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ORIGINAL RESEARCH ARTICLE

Modelling future climate change impacts on grapevine water requirements and growing cycle in three wine PDOs of NE Spain

*correspondence: inmaculada.funes@irta.cat

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Inmaculada Funes Mesa[1,*], Elisenda Sánchez-Costa[1], Xavier Aranda[2], Vicent Altava-Ortiz[3], Antoni Barrera-Escoda[3], Marc Prohom[3], Rafael Poyatos[4,5], Antoni Sánchez-Ortiz[6], Robert Savé[1], Felicidad de Herralde[1]

[1] IRTA (Institut de Recerca i Tecnologia Agroalimentàries), Torre Marimon, 08140 Caldes de Montbui, Barcelona, Spain.
[2] Experimental Fields Service, Faculty of Biology, University of Barcelona, Barcelona, Spain.
[3] Department of Climatology, SMC, Meteorological Service of Catalonia, Barcelona, Spain.
[4] CREAF, 08193 Bellaterra, Cerdanyola del Vallès, Catalonia, Spain.
[5] Universitat Autònoma de Barcelona, Cerdanyola del Vallès 08193, Spain.
[6] Universitat Rovira i Virgili, Tarragona, Spain.

ABSTRACT

Climate change is expected to heavily impact agriculture in the Mediterranean region due to higher temperatures and droughts. Within the agricultural systems, vineyards are one of the most affected by climate. Here we provide a diagnosis of the main impacts of climate change in three protected designations of origin (PDOs) in Catalonia (NE Spain) in the 21st century. This is fundamental for assessing the future suitability of grapevine cultivation in the study area. For this purpose, we estimated the annual net water needs of the vineyard and a set of agroclimatic parameters of crop phenology and ripening. Climate change impacts were estimated at 1 km pixel resolution using temperature and precipitation projections based on the IPCC AR5 RCPs 4.5 and 8.5 climate change scenarios. Water needs would be 2 to 3 times greater than current water needs and a general advance and shortening of the 'Budburst to Harvest' period were estimated. The flowering date would advance from 3 to 6 weeks and the harvest from 1 to 2.5 months, resulting in a duration of the 'Budburst to Harvest' period from 10 to 80 days shorter. Changes in temperature during ripening were also estimated. Minimum temperature and daily thermal amplitude during ripening could increase from 1.4 to 2.9 °C and from 0.4 to 2.8 °C, respectively, by the end of the century. Additionally, the number of tropical nights (nights with T min > 20 °C) at ripening would increase from 2 to 23.7 days during the second half of the 21st century. Dynamics would be similar in the three PDOs studied although the magnitude of impact would differ, leading, in some cases, to significant limitations for grapevine cultivation and wine production if no adaptation strategies are applied in the near future. Increases in water needs were slightly greater in Empordà PDO, while the potential impact on crop phenology and grapevine quality was greater in the Pla de Bages PDO. These results, despite the limitations from simplified methods, incomplete data and unaddressed uncertainties, could serve as a basis for the design of specific adaptation strategies to improve and maintain vineyards in the PDOs studied and could be extrapolated to similar PDOs and regions.

KEYWORDS: mediterranean, adaptation, agriculture, phenology, water needs

INTRODUCTION

Agriculture is the human activity that is most dependent upon and affected by climate. Climate variables such as temperature, precipitation, solar radiation, humidity or wind govern crop distribution and yields around the world (Phogat *et al.*, 2018). The Mediterranean Basin is a climate change (CC) hotspot with substantial changes in temperature and precipitation considering several greenhouse gases (GHGs) emission scenarios drawn by the Intergovernmental panel on climate change (IPCC, 2022). The temperature in the Mediterranean has already risen by 1.5 °C since the pre-industrial era, 0.5 °C more than the global average, with higher warming rates in the southern regions and an increase in temperature extremes, which promotes higher evaporation rates. Precipitation and water availability are expected to decrease, especially in spring and summer, while drought events and water demand are expected to increase. Nevertheless, total precipitation trends at the regional/local scales are not as clear as temperature trends. Thus, total precipitation has not appeared to change significantly over the past century (MedECC, 2020).

Grapevines normally grow from April to October (Northern Hemisphere) at moderate temperatures, with plenty of sunlight (Mullins *et al*., 1992). Avoiding excessive rainfall and taking microclimatic variations into account are essential for vine health and fruit quality. Thus, altitude and seasonal variations and the proper management of frost, irrigation or sun exposure are key factors in the success of grapevine cultivation from a climatic point of view (Santos *et al*., 2020). Grapevines have varying heat requirements depending on the grape variety and growth stage. It is generally considered that the optimal temperature range for grapevine growth falls between 12 °C and 22 °C. To classify these temperature requirements, Winkler regions use growing degree days (GDD), which are calculated by adding up the daily mean temperatures above 10 °C throughout the growing season (Amerine & Winkler, 1944). It is important to note that grapevines require sufficient sunlight for photosynthesis and fruit ripening. The growth and maturation of grapes are influenced by daily sunshine hours, solar radiation levels and light intensity (Jackson & Lombard, 1993). Excessive sunlight and heat can potentially cause sunburn or stress on the vines (Gambetta *et al*., 2020a). Additionally, climate change may have an impact on sunlight patterns, which could potentially affect the timing of budbreak, flowering and fruit development (Jones *et al*., 2005). It is important to note that grapevines require consistent water availability throughout the growing season while avoiding excessive moisture or drought stress (Gambetta *et al*., 2020b). The rainfall range for optimally growing grapevines in Mediterranean areas shows a high variability with total precipitation above and below the average (524 ± 130 mm), in wet or very wet years and dry or very dry years (Ramos & Martínez-Casasnovas, 2010; Jackson & Lombard, 1993).

In the Mediterranean region, grapevine production plays an important role in multiple aspects, including socioeconomics, culture and environment. Additionally, vineyards are highly climate-dependent crops strongly linked to terroir and are expected to be significantly impacted by CC in the Mediterranean. Climate has a strong effect on both grapevine production and wine quality (Jones *et al.*, 2005; Santillán *et al.*, 2019). In fact, CC impacts are already evident nowadays (Ramos *et al.*, 2008; Bécart *et al.*, 2022; Koufos *et al.*, 2022; Ramos & de Toda, 2022; Sgubin *et al.*, 2022; Xyrafis *et al.*, 2022; Yang *et al.*, 2022). The principal impacts have been, are and will be changes in phenology, in the growing cycle and grape quality parameters alterations affecting wine characteristics, heat and water stress, higher water demands and water scarcity, decreasing yields or soil salinity constraints. Grapevine production and climate suitability have already been affected and will be seriously affected in the future, especially in rainfed conditions. Furthermore, in recent decades, winegrowers have primarily managed their vineyards based on the market demand, ignoring CC. This has resulted in crop disruption and maladaptation (Santillán *et al.*, 2020). Productivity losses related to climate change can also impact human security affecting socioeconomic factors such as geography, society, culture, economics and politics. This can result in substantial and heterogeneous effects among Mediterranean countries (Behnassi *et al.*, 2020).

Several studies have assessed the recent past and projected future CC effects on grapevine (Droulia & Charalampopoulos, 2021; Koufos *et al.*, 2022; Reis *et al.*, 2022). On the one hand, some of these previous studies have analysed climate data, evaluated past trends of climate parameters and bioclimatic indices and correlated them with viticulture indices (Xyrafis *et al.*, 2022). Observed changes over the last half-century in the main annual development stages and berry quality have been analysed for the Mediterranean region since the beginning of the century (Ramos *et al.*, 2008; Bécart *et al.*, 2022; Xyrafis *et al.*, 2022). On the other hand, many studies have projected future CC impacts on vineyards over the last few years. Ramos (2017) projected the phenology response to CC of three grapevine cultivars in rainfed conditions in one site of NE Spain (PDO Penedès). Other studies have also prospected on the future of the bioclimatic indices (temperature-related and water balance) linked to viticultural zoning across Europe (Cardell *et al.*, 2019; Fraga *et al.*, 2019; Martins *et al.*, 2021; Yang *et al.*, 2022) or assessed the risk of CC in the Mediterranean region by using agronomical indices in terms of cultivar suitability, quality, drought conditions and water deficit (Phogat *et al.*, 2018; Santillán *et al.*, 2019; Chacón-Vozmediano *et al.*, 2021; Funes *et al.*, 2021; An *et al.*, 2022; Ramos & de Toda., 2022; Rodrigues *et al.*, 2022).

