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Modelling crop water demand under climate change: the case of Sardinia region

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Abstract
Water scarcity is one of the foremost concerns for the agricultural sector due to limited water resources, increasing water demand, and climate change. Currently, the agricultural sector accounts for 70% of global freshwater withdrawals, and an increase in freshwater withdrawals and use for irrigation is already expected by 2050. In this study, the impact of climate change on crop water demands, and yield losses due to water shortage, were assessed using the Simulation of Evapotranspiration of Applied Water model. This crop-soil–water model was implemented in a typical Mediterranean environment (Sardinia, Italy) across a full range of relevant crops (wheat, barley, sugar beet, potato, lentil, almond, maize, wine grape, table grape, tomato, artichoke, alfalfa, olive, irrigated pasture, and orange). The simulations were driven by climate data from five earth system models dynamically downscaled at 11 km with regional climate models and available from EURO-CORDEX for baseline (1976–2005) and future (2036–2065) climate conditions under RCP2.6, RCP4.5 and RCP8.5 scenarios. Results show that wheat and barley will foresee the most significant increase in water demand of 12%, 13%, and 14% under RCP2.6, RCP4.5 and RCP8.5, respectively, based on the ensemble mean of the climate models. Water demand for almond, maize, wine grape, and pasture were projected to increase by about 5%, 7%, and 4% under RCP2.6, RCP4.5, and RCP8.5, respectively. The increasing crop water demand represents a considerable challenge for water resource management, especially considering the shortage of water supplies and increasing competition with other sectors. This work provides a wide climate risk evaluation across most relevant crops in the Mediterranean environment to support policymakers in developing adaptation strategies and sustainable regional plans, to support food and water securities.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) consolidated significant bodies of evidence indicating that atmospheric carbon dioxide (CO_2) and other greenhouse gases act as major drivers of climate change (IPCC 2021). It is indisputable that rising CO_2 and consequent amplified global warming are largely due to human activities (IPCC 2023). Climate change is expected to increase atmospheric temperature, which may lead to higher evaporative demand (Jung et al. 2010). Globally, the highest temperatures on record occurred during the last eight years. In 2022, a record-breaking temperature was recorded in many areas of the world, especially in Europe, where the temperature was recorded at 1.4 ℃ above the mean value (Copernicus Climate Change Service 2023) using average data derived from E-OBS gridded land-based observations (Cornes et al. 2018) and ERA5 ECWMF's fifth generation reanalysis (Hersbach et al. 2023) datasets. Climate change is also often associated

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with a non-uniform variation in hydrological cycles. Changing patterns of precipitation, runoff, and soil moisture are expected with increasing frequency and intensity of extreme events such as droughts, floods, and heat waves (Ehsani et al. 2017; IPCC 2021). The combined effect of larger evaporative demand and more erratic distribution of precipitation, especially in more arid areas has led to a decline in available water resources, which threatens several socio-economic sectors depending on water resources.

Among the most vulnerable areas, the Mediterranean region is recognized as a hotspot of climate change (IPCC 2022; MedECC 2020). The Mediterranean climate is characterised by hot, dry summer and mild winter, with seasonal variability in precipitation (Galindo et al. 2018). Due to climate change, the limited water supplies through groundwater and surface reservoirs are likely to reduce their future potential to supply irrigation, with critical consequences on agriculture and food security (MedECC 2020). Agricultural water withdrawals account for up to 70% of the total water use globally and exceed 80% in the southern part of the Mediterranean region (World Bank 2017; Hengl and Gupta 2019a). In the Mediterranean basin, 25% of the total cultivated area is irrigated and this rate is currently expanding (MedECC 2020). Agricultural land use is facing extreme pressure due to climate change (Aguilera et al. 2020; Baris-Tuzemen and Lyhagen 2024), water shortage (Mekonnen and Hoekstra 2016), land degradation and rural abandonment (Lagacherie et al. 2018), and intensification to fulfil food demand for an increasing population. Agricultural productivity in the Mediterranean basin is already expected to decrease in the coming years due to less favourable climate conditions (IEMed 2021), which may be further constrained by more limited water supplies for irrigated agriculture (Fader et al. 2016; Saadi et al. 2015; Savé et al. 2012; Masia et al. 2021). A reduction in crop yield might unavoidably impact socio-economic development and food security (Abd-Elmabod et al. 2020; Saretto et al. 2024). Improving crop water management is one of the most pressing challenges, especially in arid and semi-arid areas, such as the Mediterranean basin.

Climate Change is already affecting the agricultural sector in the Mediterranean, especially in terms of crop phenology, and crop growing cycle (Caubel et al. 2015; Funes et al. 2016; MedECC 2020; Mereu et al. 2021), and the net application of irrigation water (Mancosu et al. 2011, e.g., Masia et al. 2021; Bellvert et al. 2024; Tocados-Franco et al. 2024). Due to climate change, net application (NA) requirements are already increasing in the Mediterranean basin, where water demands for grape, wheat, and maize will increase by almost 10%, 16%, and 13%, respectively, under future climate conditions (Masia et al. 2021). In the Northern Mediterranean region, the average growing season is projected as 12 and 15 days shorter for tomato and wheat in 2050, with a decrease of 5 and 6% for tomato and wheat evapotranspiration, respectively (Saadi et al. 2015). In Catalonia region, about 15% of the rainfed olive and almond orchards will no longer be suitable without irrigation (Montsant et al. 2021), and phenological changes for pasture, apple, vine, and maize will cause a constraint for crop productivity (Funes et al. 2021). Under both low (RCPs 4.5) and high (RCP 8.5) emissions scenarios, the NA for forage will increase between 38.4% and 67.1% in Portugal (Soares et al. 2022), and the net irrigation needed for olive farming is predicted to increase by 18.5% in some areas of Morocco, Algeria and Southern Spain (Tanasijevic et al. 2014).

The pressure on agricultural water demand is increasing the need to develop and improve models to assess the impacts and vulnerability of agricultural systems under current and future climate conditions (Nam 2018). Several modelling tools have been developed to simulate and analyse future changes both for yield and irrigation water demand at local and regional scales (APSIM, McCown et al. 1996; AquaCrop, Steduto et al. 2009; CROPGRO-Soybean, Batchelor et al. 2002; DAISY, Palosuo et al. 2011; EPIC, Williams et al. 1989; FASSET, Olesen et al. 2004; SIMETAW, Snyder et al. 2012 and Mancosu et al. 2016; STIC, Brisson et al. 1998; SWAP, Huang et al. 2015; WOFOST, van Diepen et al. 1989; CERES-Wheat, Ritchie and Otter 1985; CropSyst, Stöckle et al. 2003; DSSAT, Jones et al. 2003). Simulation and projections of evapotranspiration and crop water demands have gained major interest to show future dependencies of the agricultural sectors on water resources, and thereafter evaluate mitigating effects of adaptation options. Despite earlier research, a significant gap persists in the comprehensive consideration of multiple crops for the assessment of crop water demand and yield losses due to water stress, particularly for regional studies like Sardinia. Previous studies have predominantly focused on a limited number of crops, often neglecting the diverse landscape. Additionally, many existing studies have not accounted for spatial and temporal variations in crop water demand under varying climate change scenarios, failing to capture the variability and uncertainty of long-term climate impacts. Whereas emergent needs in agricultural development planning could benefit from analytical assessments that should be capable of integrating simultaneous simulation for a wider array of crops. This would effectively facilitate cross-comparisons between alternative crops for water-use effectiveness in crop allocation and agriculture development schemes that can cope with water security threats from changing climate conditions.

The aim of this work is to address the significant knowledge gap by conducting a comprehensive analysis of crop water demand and yield losses for a set of different crops in the Sardinia region. Utilizing an advanced modeling framework, this study considers the historical (1976–2005) period and climate projections from three Representative Concentration Pathways (RCP2.6, RCP4.5, and RCP8.5) to evaluate the future (2036–2065) period. By evaluating a diverse array of crops under various climate change scenarios, this study seeks to provide a detailed understanding of future crop water demand and potential yield impacts.

