Modelling the influence of atmospheric CO_2 on irrigation demand in vineyards of the Sardinia region

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Abstract. The Mediterranean countries are anticipated to face considerable warming and drying with uncertain precipitation patterns further exacerbating the vulnerability of semi-arid regions, like Sardinia. Sardinia's vineyards, crucial to the local economy and cultural heritage, are increasingly threatened by climate change risks, particularly affecting physiological processes, which can compromise grapeyields and wine quality. The research aims to assess the impact of climate change on evapotranspiration demand in Sardinian vineyards, while keeping into account mitigating effects (e.g. reduced stomatal conductance) due to atmospheric CO_2 concentration increase. This study utilizes the Simulation of Evapotranspiration of Applied Water (SIMETAW_GIS) model to evaluate the impact of climate change on water demand of vineyards in Sardinia region, Italy. The research leverages high-resolution climate future projections to evaluate how varying climate conditions will affect the water demand of vineyardsunder three Representative Concentration Pathways (RCP2.6; RCP4.5; RCP8.5). Additionally, the analysis addresses the uncertainty associated with rising atmospheric CO_2 concentration, evaluating both the direct impact of CO_2 fertilization and without these effects. Increasing CO_2 can improve water use efficiency, partially mitigating negative impacts following rising temperatures and uncertain precipitation patterns. The results revealed that grapevine water demand is projected to rise by 5%-7% *withCO_2fert* and 7%-10% *withCO_2const*reflecting a relative percentage change between the historical period (1976-2005) and mid-century (2036-2065) under future projection (RCP2.6; RCP4.5; RCP8.5). The inclusion of CO_2 effects significantly alters canopy resistance in the reference evapotranspiration (ET_0) estimation, thus limiting vegetation water demand. The research highlights the importance of integrating the CO_2 effects into crop water demand assessment and underscores the necessity for adaptive irrigation strategies to the resilience and sustainability of Sardinian vineyards amidst rapidly evolving climate conditions.

1. Introduction

Grapevine (*Vitis vinifera* L.)) is among the most economically valuable fruit crops cultivated in the Mediterranean region, with Italy, France, and Spain together contributing to 51% of global wine production [18]. In recent years, the Mediterranean basin has experienced a notable evolution, with traditional rainfed vineyards increasingly being converted to irrigated systems in certain regions [1]. This trend is particularly evident in countries like Spain, where 43% of vineyard area has shifted to irrigated in the last 10 years [1]. The changetoward irrigation has been largely driven due to the increasing challenges faced by rainfed viticulture. At the same time, climate change is expected to have a strong impact on wine grape quality [2]. In fact, in Southern Europe and the Mediterranean basin, the significanttemperature increase, associated with drying trends makes the region a so-called "climate change hotspot" [19]. Even if changes in precipitation regimes are happening at a global level, the Mediterranean basin is exposed to stronger variability with more frequent and more intense drought episodes. The general warming trend, together with the strengthening of extreme weather events is expected to be strong, particularly in summer [3]. In this context, the increase in temperature and the reduction of cloudiness and precipitation will cause an increase of potential evapotranspiration, leading to stronger soil water deficits. Together with climate variables, also atmospheric CO_2 concentration is increasing. Several studies reveal that elevated CO_2 increases photosynthetic rates and reduces leaf transpiration, because of partial closure of stomata[4-6, 17]. This closure decreases the rate at which water vapour escapes from the foliage, thus possibly leading to improved water-use efficiency[7-9]. Therefore,CO_2fertilisation effect might partially offset the negative effects of temperature increase, suggesting that should be taken into account in the estimation of evapotranspiration.

Agriculture, by far the sector with the greatest freshwater demand [20], will largely be affected by water scarcity and this may lead to yield losses, impacts on food quality and an increase in food prices[10]. To reduce soil water deficit and improve yields, the practice of irrigation is often applied, even in traditionally rainfed crops. This applies to grapevine cultivations, where the practice of irrigation is getting more popular to guarantee production standards in grapevine quality [11].

Sardinia region, located in the centre of the Mediterranean, has always had a strong dedication to grapevine cultivation. Because of its insularity, Sardinia hosts a vast heritage of endemic grapevine varieties [21], making the region a reference point for Italian wine production. However, it is observed that the irrigated surface is increasing over time in the island [22], also for grapevine, as a measure to contrast drought periods across the growing seasons. Under these circumstances, the scope of this work is to estimate the evolution of irrigation demand for grapevine in Sardinia, according to the future scenarios of climate change. The work relies on the application of the Simulation of Evapotranspiration of Applied Water (SIMETAW_GIS) [12] model, a crop-soil-

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water balance model able to estimate crop evapotranspiration, together with the irrigation requirements to return the soil to field capacity. Adopting this model makes it possible to assess the future grapevine irrigation demand under the different climate projections, the so-called Representative Concentration Pathways (RCPs)[23]. The results of this assessment can support local farmers and water managers in the evaluation of adaptive strategies to face the issue of water scarcity and improve sustainable wine production in the Sardinia region.

