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Modeling high-resolution climate change impacts on wheat and maize in Italy

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ABSTRACT

The Mediterranean basin has been identified as a prominent hotspot of climate change, with expected negative impacts on crop productivity, among others. Given the primary role that agriculture has to sustain cultural values, economic opportunities, and food security, it is crucial to identify specific risks in agriculture due to climate change, which can address more effective adaptation strategies and policies to cope with climate change. This study aims to evaluate the high-resolution impacts of climate change on the length of the growing cycle and yield of durum wheat, common wheat, and maize in Italy by using the CERES-Wheat and CERES-Maize crop models implemented in the Decision Support System for Agrotechnology Transfer (DSSAT) software. A digital platform (GIS-DSSAT) was developed to couple crop simulation models with dynamically downscaled climate projections at high resolution for Italy, which can better represent the Italian landscape complexity and the spatial distribution of different pedological and crop management features, providing more detailed information on the expected impacts on crops respect to previous studies at a coarser resolution. The projections have been extended for two climate change scenarios and accounting for uncertainty, either considering or not the potential direct effects of increasing atmospheric CO_2 concentrations ([CO_2]). Results show that climate change may affect Italian cereal production in the medium to long term periods. Maize is the main affected crop, with yield reductions homogeneously distributed from North to South Italy. Wheat yield is expected to decrease mainly in southern Italy, while northern Italy may benefit from higher precipitation regimes. Higher levels of atmospheric CO_2 concentrations may partially offset the negative impact posed by climate change and increase the benefits in the northern regions, especially for common and durum wheat.

1. Introduction

Global warming, changes in rainfall patterns, and increase in the frequency and intensity of extreme events are already affecting the agricultural systems and food production (IPCC, 2019) through direct (variation in the length of the growth cycle, crop yield and

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quality of the products) and indirect impacts (variation of available water resources, distribution and extent of pest and plant diseases). The effects on the agricultural sector vary between geographical regions and local environmental conditions, as well as its sensitivity, adaptive capacity, and degree of exposure to climate hazards (IPCC, 2014a).

The Mediterranean is a prominent hotspot of climate change, with the warming that exceeds the global rate by 20% (in the continental areas north of the basin up to 50% larger than at global scale) and a reduction of precipitation, in contrast with the general increase of the hydrological cycle in the areas between the latitudes 30° N and 46° N (Lionello and Scarascia, 2018). Several interconnected sectors are at risk and threatened to miss Sustainable Development Goals (SDGs) in the Mediterranean area (Cramer et al. 2018). Sustainable and resilient agriculture and food systems would provide environmental, health, social, and economic benefits, which are of particular relevance, especially under the current financial crisis caused by the COVID-19 pandemic (Farm to Fork Strategy, 2020), which overlaps with the risks caused by climate change.

The IPCC special report “Climate Change and Land” (IPCC, 2019) reported, with a high level of confidence, that yields of wheat and maize have been adversely affected by the observed climate changes in many lower-latitude regions, while yields have increased in many higher-latitude areas, during the recent decades. Projections at the global level for maize and wheat confirm this trend, showing yield increases for wheat and maize at high-latitude and decreases at low-latitude by the end of the century (Rosenzweig et al., 2014a, 2014b). The impacts for the Euro-Mediterranean area are likely to exceed the global average trend, with moderate to high impacts respectively in central and southern Europe expected for the coming decades with high variability depending on regions, crops and climate scenarios (IPCC, 2014b). According to Hristov et al. (2020), maize is expected to be the most affected crop by climate change throughout Europe, while wheat could benefit from more beneficial conditions in Northern Europe.

Cereals are the primary source of food supply for direct food consumption in the world, and the European Union is the leading world producer of wheat and the fourth world producer of maize (USDA, 2018). In Italy, cereal production constitutes a key asset for the food industry. Maize and wheat are the main grown cereals, accounting together for 78.6% of the total harvested area and 80.9% of total cereal production, and production of respectively 6.0 million tons for maize, 4.2 million tons for durum wheat, and 2.8 million tons for common wheat recorded in 2017 (ISTAT, 2019). Maize and common wheat are cultivated mainly in Northern Italy (Po Valley) (88.7% and 69.0% of cultivated area in 2017, respectively), while durum wheat is more widespread in Southern Italy and Islands (65.6%).

Limited information is available at a spatial scale on the impacts of climate change on cereal production in Italy, mainly from the analyses performed at the European or global level with a coarse resolution for Italy (e.g., Rosenzweig et al. 2013; Saadi et al., 2014; Ciscar et al., 2018; Hristov et al., 2020). However, the use of high-resolution climate data is pivotal in regions, as Italy, characterized by a significant variability of climatic, pedological, and topographic conditions. The cell resolution of climate data should follow the environment-vegetation dynamics as closely as possible to better reproducing topography-influenced phenomena and extremes and provide an accurate spatial assessment of climate change impacts on crop growth, development, and productivity. In this respect, Regional Climate Models (RCMs) add an accuracy value compared to General Circulation Models (GCMs), mainly in regions with variable orography and land cover characteristics (Rummukainen, 2016).

Moreover, the use of dynamic process-based models linked to high-resolution climate and crop management data allows the estimation of climate change impacts on crops, and the connection of local resources and environmental conditions with the most effective adaptation options to limit the negative effects on agricultural production and food security.

For these reasons, Crop Simulation Models (CSMs) are wide applied tools to assess the impacts of climate change on crop phenology and productivity. These tools simulate both physiological processes of plant development and physical determinants of resources available in the whole soil–plant-atmosphere environment, highlighting the effects of the climate, soil and crop management on crop growth, development, and production (Hoogenboom et al. 2004). Moreover, CSMs play a key role in evaluating the genotype (G) × environment (E) × management (M) interactions, and their effects on crop yield and other outputs (Rotter et al. 2018). Advanced crop dynamic models, such as the Decision Support System for Agrotechnology Transfer DSSAT (Jones et al., 2003; Hoogenboom et al., 2015), allow integrating the effect of atmospheric CO_2 concentrations ($[CO_2]$) on plant photosynthesis rate, biomass accumulation, and stomatal resistance (Jones et al., 2007). Although developed and implemented for field-scale simulations, the CSMs have been recently used at regional/global scales by combining simulation processes with geospatial data using different approaches (e.g., Resop et al. 2012; Rosenzweig et al. 2013; Elliott et al., 2014; Mereu et al., 2015; Ciscar et al., 2018; Webber et al., 2018; Shelia et al., 2019). However, these tools are not fully readily adaptable to perform spatialized simulations, and their applications at a gridded spatial scale require additional tools. They are often constrained by the limited availability of data for model parameterization and operation.

In such a context, this study aimed to assess high-resolution climate change impacts on the length of growing cycle and yield for selected widespread varieties of common wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* Desf.), and maize (*Zea mays* L.) in Italy, trough the development of a spatial platform DSSAT based, and the coupling with high-resolution climate data from RCM projections previously refined and validated for Italy and crop parameters obtained using field experiments at the national level. The applied method allowed us to represent the complex interactions of environments, climate projections, and crops to provide high-resolution information on climate change impacts on cereal production, missing from previous studies that provided information at coarse resolution or field level. Uncertainties emerging for various emission scenarios and the potential effect of different $[CO_2]$ were also explored.

The analysis provides fine-scale information on the main affected areas for cereal production in Italy improving the so far available data from previous studies, to better orient the decision-making process and support stakeholders and policymakers in defining the proper adaptation and mitigation measures to cope with the impacts of climate change on the Italian agricultural sector.