In this work, the Simulation of Evapotranspiration of Applied Water (SIMETAW), is used to estimate reference and actual evapotranspiration, net applications (NA), yield losses due to climate change for the Sardinia (Italy) region. SIMETAW model has been designed and validated to assess crop water use, irrigation requirements, yield losses due to water shortage, and generates hypothetical irrigation schedules for a wide range of crops experiencing full or deficit irrigation. In its spatial explicit implementation (SIMETAW_GIS, Masia et al 2021) can easily link and interact to large datasets and ensembles of climate projections, and it has been validated with a large number of Mediterranean crops (Orang et al 2013; Mancosu et al. 2013; Montazar et al 2016; Masia et al 2021; Kimball et al. 2023). This research considers fifteen most relevant -representative crops in the region, ensemble of climate models dynamically downscaled at high-resolution (~ 11 km), and three RCPs (2.6, 4.5 and 8.5), which contributes to the robustness of the results.

The outcomes of this work will support local farmers and decision-makers in evaluating climate change adaptation strategies (e.g., crop type, crop management, and suitable agricultural land) to enhance the sustainable supply of water volume for agricultural production under current and future climate change conditions.

Materials and methods

Study area

Sardinia (latitude 38°51′ and 41°15′ N, and longitude 8°8′ and 9°50′ E) is the second-largest Mediterranean island, with a population of 1.62 million (ISTAT 2019). With an area of 24,090 km^2, the Island is characterized by a heterogeneous landscape consisting of hills (68%), plains (14%), and mountains (18%) (Eurostat 2004). The climate of the Sardinia region is typical Mediterranean, with annual precipitation of 600 ± 400 mm $year^{-1}$. Agriculture accounts for about 47% of the region's total area, whereas only 7% of this area is irrigated. Irrigated Agriculture is characterized by a diverse variety of crops (ISTAT 2010): Forage crops dominate, utilizing approximately 29% of the irrigated area, underscoring their importance for livestock farming; Vegetables follow, occupying 20% of irrigated land; Maize, grapevine, and olive trees are also extremely significant economically, covering 11.6%, 8.7%, and 6.5% of the irrigated area respectively; Additionally, rice and citrus fruits each account for 5.5%, while pasture and permanent meadow cover 4.6% and cereals for grain 3.9% of irrigated land (ISTAT 2010).

Freshwater from numerous reservoirs covers 75% of the total water withdrawals on the island, while the remaining 25% is supplied from groundwater (Trabucco et al. 2018). The intensive agriculture, however, demands further development of water resources and infrastructures. This is especially true in drought years (Master-ADAPT 2017) when reservoirs were nearly empty and the use of freshwater for irrigation was regulated and limited. Sardinian water consumption is shared amongst agriculture (69.4%), domestic (25.4%), and industrial (5.2%) use. In Fig. 1, the Corine land cover map (CLC 2018) shows both the distribution of agricultural areas and main water bodies. As shown, Sardinia is divided into seven hydrological districts where several reservoirs, water distribution systems, and irrigation consortia are interconnected (Fig. 2).

Data

In order to represent plausible trajectories of future climate conditions and associated uncertainty at sufficiently high spatial resolution to reflect Sardinia topographical variation, a comprehensive ensemble of climate projections was retrieved and consolidated. In this work, daily climate data with a spatial resolution of 0.11-degrees (~ 11 km) generated through the EURO-CORDEX project was downloaded (Copernicus Climate Data service; https://climate.copernicus.eu/) and projected atmospheric CO_2 concentrations were fetched from the Inter Sectoral Impact Model Intercomparison Project (ISIMIP, https://data.isimip.org/) and presented in (Annex 2, Fig. 3). This study utilized the Coupled Model Intercomparison Project Phase 5 (CMIP5) data rather than the CMIP6 data due to the unavailability of the dynamically downscaled data. Both historical (1976–2005) and future (2036–2065) time frames were considered to assess the impact of climate change under different Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5, representing alternative mitigation policies and future emission scenarios (IPCC 2014).

Daily 2 m height relative humidity, maximum temperature, and minimum temperature, as well as precipitation, surface solar radiation, and wind speed, were obtained from five Global Circulation Model (GCMs) projections downscaled dynamically with regional climate models (Table 1). The selection of the climate model projections was driven by the availability of data projections for all three alternative RCPs.

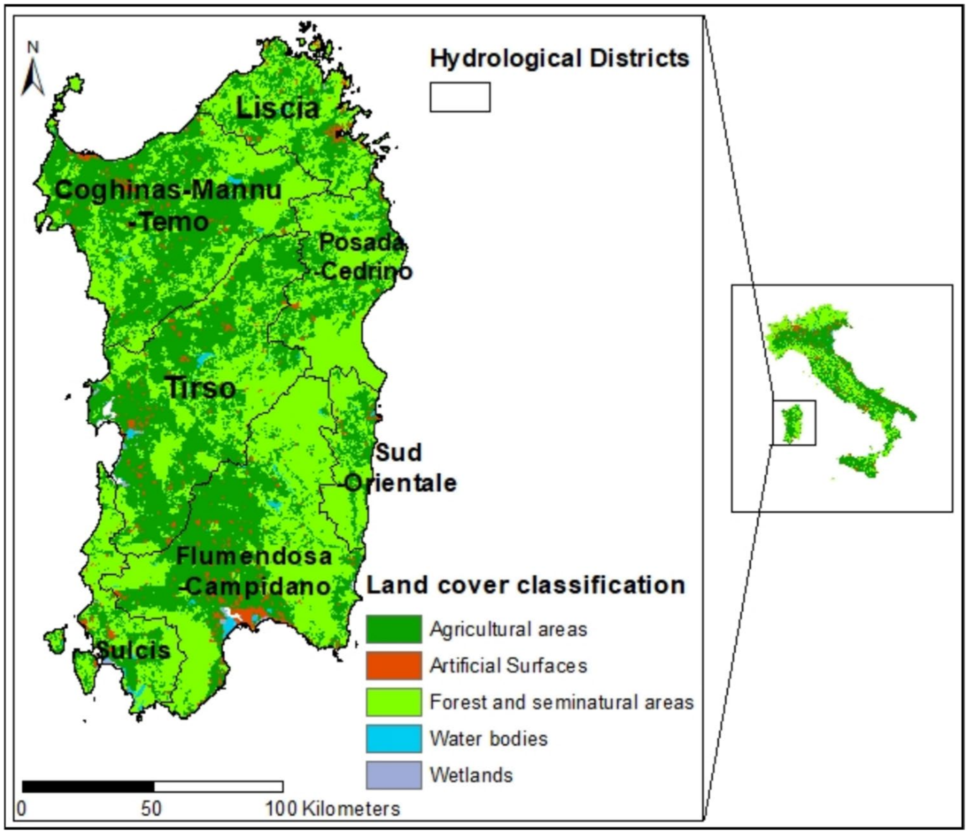

Fig. 1 Location of Sardinia region in Italy and details of its land cover and hydrological districts

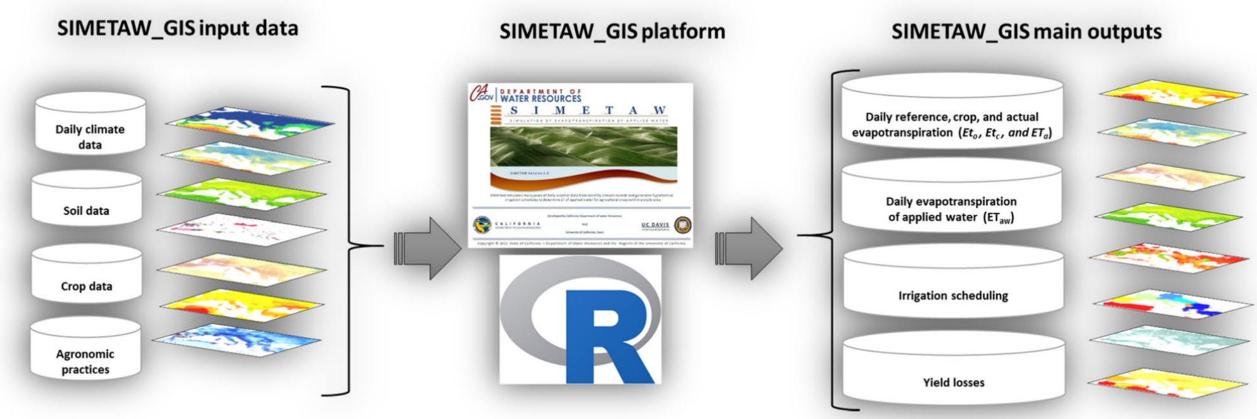

Fig. 2 Design of SIMETAW_GIS Platform (Masia et al. 2021)