2. Methodology

2.1. Case Study

The study area is the Sardinia Island, situated in the Mediterranean region (latitude 38°51′ - 41°15′ N, and longitude 8°8′ - 9°50′ E). The Mediterranean climate of the island is characterized by hot, dry summers and mild, wet winters, with an average precipitation of 600 mm/year[20]. Agriculture is central to the island's economy, especially in rural areas where traditional farming practices like olive groves, vineyards, and sheep farming are the most prominent. The Sardinia region is renowned for its unique grape varieties, such as *Cannanau*and *Vermentino* [21], which are well-adapted to the regional climate conditions. However, the increasing variability in climate patterns poses challenges for water availability and agricultural sustainability[17]. Water is critical for maintaining the grape yield and wine quality, particularly during the key growth phenological stages. As water availability becomes more unpredictable, ensuring efficient irrigation practices are essential to sustain the productivity of vineyards.

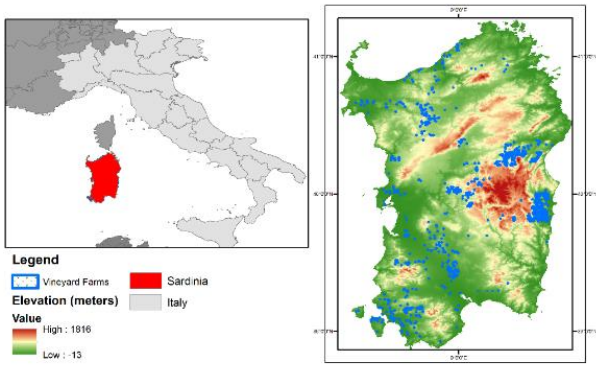

Figure 1*: Elevation map of Sardinia region and distribution of wine grapes farms (blue dots)*

2.2. Data

The SIMETAW_GIS model relies on climate data, crop characteristics, and soil properties to simulate the crop water demand [12]. In this work, climate data is retrieved from the outputs of various Global Circulation Models (GCMs) downscaled with Regional Climate models (RCMs) provided by the EURO-Cordex Platform[24]. This combination includes GCM and RCM pairs as NCC-NorESM1-M (Norway) with GERIC-REM02015 (Germany), MPI-M-MPI-ESM-LR (Germany) WITH SMHI-RCA4 (Sweden), and CNRM-CERFACS-CNRM (France) WITH KNMI-RACM022E (Netherlands) and CNRM-ALADIN63 (France). The model utilized climate meteorologicalat a high-resolution of 0.11 degrees (~11 km), including daily maximum and minimum temperatures (Tmax and Tmin), precipitation (Pr), relative humidity (hurs), wind speed (sfcwind) and short and long wave incoming radiation (rsds and rlds). The datasets include historical (1976-2005) and future projections (2006-2065) under Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5. These scenarios were selected to cover a spectrum of potential future climates, ranging from mild to severe impact, reflecting low (RCP2.6), moderate (RCP4.5), and extreme (RCP8.5) levels of greenhouse gas concentrations and their associated climate effects [20].

Additionally, SIMETAW_GIS incorporates soil data, including soil depth [25], water holding capacity [26], and elevation data[27]. Crop-specific parameters, such as planting and harvesting dates are taken from [17], and others like crop coefficient (*Kc*), phenological stages, and crop rooting depth are derived from the FAO56 paper [13].

2.3. SIMETAW_GIS model

SIMETAW_GIS model is a daily crop-water-soil balance model designed to provide an accurate and detailed assessment of agricultural water management [7]. It computes critical metrics such as reference evapotranspiration (ET_0), actual evapotranspiration (*ETa*), crop evapotranspiration (*ETc*), and the irrigation demand to return the soil to field capacity (*NAc*). ETc (ET_0 x Kc) is the evapotranspiration of a healthy, well-watered crop without soil water stress, while ETa is the actual evapotranspiration of a crop including soil water stress. SIMETAW_GIS represents a notable advancement in the field of crop water management providing a comprehensive analysis at both spatial and temporal scales. ET_0 is calculated by using the Penman-Monteith (PM) equation, which provides a standardized estimateof evapotranspiration from a well-watered grass surface. In this work, SIMETAW_GIS was run twice, in one case adopting the standard PM equation with constant CO_2 concentration at 372 ppm (CO_2*const*), using the approach of [7] and in the second including the adjustment of CO_2 fertilisation in canopy resistance (CO_2*fert*). In SIMETAW_GIS, the effect of CO_2 was integrated by adjusting the canopy resistance (rc) in the equations based on the suggestions of [14]. This adjustment allows the model to more accurately compare the difference in the estimation of ET_0 with and without the effect of CO_2 fertilisation on canopy resistance.