2. Materials and methods

Fig. 1 contains the scheme of the methodology applied in this study. A spatial platform was explicitly developed (see Section 2.1) to couple environmental and crop management spatial datasets, together with climate projections, to reconstruct a spatial distribution of crop simulations for different periods and emission scenarios, also highlighting the potential offsets due to [CO_2] on plant productivity. The crop models implemented in the DSSAT were applied, through the GIS-DSSAT platform, to evaluate the impacts of climate change on the length of growing cycle and grain yield for durum wheat, common wheat, and maize in Italy. The authors defined the model performances and crop parameters in a previous study for Italy (Mereu et al. 2019). All the required information (genetic crop coefficients; climate data; geo-datasets characterizing soil properties and crop management practices) for model operation were collected and processed to be linked with DSSAT models. Results from the platform are streamlined for geographical maps and to perform statistical analyses at various administrative scales (e.g., regional). Details on the input data, tools, and methods applied are provided in the following paragraphs.

2.1. Tools

In this study, CERES-Wheat (Ritchie and Otter, 1985; Hoogenboom et al., 2010) and CERES-Maize (Jones and Kiniry, 1986; Hoogenboom et al., 2010) CSMs, implemented in the Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6.1.0 (Jones et al., 2003; Hoogenboom et al., 2015), were applied to perform crop simulations under present and future climate conditions. The DSSAT is a software package that includes independent dynamic models to simulate crop growth, development, and yield of more than 25 crops by considering weather, soil, crop genetics, and agronomic management, for single or multiple seasons, at sites where the minimum input data required for model calibration and operation are available (Jones et al., 2003; Bao et al., 2017). A number of Cultivar-Specific Parameters (CSPs) determine the life cycle and reproductive growth rate of specific crop varieties by considering phase modifiers (e.g., vernalization and photoperiod sensitivity) and vegetative and reproductive attributes (Boote et al. 2001). Specific modules allow us to simulate soil and water dynamics according to environmental conditions and agronomic management (Jones et al., 2003; White et al., 2010). The direct effects of increasing [CO_2] on photosynthesis and water-use efficiency are also considered (Bao et al. 2017). The models use the [CO_2] to modify the radiation use efficiency, stomatal conductance and plant transpiration (Hoogenboom et al., 1995; Boote et al., 2010), with different response magnitudes according to crop types (C3 vs C4 species) (Vanuytrecht and Thorburn, 2017). These models are commonly used in climate change impact assessment on agriculture at different scales and are widely tested and applied in model intercomparison studies (e.g., Rosenzweig et al. 2013; Rotter et al., 2018; Ruane et al., 2018; Liu et al., 2019), providing good performances in reproducing observations (Palosuo et al., 2011; Bassu et al., 2014).

A digital platform DSSAT based was developed in R (R Core Team, 2019) by the authors (Trabucco et al. 2014) to perform crop simulations at a spatial scale using GIS libraries, to couple and automatize interactions with geodatasets of daily climate variables, environmental conditions, and agronomic practices. Our GIS-DSSAT platform allows the simulation of crop processes, with daily time step on a pixel by pixel basis for a variety of crop types and provides output variables (e.g., anthesis and maturity dates, yield, biomass,

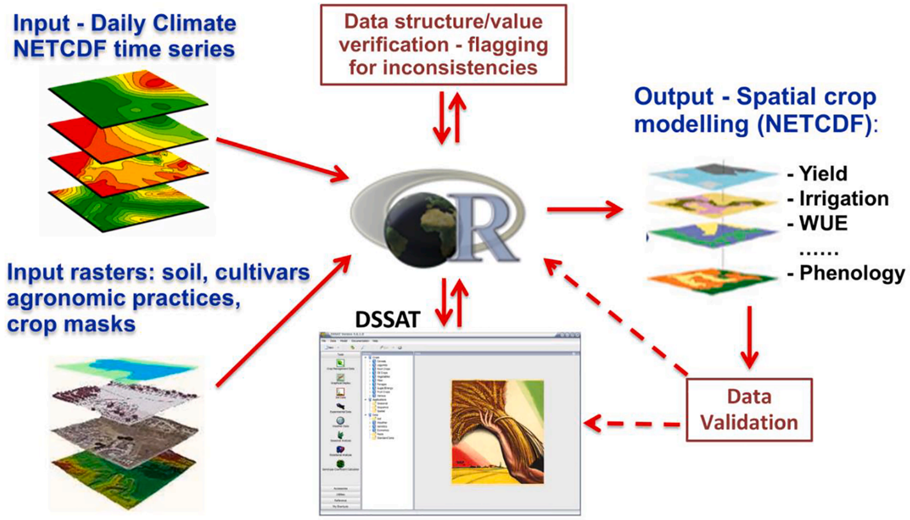


Fig. 1. GIS-DSSAT digital platform used to perform the simulations at spatial scale in Italy. Crop simulation models implemented in DSSAT at daily time step were linked via GIS libraries to netCDF input files for daily weather/climate, soil, crop management and crop masks through a platform developed in R language to perform simulations over large regions and over several projections/time frames/crop management practices. Output data of phenology, crop production, water and nutrient balances, among others, were provided as netCDF format for every grid point within a study area and post processed to assess climate change impacts and statistical summaries at regional scales.

water use, nutrient's cycle, etc.) processed from DSSAT for every grid point within a study area. The digital platform uses multi-dimensional network Common Data Form (netCDF) raster format as input (weather, soil, crop management) and output data (Fig. 1). To ensure proper operation of the platform, all input raster data were resampled at the cell-resolution of climate data with the Nearest Neighbor method, preceded by a mean spatial aggregation (Aggregate function in R) in case of upscaling. The platform allows us to automatically perform a high and parallel number of runs and provides output data in an easily readable format by various software (e.g., GIS, Panoply, NCView). The GIS-DSSAT tool, as well as the datasets generated during and/or analyzed during the current study, are available from the corresponding author on reasonable request.

2.2. Data layers

The minimum dataset for model operation includes soil data, daily weather/climate data, crop management and cultivar specific parameters.

2.2.1. Crop data

The crop management information that includes sowing dates, seeding density, fertilization rates, tillage method were collected from the available literature and mainly based on the Italian National Variety Trials (INVTs) yearly performed in different Italian regions. A detailed list of references for the observed data and the model calibration and evaluation performances are available in a previous study (Mereu et al. 2019). These data were used to simulate the ordinary crop management applied in several experimental sites located in North, Centre, and South Italy. For durum and common wheat, a row sowing was considered, with rows spaced 18 cm apart. The plant population at seeding was 450 plants m^{-2} for North and Centre areas and 350 plants m^{-2} for Southern areas for durum wheat, while 450 plants m^{-2} generally for common wheat. For maize, the seeding density was 7 plants m^{-2} with a row spacing equal to 75 cm. Conventional tillage was considered for each crop: moldboard plow one month before sowing and harrow tine the day before sowing. According to the INVT data, mean sowing dates for durum wheat vary between November 5th for the northern areas to December 15th for the South, from November 2nd (North) to December 7th (South) for common wheat, and from April 20th (North) to April 1st (South). Maize was simulated in irrigated conditions, using the "automatic irrigation when required" option (irrigation fully satisfy crop water requirements), setting sprinkler irrigation method (0.75 efficiency), with irrigation threshold at 50% of soil available water and endpoint at 100%. Durum wheat and common wheat were simulated in rainfed conditions, according to ordinary crop management. The effects of pests and diseases were not considered and the crop management options were kept constant in the simulations.