Table 1 Climate models

Global climate model	Regional climate model
NCC-NorESM1-M	GERIC-REM02015
MPI-M-MPI-ESM-LR	SMHI-RCA4
CNRM-CERFACS-CNRM-CM5	KNMI-RACM022E
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN63
NCC-NorESM1-M	SMHI-RCA4

Soil data was used to represent soil hydraulic properties in the soil water budget to compute different evapotranspiration components, i.e., ETc, ET_a, and ET_{aw}. In particular, soil water holding from Hengl and Gupta (2019b) and reference soil depth from the Food and Agriculture Organization (FAO 2012) was used and upscaled to the spatial resolution used in the analyses, namely 0.11 degrees. Similarly, SRTM elevation data were also retrieved from the United

States Geological Survey (Earth Explorer, https://earthexplorer.usgs.gov/) and used in the computation of atmospheric pressure for the calculation of ET_o with the standardized reference evapotranspiration method.

Table 2 shows the selected representative crops, as those covering the relevant portion (3000 ha) of irrigated area in the Sardinia region according to the Italian National Institute of Statistics (ISTAT 2010). The values of yield response factor (Ky) and crop coefficient K_c initial, midseason, and final and the root depth of each crop were extracted from FAO-56 (Allen et al. 2006) for the different crops. In this work, the selected crops were evaluated under both rainfed and irrigated conditions with the most common irrigation methods, i.e., drip (D), sprinkler (S), and gravity (G), used for each crop. The irrigation method designated for each crop is reported in Table 2. Full well-watered irrigation is used for most crops in order to evaluate standard crop-specific anomalies in percentage following climate change impact, despite deficit irrigation being widespread for some crops, e.g., wine grape, and olive.

Modelling approach

SIMETAW# (Simulation of Evapotranspiration of Applied Water) is a daily crop-soil–water balance model developed to compute the daily standardized reference, well-watered potential crop evapotranspiration (ET_o), actual evapotranspiration (ET_a) and observed evapotranspiration (ET_a), the evapotranspiration of applied water (ET_{aw}), and an irrigation schedule for a specific site (Mancosu et al. 2016). SIMETAW# (Masia et al. 2021) uses climate and soil input data. This model runs on an "R" platform to allow estimates of crop water consumption and irrigation demand under different climate conditions, with a GIS platform providing spatial explicit environmental data over large regions and integrate adaptation/management options as irrigation methods and under different crop growing scheduling.

Actual evapotranspiration (ET_a) is computed as: $ETc \times K_s$, where $K_s = ET_a/ETc$ is a soil water stress coefficient that varies from 0.00, when there is no evapotranspiration, up to 1.00 when there is no evapotranspiration reducing water stress; and ETc is the well-watered crop evapotranspiration, i.e. with no noticeable water stress, which is calculated as the product of reference evapotranspiration (ET_o) and a crop-specific coefficient (K_c) that accounts for the differences between ET_o from the standardized reference surface and ETc from the well-watered crop surface. The calculation of ET_o and NA assumes an even distribution of agricultural areas across the island surface as the extent of the agricultural area may likely shift due to climate change. The daily ET_o, (Eq. 1) is computed by using the standardised Penman–Monteith equation of reference evapotranspiration for short canopies (Allen et al. 1998, 2005, 2006).

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\frac{900}{T+273}\right)u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{1}$$

where, ET_o represents the daily reference evapotranspiration (mm day $^{-1}$), Δ is the slope vapor pressure curve (kPa ℃$^{-1}$), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (℃), G is the soil heat flux density (MJ m^{-2} day^{-1}), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the vapour pressure deficit (kPa) and γ is the psychrometric constant

Table 2 Crop reference table

Crop name	Planting date or Budburst	Length of Growing season (days)	Irrigation method	Sources
Alfalfa	01/01	365	Sprinkler	Mancosu (2013)
Artichoke	10/07	234	Drip	ARS (2009)
Barley	29/12	189	Sprinkler	ARS (2009)
Maize	01/05	152	Sprinkler	ARS (2009)
Lentil	10/12	232	Drip	ARS (2009)
Potato	01/02	149	Drip	ARS (2011)
Sugar beet	15/10	258	Drip	ARS (2010)
Tomato	15/05	92	Drip	Pomino–INTAVOLIAMO
Wheat	15/12	196	Sprinkler	Mereu et al. (2021)
Pasture	01/01	365	Sprinkler	Mancosu (2013)
Almond	15/02	217	Drip	ARS (2011)
Wine Grape	01/04	168	Drip	ARS (2009)
Table Grape	01/04	168	Drip	ARS (2009)
Olive	15/03	245	Drip	Local expert opinion
Orange	01/01	365	Drip	Mancosu (2013)

(kPa °C^{-1}). Further detail to calculate the variables needed to compute the ET_o with the Penman–Monteith method can be found in FAO-56 (Allen et al. 2006).

Following the effect of projected CO_2 concentration in the atmosphere, the model adjusts the canopy resistance (r_c) as shown in Eq. 2, which was developed from Snyder et al. 2011 and Mancosu et.al. 2016.

$$r_c = \frac{1000}{1.44(14.18 - 0.0112CO_2)}\left(s\ m^{-1}\right) \quad (2)$$

SIMETAW_GIS modifies the midseason value of K_c (K_c midseason) according to the local climate as shown in Eq. 3

$$K_{cmid} = K_{ctab} + 0.261\ \left(ET_o - 7.3\right) \cdot \left(K_{ctab} - 1\right) \quad (3)$$

where, K_{cmid} is the corrected midseason crop coefficient and K_{ctab} is the tabular K_c value that is expected in a climate with ET_o = 7.3 mm d^{-1} (Guerra et al. 2015).

The evapotranspiration of applied water ($ET_{aw,}$ Eq. 4) is calculated as:

$$ET_{aw} = \sum_{i=1}^{n} NA_i = CET_c - CE_{spg} - CE_r - \Delta SW \quad (4)$$

where, $\sum_{i=1}^{n} NA_i$ is the sum of net water application applied to the low quarter of the crop, CET_c is the cumulative well-watered crop evapotranspiration, CE_{spg} is the cumulative contribution from perched water tables to CET_c, CE_r is the effective contribution of rainfall to CET_c, and ΔSW is the change in soil water content from the start to the end of the season within the effective soil rooting depth.

The gross irrigation application (or applied water) for each irrigation is calculated as:

$$GA_i = NA_i/DU \quad (5)$$

where DU is the low quarter distribution uniformity of the irrigation system. If the mean depth of water applied to the low quarter of the field is equal to the soil water depletion in the effective rooting zone before irrigation, then the DU is approximately equal to the application efficiency, i.e., the ratio of the water applied that is stored in the soil and contributes to evapotranspiration to the water applied. Therefore, the gross application for a season is estimated as: $GA = \sum_{i=1}^{n} NA_i/\overline{DU} = ET_{aw}/\overline{DU}$. For most crops, the goal for good irrigation management is to maintain a high distribution uniformity and applying a depth of water that refills the low quarter rooting depth frequently enough to avoid water stress and use water efficiently.

SIMETWAW_GIS estimates the crop yield losses as a function of water stress (Mancosu et al. 2016). According to the paper FAO-33, Eq. 6 shows the relationship between crop yield and water use, and how the reduction in evapotranspiration is linked to yield losses (Doorenbos and Kassam 1979).

$$1 - \frac{Ya}{Ym} = K_y \cdot \left(1 - \frac{ETa}{ETc}\right) \quad (6)$$

where Y_a is the actual crop yield, Y_m is maximum crop yield expected, and K_y represents the yield response factor specific for each crop.