Previous studies, including research by [17] has demonstrated the model's effectiveness in evaluating how different climate conditions affect crop water requirement. Additionally, SIMETAW_GIS has been included in the Agricultural Model Intercomparison and Improvement Project (AgMIP)[15], and validated by [12]for grapevine using FLUXNET network measurements over Mediterranean sites. This validation highlights the model's accuracy and reliability, highlighting its role in advancing sustainable water management practices across diverse agricultural environments.

3. Results

The results are presented using the ensemble mean of all the climate model projections to address the heightened uncertainty. Annual reference evapotranspiration with CO_2

fertilization (*ET_0,co_2fert)* and with constant CO_2 concentration (*ET_0,co_2const*) is depicted in Figure 2, and the annual precipitation trend in Figure 3 for the historical (1976-2005) and two future periods (2006-2035 and 2036-2065)under RCP2.6, RCP4.5, and RCP8.5. Grapevine water demand is analysed for the historical timeframe (1976-2005) and compared with the future periods 2006-2035, and 2036-2065, showing the relative percentage change under RCP8.5, RCP4.5, and RCP8.5. The relative percentage change in crop water demand is illustrated to highlight the variations from the historical period. These future periods are selected to provide a clear perspective on how the crop water demand (Figure 3) evolved with increasing CO_2 concentration (*NAc,co_2fert*) and constant concentration (*NAc,co_2const*).

The results show significant variations in *ET_0,co_2const* and *ET_0,co_2fert*(Figure 2), along with a decrease in precipitation (Figure 3), leading to an increase in *NAc,co_2const* and *NAc,co_2fert* across all considered RCP. Under the RCP2.6 scenarios, *ET_0,co_2fert*isprojected to increase significantly, reaching 1435 mm/year in 2020 and 1470 mm/year by 2050, while *ET_0,co_2const* is expected to rise by 1460 mm/year by 2020 and 1490 mm/year by 2050 (Figure 2). In this scenario, annual average precipitation values are 723 mm/year (2020) and 704 mm/year (2050) as shown in Figure 3. This increasing trend of *ET_0* results in higher crop water demand. *NAc,co_2fert* is projected to rise by 3% in 2020 and 5% in 2050 but higher in the case of *NAc,co_2const*, where it is projected to rise by 4% in 2020 and 7% in 2050, as compared to the historical period.

Under RCP4.5, *ET_0,co_2const* is anticipated to increase drastically in 2020 (1460 mm/year) and 2050 (1505 mm/year), while *ET_0,co_2fert* is projected to rise slightly in 2020 (1436 mm/year) than 2030 (1440 mm/year). The effect of CO_2 moderates the rise of*ET_0*, in case of *ET_0,co_2fert*. In this scenario, the precipitation level is projected to decrease on an average 707 mm/year (2020) to 690 mm/year (2050) (Figure 3). As a result, *NAc,co_2fert* is anticipated to rise by 3% (2020) and 7% (2050) as compared to the historical period. But in the case of constant CO_2, vineyard is projected to demand 10% (2050) more water as compared to the historical period (figure 3). Under RCP8.5, *ET_0,co_2const* is projected to increase substantially, reaching 1465 mm/year (2020) and rising to 1520 mm/year (2050). In contrast, *ET_0,co_2fert* is expected to decrease, with the value falling to 1440 mm/year (2020) and further reducing to 1413 mm/year (2050). Additionally, precipitation is forecasted to decline to 676 mm/year under this scenario. Consequently, *NAc,co_2fert* in 2050 is projected to increase by 5% similar to increase estimated in 2020 compared to the historical period (Figure 3).

