Mitig Adapt Strateg Glob Change (2024) 29:52
https://doi.org/10.1007/s11027-024-10146-0

ORIGINAL ARTICLE

Climate change impact on Mediterranean viticultural regions and site-specific climate risk-reduction strategies

João Prada[1,2,3,4,5] · Lia-Tânia Dinis[1,2,6] · Elia Soriato[7] · Elodie Vandelle[7] · Oğuzhan Soletkin[8] · Şener Uysal[9] · Abdelhi Dihazi[10] · Conceição Santos[3,4] · João A. Santos[1,2,6]

Received: 4 August 2023 / Accepted: 2 June 2024 / Published online: 9 July 2024

Abstract
The global increase in extreme weather and climate events may dramatically impact agriculture, food safety, and socioeconomic dynamics. The Mediterranean basin is already exposed to extreme climatic events, severely challenging viticulture, a pivotal Mediterranean agro–industry. This study aims to understand better how climate is expected to evolve in six viticulturally important Mediterranean regions in Portugal, Italy, Turkey and Morocco, using a 4–member ensemble of climatic model projections under Representative Concentration Pathways (RCP) 4.5 and 8.5 for 2041–2070, and using the 1981–2010 period as a baseline. By comparing the main specific challenges these locations will face, we comparatively define the best strategies to reduce the impacts of climate change at the national and regional levels. Projections show increases in overall temperatures, up to + 3.6°C than the historical baseline, whilst precipitation projections indicate decreases that could reach 36% of the overall annual precipitation. Biological effective degree days, consecutive dry days, growing season length, tropical nights, or very heavy precipitation days, also show challenging prospects for viticulture in these countries. A screening of the adaptative strategies already undertaken in the studied countries suggests that growers are taking reactive rather than preventive strategies. Moreover, the discussion of the most suitable strategies in this study is region–specific, i.e., prioritised by the specific needs of each location. The conclusions drawn herein may support local growers, improving their decision–making based on the most adequate adaptive strategies to their conditions, thus optimising their sustainable production under changing climates.

Keywords Mediterranean viticulture · Grapevine protection · Climate change impacts · Climate risk–reduction · Site–specific adaptation · Comparative assessment

1 Introduction

Climatic projections indicate that significant modifications are expected, regarding temperature, precipitation, and frequency of extreme weather phenomena. In the Mediterranean basin, the climate is mainly divided into two seasons, with cool, temperate, wet winters, and hot, dry summers (Seager et al. 2019). This region is being classified as a hotspot of climate change, with critical

Extended author information available on the last page of the article

data reporting extremely long periods of dryness, and increasing temperatures, meaning that Mediterranean agriculture, and food safety and security, are endangered (del Pozo et al. 2019).

Viticulture is an ancient agricultural activity in the Mediterranean, with wine and table grapes being some of its most distinctive products, and a trademark of its landscape and environment. Furthermore, viticulture production engages agrotourism, thus promoting even further local economy and social development (Caldas and Guedes 2015). The most productive Mediterranean countries in terms of winemaking and exportation include Spain, France, and Italy (Droulia and Charalampopoulos 2021; Santos et al. 2020). Mediterranean viticulture has a high value due to its production regions' characteristics, and several factors contribute to it. The dynamic, yet fragile balance between the combination of climatic traits, topography, soil structure, water/nutrient availability, the genetic specificity of local grapevine varieties/rootstocks, and cultural practices conceive the *terroir* concept (Blotevogel et al. 2019; Czigány et al. 2020; Ricardo-Rodrigues et al. 2019).

Grapevine (*Vitis vinifera* L.) growth and development, physiological processes, and plant yield and quality are influenced by macro–, meso– and microclimate, and variations in climate allow the production of wines with different characteristics (Fraga et al. 2014). The grapevine vegetative cycle is highly controlled by temperature, which governs the cycle, including the harvesting time (Santos et al. 2020). The optimal temperature for the vineyard growing season commonly varies between 12°C and 24°C, and temperatures that fall over this interval can damage vines, mainly by causing heat stress and harming productivity (Santos et al. 2020). Furthermore, temperatures outside these values can alter the plant's cycle, namely the duration of phenological stages and product quality (Dinu et al. 2021; (Droulia and Charalampopoulos 2022).