Further details on the SIMETAW model can be found in (Mancosu et al. 2016; Masia et al. 2021). The accuracy and performance of SIMETAW_GIS were already validated by Masia et al. (2021) at ten experimental sites across the Mediterranean domain with different pedo-climatic conditions and used to assess the impact of climate change on maize, wheat, grape under different climate scenarios. SIMETAW was recently included in an Agricultural Model Intercomparison and Improvement Project (AgMIP), the study that was carried out to check the performance of the maize growth model to simulate evapotranspiration, results show that the SIMETAW model performed well compared to other models in simulating ET (ETs) for maize under irrigated conditions and especially during the crop growing season (Kimball et al. 2023).

Statistical analysis

The Mann–Kendall trend and Sen's slope were used to assess the trends in crop water demand under considered RCPs (RCP2.6, Rcp4.5, RCP8.5). The Mann–Kendall test was used to determine the direction of the trend that it is positive or negative with a p-value < 0.05 indicating a statistically significant trend. The Sense's slope method was used to quantify the rate of change in crop water demand with a p-value < 0.05 to assess whether the slope was significantly different from zero.

Results

This section summarises the results of precipitation (sub-Sect. "Precipitation"), ET_o (sub-Sect. "Reference evapotranspiration"), NA (sub-Sect. "Net applications"), actual evapotranspiration (sub-Sect. "Actual evapotranspiration"), and yield losses due to water stress (sub-Sect. "Yield losses"). The difference between rainfed and irrigated conditions represents the increasing limit on crop productivity due to climate change that can foster a shift in agriculture to irrigated systems. Results were analysed for the historical period (1976–2005) and future (2036–2065) time frames under RCP2.6, RCP4.5, and RCP8.5 scenarios by 30-years ensemble mean across the five climate model projections (Table 1). While future shifts in agricultural patterns remain uncertain due to climate change, the results are presented based on the evenly distributed agricultural areas across the island to account for potential changes in land use and crop demands. In fact, agricultural production is already widespread throughout most of the Sardinia region, except some highlands in the centre of the island. NA results are compared with and without the mask of agricultural areas showing a marginal difference for historical period (Table 4, Annex 1). The results at the spatial scale are presented at the same resolution as the input at 11 km. To better understand the results, the differences in climate for the historical mean and projected relative percentage change for maximum and minimum temperature, solar radiation, humidity, wind speed, and dewpoint temperature are shown in Table 5, Annex 1.

Precipitation

The precipitation (P_r) trends are presented in Fig. 3 as an ensemble mean and associated spread across five climate model projections (Table 1). Annual precipitation (Fig. 3a) is projected to slightly decline under all future emission scenarios. A slight variation of the precipitation decrease is projected for 2050, i.e., a 30-year mean for the three RCPs of about 691 mm year^{-1} compared to 700 mm year $^{-1}$ for the historical period. Figure 3b shows the spatial variation of such decreasing gradient of annual precipitation; the decrease is more prominent under RCP8.5 as it is projected to reach a decline up to − 7% in the south of Sardinia, while precipitation under other scenarios show a greater decline over Eastern Sardinia.

Figure 3c shows a comparison of seasonal mean precipitation for future scenarios versus the historical period. The projected precipitation decrease is greater in winter and spring (− 2.4% and − 6.9%, respectively) under RCP8.5 scenario, while precipitation falls more for RCP4.5 in summer (− 13.8%) and for RCP2.6 in fall.

Reference evapotranspiration

Figure 4 shows the reference evapotranspiration calculated for the Sardinia region using the standardized reference evapotranspiration method for short canopies (ET_o) modified to consider effects linked to CO_2 levels. Both the mean and spread among five climate model projections (Table 1) are represented over the baseline (1976–2005) and the future period (2006–2065) under RCP2.6, RCP4.5 and RCP8.5 scenarios. Annual ET_o (Fig. 4a) is projected to steadily increase over the years under all scenarios. Around 2030, the annual mean ET_o over 2006–2035 is projected to have means of 1437, 1439, and 1441 mm year^{-1} under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively, compared to a mean of 1419 mm year^{-1} calculated over the historical period 1976–2005. The biggest increase in ET_o does not correspond to the highest projected CO_2 concentration (Fig. 3, Annex 2). Increasing atmospheric CO_2 concentration leads to increased canopy resistance (Long et al. 2004), and the ET_o equation was corrected to include the impact of CO_2 concentration on canopy resistance and transpiration. In the case of RCP8.5, CO_2 concentration (Fig. 3, Annex 2) steadily increases after a certain period of time resulting in lower ET_o. As CO_2 concentration exceeds 600 ppm (Fig. 3, Annex 2) in 2065, ET_o is projected to decline (Fig. 4) and will reach a mean of 1413 mm year $^{-1}$ during 2036–2065. That is equivalent to a relative change of ET_o from − 0.38% to 2.4% under the RCP2.6, RCP4.5, and RCP8.5.

Figure 4b shows spatial variation of changing trend of ET_o, highlighting how relative changes are indeed limited and more marked at higher elevations and in inland areas, where smaller increases are more likely in Eastern Sardinia. During the winter and autumn seasons, a smaller decrease is expected for 2036–2065 of monthly values of ET_o (− 3% and − 4%, respectively) under the RCP 8.5 (Fig. 1c, Annex 1). In particular, during the spring season, ET_o is projected to increase more (5%) under the RCP2.6. On the other hand, ET_o was predicted to increase by 1% in the summer season under RCP2.6 and by 3% for the other two seasons considered future emission scenarios as compared to the historical period (191 mm month^{-1}).

Net applications

A detailed comparison of the impact of climate change on net applications (NA) in Sardinia for the most relevant crops under three RCP scenarios and the ensemble of climate projections (Table 1) is presented in Fig. 5. For the historical period, net application demand ranged from 250 to 350 mm year $^{-1}$ for crops grown over winter and spring seasons (barley and wheat), to 700–850 mm year^{-1} for orange, maize, and alfalfa Fig. 5e). The results show an increase in net application for all the crops under all the considered RCPs (Fig. 5e). The largest increase of net application (i.e., > 9%) is expected for wheat, barley, sugar beet, and potato, whose crop growing season spans mostly over winter and spring seasons when precipitation decreases are projected to be higher and especially under RCP8.5 (Fig. 3). This may lead to additional net application over those seasons, which would be otherwise minimal. For most other crops growing from spring to summer and fall seasons, the largest increases are expected mostly under the RCP4.5 scenarios, which is associated with largest precipitation decline (up to − 30%) over the summer (Fig. 3). For tomato and lentil, net applications are expected to increase by 7% under RCP4.5 and RCP8.5, while for most other crops net applications are expected to increase between 1 and 7%. Changes in net application for artichoke were estimated to be lower than for other crops. RCP8.5 indicates consistently

