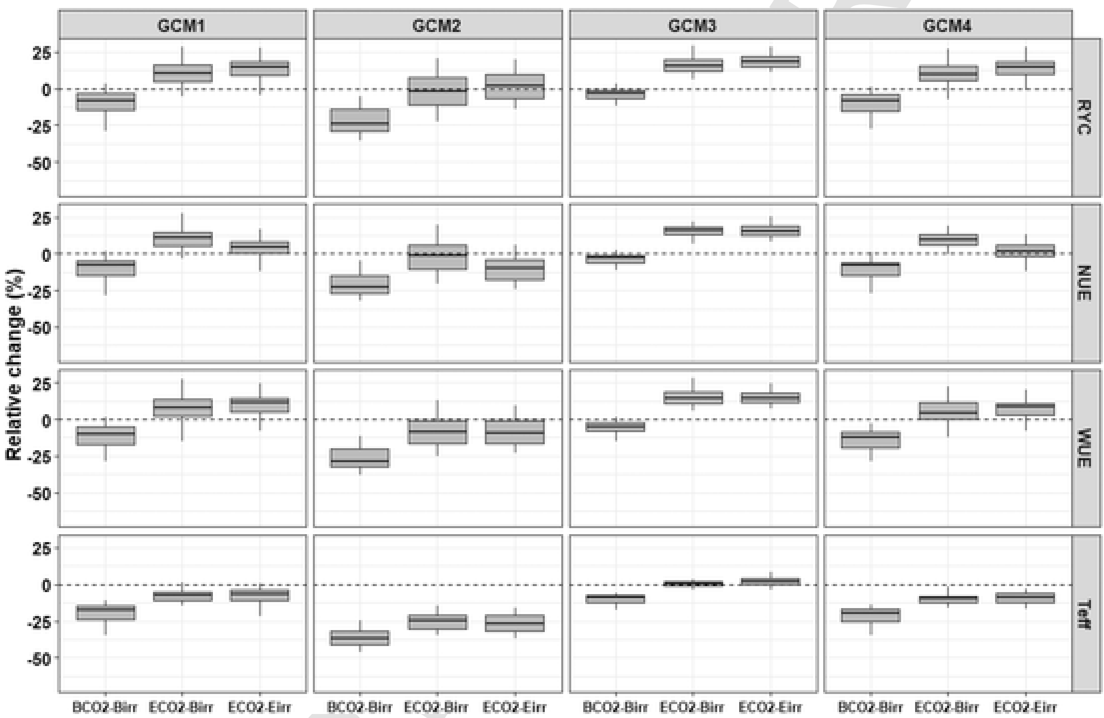

Fig. 7. Relative changes, respect to the baseline, of yield (RYC), nitrogen use efficiency (NUE), water use efficiency (WUE), and transpiration efficiency (Teff) for the four GCMs and for: i) baseline atmospheric CO_2 concentration and baseline agronomic management (fertilization and irrigation) BCO2-Birr; ii) elevated atmospheric CO_2 concentration and baseline agronomic management ECO2-Birr; and iii) elevated atmospheric CO_2 concentration and optimized agronomic management ECO2-Eirr. For each boxplot, the end of the vertical line represents, from top to the bottom, the 10th percentile and the 90th percentile. The horizontal line of the box, from the top to the bottom represents the 25th, median, and 75th percentile, respectively.

The GCM2 caused the fastest reduction in phenology and lower yield that the other projections. However, the GCM1 was the one requiring more irrigation water than the others. This means that in the future, in the growing area of South east Italy the amount of water needed to irrigate the tomato will increase by 25 %, which might not be a viable option in a future that will see a reduction in rainfall and an increased demand for extra-agricultural use of water. In addition, the increased demand for human consumption will exacerbate the debate of future water allocation. Current water-saving techniques, such as deficit-irrigation provide a documented reduction in water use with minimum effects on yield and could compensate the negative projection. In fact, as reported by Giuliani et al. (2016) the adoption of the regulated deficit irrigation strategy, can allow to save ~ 27 % of irrigation water preserving value of water use efficiency with an increase of fruit yield and quality. Among the available innovative agronomic techniques, Ronga et al. (2020) showed that the synergy effect of digestate and biochar can improve the processing tomato yield, enhancing water and nutrient plant uptakes. In addition, Bowles et al. (2016) suggested that the combined use of arbuscular mycorrhizal fungi and deficit irrigation can increase crop yield and WUE and thus having an important role in coping the increased demand of irrigation water as well as observed in the present study.