Water availability is another important factor, concerning viticulture management. Precipitation is, therefore, one of the most important atmospheric conditions for vineyard productivity, yield and product quality, as its scarcity might determine/endanger the outcomes of the cycle, such as budburst, and shoot/inflorescence development. Furthermore, the lack of hydric resources during the cycle can cause reduced morphological growth, limited photosynthetic activity, and diminished cluster production (Santos et al. 2020). However, some studies revealed that a controlled water deficit can improve wine flavour and aroma, by increasing terpene, anthocyanin, and phenol contents (Deluc et al. 2007; Savoi et al. 2016). Excessive precipitation is another issue, as it promotes plagues and diseases, especially fungi, due to the overgrowth of plant tissue and favourable weather conditions, such as higher relative humidity and increased water availability (Martínez-Bracero et al. 2020). Moreover, excessive precipitation can inclusively decrease grape and wine composition and quality, mainly due to sugar dilution in berries (Reynolds and Naylor, 1994).

The Mediterranean territory is already suffering from several difficulties linked to climate change, such as aggressive droughts, increasing extreme weather events, and high temperatures and irradiance. *The* projections indicate that the Mediterranean region's warming will be 25% more aggressive than the global mean (Giorgi and Lionello, 2008; Lionello and Scarascia 2018) and a shortage of water availability, mainly due to decreased precipitation and increased temperatures (Lionello and Scarascia 2018). Projections also indicate an intensification of interannual climatic variability, a continuing rise of extreme event frequency, and a reduction of suitable areas for traditional crop production and, consequently, for agricultural production as a whole (Grasso and Feola 2012).

These projections are challenging for viticulture sustainability, as climate change may transform viticulture and winemaking (Santillán et al. 2019). The abovementioned expected increasing temperatures in the Mediterranean basin can negatively impact grapevines, such as by decreasing plants' productivity due to a more erratic budbreak (Dinu et al. 2021), by anticipating the vegetative cycle and accelerating the accumulation of sugar in berries (Sadras and Moran 2013), by decreasing pollen grain viability (Pereira et al. 2014) and by decreasing water availability, due to strengthened evapotranspiration. Furthermore, as a decrease in precipitation is projected for the region, water availability per se will already be diminished. The impacts of a decrease in water availability may be threatening, as it decreases net photosynthesis and CO_2 assimilation, promotes stomatal closure, and lowers the yield, and total biomass (Flexas et al. 1998; Zsófi et al. 2009; Zufferey et al. 2017). However, it is also understood that mild drought stress can be beneficial to wine quality, as it enhances the production of secondary metabolites, such as anthocyanins and phenols, and promotes higher sugar concentration, improving their distinctive flavour and aroma (Zufferey et al. 2017; Drori et al. 2022).

Despite the climate change scenarios and their potential impacts on viticulture, producers have, generally, undervalued the necessity to search for and implement adaptation strategies, that could reduce climate change impacts and risks on their yields and product quality (Santillán et al. 2020). Furthermore, as is suggested, the process of developing better adapted vineyards to climate change is more demanding than other crops, as it is normally projected for decades of production, and as slight modifications could have a significant impact on both yield and quality, meaning that adaptations should be thoroughly projected.

This work aims to compare a climate projection defined for several Mediterranean regions in Portugal, Italy, Turkey, and Morocco, to understand how climate is expected to evolve, and how climatic variability is accentuated within the Mediterranean basin. An assessment of climate change impacts on viticulture in these locations, regarding the severity of the projections and the stage of strategy adoption by growers reacting to climate change prospects, will also be performed, by comparing climate projections with the information obtained by the expertise of the PRIMA VineProtect consortium, and their direct contacts with growers from each region. We also aim to use the results from those projections, and the obtained information regarding the ongoing strategies in those regions to discuss the better fitting adaptations, and promote knowledge exchange, with both the scientific community and growers, contributing to the capacity building of the growers of these regions.