The Cultivar-Specific Parameters (CSPs) to run CERES-Wheat and CERES-Maize crop models used in this study were optimized by the authors in a previous study (Mereu et al. 2019) for three cultivars of durum wheat (Iride), common wheat (Bologna) and maize (Elonora). These cultivars were chosen for their extensive cultivation in Italy and their good performances, stability and adaptability in different environments, as well as for the availability of data from the INTVs for their parameterization (Mereu et al. 2019).

2.2.2. Soil data

The soil data used in this work have been obtained from the ISRIC-WISE v.1.2 raster data set, which is derived by interpolation from soil profiles worldwide with a spatial resolution of 5 × 5 arcminutes (Batjes, 2012). The raster has been clipped for Italy to the same extent and resampled to the same resolution as the climate data (8 km), for data harmonization.

2.2.3. Climate data

The climate data projections were provided by the REHMI (Regional Model and geo-hydrological Impacts) Division of the CMCC (Euro-Mediterranean Center on Climate Change). The data were dynamically downscaled from the global model CMCC-MED (Rockel et al., 2008; Gualdi et al., 2012), with the RCM model COSMO-CLM at a spatial resolution of 4.3 arcminutes (about 8 km) (Bucchignani et al., 2016; Zollo et al., 2016) for the period 1971–2100. The COSMO-CLM projections have been highly improved over the Italian area with optimized parameterization and the validation of model performances showed that these model data agree closely with observations from E-OBS and/or different regional high-resolution observational datasets, in terms of both average values of temperature and precipitation (Bucchignani et al. 2016) and in terms of extreme events (Zollo et al. 2016).

Moreover, the climate projections obtained with COSMO-CLM are in good agreement with the projections of the ensemble mean of the EURO-CORDEX dataset (Zollo et al. 2016), providing a very conservative estimate despite uncertainties over multiple climate models/projections. These data have been used in recent studies of climate change impact and risk for Italy (e.g., Bonfante et al., 2018; Spano et al., 2020) as well as in the development of the National Climate Change Adaptation Plan by the Ministry of Environment and Protection of Land and Sea (MATTM, 2017).

The uncertainty in climate projections was considered in this study according to 2 Representative Concentration Pathways (RCPs) (Moss et al. 2008): RCP4.5 (medium stabilization scenario) and RCP8.5 (business-as-usual scenario). For each climate scenario, daily time series of minimum and maximum temperature at 2 m, total precipitation, and solar radiation were used. Transient annual values of [CO_2] from 1976 to 2100 were considered, according to the 2 RCPs.

2.3. Assessment of climate change impacts on crop growing cycle and productivity

High-resolution simulations were carried out with the GIS-DSSAT platform for the three crops for each grid point (8 × 8 km) for the period 1976–2095 (120 independent growing seasons, with simulations starting date set several months in advance respect to the ordinary sowing dates), with the two scenarios (RCP4.5 and RCP8.5), while taking in consideration or not the direct effects of [CO_2] enrichment following the selected emission scenarios. The impacts of climate change on phenology (days after planting) and grain yield (kg ha^{-1}) were made by comparing simulation outputs for three future timeframes: short-term period (2006–2035, centered at 2020), medium-term period (2035–2065, centered at 2050) and long-term period (2066–2095, centered at 2080), against baseline values (1976–2005, centered at 1990). Among the available outputs, the relative change of maturity date (in days) and grain yield (in percentage) have been analyzed and mapped in this study. Areas with a soil slope greater than 30% were excluded from this analysis, as marginally suited for cultivation.

Projected values of maturity and grain yield have been statistically analyzed for each geographical area by the unbalanced Analysis of Variance (ANOVA) using the Aunbalanced procedure of the GenStat 20th edition (VSN International, 2019) while multiple comparison means were performed by using the Fisher LSD method ($p \leq 0.05$) when the results of ANOVA were significantly different at $p < 0.05$. Boxplots are obtained by the ggplot2 package (Wickham, 2016) of R (R Core Team, 2019).

The uncertainty in the model and scenario simulations is considered using 2 RCPs (RCP4.5 and RCP8.5) for 3 different future 30-years' time frames (around 2020, 2050 and 2080), and including or not transient values of [CO_2].

3. Results

The results are presented separately for wheat and maize. The maps show the high-resolution spatial distribution of the projected anomalies on grain yield (kg ha^{-1}) for the short, medium, and long-term periods, according to the 2 RCPS. Yield projections are plotted considering [CO_2] constant at present values and [CO_2] transient according to the 2 RCPs. Maps for maturity are reported in the Supplementary Information (S.I.) (S.I. Fig. 1 and S.I. Fig. 2). Statistical analyses to summarize crop simulation results by areas (North, Centre, and South Italy) are presented in tables and graphs. Boxplots of crop yields by area are reported in Supplementary Information (S.I.) (S.I. Figs. 3–7).

3.1. Durum and common wheat

The spatial distribution of projected changes in the length of the growing cycle for durum and common wheat indicates an earlier maturity for both crops, with a progressively reduced number of days needed to reach the crop maturity moving towards the end of the century, with the RCP8.5 (S.I. Fig. 1). The shortening of the growing cycle is more pronounced for durum wheat, which shows a decrease higher than 30 days for 2080 under RCP8.5, while for common wheat, the expected changes are generally lower than 30 days. The shortening of the growing cycle, influenced by the relative warming, will also be more prominent along elevation than latitude. Thus, areas at a higher elevation, which are less suitable for wheat, would foresee a more enhanced reduction in the growing cycle length.

Variation of time needed to reach maturity in the three geographical areas (North, Centre, and South Italy) are presented in Table 1. As expected, durum and common wheat have, under current conditions, a slightly longer growing season in the northern areas (237 for durum and 257 days for common wheat), compared to central (208 for durum and 231 days for common wheat) and southern (196 for durum and 213 for common wheat) Italian areas, following a warmer gradient, that is confirmed in the future periods. The projected

Table 1

Significance of main treatment effects (RCPs and Periods) and interactions from statistical analyses on the maturity date (expressed in days after planting) aggregated for North, Centre and South Italy, for durum and common wheat.

Effect		**Durum wheat**						**Common wheat**					
		North		**Centre**		**South**		**North**		**Centre**		**South**	
RCP		***		***		***		***		***		***	
	baseline	237	**a**	208	**a**	196	**a**	257	**a**	231	**a**	213	**a**
	RCP4.5	224	**b**	195	**b**	183	**b**	246	**b**	220	**b**	202	**b**
	RCP8.5	219	**c**	190	**c**	176	**c**	243	**c**	216	**c**	197	**c**
Period		***		***		***		***		***		***	
	baseline	237	**a**	208	**a**	196	**a**	257	**a**	231	**a**	213	**a**
	2020	229	**b**	201	**b**	187	**b**	251	**b**	225	**b**	206	**b**
	2050	222	**c**	193	**c**	180	**c**	245	**c**	218	**c**	199	**c**
	2080	213	**d**	184	**d**	171	**d**	239	**d**	211	**d**	193	**d**
RCP × Period		***		***		***		***		***		***	
	baseline	237	**a**	208	**a**	196	**a**	257	**a**	231	**a**	213	**a**
	RCP4.5 2020	230	**b**	202	**b**	189	**b**	251	**b**	226	**b**	207	**b**
	RCP4.5 2050	223	**c**	194	**c**	182	**d**	245	**c**	219	**c**	200	**c**
	RCP4.5 2080	220	**d**	190	**d**	177	**e**	243	**c**	216	**c**	197	**d**
	RCP8.5 2020	229	**b**	199	**b**	186	**c**	251	**b**	224	**b**	205	**b**
	RCP8.5 2050	221	**cd**	192	**cd**	178	**e**	244	**c**	217	**c**	198	**cd**
	RCP8.5 2080	207	**e**	178	**e**	165	**f**	234	**d**	206	**d**	188	**e**