For the increasing temperature and reduced rainfall predicted by the most GCMs investigated in the present study, biostimulant can be used to reduce the effects of these abiotic stresses on processing tomato production (Goñi et al.;, 2018; Hernández et al., 2016). Another important abiotic stress in tomato production is chilling (Ronga et al., 2018); the low rainfall occurred in April and the fastest reduction in phenology showed during the growing season might suggest an earlier seedling transplant, however, chilling events can occur. To overcome chilling damages, Caradonia et al. (2019) reported that tomato seedlings inoculated with *Funneliformis mosseae* reduced the cell membrane injuries and highlighted a better seedling regrowth, after the chilling stress.

The impact of the eCO_2 on the crop physiological efficiencies was positive for the NUE and WUE but these efficiencies decreased when the irrigation and fertilization was optimized. On wheat (C3 crop like tomato) it was found that the increase of CO_2 lead to an increase in yield from 8 to 31 % and in WUE between 5 and 38 %, depending on the CO_2 concentrations (Cammarano et al., 2016). The results of the present study showed that the increase in simulated yield across the 4 GCMs was about 15 %, in line with the reported values for wheat. For the WUE the results were mostly in line with previous studies, except the GCM2 that showed a negative WUE. On the other hand, results of this study showed that under the hot conditions, the high acceleration of phenology caused a decrease in yields which in turns caused a lower efficiency in terms of water and nitrogen. The simulated transpiration efficiency was slightly offset by the increase in CO_2 concentration, however, it remained mostly negative under the climate projections. From this point of view, research in tomato physiology will play an important role to quantify the adaptation of tomato genotypes to climate change. In addition, studies on DM production and its distribution between the different organs like root, stem, leaf and fruit can provide useful information for the best application of the agronomic techniques (Heuvelink, 1996; Mori et al., 2008; Ronga et al., 2017).

During the growing season, some physiological parameters are mainly affected by water irrigation such as WUE and Teff that are also affected by soil-atmosphere-plant interactions and playing a principal role in crop yield and quality (Barrios-Masias and Jackson, 2014; Elia and Conversa, 2012; Hagassou et al., 2019). In addition, Teff also influences WUE (Sinclair et al., 2005); in fact, in our research, results of Teff and WUE showed a similar trend in all the investigated GCMs. Furthermore, it is interesting to note that in GCMs 2 and 4 under ECO2-Eirr were displayed greater values of WUE and Teff and lower value of NUE than that recorded under ECO2-Birr. These results were mainly ascribed to the higher volume of irrigation water applied under ECO2-Eirr than ECO2-Birr, causing a nitrogen dilution in the soil. Hence, plants grown in GCMs 2 and 4 under ECO2-Eirr with a higher Teff probably tried to cope nutritional stress increasing the uptake of mineral nutrients from the soil as already reported by Barati et al. (2015) in barley production. However, further studies are needed to corroborate this hypothesis to give useful information that could be considered in the future breeding programs able to increase tomato yield overcoming climate change impacts.

5. Conclusion

In conclusion, future production of processing tomato might be hampered by the projected changes in climatic conditions. The reduction in growing season rainfall and increase of growing season air temperature will cause a shortening of the tomato development and a lowering in yield, with the additional impact on the increased amounts of irrigation water and N fertilization. In a future where water resources will be scarce, even an increased amount of irrigation by deficit irrigation systems would not be sustainable. Processing tomato require whole field growing conditions and are not suitable for indoor-led based solution as it could be the case for fresh tomato. In addition, work on the processing tomato physiological response to temperature and CO_2 would help the breeding of better climate resilient crop.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106336.

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