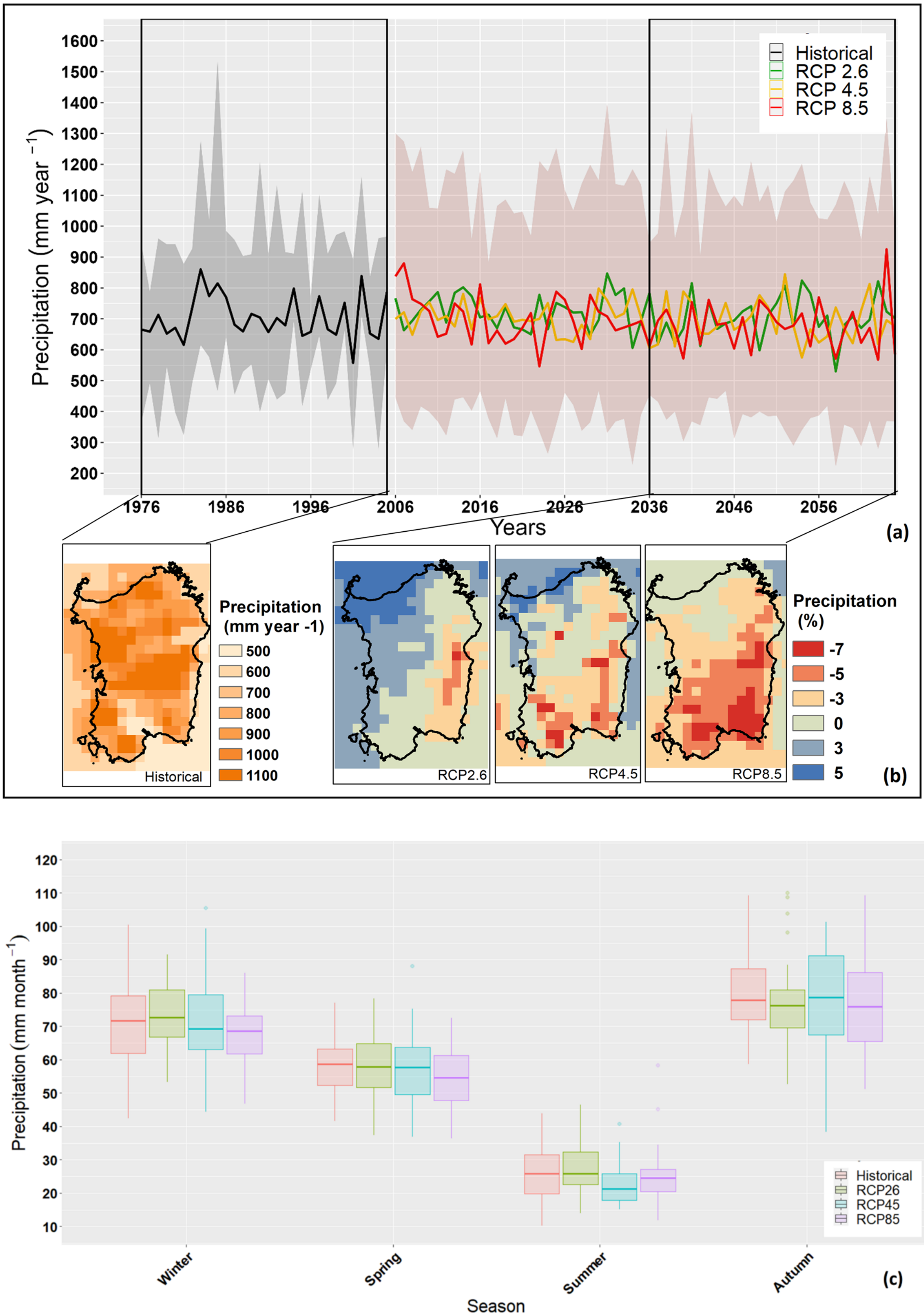

Fig. 3 Trend of annual precipitation for the historical 1976–2005 and future 2006–2065 periods under RCP 2.6, RCP4.5 and RCP8.5 (**a**). Relative percentage change of precipitation between the historical period 1976–2005 and future period 2036–2065 (**b**) and seasonal mean of monthly precipitation for the historical 1976–2005 and future 2036–2065 periods(**c**)

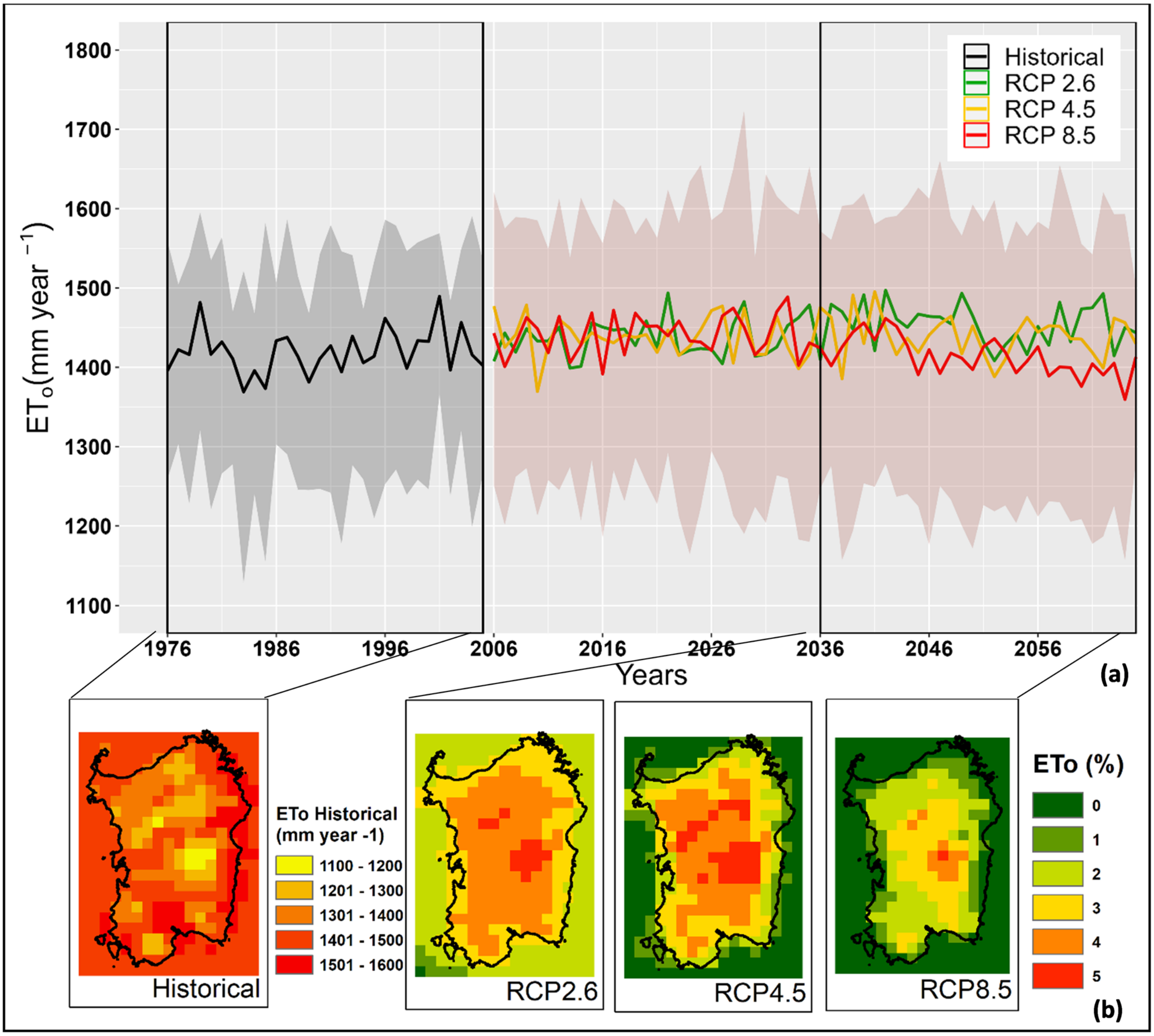

Fig. 4 Trends of annual reference evapotranspiration (ET_o) under historical 1976–2005 and future periods from 2006 to 2065 under RCP 2.6, RCP4.5, and RCP8.5 in Sardinia (**a**). Relative percentage change of ET_o between future 2036–2065 and the historical period 1976–2005 (**b**)

lower increases in NA for the considered crops compared to RCP4.5 scenarios. Increases in evapotranspiration demand under RCP8.5 is lower by 1% compared to RCP4.5 (Fig. 4b), while precipitation is expected to decrease slightly only in the fall.

The spatial distribution of changes in NA under the RCP2.6 scenario (Fig. 5b) are mostly influenced by elevation, with the largest increase of evapotranspiration and demand and NA at higher elevation and over central areas of Sardinia. The spatial distribution of changes in net application demand under RCP4.5 and 8.5 (Fig. 5c, d) are indeed influenced by both the general trend of increasing evapotranspiration demand at higher elevations (Fig. 4) and decrease in precipitation changes in the eastern and southern parts of the island (Fig. 3). Areas with increasing water demand for crops like wheat, barley, sugar beet, potato, and lentil will likely face water stress under climate change scenarios. On the other hand, regions growing artichoke and lentil exhibit the smallest relative increase in water demand is projected to face less water stress and be resilient in adapting the climate variability.