*** Indicates significant at $p < 0.001$; ** Indicates significant at $p < 0.01$; * Indicates significant at $p < 0.05$; ns indicates non-significant. For any factor and area, means followed by the same letter do not differ significantly at $p \leq 0.05$ by LSD test.

changes in the maturity date show an earlier maturity for each area, with progressive larger reductions moving towards the end of the century, and more pronounced under RCP8.5 in which warming is more severe. The highly significant RCP × Period interaction shows a different response to the factors (RCP and periods) considered in this study for both durum and common wheat crops. Projections for durum wheat show maturity dates advanced overall by −30 days in all areas, while for common wheat they range from −23 days in the North to −25 days in Centre and South Italy. Moreover, for durum wheat, the shorter growing cycle projected under RCP8.5 is more pronounced from 2050 to 2080, while with RCP4.5 the main change is projected already from the short to the medium-term period (i.e. from 2020 to 2050). A similar behavior, but less noticeable, is expected for common wheat (Table 1).

Results of spatially distributed durum wheat yield anomalies (percentage changes), under current and future [CO_2], are shown in Fig. 2 for the three future timeframes. The highest negative impacts are expected in areas of central and southern Italy, where yields may decrease by about 30% by the end of the century under RCP8.5, without considering the direct effect of [CO_2]. Yield reductions are expected mainly in southern Sicily (Piana di Catania) and western rural areas of Sicily, in Basilicata (Bradano-Metaponto) and Apulia (Murge and Capitanata), the west and central lowland areas of Sardinia (Campidano), and the coastal areas north of Lazio and Campania. On the contrary, the highest increases in yield are projected for the northern Italian areas, as in the Po river plains, with increases easily exceeding 10–20% for most scenarios and reaching more than 30% for medium-long terms scenarios under RCP8.5.

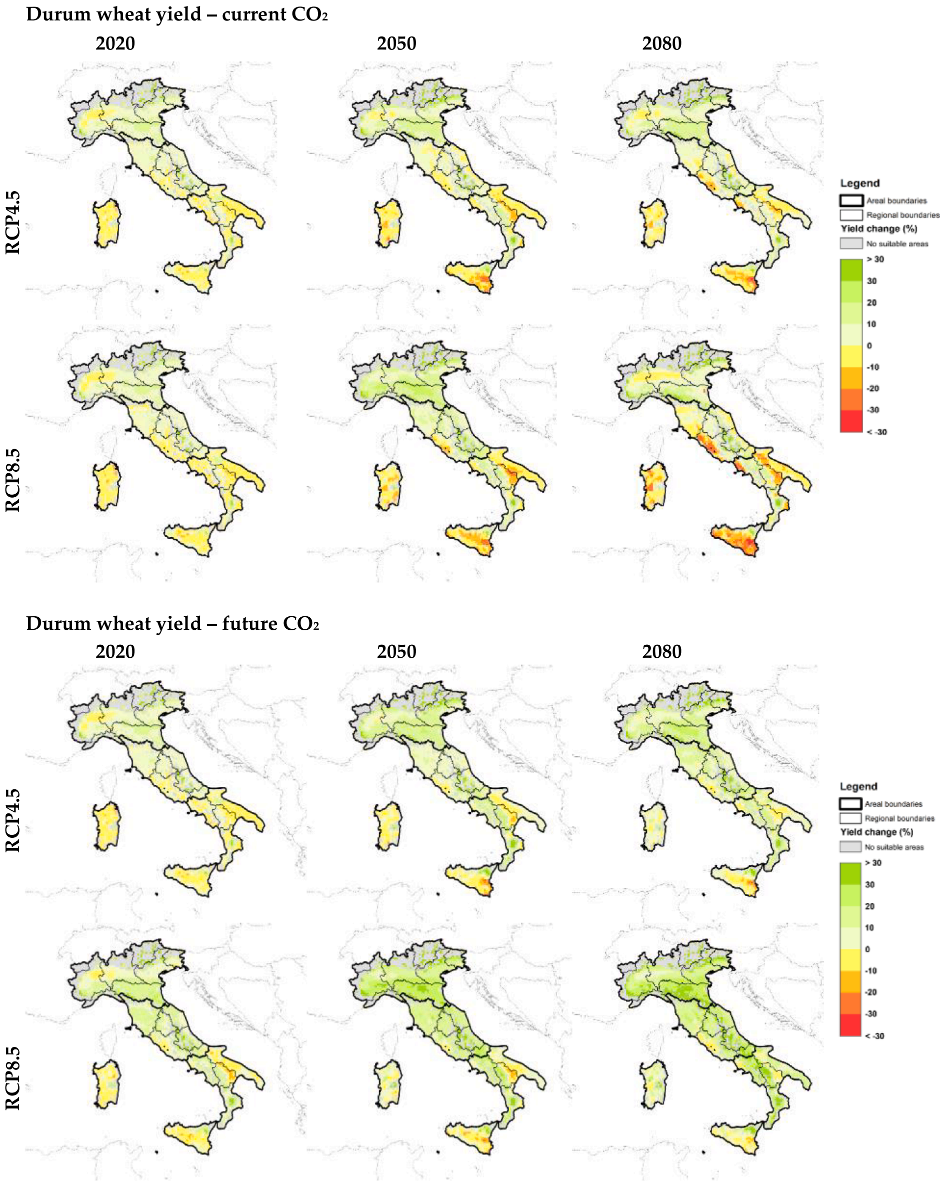
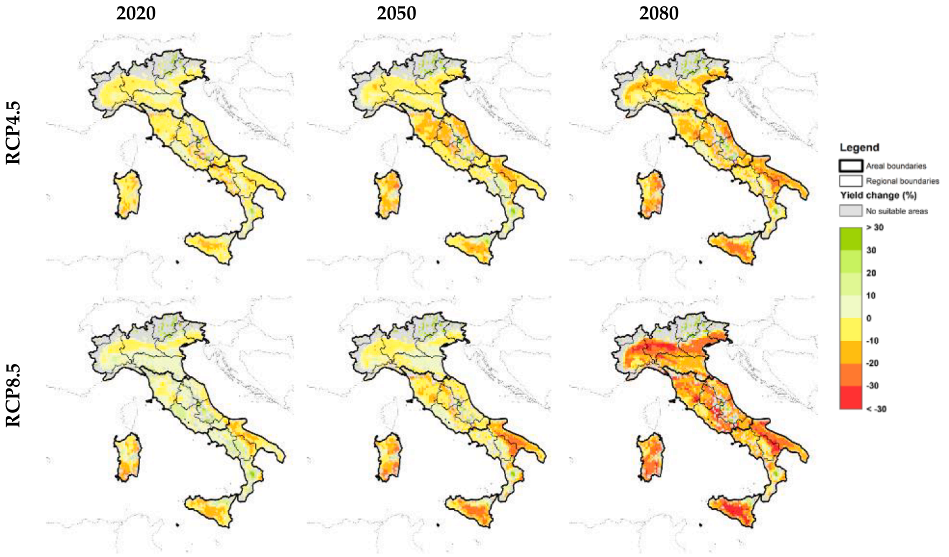


Fig. 2. Changes in average yield (%) from actual (1990) to 2020, 2050, and 2080, with RCP4.5 and RCP8.5 emission scenarios with current and projected [CO_2] for durum wheat in Italy.