Diagnosing CC impacts is extremely useful for proposing and executing adaptation strategies to make vineyards more resilient (Caubel *et al.*, 2015) by implementing appropriate adaptation measures to reduce the impact of CC efficiently (Prestele *et al.*, 2018; Ruiz-Ramos *et al.*, 2018). To identify the best strategies to reach resilient vineyards, it is necessary to first identify the impacts of CC on vineyards at the local/

regional scale, and to expose hazards and vulnerabilities (Funes *et al.*, 2021). Spatial data, such as regional/local projections of climate variables at an appropriate resolution, soil attributes and land use, are required for this purpose.

Spain has the largest vineyard areas in Europe, with 964,000 ha, according to OIV (2021), along with China, France and Italy. For this study, three Mediterranean protected designations of origins (PDOs) of wine were chosen to represent the diversity of the Mediterranean vineyard at the local scale. They feature a wide range of agroclimatic conditions in NE Spain (Catalonia), including inland vs. coastal differences and they grow the grapevine cultivars and apply the agronomical cultures most representative of the region.

This study contributes to the assessment of the spatial distribution of CC impacts on grapevine in the 21st century in an important vineyard area in NE Spain at a local scale and also improves spatial resolution. The main goal of this study was to assess the suitability of grapevine growing in three PDOs of Catalonia over the 21st century. The specific goals of this study were as follows:

1. to estimate annual net water needs (NWN) of vineyards in three Mediterranean PDOs for the baseline period and two future periods (2030s and 2070s) under two climate change scenarios to assess agricultural suitability in terms of water requirements;
2. to estimate a set of agroclimatic parameters capable of indicating the consequences of climate change for timing and duration of crop phenology, and ripening, to better understand and manage the risks posed by climate change.

MATERIALS AND METHODS

Figure 1 shows the flowchart describing all the steps of the methodology for the achievement of results described in the following subsections.

1. Study area

The study area is located in Catalonia (NE Spain) and contains the territory of three Mediterranean wine PDOs: PDO Empordà, PDO Pla de Bages and PDO Penedès. The three PDOs are located in the northeast extreme, central area and pre-coastal depression, respectively, covering the extension of all the municipalities of which they are composed (Figure 2).

1.1. PDO Empordà

PDO Empordà is delimited in two geographically separated areas (Figure 2a): Alt Empordà (delimited area above) and Baix Empordà (delimited area below). The PDO territory contains 48 municipalities separated in both districts. Alt Empordà is surrounded by the Pyrenees in the north, the Mediterranean Sea in the east and flat plains to the south. The Baix Empordà district borders two mountain masses (Montgrí at the north and Gavarres at the southeast) and the Mediterranean Sea (east). The climate in PDO Empordà is Mediterranean coastal tempered with mild winters and hot summers. Annual rainfall is around 600 mm and annual mean temperature ranges between 14 to 16 °C. PDO Empordà presents a singular landscape contrasting the mountainous area of the Pyrenees and the Mediterranean Sea). Moreover, this PDO is located in a territory marked by the presence of north winds frequently exceeding 120 km/h (Tramontane wind), which keeps vines well aerated, avoiding diseases

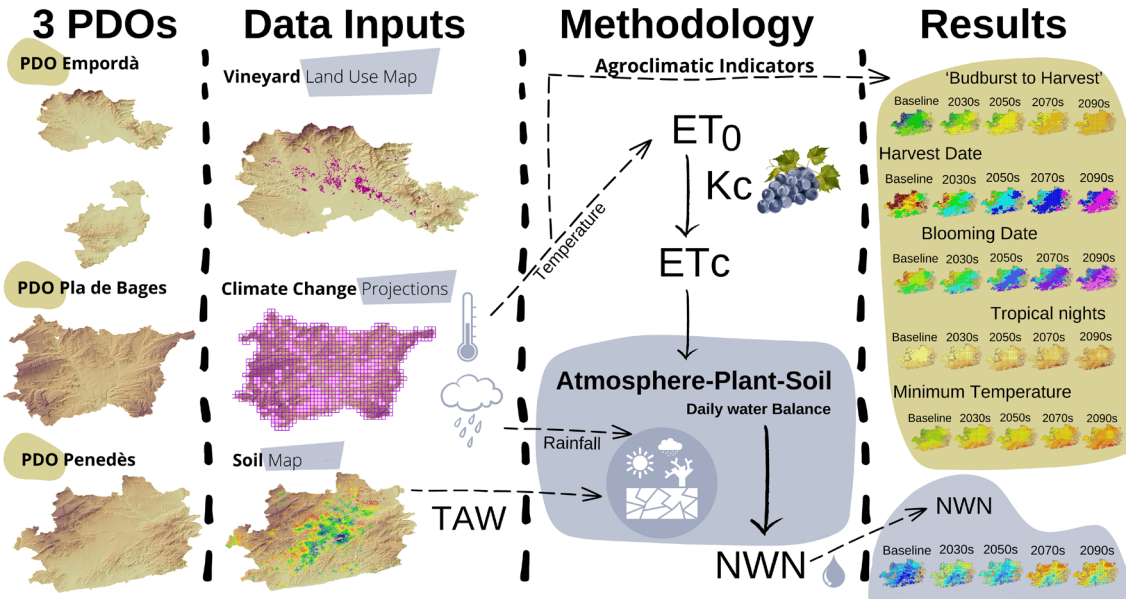


FIGURE 1. Flowchart of Methodology from data inputs to results for each PDO. ET_0 (mm · year $^{-1}$) is potential evapotranspiration, Kc (adimensional) is the grapevine crop coefficient, ETc (mm · year $^{-1}$) is crop evapotranspiration, TAW (mm) is the total capacity of soils to store available water for vines and NWN (mm · year $^{-1}$) is net water needs for vines.

and benefiting vine health. Vineyards are widespread in PDO Empordà with more than 2,110 ha, of which only 9.3 % are irrigated, according to SIGPAC (2020).

1.2. PDO Pla de Bages

PDO Pla de Bages (Figure 2b) has a Mediterranean semi-arid mid-mountain continental climate with a strong thermal oscillation. Mean annual precipitation (MAP) is 655 mm (ranging from 522 mm to 843 mm) and mean annual temperature (MAT) is from 10.5 °C to 14.4 °C. The PDO territory contains 25 municipalities. Vineyards are slightly widespread in PDO with no more than 440 ha, of which only 5 % are irrigated, according to SIGPAC (2020).

1.3. PDO Penedès

The Penedès region is wide and open, covering land between the sea and the mountains, between Barcelona and Tarragona and containing 56 municipalities (Figure 2c). Vineyards are widespread across the territory of PDO Penedès with more than 26,600 ha, of which only 1.3 % are irrigated, according to SIGPAC (2020). Penedès vineyards are located between the Catalan Coastal range and the small plains of the Mediterranean coast. Mean annual precipitation (MAP) is 670 mm (ranging from 554 mm to 810 mm) and mean annual temperature (MAT) is 13.6 °C (ranging from 11.2 °C to 16.1 °C). The PDO is made up of three distinct zones: i) the Penedès Superior, near the inland mountain range containing the Ancosa highlands and Anoia hillsides in the north, ii) the Penedès Marítim (Catalan pre-coastal range) between the sea and the Ordal mountains, the Garraf Massif and the Garraf Coast in the south and iii) the coastal hills and the plains between these areas, known as the Penedès Central, composed of the Bitlles-Anoia valley, the Lavernó hillsides, the hills of Vilafranca, the Foix Basin and Montmell hillsides. PDO Penedès presents a Mediterranean pre-coastal climate, tempered by the sea with mild winters and hot summers. Variations in altitude and proximity to the sea results in a diversity of mesoclimates. The Penedès Marítim is milder due to the proximity of the sea, the Penedès Superior has higher rainfall and larger thermal amplitude and the Penedès Central is a mixture of these two microclimates. Vineyard management techniques within the PDO Penedès are firmly rooted in ecologically sustainable and innovative paradigms. Moreover, the region's dedication to organic farming methodologies underscores its commitment to environmentally conscious viticulture.

