Climate change and durum wheat crop projections in the Capitanata (Apulia, southern Italy)

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Abstract

In this study we analyze the effect of anthropogenic emissions on the future durum wheat production and phenological cycle. Durum wheat is a fundamental crop for the Apulia agricultural sector and it may be sensibly affected by decreasing precipitation or increasing temperature and evaporation, having important consequences on regional economy. The study focuses on the Foggia area by analyzing the climate conditions for three 30-years periods in autumn, winter and spring. A first part, based on COSMOMed simulations for the medium RCP4.5 and the high RCP8.5 emission scenarios, examines how mean seasonal minimum and maximum temperature and cumulated precipitation will vary. Results highlight very substantial minimum and maximum temperature increases. They, further, show that reduction of precipitation is mostly not significant for the medium emission scenario, but significant particularly for spring in the high emission scenario. In the second part, daily meteorological values produced by COSMOMed are used in the CropSyst crop model to estimate future crop productivity and phenology. Results show that negative effects of future warmer temperature and lower precipitation are more than compensated by the carbon dioxide fertilization effect, leading to an increase of yield and biomass production. This outcome needs to be validated in further analyses.

Keywords: climate change, agriculture, durum wheat, COSMOMed, CropSyst

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1.Introduction

IPCC Assessment Reports document that climate is changing and it is expected to significantly further change in the future due to increasing emission of anthropogenic greenhouse gases, land use and aerosol concentration changes (IPCC, 2013). Observations and model simulations agree on a general increase in temperature and suggest changes of precipitation regimes, whose with sign and magnitude will be unequally distributed across the globe. The Mediterranean basin is among the most sensitive regions to climate change at global scale (Giorgi, 2006; Lionello and Scarascia, 2018).

In general, the agricultural and food system is among the most sensitive sectors due to its socio-economic importance and vulnerability to meteorological events and climate conditions. Here, we base our investigation on the results of a regional climate model (RCM), which, in the Mediterranean region, because of its complex morphology (Lionello et al., 2012, Ruti et al., 2016), is needed to investigate the impacts at the small spatial scale that is relevant for human activities and ecosystems. Impacts of climate change are estimated using a crop growth simulation model, which allows to evaluate responses to climate change, combining climate conditions (obtained from Global or, in our case, Regional Climate Models) and the fertilization CO_2 physiological effect, able to counterbalance increasing temperature negative effects (Ainsworth and Long, 2005; Kimball et al., 2002).

This study is focused on the “Capitanata area” (Foggia), located in the northern part of Apulia region in southern Italy. This area is predominantly cultivated with winter durum wheat (*Triticum durum Desf.*) and is considered one of the most important areas in Italy for this crop production, together with other crops such as tomato, sugar beet, cabbage, olive and grapes. A former study has investigated impacts on crops in this region (Lionello et al., 2013), but using a statistical method (and not a growth simulation model) and RCMs with lower resolution than presently available. We a) describe the change in mean seasonal maximum and minimum temperature and rainfall, b) use daily model outputs to drive the crop model and c) estimate how crop yield and growth season will be affected by future climate change. We consider a middle and a high scenario (Representative Concentration Pathways RCP4.5 and RCP8.5, van Vuuren et al, 2011) and a near-term (2021-2050) and long-term (2071-2100) periods. Durum wheat growth period extends from winter to spring: sowing takes place at the beginning of November and harvest is made in the middle of June. Therefore, summer is not included in our analysis. Section 2 focuses on the dataset used for this work, describing the two different models used and the methods used for analysis. Results are presented in Section 3. Section 4 contains a discussion and possible future work.

2.Data and methods

The analysis carried out is based on two models: the COSMOMed regional climate model and the CropSyst agronomical model. The subdaily outputs of the COSMOMed model are used to produce the variables forcing CropSyst.

2.1 COSMOMed

COSMOMed is a regional coupled atmosphere-ocean system, consisting of COSMO-CLM, the limited area, atmospheric climate model in use at CMCC (“Centro Euro-Mediterraneo per i Cambiamenti Climatici”), and the ocean-sea model NEMO, implemented in the Mediterranean Sea (Med). The two-way coupling between COSMO-CLM and NEMO is performed by the coupler OASIS3-MCT, which, in turn, is formed by the Ocean Atmosphere Sea Ice Soil coupler (OASIS), interfaced with the Model Coupling Toolkit (MCT) from the Argonne National Laboratory (Conte et al., 2020). The model domain includes the whole Mediterranean region with a resolution of 0.11degs for the atmospheric component and 1/16deg for the ocean-sea component.