It is evident that CO_2 fertilisation has a non-negligible effect on evapotranspiration and consequently on irrigation requirements, nevertheless differences between *CO_2 fert* and *CO_2const* do not appear exceptionally sharp for the period of study. This is quantified in Table 1, where mean values of NAc of historical and future periods are compared, considering the different RCPs. Moreover, the table includes the p-values of statistical tests to investigate significant differences between the *CO_2fert* and *CO_2const* approaches by conducting a t-student test (p-value section), plus it explores the presence of linear trends of NAc with the Sieve bootstrap inference test (Trend Significance section). It is observed that, while for RCP 2.6 there are no statistically significant differences between the two approaches, nor significant trends, for RCP 4.5 and RCP 8.5 differences are more evident. Specifically, it is expected to have significant increasing trends under the *CO_2const* approach for both scenarios (p-value lower than 0.001 and equal to 0.002 for RCP 4.5 and 8.5 respectively), even if a significant difference between *CO_2fert* and *CO_2const* is not detected, except for RCP 8.5 in the period 2006-2035. Also, the mean values of NAc and trend analysis reveal that RCP 4.5 is the scenario forecasting the greatest increase of irrigation demand in 2050. Overall, results show that for the period 1976-2065 it is expected to have strong increasing trends of NAc under RCP 4.5 and 8.5 with *CO_2const* approach, while with *CO_2fert* the trend is expected to remain rather flat, even with the very mild increases between historical period and 2050.

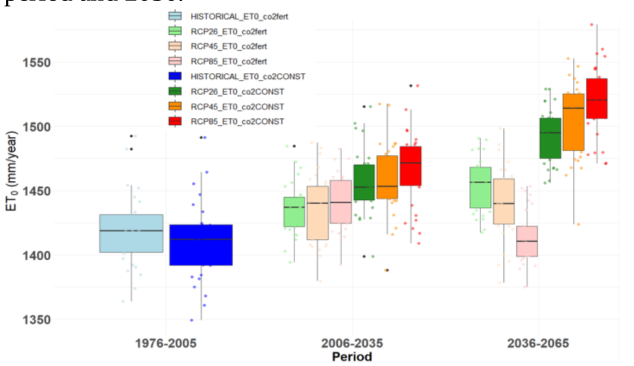

Figure 2*. The boxplot shows the reference Evapotranspiration with (ET_0,co_2fert) and without CO_2 fertilization effects (ET_0,co_2const) trends across the historical (1976-2005) and future periods (2006-2035, 2036-2065) under different climate scenarios (RCP2.6, RCP4.5, RCPP8.5).*

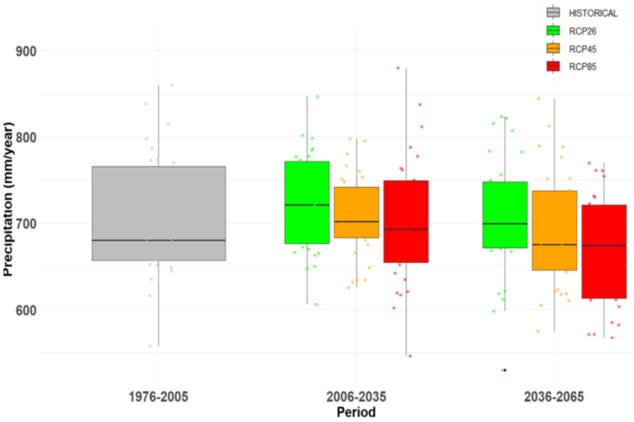

Figure 3*. The boxplot shows the precipitation trend for the historical (1976-2005) and future periods (2006-2035, 2036-2065) under RCP2.6, RCP4.5 and RCP8.5 scenarios.*

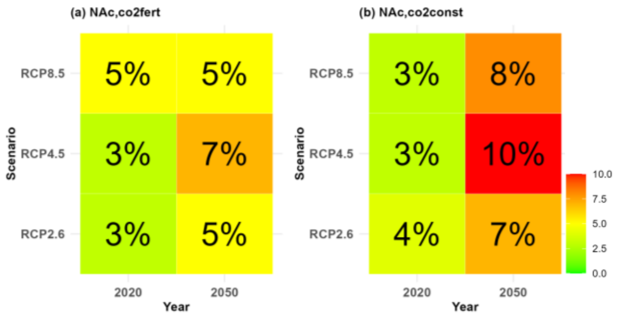

Figure 4*. The heatmaps show the relative percentage change in grapevine water demand for 2020 (2006-2035) and 2050 (2036-2065) under RCP2.6, RCP4.5, and RCP8.5 as compared to the mean over the historical period (1976-2005). Heatmap (a) shows the relative percent change with CO_2 fertilization (NAc,co$_2$fert) compared to the historical time mean of 451 mm/year, while heatmap (b) displays the relative percent change with constant CO_2 fertilization (NAc,co$_2$const) compared to historical time mean of 446 mm/year.*