This impact would be more enhanced when the effect of raising [CO_2] is included in the simulations, more marked under RCP8.5 scenarios, in particular at the end of the century. However, the direct effect of [CO_2] is not always able to completely reverse the negative impacts expected especially in some southern areas as in the Piana di Catania (South Sicily).

Spatial distribution of projected yield changes from the baseline period for common wheat (Fig. 3) shows negative impacts mainly in Southern and Central Italy in the short (2020) and medium (2050) periods, which become widespread also in Northern Italy in the far future (2080) under high emission scenarios (RCP8.5). Decreases in yield may potentially exceed −20% in several rural areas of Apulia, Sicily, and Sardinia already by 2050 (that are however more devoted to durum wheat cultivation than common wheat), and over −30% by 2080, while encompassing further rural areas with particular cereal vocation in central Italy and throughout the Po plains of Northern Italy. While including the direct effects of [CO_2], the negative impact on yields projected for common wheat is mostly mitigated, and positive outcomes enhanced, especially in the more humid periods (i.e., 2050 under RCP8.5). Northern Italy (the main production area), particularly in 2050, and several areas in central and southern Italy along the Tyrrhenian Sea will foresee beneficial impacts with marginal increases in common wheat yields. However, under future extended conditions, the evolution of changes in the spatial distribution of common wheat yield will still highlight a severe decrease (more than −20%) for several areas in Apulia, Southern of Sicily, and Central-Western parts of the Po Plains, especially in 2080, showing that the negative effect due to

Common wheat – yield – current CO_2



Common wheat – yield – future CO_2

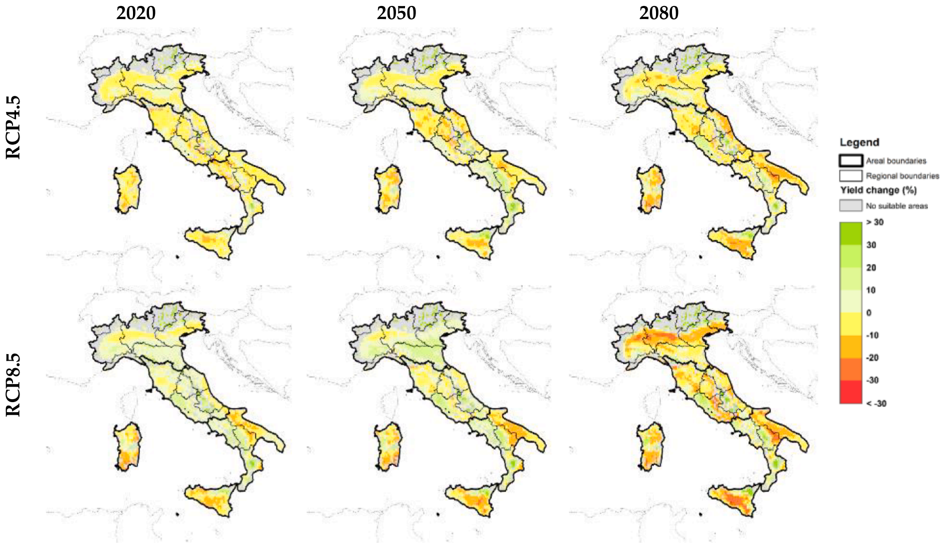


Fig. 3. Changes in average yield (%) from actual (1990) to 2020, 2050, and 2080, with RCP4.5 and RCP8.5 emission scenarios with current and projected [CO_2] for common wheat in Italy.

changed climatic condition is only partially counterbalanced by the positive effect of future [CO$_2$].

Durum and common wheat grain yields aggregated for the three geographical areas are reported in Table 2. No significant interactions were observed, excluding [CO$_2$] × Period for durum wheat and RCP × Period for common wheat in North and Centre Italy. For this reason, the grain yield changes observed in different scenarios can be mainly explained by the fixed factors ([CO$_2$], RCP, and Periods) considered in this analysis.

The direct effect of [CO$_2$] is statistically significant in all areas for both common and durum wheat, with high levels of significance (from $p < 0.001$ in all areas for durum wheat and the South for common wheat and $p < 0.01$ in North and Centre for common wheat). An increase of durum grain yields with respect to baseline is expected in northern and central areas and only for durum wheat. The RCP effect is statistically significant in northern and central areas for durum wheat, and higher increases are estimated for RCP8.5. No differences are assessed for the RCP effects for common wheat in all areas and for durum wheat in southern Italy. The period effect is significant only for the northern area for durum wheat: yield increases with respect to baseline are expected since 2020 with further yield increases in 2050, which do not statistically differ from yield values projected for 2080. While for common wheat, yield reductions are expected only in 2080 in southern Italy. A graphical representation of the complex relationships existing in significant interactions, [CO$_2$] × Period for durum wheat and RCP × Period, for common wheat grain yields is shown in Fig. 4. Increases in durum wheat yields are projected already in the short and medium periods, with current levels of [CO$_2$] in North Italy, followed by a decrease in 2080. Considering the direct effect of [CO$_2$], yields do not statically differ from yields without [CO$_2$] in 2020, while they diverge progressively in 2050 and 2080 due to increasing [CO$_2$]. Similar but less pronounced behavior is estimated in central Italy, whereas in the South, yields are stable with current [CO$_2$] and increase significantly only in 2080, considering the [CO$_2$] direct effect.

The significant RCP × Period interaction obtained for common wheat simulations in the North and Centre is displayed in Fig. 4, where higher yields are expected in 2020 and 2050 under the RCP8.5 than under RCP4.5, while for 2080 the behavior is the opposite.

Although the results reported in the maps show the high spatial variability of climate impacts on crop yields, they do not reveal the projections' inter-annual variability. This is reflected in the performed statistical analyses where years, included in each period, are considered as a random factor. Moreover, the inter-annual yield variability displayed in the boxplots for each area, RCP and [CO$_2$] effect, shows no relevant changes from the baseline for both durum and common wheat yields (S.I. Figs. 3 and 4), with the exception for southern areas that show an increase in inter annual yield variability in 2050 under RCP8.5, both with current and future [CO$_2$] for durum wheat, and in northern areas for all periods and [CO$_2$] under RCP4.5 and at the end of the century under RCP8.5 for common wheat. However, aggregating results by area partially mask the high territorial variability, which could be better highlighted by regional analyses, such as those reported as an example, for durum wheat under RCP8.5 and current and future levels of [CO$_2$] (S.I. Fig. 6 and S.I. Fig. 7).

3.2. *Maize*

Climate change is expected to affect maize phenology by reducing its growing season under both emission scenarios and for all the future period analyzed (S.I. Fig. 2 and Table 3).

The spatial distribution of projected changes in the length of maize growing season (S.I. Fig. 2) shows relatively homogenous trends along Italy, with differences influenced mainly by topography than by latitude. Quite similar changes are expected in all areas in the

Table 2

Significance of main treatment effects ([CO$_2$], RCPs, and Periods) and interactions from statistical analyses on grain yield (kg ha^{-1}) aggregated for North, Centre and South Italy, for durum and common wheat.