COSMO-CLM (COnsortium for Small-scale Modelling in Climate Mode) performs dynamic downscaling of global climate simulations. The model was developed by the German Weather Service, implemented by the European consortium COSMO and is still developed by the CLM-Community. It is a nonhydrostatic regional climate model, in a way to provide a better description of convective phenomena generated by vertical movement of energy, momentum and water vapor. Besides, the model is based on the fluid dynamic equations for a compressible flow: the atmosphere is seen as a multicomponent fluid (dry air, water vapor, liquid and solid water) subject to gravity and Coriolis force and respecting the perfect gas equation. It considers, as prognostic variables, horizontal and vertical Cartesian wind components, pressure perturbation, temperature, specific humidity, cloud water content, cloud ice content, turbulent kinetic energy and specific water content of rain, snow and graupel. Phenomena at unresolved scales, that have significant meteorological effects, are parametrized, such as subgrid-scale turbulence (e.g., surface layer parameterization, moist convection, soil model, radiation) and urban parameterization (COSMO, 2020).

Model outputs include different runs, among which historical ones, covering the period 1960 to 2005 can be used as reference for comparison with future scenario runs. Years from 2005 to 2100 are covered by runs using different Representative Concentration Paths (RCP) forcing scenarios (Moss et al., 2010). In particular, RCP4.5 (intermediate scenario) corresponds to a radiative forcing of 4.5 W/ m^2 and RCP8.5 (business as usual) to 8.5 W/ m^2 at the end of the 21st century. The former implies a warming of 2.5-2.7°C, the latter of 3-5.1°C (IPCC, 2013). Though, climate projections have intrinsic uncertainties, such as the radiative forcing due to the future greenhouse gas emissions, the representation of those physical processes not sufficiently well understood or with subgrid characteristic scales, the natural variability of the climate system at multiple spatial and time scales, possibly hiding anthropic contribution to climate change (Giorgi, 2005).

2.2 CropSyst

CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time-step crop growth simulation model. It was developed, starting from the early 1990s, to study effects of climate, soils and management on cropping system productivity and on the environment (Stöckle, 2003). Version n. 4.05.5 is used for this work. The model can be considered a generic crop simulator, being able to simulate for different crops soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition, erosion. Management options can be chosen for cultivar selection, crop rotation, irrigation, nitrogen fertilization, tillage operations and residue management. Daily potential crop growth is a function of solar radiation and water transpiration; the duration of the phenological phase is obtained as the sum of heat units; crop yield production is calculated according to the harvest index and a translocation factor.

Water balance includes rainfall, irrigation, runoff, interception, infiltration, redistribution in the soil profile, crop transpiration and soil evaporation. Water dynamic in the soil is modelled by a simple cascading approach or by Richards' equation, the latter solved numerically using the finite difference technique.

Nitrogen balance considers soil N transformations, such as mineralization, nitrification, denitrification, volatilization, ammonium sorption, symbiotic N fixation, crop N demand, and crop N uptake (Garofalo et al., 2009).

The potential daily above-ground biomass production (AGBpt) is calculated as the minimum value between the approach for transpiration use efficiency and that for radiation use efficiency, then water and nitrogen limits are applied to AGBpt to calculate actual AGB production (AGBa) (Stöckle and Debaeke, 1997). The model has been evaluated in many world locations for different crops by comparing model estimates to data collected in field experiments. In southern Italy it has been calibrated, among others for durum wheat (Ventrella and Rinaldi, 1999; Garofalo et al., 2009). The settings of CropSyst adopted in this simulation are reported in Table 1.

2.3 Methods

Linked to the phenological cycle of the durum wheat, autumn (September, October, November SON), winter (December, January, February DJF) and spring (March, April, May MAM) seasons are examined. Three-hourly values for precipitation (*pr*), temperature (*tas*), relative humidity near-surface (*hurs*), surface downwelling shortwave radiation (*rsds*), near-surface wind speed (*sfcWind*) produced by COSMOMed are used to force CropSyst. Precipitation is converted from kg/(m^2s) to mm/day, temperature from K to °C, radiation from W/m^2 to MJ/(m^2day). Concerning other variables, relative humidity is expressed as a percent and wind speed in m/s.

The RCM's domain representing the Foggia area, identified by longitudes from 15°N to 16°N and latitudes from 41°E to 42°E, has been selected. The RCM values, on a pole rotated grid, are interpolated on a lon-lat regular grid with a spatial resolution of 0.11deg and 9x9 grid points. Assuming the area is orographically homogeneous, in this analysis we averaged all values over the entire field.

The analysis considers three 30-years periods (following the WMO recommendations): 1960-1990 (baseline period), 2021-2050 (near-term) and 2071-2100 (long-term). Second and third periods are examined both in RCP4.5 and RPC8.5 scenarios. In the following, RPC4.5 projections for 2020-2050 will be referred to as

"RCP4.5 near-term", those for 2070-2100 as "RCP4.5 long-term" and, similarly in RCP8.5 the period 2020-2050 as "RCP8.5 near-term", the years 2070-2100 as "RCP8.5 long-term".