2 Materials and Methods

2.1 Description of Mediterranean viticulture regions under study

Vineyards from six Mediterranean regions, namely in Portugal, Italy, Turkey, and Morocco were considered. These regions have been selected because they are the object of a study conducted by the consortium of the PRIMA "VineProtect" project (https://vineprotect–prima.com/). Their description is summarised in Table 1, and their location in each country is shown in Fig. 1:

2.2 Climatic data collection and analysis of agronomic parameters

Agroclimatic indicators (Nobakht et al., 2019) from the COPERNICUS Climate Data Store were obtained (0.5^0 latitude × 0.5^0 longitude resolution), as described in Table 2. The presented data represent an average of the values of each indicator for the grid containing each of the analysed locations of the PRIMA VineProtect project's vineyards. Regarding Vila Real, the selected grid was the 7°30'W – 8°0'W, 41°0'N – 41°30'N. Considering Foz Côa, the selected grid was the 7°0'W – 7°30'W, 41°0'N – 41°30'N. Verona's climate was analysed recurring to the 11°30'E – 11°'0'E, 45°0'N – 45°30'N grid. For the two Turkish regions, Aegean Sea–near and Alasehir, the analysed grids were 27°30'E – 27°0'E, 38°0'N

Table 1 Identification of the selected regions for the climatic and adaptation strategies analysis

Countries	Regions	Sub–regions	Main varieties	Climate	References
Portugal	Douro Demarcated Region	Vila Real and Foz Côa	Touriga–Nacional, Touriga–Franca, Tinta–Roriz	Warm and dry summers, cool and wet winters	(Instituto dos Vinhos do Douro e do Porto 2024)
Italy	Demarcated Region of Veneto	Verona	Corvina, Corvinone, Rondinella, Glera	Temperate humid climate, with warm summers and cool winters	(Onofri et al. 2018; Italian Wine Central 2023)
Turkey	Aegean Viticultural Region	Aegean Sea–near and Alasehir	Kalecik Karasi, Bornova Misketi, Syrah, Merlot, Cabernet Sauvignon	Hot summers, amene winters	(Wine–Searcher 2021)
Morocco	Marrakech	Marrakech	Italia, Cinsaut, Muscat d'Alexandrie	Hot and dry climate, influenced by the Saharan desert	(wein.plus 2022)