The trends of NA vary based on the intrinsic characteristics of the climate model (Table 6, Annex 1). Table 3 shows the statistical significance results of the Mann–Kendall trend test and Sen's slope for the NA. Under RCP26, alfalfa, almond and artichoke show negative trends in water demand (e.g. Mann–Kendall trends of – 1 for Alfalfa and – 1.43 for Almonds) illustrating reduced water

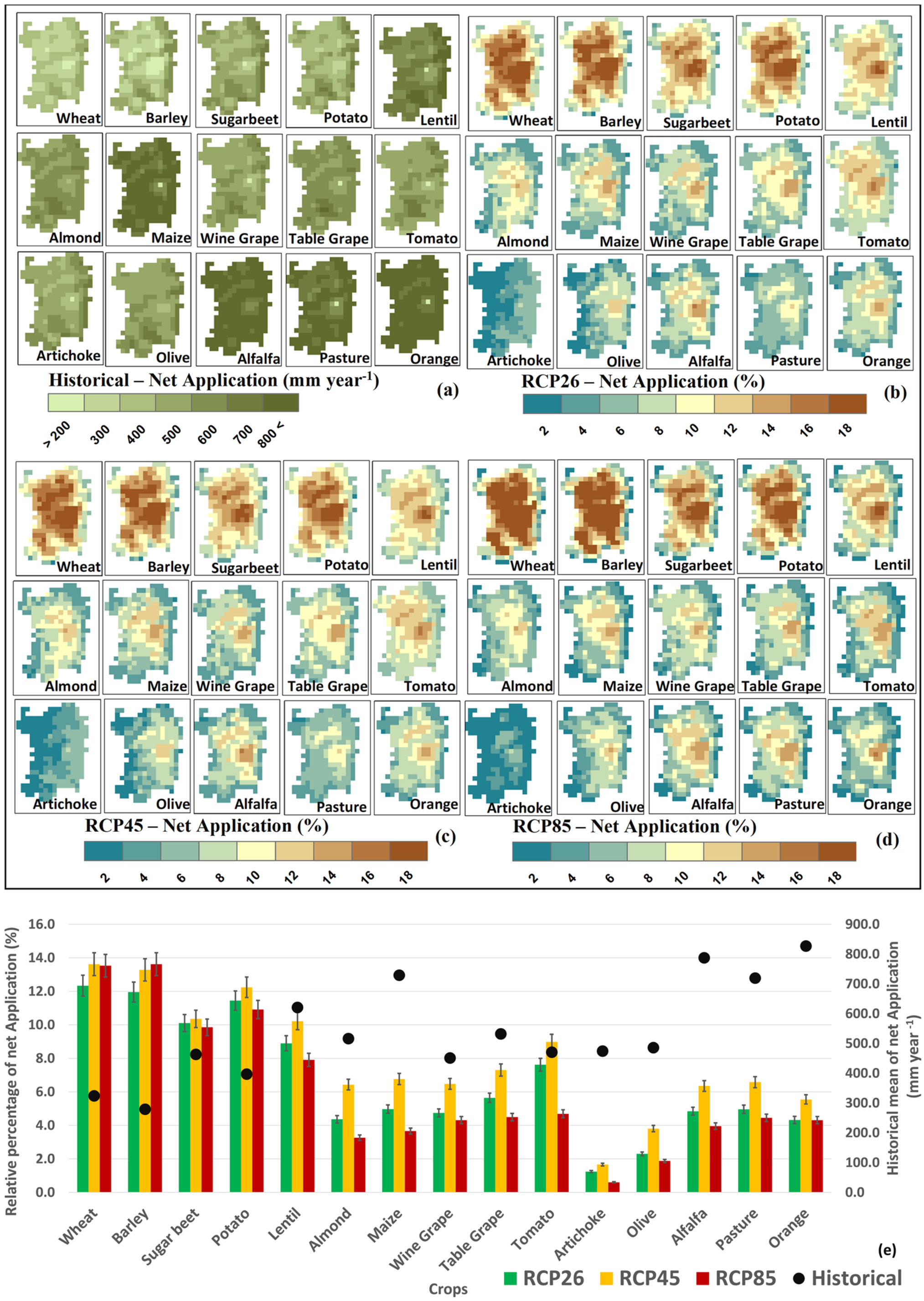

Fig. 5 Net applications (NA) for the selected crops under the historical (1976–2005) and future scenarios (2036–2065) under RCP2.6, RCP4.5 and RCP8.5. **a** Historical mean of crops NA (1976–2005). **b** Relative percentage change of NA under the RCP2.6 scenario. **c** RCP4.5. **d** RCP8.5 scenario. **e** Comparison between the historical mean (black dots) and relative percentage change of NA for the future scenarios (RCP2.6, RCP4.5, RCP8.5)

demand. Contrarily, crops like Barley, Lentil, and Potato show increasing trends with Potato having the highest trend under RCP8.5 (Mann–Kendall trend of 2.11 and Sen's slope of 1.43).

Actual evapotranspiration

Although reference evapotranspiration is expected to increase in Sardinia due to climate change (Fig. 1, Annex

Table 3 Mann–Kendall Trends and Sens Slope estimates for the projected net application under RCP2.6, RCP4.5, and RCP8.5

Crops	RCP26		RCP45		RCP85	
	Mann–Kendall trend	Sen's slope	Mann–Kendall trend	Sen's slope	Mann–Kendall trend	Sen's slope
Wheat	− 0.17	− 0.11	− 0.04	− 0.06	1.32	1.08
Barley	0.07	0.1	0.04	0.07	1.21	1.14
Sugar beet	0.28	0.37	0.21	0.22	1.21	0.99
Potato	− 0.07	− 0.05	0.29	0.3	2.11	1.43
Lentil	0.07	0.04	0.39	0.34	1.28	1.38
Almond	− 1.43	− 0.87	− 0.64	− 0.53	− 1	− 0.69
Maize	− 1.53	− 1.59	− 0.89	− 1.1	− 0.5	− 0.43
Wine grape	− 1.14	− 0.67	− 0.89	− 0.44	− 0.18	− 0.29
Table grape	− 1.33	− 0.84	− 0.86	− 0.51	− 0.25	− 0.37
Tomato	− 0.71	− 0.41	− 0.14	− 0.19	0	0.02
Artichoke	− 1.25	− 0.78	− 1.03	− 0.65	− 1.07	− 0.67
Olive	− 1.18	− 0.77	− 0.86	− 0.6	− 0.93	− 0.56
Alfalfa	− 1	− 1.1	− 1.48	− 1.25	0.07	0.14
Pasture	− 1.07	− 0.99	− 1.14	− 0.94	0.11	0.15
Orange	− 0.82	− 0.98	− 0.06	− 0.08	0.29	0.26

2), decreasing precipitation availability during the growing season is not able to offset such changes in actual evapotranspiration. This offset may be a leading cause for changing in NA, but also for yield loss linked to ET_a if crops are cultivated under rainfed conditions. Changes in ET_a due to climate change, hypothetically under rainfed conditions, were considered to evaluate both leading causes to increasing crop water demand and yield losses if the crops were not irrigated. Comparison between historical and future actual evapotranspiration (ET_a) under the RCP2.6, RCP4.5, and RCP8.5 of crops cultivated under rainfed conditions are reported in Fig. 2, Annex 2. The map of ET_a shows the gradient of the rainfed crops in the historical period (Fig. 2a, Annex 2), the mean of actual evapotranspiration for the rainfed crops ranged from 252 mm year $^{-1}$ (Almond) to 607 mm year $^{-1}$ (Orange).

In general, the results show that a decrease in ET_a is expected for most crops under climate change if cultivated under rainfed conditions or limited irrigation (Fig. 2e, Annex 2). Projections are expected to negatively affect particularly crops that are already mostly sensitive and grown under irrigation methods, such as maize, wine grape, table grape, tomato, olive, and orange. In particular, the highest negative trends were estimated for grapes and maize under RCP4.5 and RCP8.5, with decreasing values reaching about − 6 to − 7%, respectively (Fig. 2e, Annex 2). A detailed comparison between the historical and future actual evapotranspiration is demonstrated according to each climate model in Table 7, Annex 1.

Yield losses

Yield losses due to water shortage (rainfed conditions) (Eq. 5, 6) under climate change reflect the effects of a combination of changes in NA (Sect. "Reference evapotranspiration") to fulfil crop evapotranspiration demand, increasing ET_a (Sect. "Net applications"), and crop-specific yield response factors (K_y). Figure 6 indicates both historical average and relative change of yield losses between rainfed and fully irrigated conditions for an ensemble of five climate projections (Table 1) and RCPs. Cereal crops such as wheat and barley were projected to show the highest reduction in yield (> 13%) under future scenarios as compared to the historical period. In contrast, yield losses for maize were reported to be 3%, 6%, and 4% under the RCP2.6, RCP4.5 and RCP8.5 scenarios, respectively.