Table 1*: comparison of the evolution of mean irrigation requirements of wine grapes (in mm) among the historical period 1976-2005 and the future (2006-2035 and 2036-2065) under RCP 2.6, 4.5 and 8.5, with and without the effect of CO_2 fertilisation. "Trend Significance" tests the presence of significant trends across the period, while "p-value" investigates the statistical difference between NAc obtained with the two approaches.*

Approach	**Historical**	**RCP 2.6**			**RCP4.5**			**RCP8.5**		
Period	1976-2005	2006-2035	2036-2065	Trend Significance	2006-2035	2036-2065	Trend Significance	2006-2035	2036-2065	Trend Significanc
CO_2fert	451.2	465.4	472.4	0.553	462.4	479.9	0.160	474.7	475.1	0.788
CO_2const	446.6	463.4	478.6	0.228	458.6	489.9	<.001***	458.1	480.0	0.002**
p-value	0.607	0.792	0.280		0.628	0.146		0.026*	0.378	

Significance: *$p<0.05$ **$p<0.01$ ***$p<0.001$

4. Discussion

The impact of CO_2fertilisation on crop water demand remains a debatable and evolving topic, with significant implications for water resource management. Our analysis highlights that CO_2 fertilisation partially compensates for temperature increase on ET_0 estimation due to its physiological effects on crops, notably through decreased stomatal conductance. This leads to a reduced increase in grapevine water demand, thus offering some support to managing crop water requirements. Specifically, in the Sardinia region, the reduction in $ET_{0},co_{2}fert$ is projected to reach 1413 mm/year in 2050 under RCP8.5 (Figure 2). Our findings align with the studies by [5, 12, 17,], which also examines the impact of CO_2 on ET_0. For instance, [5, 17] found that an increase in CO_2 concentrations moderates the elevated ET_0. Under high emission scenarios like RCP8.5, CO_2 fertilisation has a stronger effect in reducing the ET_0 more significantly, showing strong mitigation effects, while under moderate emissions scenarios like RCP4.5, the reduction is less pronounced, suggesting that CO_2 can alleviate some water demand pressure from crops but with limited impact.

Despite this reduction, it is crucial to recognize that CO_2 fertilization does not entirely offset the increasing crop water demand. Rising temperatures and changing precipitation patterns also significantly drive the crop water demand [5]. Although increasing trends are visible for the *CO_2fert* approach, Table 1 does not generally highlight significant differences between the two approaches, suggesting that under RCP 8.5, CO_2fertilisation does not actively impact irrigation demand. The effect of CO_2 fertilisation on crop transpiration has been quantified through various experiments, however, they have been tested up to limited levels of CO_2 concentration [16] and did not take into account different bioclimatic zones, which may as well play a role in the assessment of this effect. In any case, irrigation requirements are expected to increase in all scenarios for both approaches (7%-10% increase between the historical period and 2050, RCP 4.5), with data averaged over the whole island. Considering the heterogeneous landscape of Sardinia, possible extensions of this work can investigate irrigation demand variations in sub-regions of the island, especially the ones with the greatest concentration of grapevine fields, to check whether the warming effect can be stronger in those locations.

5. Conclusion

This work provides evidence of the fact that climate change has an impact on grapevine's evapotranspiration estimatesin Sardinia. For ET_0, it is expected to significantly increase under all climate scenarios for the*CO_2const* approach, while *CO_2fert* shows strong differences in the trend, with a milder increase for RCP 2.6 and 4.5 and a decrease under RCP 8.5, due to the stronger effect of CO_2 fertilisation. At the same, total yearly precipitation will decrease, reducing the available water and making irrigation necessary to avoid water stress. The results of SIMETAW_GIS show an increasing demand for irrigation of about 5%-7% under *CO_2fert* and 7%-10% under *CO_2const* between the historical period and 2050. The CO_2 fertilization is expected to show a non-negligible effect in the trends of irrigation demand, with the one of *CO_2fert* remaining rather constant through the period, while *CO_2const* sharply increases

Despite variations in the observed trends, both approaches yield comparable results regarding irrigation demand. This is attributed to the minimal differences in CO_2concentrations across the climate scenarios, which are insufficient to produce significant deviations in reference evapotranspiration (*ET_0*).

In conclusion, this research suggests that adaptive measures for grapevine cultivation must be taken into account, considering the increase in irrigation demand of the climate scenarios and the reduced availability of water resources in the region. It is essential to identify strategies to preserve crop yield and quality and for a more sustainable use of water supplies in light of future climate change challenges.

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