Effect		**Durum wheat**						**Common wheat**					
		North		**Centre**		**South**		**North**		**Centre**		**South**	
CO$_2$		***		***		***		**		**		***	
	baseline	5357	**c**	5751	**c**	4742	**ab**	6310	**ab**	5765	**ab**	4074	**a**
	current CO$_2$	5988	**b**	6046	**b**	4658	**b**	6205	**b**	5490	**b**	3780	**b**
	future CO$_2$	6291	**a**	6432	**a**	4988	**a**	6557	**a**	5871	**a**	4052	**a**
RCP		***		***		ns		ns		ns		ns	
	baseline	5357	**c**	5751	**c**	4742		6310		5765		4074	
	RCP4.5	5993	**b**	6095	**b**	4772		6336		5580		3919	
	RCP8.5	6287	**a**	6383	**a**	4874		6426		5781		3913	
Period		***		ns		ns		**		*		*	
	baseline	5357	**c**	5751		4742		6310	**ab**	5765	**ab**	4074	**a**
	2020	5818	**b**	6139		4746		6429	**a**	5886	**a**	3996	**a**
	2050	6279	**a**	6283		4831		6579	**a**	5680	**ab**	3967	**a**
	2080	6323	**a**	6295		4892		6135	**b**	5475	**b**	3785	**b**
CO$_2$ × RCP		ns		ns		ns		ns		ns		ns	
CO$_2$ × Period		**		**		**		ns		ns		ns	
RCP × Period		ns		ns		ns		**		*		ns	
CO$_2$ × RCP × Period		ns		ns		ns		ns		ns		ns	

*** Indicates significant at $p < 0.001$; ** Indicates significant at $p < 0.01$; * Indicates significant at $p < 0.05$; ns indicates non-significant. For any factor and area, means followed by the same letter do not differ significantly at $p \leq 0.05$ by LSD test.

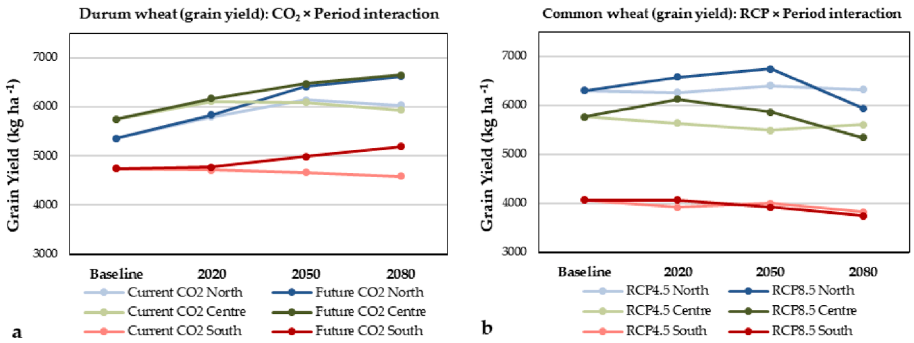


Fig. 4. Graphical representation of [CO$_2$] × Period interactions for durum wheat (a) and RCP × Period interactions common wheat (b) grain yields.

short period (from −10 to −15 days) while increasing differences are expected in the medium (from −20 to −30 days) and mainly in the long period (over −30 days) under both RCP scenarios considered.

The maturity date is expected to occur earlier under RCP8.5 than RCP4.5, and these reductions are significantly different from the baseline in each future period (Table 3). However, the highly significant interaction RCP × Period highlights the reductions in periods depending on RCPs. The maturity is projected to occur −39, −43, and −47 days earlier by the end of the century, respectively in southern, northern, and central areas with the RCP8.5 and only −28 days earlier in North and South Italy with RCP4.5 and −31 days in Centre (Table 3).

The faster-growing cycle projected for maize is reflected in lower grain yields, as presented in Fig. 5 and Table 4.

Under current [CO$_2$], simulations indicate a progressive decrease in the average yield in all areas with both climate scenarios, especially for the end of the century, under the RCP8.5 scenario. The impacts of climate change on maize yield are relatively homogeneous over the Italian territory and affect a considerable portion of the Po plains in the North of Italy with decreases in yields exceeding −20% in 2050 and −30% in 2080. Other areas where maize productivity may be profoundly affected are Sardinia, Apulia, eastern Sicily, North of Lazio and Umbria, where decreasing yield may reach 30% by 2080 (Fig. 5).

The results obtained with the simulations carried out considering the projected increases in [CO$_2$] for future periods confirm that the direct effect of future [CO$_2$] on maize is very low (as for C4 plants) in all areas (Table 4 and Fig. 5). Thus there is a slight offset on maize productivity when comparing yield with current and future [CO$_2$]. Moreover, as irrigated crops, the impact of climate change on maize is mostly to ascribe to increasing temperatures that reduce crop growing cycle and hence, biomass accumulation. The projected seasonal amount of irrigation decreases compared to the baseline in the South while in the Centre, and even more in the North, is expected to increase. This aspect is mainly influenced by the rainfall trend during crop growing season, that is projected to strongly decrease especially in the North (data not shown). Moreover, the Water Use Efficiency (WUE) decreases in all areas under future scenarios regarding the baseline period, with a greater extent in the South, mainly due to the higher yield reductions (data not shown).

Table 3
Significance of main treatment effects (RCPs and Periods) and their interactions on the maturity date of maize (expressed in days after planting) aggregated for North, Centre, and South Italy.

Effect		**Maize**					
		North		**Centre**		**South**	
RCP		***		***		***	
	baseline	157	**a**	171	**a**	155	**a**
	RCP4.5	136	**b**	147	**b**	134	**b**
	RCP8.5	131	**c**	143	**c**	130	**c**
Period		***		***		***	
	baseline	157	**a**	171	**a**	155	**a**
	2020	146	**b**	158	**b**	143	**b**
	2050	133	**c**	144	**c**	132	**c**
	2080	122	**d**	132	**d**	122	**d**
RCP × Period		***		***		***	
	baseline	157	**a**	171	**a**	155	**a**
	RCP4.5 2020	145	**b**	157	**b**	143	**b**
	RCP4.5 2050	133	**c**	144	**c**	133	**c**
	RCP4.5 2080	129	**c**	140	**c**	127	**d**
	RCP8.5 2020	146	**b**	159	**b**	142	**b**
	RCP8.5 2050	133	**c**	145	**c**	131	**cd**
	RCP8.5 2080	114	**d**	124	**d**	116	**e**

*** Indicates significant at $p < 0.001$; ** Indicates significant at $p < 0.01$; * Indicates significant at $p < 0.05$; ns indicates non-significant. For any factor and area, means followed by the same letter do not differ significantly at $p \leq 0.05$ by LSD test.