2. Data inputs

2.1. Climate change projections and meteorological regionalisation at 1 km resolution

Calculations were performed by using climatic data (daily accumulated precipitation, maximum and minimum temperatures) from simulations regionalised at 1 km spatial resolution for a control period (1971–2005) and the whole 21st century (2006–2100) under two climate change scenarios: RCP 4.5 and RCP 8.5, stabilisation and worst-case scenarios, respectively (IPCC, 2014). The RCP 4.5 scenario is described by a radiative forcing stabilised after 2100, without overshooting the long-run radiative forcing target level. The RCP 8.5 scenario represents the "business as usual" scenario, in which low efforts are implemented to curb emissions. RCP 8.5 scenario can be very useful for

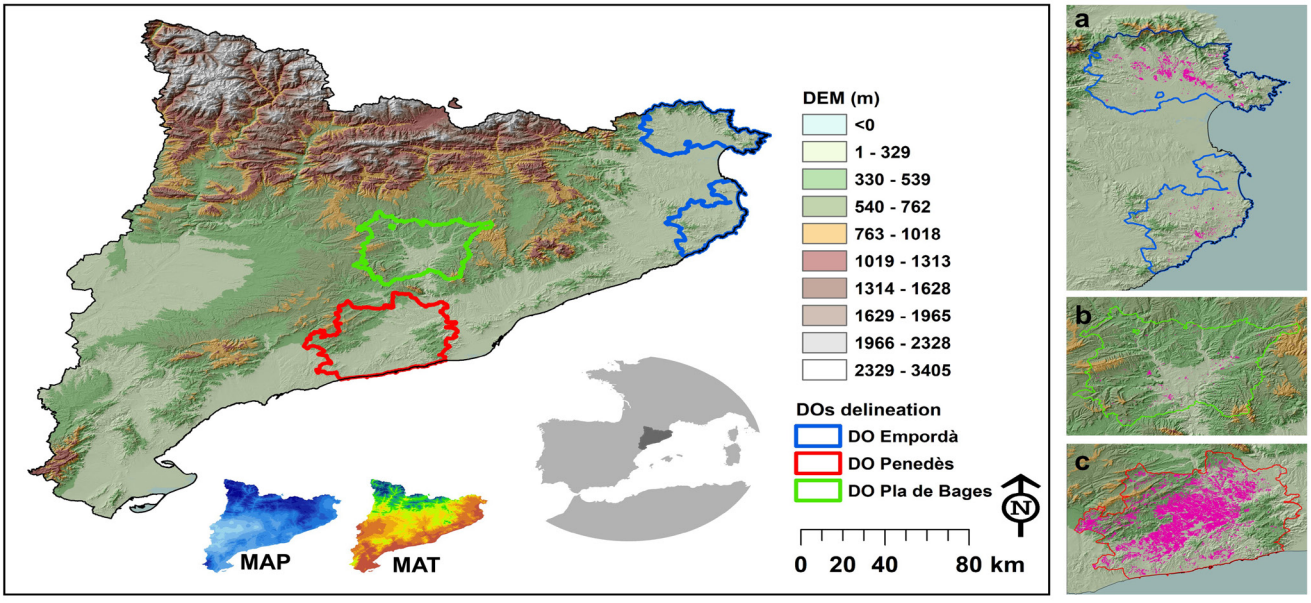


FIGURE 2. Location of the three PDOs case of study in Catalonia (NE Spain). DEM is the digital elevation model representing altitude above sea level. Vineyard spatial distribution in the territory of each PDO is represented in magenta colour in the maps on the left: a) PDO Empordà, b) PDO Pla de Bages, c) PDO Penedès. Mean annual precipitation (MAP) is represented for Catalonia in a blue ramp from 300 mm (light blue) to 1500 mm (dark blue) each 100 mm. Mean annual temperature (MAT) is represented for Catalonia in a colour ramp (from cold to warm colours) from < 3 °C (blue) to 18 °C (orange) each 2 °C.

policymakers to illustrate climate risks in the short- and mid-term because it seems to be the most plausible GHG emissions scenario in the 21st century if current policies are still implemented (Schwalm *et al.*, 2020). A grid of observations of temperature and precipitation at 1 km of spatial resolution covering the period 1971–2015 was used for climate change projections. The IPCC-AR5 global simulation model MPI-ESM (Germany; Giorgetta *et al.*, 2013) has been used for the calculation of the regionalised simulations, because of their best performance simulating the climate characteristics of the area under study during the 1971–2005 control period (Altava-Ortiz & Barrera-Escoda, 2020) and considering previous versions of this model for the Euro-Mediterranean area (van Ulden & van Oldenborgh, 2006). For this purpose, a statistical regionalisation, at a daily resolution, based on the concept of meteorological analogy (Baur *et al.*, 1951; Namias, 1951; Altava-Ortiz, 2010) according to the weather type from the observational grid at 1 km was performed for the control period and the projections forced under both scenarios of emissions. This technique is included in the category of methods on time classifier types, based on the classification and simplification of the spatial and temporal variability of drivers. This technique consists of searching for a set of past days with predictor data most similar to a future day (candidate days), to transfer the observational values (predictands) of the best analogue. The predictor variables are previously bias corrected taking into account the monthly performance of the climate model compared to meteorological reanalyses (NCAR-NCEP; Kistler *et al.*, 2001) before searching for the best analogue. The best analogue is found by a three-step procedure taking into account different meteorological variables at atmospheric levels within three different domains, which are defined to account for global to local scale variability. Thus, an initial set of analogue days is obtained for a large domain covering the North Atlantic and Euro-Mediterranean area (large scale), then a subset of those days is selected for a domain covering South-Western Europe (regional scale), and finally the last subset of days from a domain centred over Catalonia and surrounding areas (local scale).

However, downscaling methods based on the concept of meteorological analogy among past and future meteorological situations could suffer from a lack of analogy in case of future extreme situations, especially for temperatures at mid and high levels. That is, within the context of climate change, future meteorological situations might not have an appropriate analogy with respect to past observations. To address this issue, we have applied a correction factor based on the monthly covariance matrix among daily anomalies for maximum and minimum temperature observations and their respective daily anomalies for temperature at 850 hPa (one of the predictor variables) from the NCEP-NCAR variables in the past (Altava-Ortiz & Barrera-Escoda, 2020) for future temperature values, but no correction was applied for precipitation. With the computed monthly covariance matrix, it can be seen how surface maximum and minimum temperatures respond in units of temperature at 850 hPa. Therefore, for those future days that have no analogue in the control period, a thermometric increment must be applied to the surface temperature field of the closest analogue day. This increment depends on the difference, in standard deviations (computed monthly covariance matrix), for the temperature field at 850 hPa between the future day and the closest analogue in the control period.

2.2. Grapevine land use and available water capacity of vineyards

Vineyard land use information was extracted from SIGPAC (2020) which contains updated agricultural information at the plot level.

Soil maps were not available for the study area except for PDO Penedès. The Soil Map of Catalonia 1:25,000 (MSC25) is incomplete and only 25 % of the Catalan soils are detailed (see Figure S1). Soils in PDO Penedès were described in detail in most of this PDO and soil maps were available presenting some soil attributes needed for calculations:

1. maximum rooting depth of soil profile (Z; mm);
2. and available water capacity of the soil layer (AWC; mm H_2O · mm soil $^{-1}$).

By multiplying Z and AWC, a mean value of Total Available Soil Water (TAW; mm) as a maximum soil water capacity

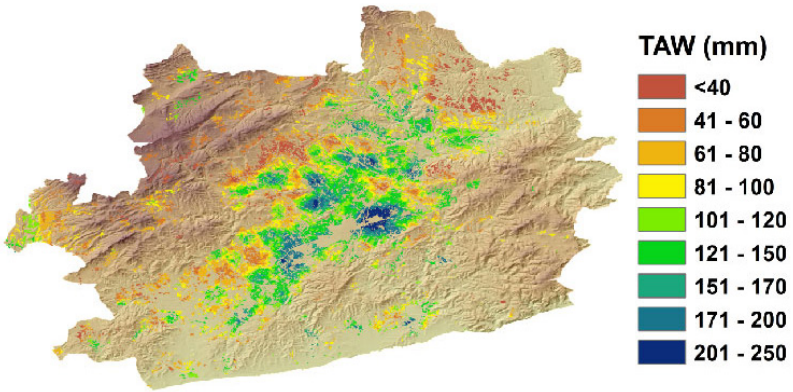


FIGURE 3. Spatial distribution of the maximum available water capacity of vineyard soils (TAW in mm) of PDO Penedès. Relief is shown in non-vineyard areas.

was obtained. Spatial interpolation techniques were used for TAW values in those areas of PDO Penedès where soil maps were not available. Therefore, for each vineyard plot in PDO Penedès, we could associate TAW values (Figure 3).

However, for PDO Empordà and PDO Pla de Bages, no proper soil map was available, and a global TAW value of 80 mm was assumed, following TAW mean values from some sampling soils under vineyard in the region (data not shown) and from mean values extracted from the European Soil Database v2 (ESDB; Panagos *et al.*, 2022) from the European Soil Data Centre (ESDAC).

3. Modelling phenology, crop water balance and indicators affecting ripening

Calculations of net water needs, phenological and agroclimatic indicators were performed by pixel and by year (1971–2100), using the R programming language (R Core Team, 2021) and restricted to only those pixels with vineyard presence, *i.e.*, pixels intersecting with vineyards plots. For this purpose, we extracted vineyard polygons from SIGPAC (2020).