Daily value for each variable, period and scenario is obtained by averaging over the three-hourly values for *rsds* and *sfcWind*, by sum of all the values for the same day for *pr*, by extracting the minimum and maximum value in a day for *tas* and *hurs*. Mean seasonal values for precipitation, minimum and maximum temperature (respectively, *tasmin* and *tasmax*) are considered for describing climate change . The statistical significance of differences among periods and simulations is based on the Mann–Whitney test which is a nonparametric test that allows to determine the difference in location between two data samples and is resistant in the sense that it will not be invalidated by extreme data. Null hypothesis is that the two samples have been drawn from the same distribution, while the alternative hypothesis in this analysis is one-sided. We expect the center of the baseline sample to be smaller than the one of the samples from projections for *tasmin* and *tasmax* (increase in temperature) and to be larger for *pr* (decreasing in precipitation). Because samples are sufficiently large, the null distribution can be assumed Gaussian, where mean and variance are expressed by:

$$\mu = \frac{N1N2}{2}\ ,\ \sigma = \sqrt{\frac{N1N2(N1+N2+1)}{12}}$$

where N1 and N2 represent the number of observations in sample 1 (i.e., baseline) and sample 2 (i.e., near-term and long-term in RCP4.5 or RCP8.5). In this study a 5% significance level is adopted.

Atmospheric CO_2	constant rate (ppm/year)[4]
Evapotranspiration	from Penman-Monteith formula[5]
Water dynamic	cascading approach
Organic matter	microbial, stable organic matter and residue with carbon decomposition

SOIL and CROP MANAGEMENT

Date	**Tillage operations**
90 days b.p.[6]	primary Moldboard plow
60 days b.p.	secondary Disc harrow
1 day b.p.	secondary Rotary tiles
0 days b.p.	Planting Aerial seeding
	Nitrogen fertilization
10 days b.p.	Urea
90 days a.e.[7]	Ammonium nitrate
	Residue management
10 days a.p.m.[8]	70% stubble 30% surface residue

Table1: CropSyst settings and soil and crop management for durum wheat in Foggia area

CropSyst simulations are obtained for the baseline and for the near-term and long-term RCP4.5 and RCP8.5 scenarios. In this work we consider the change in biomass productivity, in evapotranspiration and in emergency and maturity date.

3. Results

Results are reported in two sections. "Climate change in the Capitanata" focuses on the change in precipitation and temperature, minimum and maximum, mean seasonal values from baseline to RCP4.5 and RCP8.5 projections. "Climate change impacts on wheat" concerns the effect of climate change on durum wheat

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[4] See Appendix A for details

[5] According to the Penman-Monteith method the reference surface evapotranspiration ET_0 can be unambiguously determined by: $ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)}$ [mm/day] where R_n is the net radiation at the crop surface, G is soil heat flux density, T is mean daily air temperature at 2m, u_2 is wind speed at 2m, e_s-e_a is saturation vapor pressure deficit, γ is the psychrometric constant and Δ is the slope of vapor pressure curve (FAO, 1977).

[6] b.p. stands for "before planting"

[7] a.e. stands for "after emergence"

[8] a.p.m. stands for "after physiological maturity"

productivity and phenological cycle. For all variables, plots show box and whiskers diagrams: the whiskers represent 10th and 90th percentiles, the box limits represent the first and the third quartile, and the central line the median.

3.1 Climate change in the Capitanata: seasonal precipitation, maximum and minimum temperature

Figure 1 shows the boxplots for all periods and scenarios for mean seasonal minimum and maximum temperature. Each diagram is representative of one season: autumn (SON), winter (DJF) and spring (MAM). The analogue quantities for cumulated precipitation (mm/season) and related boxplot are shown in Figure 2.