Among root crops, some relevant risk of larger decline in yield following water shortage are found for sugar beet (11–15% yield decline under the three considered RCPs) and potato (9–12% yield decline). Tomato and lentils show slightly lower reduction in yield for water shortage under climate change, with values of yield losses ranging between 5 and 9%.

Most tree crops, such as almonds, grapes, olives, and oranges, witness increasing yield loss due to water shortage between 6 and 8% under RCP45 and below 6% under RCP2.6 and 8.5 In the case of forages, alfalfa yield loss was projected to increase by 3%, 6% and 4% under RCP2.6, RCP4.5, and RCP8.5, respectively, whereas pasture shows

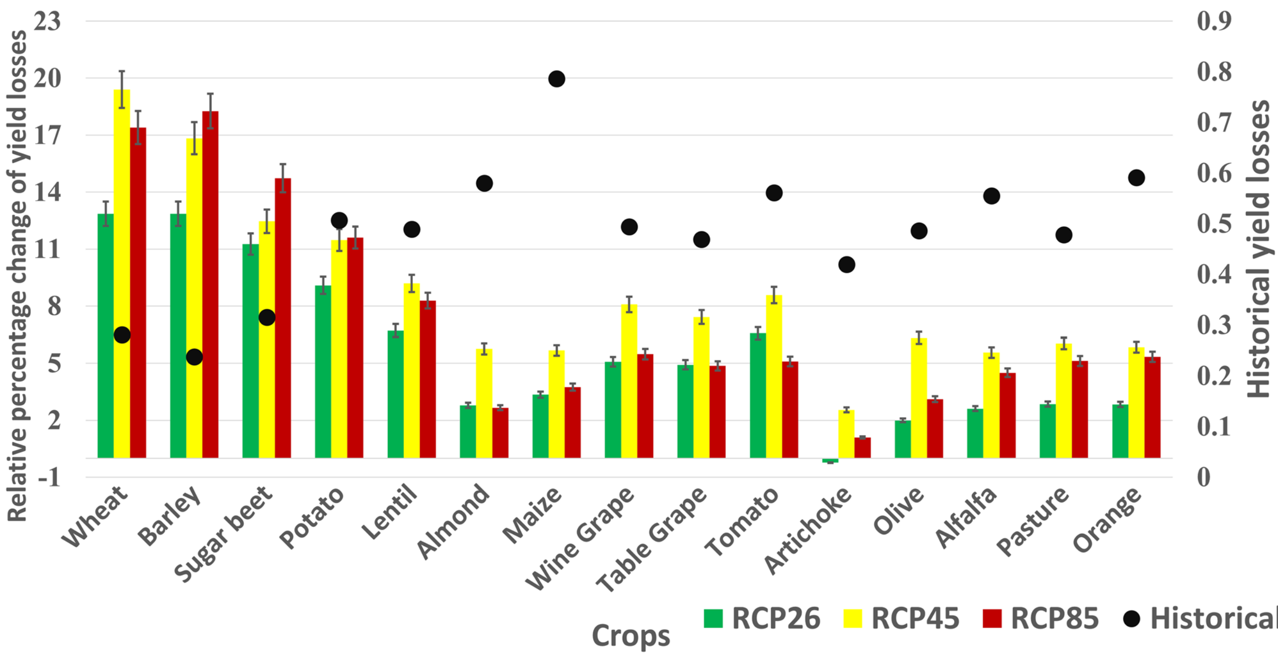

Fig. 6 Historical mean (black dots) and relative percentage change of yield losses under RCP2.6, RCP4.5 and RCP8.5

a 1% higher reduction in yield than alfalfa. Furthermore, the detail of yield losses of crops estimated under each climate model is illustrated in Table 8, Annex 1.

Discussion

Results from this study indicate that climate change is projected to lead to an overall increase in crop water demand, but also worsening yield losses due to water shortage under rainfed conditions, for the Sardinia region under all three considered scenarios, with the most severe impact anticipated under RCP8.5. However, both crop water demand and crop yields were significantly dependent on the specific climate model projections utilized (Annex 1, Tables 6 and 7). The climate models (Table 1) were selected based on their ability to simulate the regional climate conditions with high-resolution dynamic downscaling in the Sardinia region. Each climate model provides distinct projections of future climate scenarios under various emission pathways, contributing to a comprehensive assessment of climate impact uncertainty. Initially, each climate model was evaluated for its performance in producing the climate pattern in the Sardinia region, including key variables such as precipitation (Annex 1, Table 6). Notably, the uncertainty in climate models is evident, as the NCC-GERIC climate model simulated the highest historical ET_o average (1529 mm year $^{-1}$ for 1976–2005), while the CNRM-KNMI model shows the lowest values at 1252 mm year $^{-1}$, highlighting the variability in climate models outputs (Annex 1, Table 6). To integrate diverse outputs from these climate models, this study utilized a rigorous methodology aimed at synthesizing and interpreting the ensemble of results, addressing the associated uncertainty. Subsequently, this study analysed the model's projections of future relative percentage changes for precipitation under considered emission scenarios (Annex 1, Table 6). In the absence of dynamically downscaled Coupled Model Intercomparison Project Phase 6 (CMIP6) climate data from EURO-CORDEX, CMIP5 data remains the most reliable source of regional climate studies at high resolution. CMIP5 offers a comprehensive set of climate projections that have been extensively validated and utilized in numerous climate impact assessments, ensuring robust and reliable data for analysis (Galmarini et al. 2024; Villani et al. 2024). Given the complex relationship between the climate and landscape in mountain regions and coastal areas like of Sardinia region, having dynamically downscaled data is crucial for accurate and meaningful climate projections and analyses (https://www.euro-cordex.net/).

In Mediterranean countries, crops show different magnitude of changes in water demand (Darko et al. 2024). The literature indicates that crop water demands are projected to increase by range from 4 to 20% depending upon the location, methodology, and scenarios considered for Mediterranean crops such as pasture, apple, vineyards, maize, tomato, wheat, almond (Rodríguez et al., 2007, Tanasijevic et al. 2014; Saadi et al. 2015; Fader et al. 2016; Masia et al. 2021; Montsant et al. 2021; Funes et al.

2021). In our results, crop water demand is projected to increase on average in Sardinia by 2050 due to climate change ranging from 5% (maize and wine grape) to 13% (wheat and barley). Our modelling approach also accounts for benefits linked to raising CO_2 levels, specifically those linked to increasing the canopy resistance component of the Penman–Monteith equation. The addition of CO_2 (Snyder et al. 2011) in Eq. 2 minimizes the increase in future ET_o compared to the historical ET_o (Ben Hamouda et al. 2021; Moratiel et al. 2011). Incorporating the changes in CO_2 levels in the Penman–Monteith equation provided more robust assessments of crop water demand. The analysis was constrained to the year 2065 due to the heightened uncertainty associated with CO_2 concentration surpassing 660 ppm under RCP8.5. Villani et al. 2024 reported a sharp decline in reference evapotranspiration (ET_o) projections beyond this threshold, although large modeling uncertainties are plausible to such high values. Similar values were reported by Fader et al 2016, who accounted for CO_2 fertilization effect, highlighting that irrigation demands in the Mediterranean region are expected to increase between about 4% and 18%. Masia et al. 2021 reported that an increase in crop water demand is projected by about 13% for maize, 16% for wheat, and 10% for grapes, while including CO_2 fertilization effect. These results are consistent with the trends reported in our study, illustrating a clear pattern of increasing crop water demand under changing climate conditions. As far the author's knowledge, there are no high-resolution studies available that assess the impact of climate change on a full range of crops in Mediterranean environments, facilitating direct comparisons based on the same methodological and modelling implementation.