3.1. Estimating net water requirements

Methodology used for calculations of net water needs (NWN) followed the FAO-56 document (Allen *et al.*, 1998), estimating potential evapotranspiration (ET_0) according to Hargreaves and Samani (1985), effective precipitation (Pef), potential crop evapotranspiration (ETc) and using the vineyard crop coefficient (Kc) following the crop growth function (Funes *et al.*, 2021), based on accumulated growing degree days (GDD). Kc values were based on those published in ACA and IRTA (2008), a compilation of different studies estimating Kc coefficients for different crops in Catalonia. Vineyard-specific Kc coefficients are defined in this publication following the crop growth function, based on accumulated growing degree days (GDD). For this study, GDD were adapted to the vineyard base temperature. More details are described in Vicente-Serrano *et al*. (2014).

Then, ETc was estimated as follows:

$$ETc = ET_0 * Kc$$

A daily water balance of atmosphere–plant–soil was recurrently calculated to obtain actual evapotranspiration (ETa) from ETc, Pef (mm · day $^{-1}$) and soil water content (SWC, mm · day $^{-1}$). ETa is equal to ETc but limited by water availability: water coming from precipitation plus water stored in the soil (SWC). The water balance is initialised from October 1st (the beginning of the water year) of the first year of the simulation and assumes soil water depletion after the summer (SWC = 0). Finally, we estimated NWN as the difference between ETc and ETa. This daily water balance follows the same methodology for water balance on a monthly basis described in Funes *et al.* (2021).

Calculated in this way, NWN does not estimate water inefficiencies in the irrigation system or water distribution and only water requirements at the plant level were considered. Furthermore, water stress coefficients (Ks), which are used to adjust Kc for different stresses and environmental factors impacting crop evapotranspiration, were not considered in this study for NWN estimations. Moreover, projections of NWN estimations in this study do not take into consideration land use change scenarios in the 21st century and theoretical net water needs for vines were calculated for both rainfed and irrigated cropland in the territory of each PDO.

3.2. Modelling agroclimatic indicators for grapevine phenology

Thermal needs, estimated as GDD accumulation (Tª threshold as Tmean = 10 °C (Winkler *et al*., 1974); Tª optimum as T mean = 25 °C and Tª top threshold as Tmax = 3 °C; following Anderson *et al*., 1986), defining days elapsed between each phenological stage from 1st January, were calculated following Ramos *et al.* (2008) main phenological stages from budburst to harvest and based on several phenological records(following the BBCH scale) over Catalonia from a few varieties (data not shown). Phenological indicators calculated were the mean date of the main phenological phases: Budbreak, Flowering, Fruitset, Peasize and Harvest. The mean date of each phenological phase was estimated when a certain amount of GDD was accumulated from 1st January: 406 GDD for Budbreak, 517 GDD for Flowering, 798 GDD for Fruitset, 1,322 GDD for Peasize and 1,962 GDD for Harvest. The number of days occurring in the phenological intervals between each phenological event was estimated as well as: Budbreak (from the end of dormancy to 50 % of buds were break), Flowering (from Budbreak to 50 % of flowers were open), Fruitset (from flowering to the 50 % of grapes were set), Peasize (from fruitset to 50 % grapes at Peasize) and ripening (from the beginning of veraison to harvest). The Post-Harvest/ Dormancy stages went from harvest to the end of the year and restarted to zero from 1st January to 107 GDD.

The duration of the "Budburst to Harvest" period was estimated and assumed as the number of days from Budbreak to Harvest (from 107 to 1,962 GDD).

3.3. Performing agroclimatic indicators affecting ripening

Agroclimatic indicators affecting berry quality are related to a specific phase of the crop cycle: the phase from veraison to harvest called the ripening phase (phase III), which was previously estimated year by year following the methodology described in the previous section. Ripening is a vital stage of grape development during which numerous metabolites that influence wine quality build up in the berries. Key shifts in berry composition involve a sharp rise in sugar levels and a decline in both the content and concentration of malic acid. Agroclimatic indicators calculated during the ripening phase were DTR III (daily thermal amplitude, in °C, during phase III), NT20 III (number of tropical nights during phase III or days with Tmin > 20 °C) and TN III (mean value of daily minimum temperature, in °C, during phase III).

TABLE 1. Averaged values of grapevine annual net water needs (mm · year $^{-1}$) for the baseline period (1972–2005) and differences from the baseline period of projections (Δ mm · year $^{-1}$) of two climate change scenarios (RCP) for future decades of the 21st Century in Alt Empordà (AE), Baix Empordà (BE), Pla de Bages (PB) and Penedès (PN). The standard deviation (± SD) of each baseline period and changes in SD in future periods are shown in brackets.

PDO	Baseline (1972–2005)	CC Scenario	Future projections						
			2030s	2040s	2050s	2060s	2070s	2080s	2090s
			Δ mm · year $^{-1}$						
AE	25.3 (± 6.7)	RCP 4.5	+25.5 (± 1.1)	+19.6 (± 0.0)	+24.9 (± 0.9)	+32.3 (± 2.0)	+34.9 (± 1.8)	+51.5 (± 2.1)	+25.1 (± 2.6)
		RCP 8.5	+24.3 (± 3.0)	+28.7 (± 1.4)	+40.4 (± 3.9)	+43.6 (± 2.0)	+89.8 (± 4.6)	+79.9 (± 6.1)	+95.8 (± 6.4)
BE	30.0 (± 6.7)	RCP 4.5	+20.4 (± 4.2)	+18.5 (± 4.7)	+21.3 (± 5.1)	+40.4 (± 9.3)	+27.9 (± 5.0)	+37.8 (± 8.1)	+30.1 (± 6.5)
		RCP 8.5	+17.7 (± 5.2)	+19.7 (± 5.2)	+26.8 (± 5.1)	+38.1 (± 9.5)	+70.8 (± 12.3)	+82.8 (± 12.5)	+89.2 (± 16.3)
PB	42 (± 7.2)	RCP 4.5	+35.4 (± 3.7)	+30.1 (± 3.3)	+39.7 (± 5.7)	+15.8 (± 1.7)	+40.9 (± 6.1)	+38.3 (± 3.2)	+33.2 (± 1.9)
		RCP 8.5	+59.2 (± 1.5)	+39.9 (± 4.0)	+40.1 (± 6.0)	+54.9 (± 5.1)	+81.1 (± 3.2)	+94.6 (± 4.4)	+84.7 (± 5.3)
PN	43 (± 18.7)	RCP 4.5	+22.8 (± 7.4)	+22.2 (± 5.4)	+36.4 (± 9.2)	+27.1 (± 4.3)	+35.1 (± 8.4)	+36.9 (± 4.7)	+38.3 (± 3.0)
		RCP 8.5	+40.6 (± 9.2)	+31.3 (± 4.9)	+28.7 (± 1.1)	+43.3 (± 10.2)	+80.9 (± 13.7)	+81.1 (± 12.7)	+80.9 (± 9.5)

RESULTS

1. Net water needs projections over the 21st century

For the most optimistic CC scenario analysed (RCP 4.5), NWN could rise in PDO Empordà, PDO Pla de Bages and PDO Penedès in the next decade (2030s), supposing increments ranging from more than 50 % to 100 % from the baseline period, depending on the PDO. Regarding the long-term decades (2070s), increases could result in increments of more than 80 % in the optimistic scenario for the three PDOs (Table 1 and Figure 4).

Results showed that NWN could increase from 18 to 25 mm · year $^{-1}$ in PDO Empordà and around 59 and 41 mm · year $^{-1}$ in the short term (2030s) for the most dramatic scenario (RCP 8.5) in PDO Pla de Bages and Penedès, respectively. These increments for the short-term decade could suppose rise percentages of 60–100 % for PDO Empordà, 140 % for PDO Pla de Bages and 95 % for PDO Penedès. Increases at the end of the century (2070s) projected for RCP 8.5 were 70–90 mm · year $^{-1}$ for PDO Empordà and around 81 mm · year $^{-1}$ in PDO Pla de Bages and Penedès. In general, and for RCP 8.5, water needs increased by 2 and almost 4 times more than current water needs at the end of the 21st century (Table 1 and Figure 4). Moreover, interannual variability would increase along the century as shown by standard deviation values in Table 1. A sensitivity analysis was conducted for PDOs Pla de Bages and Empordà, using a range of TAW values (60–100 mm) to validate the findings against a mean TAW value of 80 mm. The results of this sensitivity analysis demonstrated an overestimation of NWN variations (from the baseline period) by approximately 2.2 mm and an underestimation of NWN by approximately 2.8 mm (Table S1), values within the range of the interannual variability of NWN variations observed for each projected decade and using a mean TAW of 80 mm.