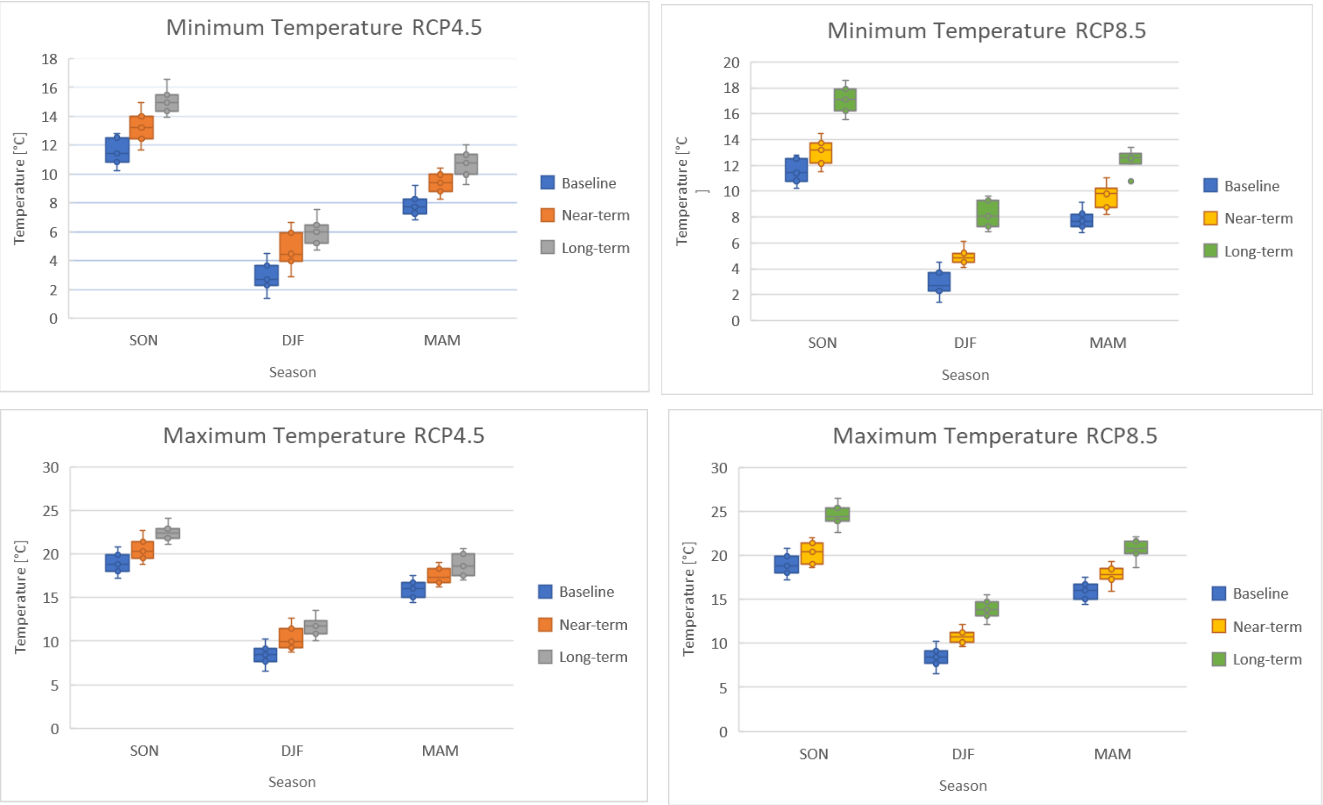

Figure 1 upper left panel: Mean seasonal minimum temperature in °C for autumn (SON), winter (DJF) and spring (MAM) seasons for baseline (blue), near-term (orange) and long-term (grey) periods in RCP4.5 scenario. Each diagram represents 10th percentile, first quartile, median, third quartile and 90th percentile. Upper right panel: same as left panel for RCP8.5. Baseline (blue), near-term (yellow) and long-term (green) periods are examined.
Bottom left panel: Mean seasonal maximum temperature in °C for autumn (SON), winter (DJF) and spring (MAM) seasons for baseline (blue), near-term (orange) and long-term (grey) periods in RCP4.5 scenario. Bottom right panel: same as left panel fir RCP8.5. Baseline (blue), near-term (yellow) and long-term (green) periods are examined.

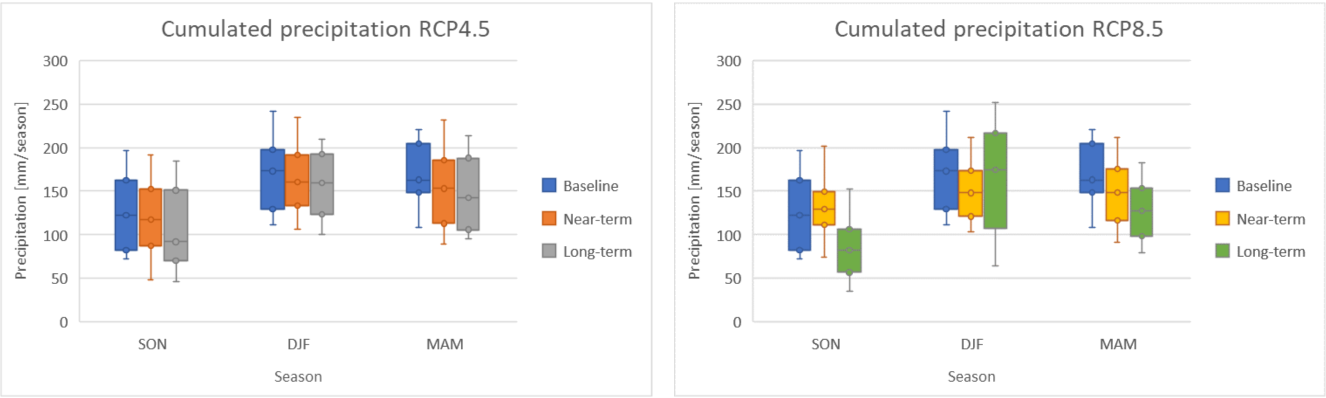

Figure 2 left panel: Mean seasonal cumulated precipitation in mm/season for autumn (SON), winter (DJF) and spring (MAM) seasons for baseline (blue), near-term (orange) and long-term (grey) periods for RCP4.5 scenario. Each diagram represents 10th percentile, first quartile, median, third quartile and 90th percentile. Right panel: same as left panel for RCP8.5 scenario. Baseline (blue), near-term (yellow) and long-term (green) periods are examined.