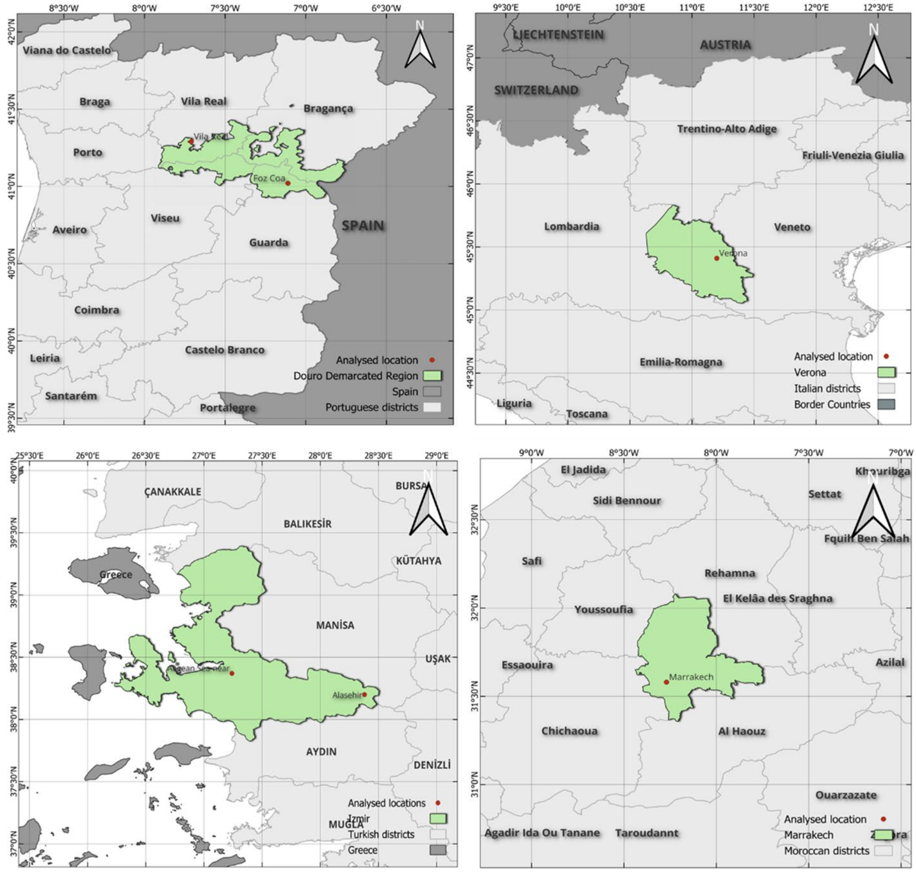

Fig. 1 Geospatial location of the analysed regions regarding their climatic characteristics and their viticulture adaptation strategies to climate change

– 38°30’N and 28°30’E – 28°0’E, 38°0’N – 38°30’N, respectively. Finally, the analysed Moroccan region of Marrakech is in the 8°0’W – 8°30’W, 31°30’N – 32°0’N grid.

A 30–year average of the ERA–Interim reanalysis (observed data) for each agroclimatic indicator, in the 1981–2010 period, was used as a baseline. For the climate projections, four predictive models with yearly mean values, for each analysed parameter, were used, namely the MIROC–ESM–CHEM Model (JAMSTEC, Japan), the IPSL–CM5A–LR Model (IPSL, France), the HadGEM2–ES Model (UK Met Office, UK), and the NorESM1–M Model (NCC, Norway). A 4–model ensemble, also with yearly mean values, was selected for the historical period 1981–2010 and the simulated data was compared to the corresponding observational ERA–Interim reanalysis. The difference between them was subsequently subtracted from the yearly mean ensemble projections for the 2041–2070 period. This bias correction methodology is critical to ensure consistency between simulated and observed data.

In this analysis, data collected from the four Representative Concentration Pathways (RCP) 4.5 and 8.5 models were retrieved, and their respective ensembles were corrected. The selection of RCPs for this work was based on the consensus that they have among the scientific community and their utility in climate projections. In RCP4.5, projections are

Table 2 Agronomic indicators analysed for each region, abbreviations, units, and explanation of the indicators analysis;