2. Modelled changes in grapevine phenology

2.1. Length of 'Budburst to Harvest' period

In general, the duration of the 'Budburst to Harvest' period would be shortened and advanced in the three PDOs over the 21st century and was modelled for both climate change scenarios (Table 2 and Figure S2). The 'Budburst to Harvest' period advancement was modelled by different phases: budbreak, flowering, fruit set, pea size and ripening (from veraison to harvest). All these phases were projected to advance and some of them to be shortened (Figure S2). For the next decade (2030s) the duration of the 'Budburst to Harvest' period could be shortened by about 1 month in PDO Pla de Bages and PDO Penedès and Baix Empordà when modelled for both CC scenarios. At the end of the

century, the duration of this period could be up to 57, 48 and 32 days shorter than the baseline period in PDO Penedès, Pla de Bages and Baix Empordà, respectively, if considering RCP 8.5. Nevertheless, Alt Empordà showed the smoothest duration from budburst to harvest shortenings, around 15 and 20 days (Table 2 and Figure S4).

2.2. Harvest date

Harvest date could advance more than one month on average in most of the PDOs when modelled for the next decade (2030s) regardless of the CC scenario and from 45, 69, 87, 57 days in Alt Empordà, Baix Empordà, Pla de Bages and Penedès, respectively, for the 2070s, if RCP 8.5 scenario is considered (Table 2 and Figure S3).

2.3. Flowering date

The flowering date could advance in the same magnitude in the three PDOs by one month when modelled at the end of the century if the most dramatic scenario is considered (Table 2 and Figure 5). Notwithstanding all this, flowering advances from 1 to 2 weeks were projected for the next decade (2030s) even if the optimistic scenario is considered (Table 2).

3. Agroclimatic indicators affecting ripening

Here we have assessed three agroclimatic indicators based on temperature to estimate CC impact during the ripening phase, which is the phase most affected by climate change and most affects grapevine quality (Arias *et al.*, 2022). The three grapevine indicators augmented in all PDOs studied

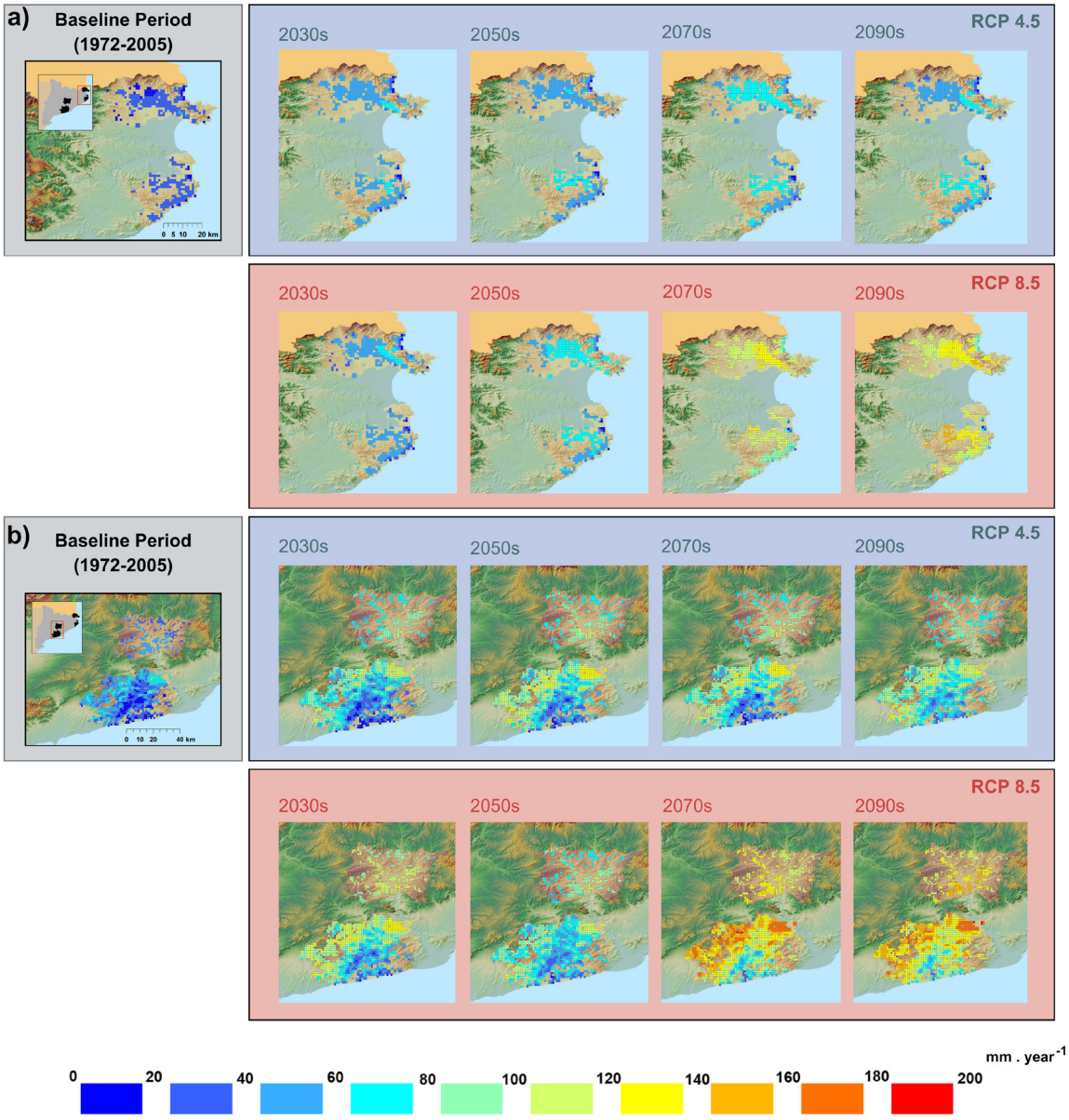


FIGURE 4. Timeline of grapevine mean net water needs (NWN in mm · year $^{-1}$) estimated for the Baseline period (1971–2005) and projected over four future decades along the 21st century under two climate change scenarios (RCP 4.5 and RCP 8.5) for the vineyard area of: a) PDO Empordà and b) PDO Pla de Bages and PDO Penedès, at 1 km resolution.

over the 21st century and in both CC scenarios, following temperature increase during this phase (Table 3), especially under RCP 8.5.

3.1. Tropical nights

The number of tropical nights (Table 2 and Figure S5) could rise from about +4–5 and +9–10 days in Alt and Baix Empordà, respectively, for the next decade, depending on the scenario. PDO Penedès could increase as well tropical nights around +4–5 days for the next decade, in both scenarios. Increases of tropical nights were projected between +18 and +12 days above the baseline period in PDO Empordà (Baix Empordà) and Penedès, respectively, for the long term (2070s) under RCP 8.5. Pla de Bages, barely increased from +1 or +2 days for the next decades and +2 and +3 days in the 2070s, considering both scenarios.

3.2. Daily minimum temperature

On the other hand, the daily minimum temperature (Table 3 and Figure S6) could increase from +1.7 to +2.5 at the end of the century for the dramatic scenario depending on the PDO, showing Baix Empordà the greatest increase.

3.3. Daily thermal amplitude

Finally, daily thermal amplitude (Table 3 and Figure S7) could increase ranging from +1 to +2 at the end of the century for the dramatic scenario depending on the PDO, presenting PDO Pla de Bages as the highest increases.

The findings described in the Results section must be read cautiously considering the limitations raised by the present study and detailed in Section 4 of the Discussion, concerning simplified methods, incomplete data and unaddressed uncertainties.