The Mann-Whitney test is computed for the near-term and long-term of both RCP scenarios for minimum temperature, maximum temperature and cumulated precipitation. Statistic values are reported in Table 2. In general, minimum and maximum temperature present statistically significant increases with respect to baseline, while precipitation decreases are not always significant in future scenarios.

	RCP4.5 Near-term			RCP4.5 Long-term			RCP8.5 Near-term			RCP8.5 Long-term		
	SON	DJF	MAM	SON	DJF	MAM	SON	DJF	MAM	SON	DJF	MAM
tasmin	4,414	4,391	5,188	6,610	6,485	6,497	4,132	5,572	5,357	6,765	6,875	6,751
tasmax	3,682	4,028	4,442	6,567	6,311	5,864	3,231	5,519	4,822	6,765	6,848	6,610
pr	-0,443	-0,161	-1,260	-1,640	-0,859	-1,865	0,528	-1,571	-2,048	-3,315	-0,470	-3,625

Table 2: Statistics for Mann-Whitney test for mean seasonal minimum (tasmin), maximum (tasmax) temperature and cumulated precipitation (pr). The comparison is between baseline and near-term and long-term periods for both RCP4.5 and RCP8.5.

Concerning *tasmin*, with a 5% significance level, null hypothesis can be rejected for all periods, seasons and scenarios under investigation. The alternative hypothesis of a shift of the distribution center towards larger value can be accepted. The greatest deviations for RCP4.5 scenario are in spring, while for RCP8.5 scenario they are in winter season. Furthermore, previous observations remain valid also for a 1% significance level, where threshold value is 2.375.

For a 5% significance level, null hypothesis in *tasmax* can be rejected in all cases here reported. Larger values can be seen for RCP4.5 Long-term autumn season and for RCP8.5 Long-term winter season. Again, for maximum temperature an increase is predicted, also for 1% significance level.

Differently than temperature, null hypothesis cannot be rejected everywhere for *pr*. In winter season (DJF) the requirement is never satisfied, even if in RCP8.5 Near-term value is close to threshold. For autumn (SON) the only observation where null hypothesis can be rejected is RCP8.5 Long-term, even if the value is very close to the critical one also in RCP4.5 Long-term. Spring values are in general significant also at 1% significance level, except for RCP4.5 Near-term where null hypothesis cannot be rejected. All values show a shift towards a smaller distribution center, denoting a decrease in precipitation. Only autumn for RCP8.5 Near-term scenario highlight a positive value, but it is not statistically significant.

3.2 Climate change impacts on wheat: phenology, biomass and yield, actual evapotranspiration

Change highlighted by the analysis in Section 3.1 will clearly have consequences on the growing cycle and productivity of crops. An increase in temperature is expected to shorten the growing season of crops with a subsequent shorter time for biomass accumulation, also resulting in a lower yield. However, the latter is in general dependent also on crop distribution, crop type and environmental condition, that is water and nutrient availability (Moriondo et al., 2011; Giannakopoulos et al., 2009).

In the following, the term "growing season" refers to the period ranging from the crop emergence (November) to the harvesting (June). CropSyst gives in output, between others, the emergence date, the flowering date and the maturity date. We calculate the length of the growing season as the number of days between the emergence date and the maturity date (Figure 3).

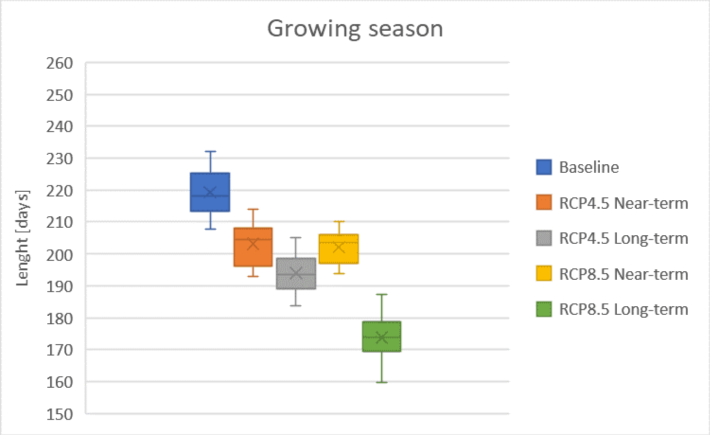

Figure 3: Growing season length in days for baseline (blue), RCP4.5 Near-term (orange) and Long-term (grey), RCP8.5 Near-term (yellow) and Long-term (green) projections. Each diagram shows 10th percentile, 25th percentile, median, 75th percentile, 90th percentile.