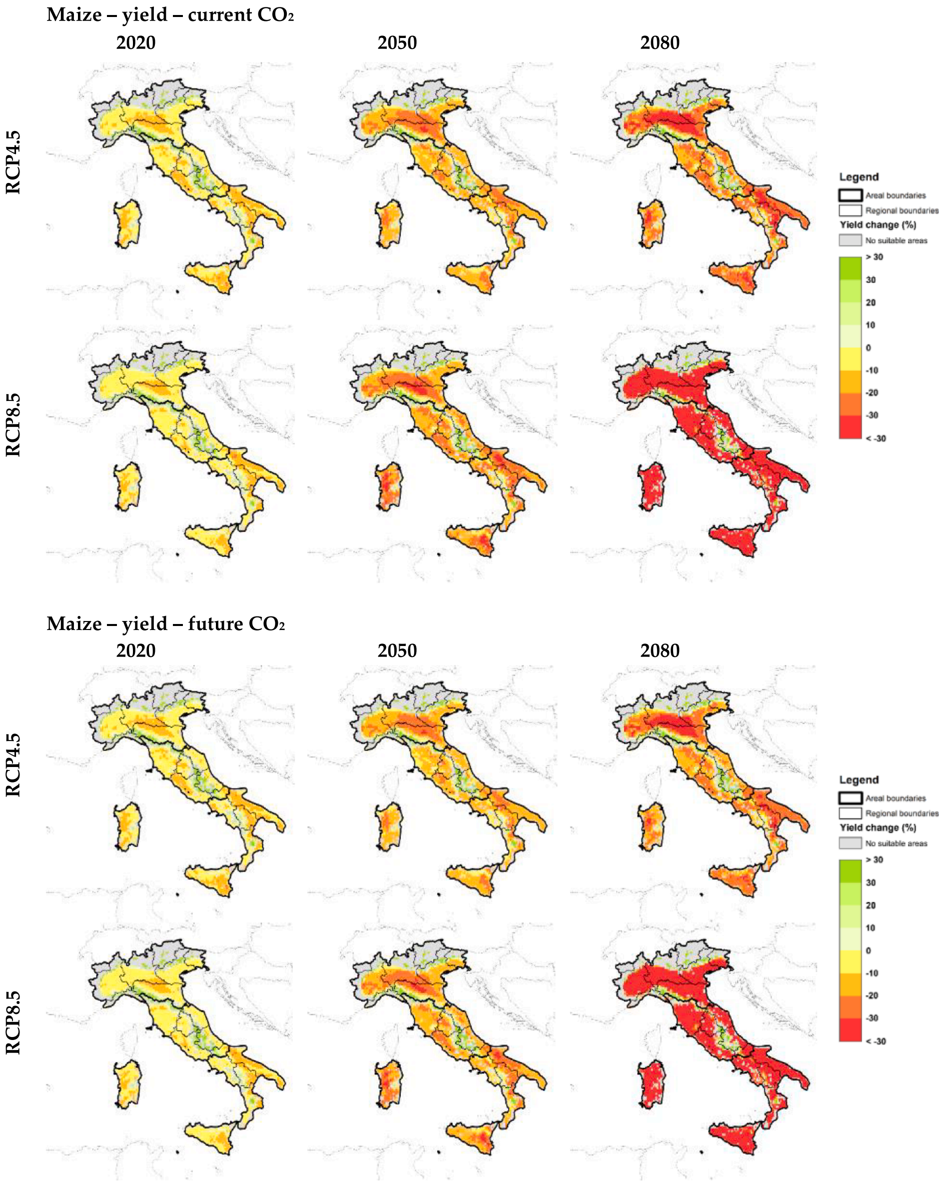


Fig. 5. Changes in average grain yield (%) from actual (1990) to 2020, 2050, and 2080, with RCP4.5 and RCP8.5 emission scenarios with current and projected [CO_2] for maize in Italy.

As reported in Table 4, and expected for C4 species, not significant differences are observed in the simulations with current and future [CO_2] for maize. The RCP effect is statistically highly significant in all areas, with higher values under RCP8.5 than RCP4.5, signing the greater importance that an increase in temperatures may have to limit maize productivity.

A significant decrease in grain yield is expected starting from the 2050 period for North and Centre of Italy, whereas it is already evident from the 2020 period in southern Italy.

The significant RCP × Period interaction reported in Table 4, are graphically displayed in Fig. 6, where a remarkable decrease in maize grain yields is reported for 2080 in all areas, especially under the RCP8.5 due to the worse climatic conditions projected.

The inter-annual yield variability displayed in the boxplots for each area, RCP and CO_2 effect, shows a great increase respect to the baseline period in particular for 2050 and 2080 periods in all areas (S.I. Fig. 5), with the highest increases in variability projected under RCP8.5 for 2080.

4. Discussion

Our study confirms that climate change impacts in Mediterranean areas could be more detrimental for summer than for winter

Table 4
Significance of main treatment effects (CO_2, RCPs, and Periods) and their interactions on grain yield (t ha^{-1}) for maize aggregated for North, Centre, and South Italy.

Effect		**Maize**					
		North		**Centre**		**South**	
CO_2		***		***		***	
	baseline	9419	**a**	10,929	**a**	10,948	**a**
	current CO_2	8264	**b**	9823	**b**	8906	**b**
	future CO_2	8368	**b**	9943	**b**	9024	**b**
RCP	***		***		***		
	baseline	9419	**a**	10,929	**a**	10,948	**a**
	RCP4.5	8706	**b**	10,295	**b**	9428	**b**
	RCP8.5	7925	**c**	9471	**c**	8502	**c**
Period	***		***		***		
	baseline	9419	**a**	10,929	**a**	10,948	**a**
	2020	9379	**a**	10,953	**a**	10,224	**b**
	2050	8602	**b**	10,114	**b**	9220	**c**
	2080	6966	**c**	8582	**c**	7450	**d**
CO_2 × RCP		ns		ns		ns	
CO_2 × Period		ns		ns		ns	
RCP × Period		***		***		***	
CO_2 × RCP × Period		ns		ns		ns	

*** Indicates significant at $p < 0.001$; ** Indicates significant at $p < 0.01$; * Indicates significant at $p < 0.05$; ns indicates non-significant. For any factor and area, means followed by the same letter do not differ significantly at $p \leq 0.05$ by LSD test.

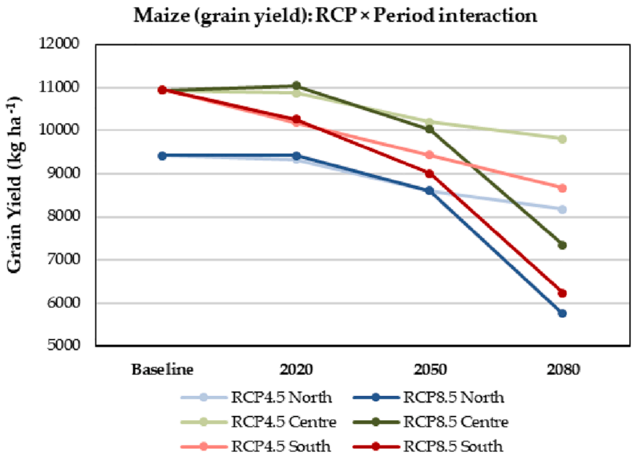


Fig. 6. Graphical representation of RCP × Period interaction observed for maize grain yields.

crops (Ciscar et al. 2018). Maize has shown the most considerable changes in the length of growing cycle, particularly in the Central Italian regions (maturity date up to more than 40 days in advance with respect to the present period by the end of the century with RCP8.5) due to the increase in temperature that accelerates crop phenology. In contrast, durum and common wheat have shown relatively homogeneous and lower reduction in the length of the growing cycle in each future period and area compared to maize (lower than 30 days by the end of the century with RCP8.5). The higher negative impacts projected for maize can be explained considering that the expected increase in seasonal temperatures by the end of the century is more pronounced in the summer than in the winter season (Bucchignani et al. 2016), affecting mainly maize than wheat (both durum and common) as they are sowed respectively in Spring and in Autumn. Similar results were reported in the analysis of Saadi et al. (2014) for Italy that estimated a shortening of the length of wheat crop season ranging from −10 to −20 days by 2050 and in the work of Ventrella et al. (2012) where was highlighted the higher impacts of climate change for winter than for spring sowings in southern Italy. The shortening of the growing cycle indicates that the phenological stage succession occurs earlier, reducing the opportunity to capture solar radiation and hence the total dry matter accumulation, with negative consequences on grain yield. Moreover, this acceleration might significantly impact the main agronomic practices (fertilization, irrigation, and pest and diseases control) making farm management more difficult due to the shorter time for timely interventions.

The impacts on grain yields are higher for maize than for wheat, reflecting the effects on phenology.