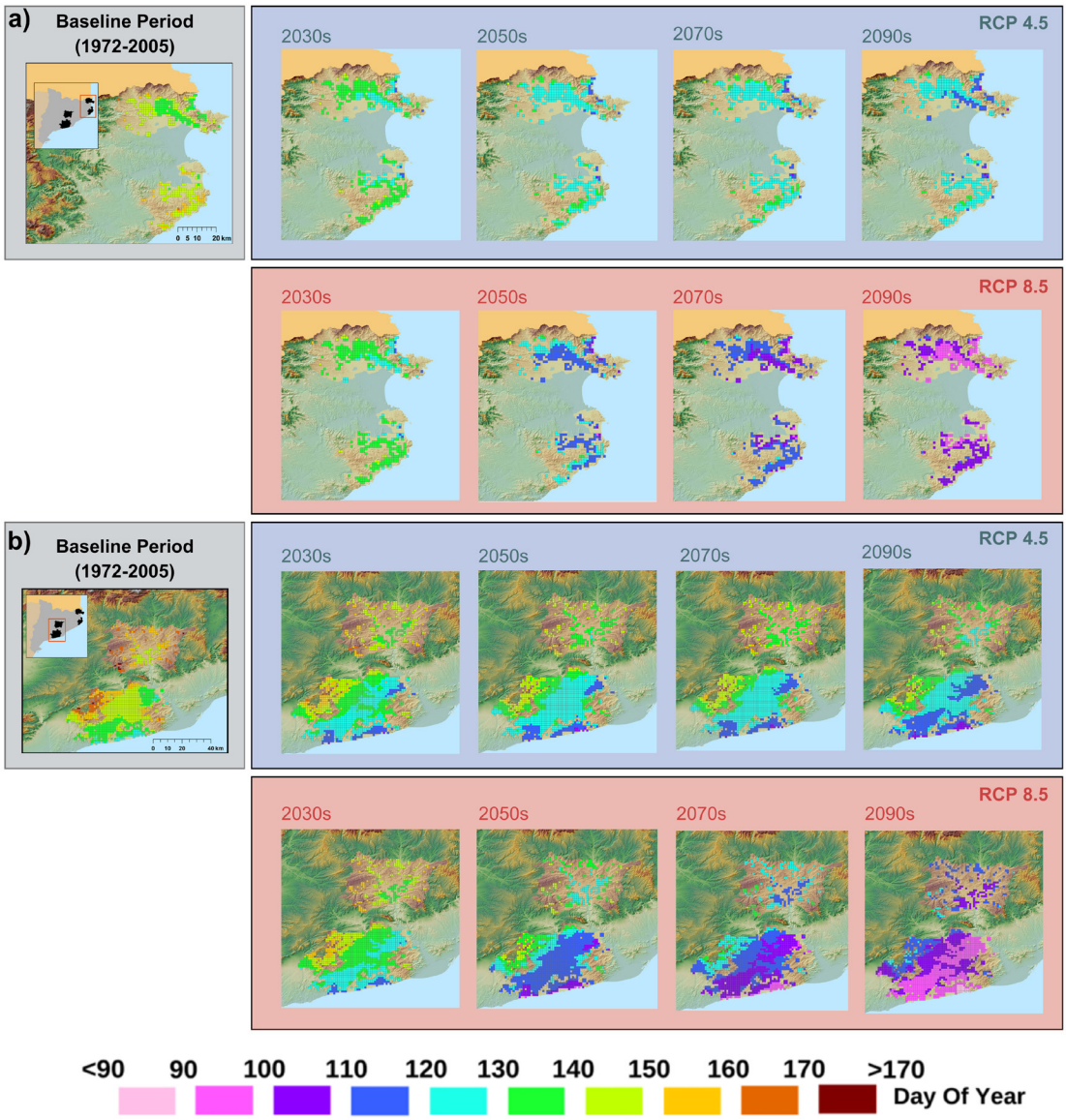


FIGURE 5. Timeline of mean grapevine flowering date estimated for the Baseline period (1971–2005) and projected over four future decades along the 21st century under two climate change scenarios (RCP 4.5 and RCP 8.5) for the vineyard area of a) PDO Empordà and b) PDO Pla de Bages and PDO Penedès, at 1 km resolution.

TABLE 2. Average values of phenological indicators for the baseline period (1972–2005) and projections of two climate change scenarios (RCP) for future decades of the 21st century in Alt Empordà (AE), Baix Empordà (BE), Pla de Bages (PB) and Penedès (PN).

Phenological Indicator	PDO	Baseline (1972–2005)	CC Scenario	Future projections						
				2030s	2040s	2050s	2060s	2070s	2080s	2090s
				Δ days						
Duration of the 'Budburst to Harvest' period (days)	AE	200.5	RCP 4.5	–11.1	–13.8	–14.5	–10.3	–12.8	–13.4	–8.6
			RCP 8.5	–7.0	–8.5	–9.9	–13.7	–16.3	–18.6	–23.0
	BE	222.6	RCP 4.5	–25.5	–28.5	–30.2	–27.6	–29.2	–30.7	–26.3
			RCP 8.5	–25.5	–25.5	–27.8	–30.5	–32.3	–36.1	–40.7
	PB	227.0	RCP 4.5	–35.1	–37.9	–47.5	–40.7	–41.2	–44.5	–42.7
			RCP 8.5	–38.6	–34.9	–42.8	–46.3	–48.1	–52.7	–57.2
	PN	287.4	RCP 4.5	–28.9	–32.5	–38.5	–37.2	–40.4	–40.2	–43.8
			RCP 8.5	–31.5	–31.3	–44.5	–51.2	–57.1	–60.5	–68.4
				Δ days						
Flowering date	AE	May 21st	RCP 4.5	–8.5	–11.6	–13.7	–14.5	–13.8	–17.3	–18.1
			RCP 8.5	–8.4	–8.8	–21.1	–28.2	–29.4	–32.3	–40.2
	BE	May 28th	RCP 4.5	–14.5	–17.7	–19.2	–20.5	–19.6	–22.4	–23.3
			RCP 8.5	–13.7	–14.5	–27.2	–34.1	–35.0	–38.4	–44.6
	PB	June 5th	RCP 4.5	–10.3	–13.2	–16.0	–16.0	–15.4	–19.9	–19.9
			RCP 8.5	–9.8	–9.9	–22.5	–29.5	–30.5	–33.4	–41.0
	PN	May 24th	RCP 4.5	–10.8	–12.6	–14.7	–16.0	–15.3	–18.3	–19.4
			RCP 8.5	–9.8	–9.7	–22.3	–29.8	–31.4	–32.9	–42.4
				Δ days						
Harvest date	AE	September 29th	RCP 4.5	–19.9	–30.2	–23.8	–28.8	–26.7	–31.0	–33.3
			RCP 8.5	–21.8	–21.8	–34.1	–39.5	–45.4	–49.0	–56.2
	BE	October 27th	RCP 4.5	–43.1	–53.5	–47.4	–51.8	–50.9	–54.3	–56.9
			RCP 8.5	–45.4	–45.3	–57.2	–63.1	–69.0	–73.0	–79.3
	PB	November 19th	RCP 4.5	–50.8	–67.0	–55.1	–64.7	–63.1	67.3	–71.1
			RCP 8.5	–54.6	–54.1	–71.6	–79.4	–86.7	–90.3	–99.1
	PN	October 14th	RCP 4.5	–29.0	–40.3	–32.5	–38.5	–37.2	–40.2	–43.7
			RCP 8.5	–31.5	–31.3	–44.5	–51.1	–57.1	–60.5	–68.3

DISCUSSION

The present study highlights the remarkable effects of CC for viticulture in the three Mediterranean PDOs studied which allows drawing future challenges that the sector should face. This work assessed future CC impacts on vineyards based on regionalised climate projection at high spatial resolution and representative of wine region diversity. Moreover, not only rising temperature impacts on vines were assessed but also water requirements based on soil water balance. Despite several limitations arising from modelling assumptions and data uncertainties (see Section 4 of this "Discussion"), we show substantial climate change effects on Catalan vineyards. Rising temperatures will have adverse effects on the grapevine growing cycle, water balance and berry quality, particularly during the late spring and summer months when fruit set and ripening take place. The results showed differences in how CC impacts vineyard water needs, phenology and ripening indicators across PDOs. For example, in Alt Empordà, CC impacts could appear later into the 21st century and smoother than in the other PDOs, highlighting the importance of regionalisation when assessing CC vulnerabilities.

1. Impacts of climate change on vineyard water needs

Vineyards in the Mediterranean are in fact very well adapted to water stress because of their canopy structure (Alsina *et al.*, 2011) and their roots penetrate very deep into the soil (Marín *et al.*, 2021; Cardell *et al.*, 2019). However, the reduction of precipitation during spring and summer is already causing important constraints in the study area because of water availability during growth and ripening. Water stress (moment and duration) has important consequences not only on productivity but also on berry quality (Chaves *et al.*, 2010).

TABLE 3. Average values of agroclimatic indicators affecting ripening for the baseline period (1972–2005) and projections of two climate change scenarios (RCP) for future decades of the 21st Century in Alt Empordà (AE), Baix Empordà (BE), Pla de Bages (PB) and Penedès (PN).