We see that both RCP4.5 and RCP8.5 scenarios predict a decrease in the number of days. The median of baseline is 218 days and becomes 204 and 203 days (respectively for RCP4.5 and RCP8.5) for the period 2021-2050, while for the Long-term projection a huge decrease is predicted: 193 days for RCP4.5 and 174 days for RCP8.5. This means a shorten, in the worst scenario, of 44 days (a reduction of approximately 20%). This result is explained if we consider that the length of every phenological phase (the sum of which represent the growing season) is determined by a fixed number of growing degree days[9]. A rise in temperature allows the crop to reach the requested degree days in a shorter time.

Yield is a measurement of the amount of a crop grown per unit area of land. It is linked to AGB by the Harvest Index (HI), that represents the percentage of useful product from total biomass. A potential HI is defined for each crop: for durum wheat it is fixed to 0.3. CropSyst evaluates the actual HI from the potential one depending on the occurrence of water and/or nitrogen stress during flowering and grain filling phases. The ratio between the yield and the AGB is an index of the magnitude of the crop stress: smaller ratios correspond to a greater stress.

A reduction of the growing season is expected to involve a decrease in productivity too. We show an opposite effect (Figure 4): AGB and yield seem to increase in both Long-term and Near-term projections.

We calculate Harvest Index for the scenarios analyzed in order to quantify the amount of water and nitrogen stress. Here reported are the values of the HI median for every simulation (Table 3).

	Baseline	**RCP4.5 Near-term**	**RCP4.5 Long-term**	**RCP8.5 Near-term**	**RCP8.5 Long-term**
HI Median	0.28	0.28	0.29	0.30	0.28

Table 3: Median value for the harvest index calculated for baseline, Near-term and Long-term for RCP4.5 and RCP8.5 projections.

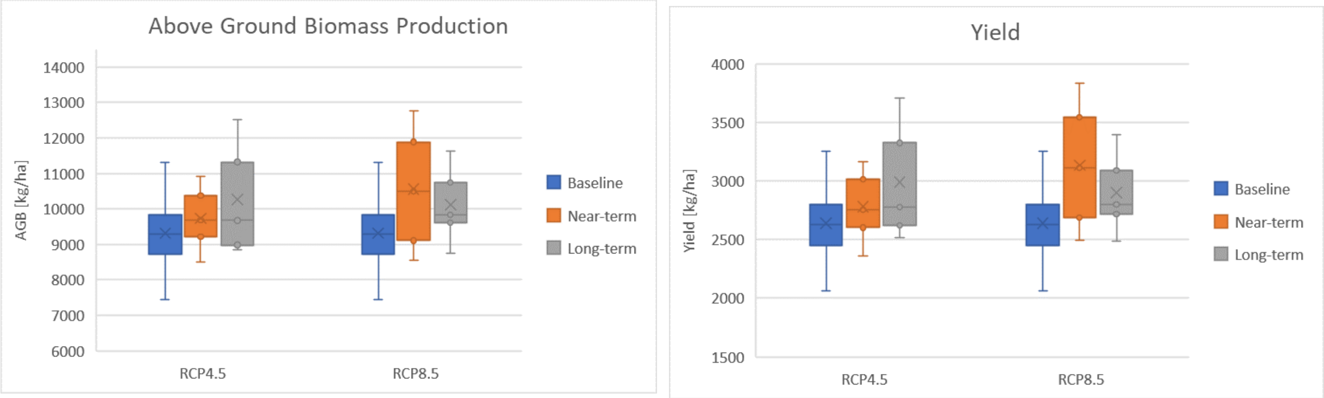

Figure 4: Above Ground Biomass Production (left panel) and Yield (right panel) in kg/ha for Near-term (orange) and Long-Term (grey) simulations for RCP4.5 (left) and RCP8.5 (right) scenarios. Baseline (blue) is duplicated for simplifying comparison.

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[9] Growing degree days (GDD) represent the sum of useful temperature degrees daily perceived by the crop. They are calculated as $GDD = \overline{T_d} - T_b$ where $\overline{T_d}$ is the mean daily temperature and T_b is the basal temperature (under this temperature the crop will not develop). Durum wheat T_b is equal to 0°C.

We observe that the evolution for both these quantities is very similar. HI, in fact, does not change significantly for the analyzed scenarios, being always greater than 0.28: the crop is expected to suffer only a little stress. We can observe that periods where HI is greater a larger production is expected (i.e., RCP8.5 Near-term).

Starting from the Penman-Monteith derived evapotranspiration (ET_0), CropSyst obtains potential evapotranspiration (ET_P), the maximum ET for the crop, and the actual evapotranspiration (ET_a). The ratio between ET_a and ET_0 is the water deficit, that is the lack of water for the crop to reach its maximum development. We show the predicted evolution for ET_a and for water deficit for every simulated scenario (Figure 5).