Moreover, as expected, the simulations with the projections of [CO_2] show a higher positive impact for wheat (C3 crop) than for maize (C4 crop), as reported in other studies (Rosenzweig et al. 2014; Hristov et al. 2020), as well as the higher positive effect on rainfed than irrigated crops (Tubiello and Ewert, 2002; Nelson et al., 2009). Despite the [CO_2] effects on crop productivity are still debated, due to the complexity of the phenomena that regulate these mechanisms and needs to further integrate FACE experiments under different conditions into modelling schemes (Webber et al., 2018), the recently published review of Toreti et al. (2020) confirms the ability of several crop models to capture the main effects of [CO_2] on plants under various growing conditions, suggesting to consider the simulations without [CO_2] only for quantifying the isolated effect, as made in this study. Moreover, high levels of [CO_2] can adversely affect the nutritional quality of food by reducing the protein content of cereals (Fernando et al., 2015; Zhou et al., 2018), the baking quality of wheat (Högy et al. 2013), the content of iron and zinc (Beach et al. 2019), and B vitamins in rice, posing a serious threat on nutrient status of million people (Toreti et al., 2020).

Projections for maize show lower yields with respect to present in all areas and both climate scenarios, independently on the direct [CO_2] effect, with values up to −20% for 2050 and ranging from −33% (Centre) to −39% (North), and −43% (South) by 2080 under RCP8.5. The increase in temperature appears to be the main factor altering maize yields by the end of the century, with respect to [CO_2] effect, according to the results of a crop model intercomparison study for maize (Bassu et al. (2014). To the author's knowledge, there are no high-resolution climate change impact assessment studies on maize for Italy with which to compare our results. However, yield reductions for fully irrigated maize in Italy up to −25% for the medium period (2030–2040) under RCP8.5 were reported by Hristov et al. (2020) for Italy, although their results are reported at the regional level. Considering that maize was simulated in irrigated conditions, assuming that water resources will be still available in the future, impacts could probably be much more detrimental, especially in southern regions, where the conflicts among different sectors (e.g., agriculture, civil, and industry) for the use of water resources can be very tricky, increasing the cost for irrigated crops. Moreover, the CERES-Maize, as the majority of the statistical models and CSMs for maize, does not include the explicit simulation of heat stress affecting male and female flowering and kernel abortion and this can affect the potential impacts on crop production (Sánchez et al., 2014; Lizaso et al., 2017).

On the contrary, impacts on durum wheat yields are statistically different from the baseline only in the northern regions (increase) starting from 2020 and common wheat only in the southern regions (decrease) in 2080. Indeed, a significant increase in precipitation in the winter season over central and northern Italy is expected under RCP8.5 by the end of the century (Bucchignani et al. 2016), which may benefit rainfed winter crops. Moreover, the varieties of durum (Iride) and common (Bologna) wheat used in this study show a different behavior also in the INVT field observations, with decreases in yields that are more pronounced for common than for durum wheat from North to South Italy, highlighting a higher sensitivity to the driest and warmer conditions of the common wheat cultivar respect to durum wheat.

Also, the shorter crop growing cycle of the durum wheat variety, with respect to the common wheat variety, may help escape the high summer temperature and reduce negative impacts on crop yield through stress avoidance. The comparison with results obtained in other studies has only a limited value, considering the extensive heterogeneity of climate and impact models used, scenarios, cultivar characteristics, and especially the difference in time and spatial scales of the analyses. Results from the most recent studies for Italy seem in accordance; however, they were obtained at a coarser scale: yield reduction in southern Italy ranging from −25 to −50% are projected for rainfed wheat for the medium period under the most negative emission scenarios by Hristov et al., 2020 and Saadi et al. (2014). According to our study, yield increases are expected for wheat yield for the medium period under RCP8.5 scenario up to + 25% for some central and northern regions (Hristov et al., 2020). A similar result was obtained by Senapati et al., 2020, even if in a single-site simulation in North Italy (about +15%). The analysis of Webber et al. (2018) reported stable yields for wheat or increases of up to + 20% in some areas of the country in projections that consider the water stress. Liu et al. (2019) estimated an increase in grain yield for Italy ranging from + 5 to + 10% for scenarios that limit global warming under 1.5 °C and 2.0 °C respectively.

One of the most relevant improvements in our results compared to the previous analyses is the high-resolution of the simulations. This allows us to provide detailed information at different spatial scales to inform the decision making process (from local to regional and national level) and explore the uncertainty associated with simulations due to the complex orography that characterize Italian landscape, environments, and hence cultivation conditions. The results highlight the site-specific impacts of climate changes, suggesting that higher resolution of both climate and soil data could improve the projections of simulated soil–plant-atmosphere processes and the consequent climate change impacts on crops. Moreover, the inclusion of multi-crop models and multi-climate models would allow to better explore the uncertainty associated with the different modeling approaches. It should also be highlighted that our results do not include the potential negative effects of pest and diseases on crop yield, as well as they not include the positive effects of autonomous adaptation options that farmers are used to apply to respond to changes in weather conditions and market request.

The spatial tool applied in this study can be easily adapted to simulate other crops in different geographical areas, under different climate dataset, and at different spatial resolutions, according to the availability of data for model parameterization and operation. This could be particularly useful in simulating changes in management options (e.g., crop calendars, irrigation, fertilization, tillage) and cultivars (early or late cultivars) to evaluate their potential effects as adaptation and mitigation options to cope with climate change, orienting operational, strategic and tactical decisions.

In particular, the assessment of sustainable crop managements as conservation agriculture and precision farming, that enable to preserve soil, water, and nutrient resources, could be pivotal in driving a more sustainable and resilient transformation of the agricultural systems. However, the effects of these options should be carefully evaluated and explored for the different environmental conditions, with in depth analyses at field/district scale to fully describe the complex relationships between the involved factors.

5. Conclusions

The digital platform GIS-DSSAT and the high-cell resolution RCM used in this study have enabled a highly detailed assessment of the climate change impacts on phenology and yield of the main grown cereals in Italy.

The shortening of the crop growing cycle for wheat and maize may influence crop management and production, potentially relevant to the Italian agricultural economy. The direct effect of [CO_2] on crop yields confirm negligible effects for irrigated maize and substantial for rainfed wheat in some areas, especially under the RCP8.5 scenario, although not always able to counterbalance the negative effects of climate change projections. The projected yield increases for durum wheat in northern Italy may cause competition between these two crops for the same cultivation areas. However, as each species' characteristics and variety strongly influence crop yield, further analyses considering other genotypes can allow us to explore different genotype × environment interactions in response to the same climate stimulus.

Moreover, the projections of impacts on crops could be improved using an ensemble of bias-corrected climate data and more detailed soil, crop, and agronomic management data (not available at the moment for Italy, as far as for authors knowledge), as well as including simulations with different crop models to including uncertainties in modelling crop processes. More accurate input can increase the analysis detail and provide more precise information for subsequent applications.

The results obtained in this study can be combined with socio-economic data to provide detailed and differentiated information to support stakeholders (farmers, researchers, insurance companies) and policy makers at various government levels (from municipality to regional and national level). Particularly relevant would be implementing the platform to evaluate alternative management options as potential adaptation and mitigation strategies to climate change. In fact, as our results suggest, it is crucial identify and implement specific adaptation options, tailored to the highly different local scale conditions and exploit any potential agronomic opportunity.

Informing on the optimal agronomic practices is pivotal to increase the adaptive capacity of a system to cope with weather and climate hazards and make the agricultural sector more sustainable, robust, and resilient to potential risks.

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 data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100339.

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