Decrease in precipitations combined with significant increases in evapotranspiration is projected to increase the need for more net irrigation application and decrease crop yield throughout Sardinia if such water demand is not satisfied. On average, the yield reduction in the Sardinia region under rainfed or missing irrigation is more prominent for cereals (wheat, barley, sugar beet) by about 16% under climate change scenarios. Due to climate change, water supplies and irrigation applications are inadequate to meet crop water demands resulting in reduced evapotranspiration and yield. Yield losses in vegetables, beans, fruits, and forages are 8%, 8%, 5% and 3% respectively under the RCPs 2.6, 4.5, and 8.5 projections, and more water resources are needed to avoid these losses. In our research, the greatest yield losses are foreseen for maize (Fig. 6). Ventrella et al. 2012 highlighted a projected reduction in tomato crop yields by about 7% in Southern Italy for 2030–2059 period due to climate change. Additionally, Mereu et al. 2021 showed a higher impact of climate change on maize crop yield than on wheat in Southern Italy. However, studies indicated an expected general decline in maize yield across the Mediterranean region (Villani et al. 2024; Masia et al. 2021; Bocchiola et al. 2013; Rey et al. 2011; El Afandi et al. 2010; Gabaldón-Leal et al. 2015). In the Mediterranean region, climate change is expected to increase the reference evapotranspiration worsening the drought stress for rainfed crops (MedECC 2020). Under RCP8.5, the decrease in wheat and maize yield potentially exceeds 20% and 30% respectively in several areas of Sardinia region by 2050 (Mereu et al. 2021). These findings are aligned with our findings, although the maize yield reduction in Mereu et al. 2021 is expected higher likely due to their consideration of phenological changes while calculating the yield losses. In Rio Mannu di San Sperate (south of Sardinia region), the AquaCrop model projected an 8% decrease in wheat yield on sandy loam soil during the 2040 to 2070 period (Bird et al. 2016), which is consistent with our spatial analysis (Fig. 5) for the southern part of Sardinia. Overall, climate change is projected to significantly reduce the crop yield in the Mediterranean region, even accounting for beneficial effect of CO_2 fertilization in analysis that tends to mitigate yield declines (Zhao et al. 2015).

Many studies suggest that extensive agriculture will decline in the Mediterranean in the future, and increasingly intensive agriculture will replace it (Debolini et al. 2018), which will lead to growing irrigation demand. In southern Europe, especially where soil water content is expected to decrease, only spring and winter seasons are likely to have soil saturation and drainage conditions (García-Ruiz et al. 2011) with significantly lower groundwater recharge levels (Senatore et al. 2011). This reduces streamflow, surface, and groundwater resources with negative impacts on various ecosystems.

To effectively mitigate the future impacts of climate change and enhance the resilience of the agricultural system in Sardinia region, agricultural water management strategies should be aligned with the findings presented so far. Precipitation and reference evapotranspiration are projected to increase from the North to the South, so the less water stress tolerant crops (e.g. maize) should be planted in the North and less in the South. Similar results were reported for Sardinia in the analysis of Mancosu 2013 and Masia et al. 2018 for seven zones (San Teodoro, Sassari, Villagrande Strisaili, Siurgus Donigala, Guasila, Decimomannu and Sardara) and three agricultural areas (Sulcis, Gallura and Nurra) due to climate change projected freshwater shortage. In Sardinia, as in many other areas of the Mediterranean, the balance between water demand and availability has reached a critical level to the point where levels of exploitation are not sustainable (Trabucco et al. 2018). Based on our results, increasing water demand to sustain crops in the Sardinia region is expected to grow more under the scenarios with larger GHG concentrations (RCP8.5) than under lower ones (RCP2.6). There is great urgency and relevance for increasing the mitigation effort to keep the CO_2 emission scenario close to the Paris Agreement to minimize the impact of climate change on water security.

The limitation of SIMETAW_GIS exists of assuming static growing seasons failing to capture the temporal variation of shifting growing seasons due to climate change. The model does not accurately represent the actual distribution of crops simplifying the complex factors that influence crop patterns. However, the availability and implementation of models like SIMETAW_GIS enable the provision of high spatial resolution results for several crops to different users from farmers to policymakers to guide both short, medium, and long-term investments and inform adaptation planning in the agricultural sector. The findings of this study provide a robust knowledge base that, integrated with socio-economic information can provide an indication of the potential risk for the agricultural sector and highlight the priority areas of intervention, supporting policymakers in developing strategies and plans for more resilient agriculture water management systems throughout Sardinia.

Recommendation and future work

The availability of dynamically downscaled high-resolution climate input data, and in particular driven by CMIP6 projections proving higher climate sensitivity, would allow a further improvement of the climate change impacts assessment in Sardinia and inform the decision-making process. In Sardinia, barriers to adaptation in water management are not only technical in nature, but also include issues related to human and institutional capacities, financial resources, lack of awareness, and communication. To meet the water challenges in agriculture, irrigation systems need improvement to support food and water security (Daccache and Lamaddalena 2010) and investment is needed for more efficient irrigation (van der Velde et al. 2010) to reduce water distribution losses, which are quite consistent around 50%. This would require changes in institutional and market conditions with more prudent water management including prices, recycling policies and improvement of infrastructures to ensure an adequate future water supply and prevent tensions between different sectors (García-Ruiz et al. 2011). However, it is important to consider that irrigation efficiency does not necessarily lead to overall water savings (Lopez-Gunn et al. 2012; Pérez-Blanco et al. 2020, 2021; Grafton et al. 2018; Perry et al. 2017). Future research should evaluate the potential rebound effects of irrigation modernisation and ensure that efficient improvements are paired with sustainable water allocation policies. Furthermore, irrigation modernization like replacing with pressured irrigation system can increase energy demand and carbon emission (Aguilera et al. 2019). Although the present work does not account for the potential shifts in crops growing season and growing area due to changing climate conditions for the assessment of NA, future research should consider these factors. Further research will also cover the economic evaluation such as cost benefits upon data availability. Future studies should explore how to balance irrigation improvements with energy efficiency and sustainable goals within the water-energy-food (WEF) nexus of the Sardinia region. This would be an important step to identify and understand synergies and trade-offs among the most relevant sectors that characterize the region, and grant sustainable water uses to sustain several social securities. The WEF analysis is useful to obtain a more in-depth understanding of the Sardinia complex system, and it is useful to reduce conflicts among sectors.

Conclusion

In this study, the SIMETAW_GIS platform was used to assess the impact of climate change on crop water demand, actual evapotranspiration, and yield losses of 15 crops under the historical (1976–2005) and future climate conditions (2036–2065; RCP2.6, RCP4.5, RCP8.5) throughout the Sardinia region.

The analysis showed that the crops will need more water in 2036–2065 than in 1976–2005 to reduce potential yield losses linked with higher temperatures and evapotranspiration. The SIMETAW_GIS model adjusts the canopy resistance as due to lower stomatal conductance from increasing CO_2 levels has a higher impact on future estimates of reference evapotranspiration and crop water demands. The variations in percentage changes for net irrigation application demand are 13% (wheat) to 1% (artichoke) under the RCP2.6, RCP4.5 and RCP8.5 scenarios. Crop water demand increase is often greater under RCP4.5 than RCP8.5 in summer and spring seasons and vice versa for other seasons. Due to water shortages, crop yield reduction is predicted with values greater at high altitudes and in Southern Sardinia. The variability of yield reduction was 19% (wheat) to 1% (artichoke) under the climate change scenarios, and the most affected crops are wheat (19%), barley (18%), and sugar beet (15%).

This study contributes to increasing knowledge targeted to sustain the crop water productivity not only in Sardinia but in the Mediterranean environment and adds valuable information to support the climate-risk assessment and the adaptation planning process by taking into account the uncertainty of climate change forecasts and associated impacts. To this end, taking into account the multiple interests linked to inland water management, it is appropriate to involve all stakeholders and coordinate the integrated water management in planning processes, which makes use of optimal complementarity in the use of surface water and groundwater and recognizes links between water quantity and quality in restoring natural systems for sustainable adaptation planning.

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Author contributions Conceptualization: MFA, AT, SM; Methodology: MFA; Formal analysis and investigation: MFA; Data curation: MFA, AT, SM; Writing—original draft preparation: MFA; Writing—review and editing: All authors; Supervision: AT, SM.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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