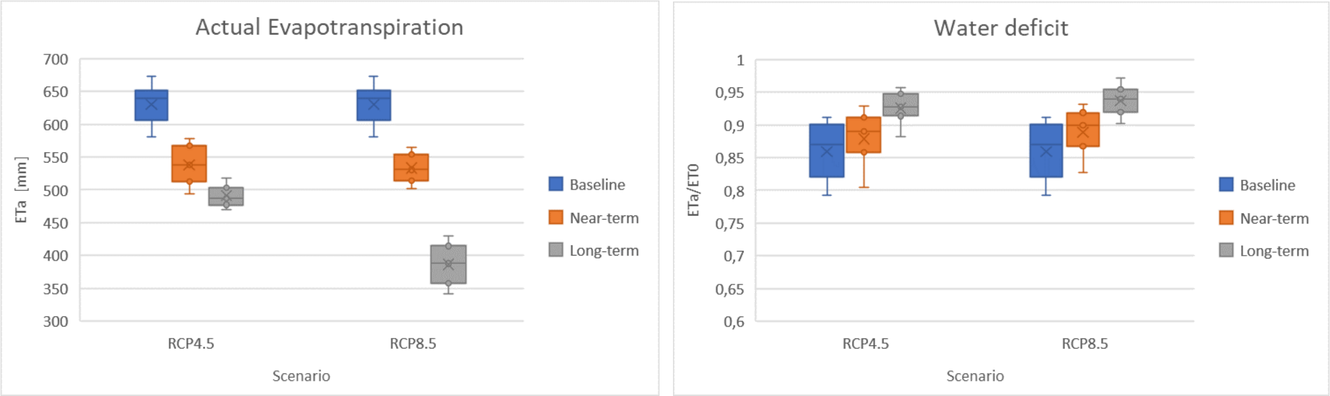

Figure 5 left panel: Actual evapotranspiration for the growing season (in mm) for durum wheat for RCP4.5 (left) and RCP8.5 (right) Near-term (orange) and Long-term (grey). Baseline (blue) is duplicated for an easier comparison. Right panel is the same as left one for water deficit.

As much as the water deficit value is lower than 1, the crop is subject to greater stress conditions. Our simulations predict conditions of smaller stress for Long-term scenarios with respect to the reference period. In parallel, ET_a shows that the amount of water consumed by durum wheat will greatly decrease because of climate change.
The ratio between the AGB and ET_a represents the water efficiency, that is how much the crop is able to transform water in biomass (Figure 6) (Garofalo et al., 2011).

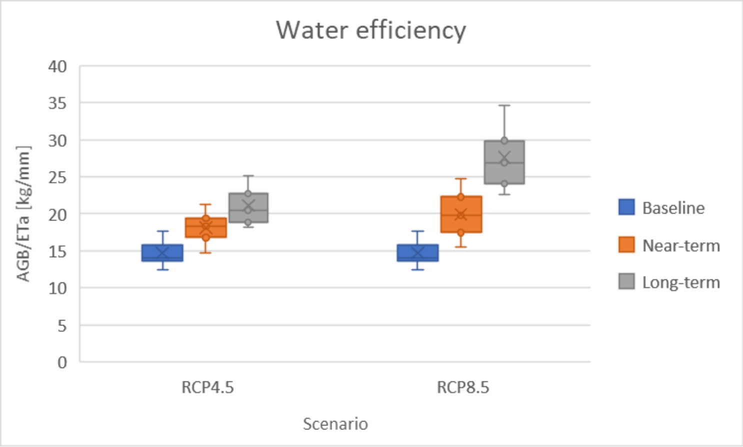

Figure 6: Water efficiency in kg/mm for durum wheat for RCP4.5 (left) and RCP8.5 (right) Near-term (orange) and Long-term (grey). Baseline (blue) is duplicated for an easier comparison.

The ratio between the biomass production and the actual evapotranspiration shows a significant increase for the future scenarios, for both RCP4.5 and RCP8.5, though in the latter the magnitude of the phenomenon is greater. This implies that the same quantity of biomass is produced with less water consumption.

As for climatic variables, the Mann-Whitney test is calculated for the agronomic quantities described.

	RCP4.5 Near-term	RCP4.5 Long-term	RCP8.5 Near-term	RCP8.5 Long-term
Phen	-5.197	-6.461	-5.862	-6.653
AGB	1.996	2.277	2.602	2.883
Yield	2.025	2.779	3.533	2.853
ETa	-5.988	-6.609	-6.313	-6.653
WD	1.405	4.938	1.745	5.293
WE	4.273	6.032	4.997	6.520

Table 4: Statistics for Mann-Whitney test for growing season length (Phen), above ground biomass production (AGB), yield, actual evapotranspiration (ETa), water deficit (WD) and water efficiency (WE). The comparison is between baseline and near-term and long-term periods for both RCP4.5 and RCP8.5.