Agroclimatic Indicator	PDO	Baseline (1972–2005)	CC Scenario	Future projections						
				2030s	2040s	2050s	2060s	2070s	2080s	2090s
							Δ days			
Tropical nights (days)	AE	12.5	RCP 4.5	+5.0	+4.4	+7.1	+4.6	+6.2	+5.8	+7.8
			RCP 8.5	+4.0	+5.1	+6.3	+10.5	+11.5	+13.3	+16.4
	BE	8.3	RCP 4.5	+9.4	+9.9	+11.9	+11.0	+11.8	+12.3	+13.1
			RCP 8.5	+10.4	+10.6	+11.3	+15.7	+17.8	+19.7	+23.7
	PB	0.7	RCP 4.5	+1.6	+0.8	+2.1	+2.1	+2.3	+2.1	+2.0
			RCP 8.5	+2.0	+1.3	+2.0	+3.0	+3.6	+4.4	+7.6
	PN	9.7	RCP 4.5	+4.4	+4.0	+6.6	+6.4	+7.4	+6.2	+8.6
			RCP 8.5	+5.5	+5.4	+7.6	+10.2	+11.9	+14.87	+19.3
							Δ °C			
Daily thermal amplitude (°C)	AE	11.8	RCP 4.5	+0.5	+0.4	+1.0	+0.9	+1.1	+1.0	+1.0
			RCP 8.5	+0.5	+0.9	+1.0	+1.3	+1.7	+1.7	+2.2
	BE	11.3	RCP 4.5	+0.1	+0.0	+0.5	+0.3	+0.5	+0.4	+0.4
			RCP 8.5	-0.2	+0.2	+0.4	+0.5	+0.9	+1.0	+1.4
	PB	14.8	RCP 4.5	+0.6	+0.4	+1.1	+0.7	+1.0	+1.1	+1.1
			RCP 8.5	+0.3	+0.7	+1.0	+1.4	+1.9	+2.1	+2.8
	PN	11.8	RCP 4.5	+0.4	+0.2	+0.7	+0.5	+0.8	+0.7	+0.7
			RCP 8.5	+0.1	+0.5	+0.6	+0.9	+1.2	+1.4	+1.9
							Δ °C			
Daily minimum temperature (°C)	AE	17.4	RCP 4.5	+0.8	+0.8	+1.0	+1.0	+1.1	+1.1	+1.4
			RCP 8.5	+0.8	+0.9	+1.1	+1.6	+1.7	+1.9	+2.1
	BE	16.7	RCP 4.5	+1.5	+1.5	+1.7	+1.8	+1.8	+1.9	+2.0
			RCP 8.5	+1.3	+1.3	+1.6	+2.1	+2.2	+2.4	+2.7
	PB	15.0	RCP 4.5	+1.1	+1.1	+1.4	+1.6	+1.6	+1.5	+1.8
			RCP 8.5	+1.6	+1.7	+1.8	+2.3	+2.5	+2.6	+2.9
	PN	17.0	RCP 4.5	+0.9	+0.9	+1.1	+1.2	+1.3	+1.2	+1.5
			RCP 8.5	+1.0	+1.1	+1.3	+1.7	+1.9	+2.1	+2.4

In fact, Yang *et al.* (2022) demonstrated water stress from flowering to veraison seriously affects yield. Moreover, the runoff risk producing higher erosion rates in vineyards would increase because of increased extreme precipitation events (Cardell *et al.*, 2019; Ramos, 2017). Vineyard soil and relief characteristics can worsen runoff risk by soil sealing ("crust") and slopes. These conditions decrease severely water infiltration in the soil that together with scarce organic matter, significantly reduces the available water at the root zone (Ramos, 2017). Increasing droughts could result in increased soil salinity seriously affecting grapevine growth, productivity and quality (Phogat *et al.*, 2018). Projected changes in precipitation patterns coupled with increased evapotranspiration rates due to warmer climates are expected to reduce overall water availability in southern Europe. This is particularly concerning during the summer months, leading to heightened water requirements and the likelihood of severe water stress across various regions. Areas such as Andalucía, La Mancha (Spain), Alentejo (Portugal), Sicily, Apulia and Campania (Italy) are forecasted to experience significant water deficits (Droulia & Charalampopoulos, 2021).

In the three PDOs water balance is negative even for the baseline period (from 25 to more than 40 mm · year $^{-1}$, depending on the PDO). Although it is widely known that grapevines are currently growing under rainfed conditions in most of the vineyards in the study area, these deficits referred to mean values of a period (1972–2005) when high interannual variability characterised by the alternance of humid and dry years was presented. In this regard, irrigation needs around 40–60 mm were modelled by Gaudin and Gary (2012) from South France for 39 years (1972–2010). Previously, Ramos *et al*. (2008) assessed water demand

changes during the last decades (1952–2006) and found increases from 4 and 16 % in different NE Spain regions, including PDO Penedès, which demonstrates the trends in increasing water demands. Temperature increases create greater evaporative demand on the atmosphere and, together with annual pluviometry stability projected for the study area, water balance will be increasingly negative at the three PDOs (ranging from 25 to 95 mm for the end of the 21st century), as described by Cardell *et al*. (2019) across Europe. They predicted future increases up to 18 % for Spain and Portugal (around 300 mm) and they found present water needs for south-eastern Spain close to 100 mm, even though the numbers cannot be compared as they did not consider the water retention capacity of soils in their water balance. Irrigation requirement increases were estimated from 208 to 500 mm at the end of the 21st century by Phogat *et al*. (2018) in South Australia, supposing an increase of 16.9 % compared to the baseline period. In line with our findings, Ramos (2017) estimated water deficit increases of around 40–50 mm for 2070 under RCP 4.5 and 70–84 mm under RCP 8.5 for the Penedès Depression (NE Spain). Therefore, droughts would be more and more intense, as projected in other studies for Southern Europe (Lopez-Bustins *et al.*, 2013; Moriondo *et al.*, 2013; Cardell *et al.*, 2019). In this context, territorial and land use disputes for water use could arise due to water depletion. Moreover, vineyard water needs increased lightly in those pixels where vineyards are growing over high TAW soils. Therefore, CC impacts on water requirements will be low in vineyards growing over soils with higher TAW values. Therefore, highlighting the importance of soils becomes essential when building climate-resilient agriculture to effectively cope with CC risks.

2. Impacts on grapevine phenology and ripening

Warmer conditions imply advanced and shorter phenological phases and finally earlier harvest dates (Jones, 2012). Phenological observations over the last decades have already shown advancements in phenology over the Mediterranean region. Bécart *et al.* (2022) found advancements in Grenache grape cultivar around 10–15 days earlier at initial stages and 15–20 days earlier at final stages over the last half century in southern France moving maturation to warmest periods. Advanced harvest dates at a mean rate of 3 days per decade during the last 45 years in Greece were presented by Xyrafis *et al.* (2022). If ripening moves to August instead of September, warmer temperatures in August will accelerate maturation and increase sugar concentrations rapidly and beyond control (Bécart *et al.*, 2022). Our results show how phenology will continue these trends advancing phenological stages such as flowering around a month and harvest more than two months at the end of the century regarding the baseline period in some PDOs, as several studies show at a similar order of magnitude (Droulia & Charalampopoulos, 2021).

Flowering advancements around 17–19 days were estimated by Chacón-Vozmediano *et al.* (2021) in La Mancha (Spain) for 2070 under the warmest scenario. However, they estimated the maturity advance for 2070 under RCP 8.5 at 16–17 days, while our results were almost twice as high. Similar comparisons can be made using the finding from Ramos and de Toda (2022), where flowering presented advancements from 6–13 days and maturity from 14–26 days for 2070 under the warmest scenario in La Rioja (NE Spain). The advancement of budbreak or flowering dates could additionally increase frost risk in certain locations due to flowering could overlap with frost events during early spring (Darbyshire *et al.*, 2013; Sgubin *et al.*, 2018), causing irrevocable damage to vineyards (Spellman, 1999). Nevertheless, there is no significant change in risk from current conditions when spring frosts are projected from the mid-21st century (Zito *et al*., 2023). Shortened 'Budburst to Harvest' period were also observed and predicted by other authors due to warmer conditions and faster accomplishment of GDD. Ramos (2017) predicted shortenings up to 20 days for the Chardonnay cultivar in Penedès Depression for RCP 8.5 for 2070, being the highest shortening between veraison and harvest. However, these findings (Ramos, 2017) are far from ours where predicted shortenings from the baseline period to the 2070s decade at the RCP8.5 scenario were almost 3 times bigger than ours for the shortened 'Budburst to Harvest' period as well as for the harvest date advancement. Predicted phenology advancements in different vine French regions are also far from those shown here for NE Spain, supposing 10 days earlier for the Flowering date and from 25 to 30 days earlier to the maturity date for the worst-case scenario (Zito *et al*., 2023).

Grape quality and yield are directly influenced by climate conditions during the 'Budburst to Harvest' period. Higher temperatures also accelerate the accumulation of sugar, leading to a higher level of sugar in the grapes and, therefore a higher alcohol content and, consequently, to unbalanced wines after fermentation. Specifically, malic acid degradation is being favoured by high temperatures during ripening resulting in less acidic wines. The combined effect of increased temperatures and advanced phenology caused more sugar and less organic acids in berries, and altered secondary metabolites composition, particularly aroma precursors (van Leeuwen & Destrac-Irvine, 2017). The degree to which high temperature affects the anthocyanin-to-sugar ratio is believed to be cultivar-dependent, due to the different sensitivity of berry anthocyanin to critical ranges of temperature (Fernandes de Oliveira *et al.*, 2015). Similarly, if mean temperatures during the Fruit Set-Lag phase are higher, then the berry weight will be lower and grapevine production will be affected because of growing under conditions exceeding its optimum and under extreme heat stress (Bécart *et al.*, 2022; Cardell *et al.*, 2019; Ramos & de Toda, 2022). However, berry growth highly depends on both temperature and water. Water deficit normally impacts closing stomata, reducing carbon fixation and producing heterogeneous berry ripening (Martínez-Lüscher *et al.*, 2016). High temperatures and water deficits occurring between veraison and maturity impact more on quality parameters, such as acidity or phenolic composition than those occurring between fruit set and veraison (Ramos & de Toda, 2022). As a result, grapevine exposure during

long-time periods to temperatures exceeding 30 °C results in lower grapevine quality: fruits with higher sugar content, very low acidity, heterogeneous maturation of tannins, less aromas, colour oxidation and less pigments.