For a 5% significance level, null hypothesis can be rejected for all variables, except in RCP4.5 Near-term scenario in water deficit (WD) where the value is quite similar to the threshold but not sufficient to conclude that the expected variation is not only a statistical fluctuation.

4. Discussion and conclusions

The COSMOMed climate simulations agree with the very substantial minimum and maximum temperature increase suggested by practically all model simulations (Lionello and Scarascia 2018). All seasons are affected. Changes are larger for the high RCP8.5 emission scenario than for the medium RCP4.5 emission scenario and for the long-term than for the near-term period. Changes of precipitation are mostly not significant for the medium emission scenario, where a significant decrease is expected only in spring and for the long-term period. For the high emission scenario, the reduction of precipitation is larger than for the medium emission scenario and it affects significantly spring for both the near- and long-term periods, but also autumn in the long-term period.

In order to estimate how wheat will be affected, a crop model is required. In fact, anthropogenic emissions can impact crops through different factors, which can act in opposite directions, either reducing or increasing productivity. Therefore, depending on the prevailing factors the net effect on crops can be positive or negative. In the case of Capitanata, temperature increase (with its effect on potential evapotranspiration and decrease of precipitation) would negatively affect the crop life cycle, but it is compensated by the fertilization effect of the increase in CO_2 concentration (see RCP4.5 and RCP8.5). Water stress in plants depends not only on soil water content and air temperature, but also on CO_2, because of the effect of the latter in photosynthesis.

Transpiration by vegetation happens through the opening of leaf stoma. If CO_2 concentration increases, the crop takes a shorter stomatal opening time to absorb the same quantity of carbon dioxide. This reduced time involves a decrease in water losses, and a lower amount of precipitation, as predicted by our analysis, will scarcely influence the crop cycle. At the same time, expected shortening of the growing season, because of increasing temperatures, involves less water consumption, particularly during the warm months when evapotranspiration is larger. Moreover, the anticipation of the maturity phase allows the crop not to suffer the summer temperature extremes that will affect its well-being. Therefore, CO_2 increase positively and influences the water efficiency with its fertilization effect (Rinaldi et al., 2015).

Our results agree with studies performed on the durum wheat response to climate change in Southern Italy. In particular, a positive CO_2 fertilization effect on yield is predicted for temperature increase up to 2.5°C, even if an increase of more than 3°C is expected to negatively affect crop productivity (Ventrella et al, 2011). A more recent study reports that, for an increment in atmospheric CO_2 concentration from 360 ppm to 770 ppm in Mediterranean environment, wheat production will change from 2.0 t/ha^{-1} to 3.1 t/ha^{-1}, also when the cultivation was carried out under an incremented average temperature equal to 5 °C (Garofalo et al., 2015). Furthermore, the decrease of ET_a at seasonal scale and the increase of water use efficiency are also reported in Ventrella et al, 2012. Increased temperature coupled with drought (i.e. for Mediterranean area) would result in a decrement of water loss by evapotranspiration, improved the gas concentration in intercellular tissues and net photosynthesis rate (Rinaldi et al., 2015).

As our analysis shows, climate change will increase mean seasonal minimum and maximum temperature, with differences that can reach up to 5°C in the worst scenarios, increasing potential evapotranspiration, and reduce seasonal cumulated precipitation, even though its reduction is significant only for a few seasons and especially in RCP8.5 scenario. Durum wheat is expected to be significantly and negatively influenced by these changes with a reduction of the growing season and larger water stress, which both deteriorate crop productivity. However, better efficiency in water use, that can be explained considering the CO_2 fertilization effect,

overcompensates for these negative effects and the reduced length of the growing season decreases the crop water demand. In conclusion, somehow surprisingly anthropogenic emissions increase the crop yield.
Further investigations are needed to confirm these results. Particularly, a) repeating the simulations with agronomic models other than CropSyst and b) using inputs from other regional climate models will be important to explore the inter-model variability of the climate change impacts. Moreover, it will be worth, on one hand to analyze the fine-scale spatial variability of the model, comparing the results that we have obtained averaging over the entire area with those at specific grid points, and, on the other hand, to analyze other areas in the Mediterranean besides Capitanata, where wheat has a comparable economic relevance.

Appendix A

For CropSyst simulation a CO_2 information is needed. In this work, we referred to Potsdam Institute research (Meinshausen, M. et al., 2011) and from the first and the last value of each simulation a constant rate is calculated. Table A1 summarizes initial concentration value and annual rate for CO2 for performed simulations.

	Initial CO_2 [ppm]	**Annual rate [ppm/year]**
Baseline	316	+1.2
RCP4.5 Near-term	411	+2.4
RCP4.5 Long-term	524	+0.4
RCP8.5 Near-term	416	+4.0
RCP8.5 Long-term	677	+8.4

Table A1: Initial and annual rate expressed in ppm for CO2 concentration as used for CropSyst settings

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