3. Limitations of the study

Some limitations must be acknowledged when performing the water balance to estimate NWN. First, ET_0 was estimated using the Hargreaves equation because of the lack of more projected climate variables (wind, HR, solar radiation), which are generally not explored. These climate variables are usually difficult to project to the future and long past time series are difficult to find. Second, cultivar-specific Kc were not adjusted and a general Kc for vineyards in certain conditions of Catalonia were applied. Furthermore, it should be noted that stress coefficients (Ks) were not applied in the present study.

While evaluating water needs by applying Ks coefficients could have been an interesting option, it was not considered within the scope of the present study, since the primary objective was to assess the water requirements for optimal yield, and using Ks alone may not fully account for preserving optimal production. Third, a Catalan soil map was not available for the three PDOs. In fact, soil maps were only available for PDO Penedès and TAW values could be extracted only for this PDO. For the rest of the PDOs, a mean TAW value was assumed based on the averaged value from the European soil map (ESDAC) in these areas. This may result in a significant under- or over-estimation of NWN, particularly when considering the lowest and highest TAW values. Nevertheless, a sensitivity analysis was performed using a range of TAW values. The findings, presented in Table S1, indicate that using TAW values between 60 and 100 mm would not significantly alter the results. Fourth, the effect of increasing CO_2 on vine transpiration in the water balance was not considered. Extended discussion on this limitation can be found in Funes *et al.* (2021) and Savé *et al.* (2012).

Fifth, estimated changes in the duration of 'Budburst to Harvest' here used very simple models based on GDD accumulation and grapevine phenology from a few years and points over Catalonia. The lack of phenological data is a strong limitation when performing CC impacts on crops. Data networks presenting long-time series of vine phenological records have enormous scientific value and are an essential tool for understanding and anticipating CC (Bécart *et al.*, 2022). Moreover, the harvest date is generally considered to be a false phenophase because it is highly influenced by oenological decisions. Nevertheless, we considered the harvest date as the date when the grapes reach the minimum sugar content regulated by every PDO Regulatory Council as the sugar content is clearly driven by the climate.

Sixth, climate projections based on the regionalisation of a single GCM (the German model MPI-ESM) were used as inputs for the present assessment. This approach could lead to an important limitation by underestimating climate variability, as the use of other models may result in different outputs. Moreover, the use of a single global simulation model (MPI-ESM) for regionalised simulations may introduce bias if the model does not fully capture the regional climate characteristics (Altava-Ortiz & Barrera-Escoda, 2020). Notwithstanding this, high-resolution projections based on statistical downscaling from MPI-ESM climate simulations proved an extraordinary capability of simulating observed precipitation and temperature characteristics at a local scale in the study area. However, our methodology relies on the assumption that the concept of meteorological analogy is valid for future extreme scenarios and this assumption may not hold true, particularly in the context of CC where unprecedented events could occur. Moreover, an assessment of the propagation of uncertainties of the projections associated with this downscaling approach, climate models and emission scenarios, to interpret the reliability and for a more trustworthy assessment, was not possible due to computational constraints. Therefore, the validity of the findings should be accurately tested to narrow down the associated large uncertainty. Seventh, pests and diseases are expected to increase as well seriously affecting vine health (Castex *et al.*, 2023). This fact was not considered in the present assessment and could surely affect the results. Finally, no specific agronomical and cultivar performance or market needs were considered in our estimations.

4. Adaptation strategies for Mediterranean viticulture.

Adapting viticulture to CC in the Mediterranean region is supposed to find different ways to conquer difficulties and face challenges (Mrabet *et al.*, 2020) such as those estimated in the present study. Many promising adaptation strategies have been explored:

- **New varieties**. Growing potential new varieties better adapted to warmer conditions through genetic breeding or clonal selection and growing them on better-adapted rootstocks could lead the changes in the new agronomy for CC adaptation (Santillán *et al.*, 2019; Santos *et al.*, 2020; Naulleau *et al.*, 2022).
- **Agronomy and new growing techniques**. Agronomical practices such as trellising, pruning, shading or row orientation could also be essential for adaptation (Naulleau *et al.*, 2022; Oliver-Manera *et al.*, 2023). Viticulturists must take into account the vineyard aspect and consider other techniques as strategies to cope with climate change such as (i) varietal and clone selection, (ii) managing canopy to keep grapes under the shade, (iii) removing fruit to promote better phenolic ripeness, (iv) harvest at night at cooler temperatures, (v) implementing precision viticulture or (vi) choosing harvest time depending on the water status of the plant.
- **Regenerative viticulture**. This holistic management has become an alternative to conventional agriculture to manage crops towards resilience and to cope with both CC mitigation and adaptation, improving soil balance (structure, nutrition, effective irrigation or erosion control), enhancing biodiversity and sequestering carbon (Andrés *et al.*, 2022). In fact, vineyards can sequester

and store carbon in their soils and grapevine-standing woody biomass for decades (Miranda *et al.*, 2017; Funes *et al.*, 2022).

- **Irrigation**. Irrigation techniques based on the improvement of water use efficiency are vital to viticulture suitability in the study area and the whole Mediterranean region (Basile *et al.*, 2012). Moreover, increasing water use efficiency through deficit irrigation strategies could help for adaptation (Sánchez-Ortiz *et al*., 2024).
- **Moving vineyards to cooler areas**. Moving vineyards to new areas that will have favourable thermal conditions for growing grapevine varieties from now to the mid-century would be an option. Moving vineyards to countries in Central Europe or even to higher altitudes in Southern Europe that currently have cool conditions for growing vineyards could be explored in the near future (Cardell *et al.*, 2019). In fact, some vineyards are now at high altitudes in the Catalan Pyrenees. However, more efforts are necessary to facilitate vineyard establishment at higher altitudes such as improvements in land access, legislation and logistic issues.
- **New oenology**. Oenology to manage new quality issues can help to cope with undesirable effects on wine quality such as temperature control of fermentation to prevent quick transformation of sugar into alcohol or adapting the techniques of extraction of colour and tannin during fermentation.
- **Grape production legislation update**. Local grape production legislation should adapt to new climate and socioeconomic scenarios. PDO regulations could become more flexible to allow winegrowers to experiment with new practices even in specific periods and under their evaluation. This facilitates collaboration between viticulturists, winemakers, scientists and climate change experts to share knowledge and better adjust practices in the field in real time.

It is important to consider that no general or single adaptation measure or strategy will be enough to adapt Mediterranean agriculture to CC, and it would be necessary to consider various site-specific strategies simultaneously (Ruiz-Ramos *et al.*, 2018).

5. Future work

Assessing CC impacts on viticulture is essential to assume the magnitude of future reality. Planning future scenarios addressed to adaptation and resilience implies exploring future CC effects on crops such as grapevine presenting high socio-economic, cultural and landscape relevance (Droulia & Charalampopoulos, 2021). More efforts must be made to spatially extend CC impact assessments locally to other viticulture regions. Moreover, viticultural zoning for evaluating potential suitability (Sgubin *et al.*, 2022) and quantitatively testing promising adaptation strategies at the local and regional levels involving local stakeholders in the process (Naulleau *et al.*, 2022) becomes necessary.

CONCLUSION

This study presents the first regional assessment of CC impacts on vineyards in three PDOs in NE Spain along the 21st Century at 1 km resolution identifying future challenges that the sector should overcome for adapting to the new climate conditions. Results show significant water needs increases over the 21st century for vineyards in the three PDOs studied, directly related to increased evapotranspiration during the growing season. The generalised NWN increase together with low water availability for irrigation will challenge the feasibility of maintaining grapevine production in the study area if no adaptations are implemented. Moreover, a general advancement and shortening of the growing cycle and changes in temperature during ripening affecting grapevine quality were estimated at both CC scenarios RCP 4.5 and RCP 8.5. These results represent a baseline to simulate adaptation strategies to design a resilient vineyard and support the decision-making in the Mediterranean region to ensure economic profitability and environmental maintenance. Future research should therefore look more closely at different space-time scales, to improve grapevine adaptation in the study area.

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