Agronomic Indicators	Abbreviation	Units	Indicator Information	Impact on grapevine	Mathematical formulation/explanation
Annual Precipitation Sum	AnnP	mm	The sum of the precipitation occurrence in one year	Provides information on water shortage or excess	$RR_{ij} = \sum_{i=1}^{I} RR_{ij}$, being RR the volume, in mm, of precipitation at day i of period j
Mean of Maximum Daily Temperature	MaxT	°C	The yearly mean of the maximum daily temperature	Provides information on long-term climate variability and change	$TX_j = \frac{\sum_{i=1}^{I} TX_{ij}}{I}$ Being TX_{ij} the daily maximum temperature at day i of period j
Mean of Minimum Daily Temperature	MinT	°C	The yearly mean of the minimum daily temperature	Provides information on long-term climate variability and change	$TN_j = \frac{\sum_{i=1}^{I} TN_{ij}}{I}$ Being TN_{ij} the daily minimum temperature at day i of period j
Biological Effective Degree Days	BEDD	°C	The yearly sum of the daily mean temperatures comprised between 10°C and 30°C	Determines a crop's development stages/rates: Shows deceleration/acceleration of the grapevine cycle	$BEDD = \sum_{i=1}^{I} \min\left[\max\left[TG_{ij} - T_{low},0\right], T_{high} - T_{low}\right]$ Being $T_{high} = 30°C$ and $T_{low} = 10°C$
Growing Season Length	GSL	days	Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after july 1st of at least 6 consecutive days with mean temperature < 5°C	Provides an indicator of whether a crop or a combination of crops can be sown and subsequently reach maturity within a certain time frame	GSL is the number of days between the first occurrence after 1st January (1st July in southern hemisphere) of at least 6 consecutive days with: $TG_{ij} > 5°C$ and the first occurrence after 1st July (1st January in southern hemisphere) of at least 6 consecutive days with: $TG_{ij} < 5$ °C, being TG_{ij} be the mean temperature at day i of period j
Consecutive Dry Days	CDD	days	The longest period in a year of consecutive <1mm of precipitation days	Drought monitoring, drought damage indicator	Largest number of consecutive days where: $RR_{ij} < 1$ mm, being RR the volume, in mm, of precipitation at day i of period j

Table 2 (continued)

Agronomic Indicators	Abbreviation	Units	Indicator Information	Impact on grapevine	Mathematical formulation/explanation
Tropical Nights	TropNights	days	Number of days with minimum temperature >20°C	Provide an indication of the occurrence of various pests	$TN_{ij} > 20°C$, Being TN_{ij} the daily minimum temperature at day i of period j
Very Heavy Precipitation Days	VHPD	days	Number of days with precipitation >20mm	Provides information on crop damage and runoff losses	$RR_{ij} \geq 20$ mm, being RR the volume, in mm, of precipitation at day i of period j

moderate, in which it is predicted that, by 2100, the radiative forcing level will increase and stabilize at 4.5 W/m^2 (Science On a Sphere 2013). In this scenario, it is expected a rising in global mean temperature, reaching, in 2100, +1.7 to +3.2°C. RCP4.5 implies that the emissions from fossil fuels and cement start declining around 2040, establishing the CO_2eq in the atmosphere at the interval of 580–720 ppm. RCP8.5 represents the most serious and worrying projection, in which, until 2100, is projected that the radiative forcing level will reach 8.5 W/m^2. RCP8.5 projects a range of increased temperatures for 2100 of around 3.2–5.4°C. However, this scenario projects that fossil fuel and cement emissions will start decelerating only around 2060, though continuing to increase until 2100, projecting that the CO_2eq in the atmosphere will be higher than 1000 ppm (Climate Nexus 2019).

2.3 Data on grapevine physiological responses to stress

Concerning the analysis of grapevine physiological responses to climatic–based stresses, literature revision was performed based on peer–reviewed journal articles using relevant keywords in our search, such as *grapevines*, *Vitis vinifera*, *climate change*, *drought stress*, *heat stress*, and *Mediterranean viticulture*. The review of the main effects was focused on the type of stress applied/induced, plant responses regarding physiological activity, yield, fruit quality, varieties involved in the work, location, and the corresponding authors.

2.4 Data on implementation of adaptation strategies

The analysed adaptation strategies were compiled based on literature revision on peer–reviewed journal articles using relevant keywords in our searches, such as *climate change*, *viticulture*, *Mediterranean*, *adaptation strategies*, and on entities' official documents related to viticulture and agriculture, such as the MedECC report (2020), Turkey's climate change policy, legal and institutional framework (2019), Moroccan Country Climate and Development Report (2022), and European Union's Common Agriculture Policy (2023–27) and European Green Deal (Agriculture and Rural Development 2021). The information on the ongoing adaptation strategies in the field was obtained through literature revision, the knowledge and experience of the PRIMA VineProtect's experts in their respective regions, and direct contact with local producers (at least one per region). This information gathering allowed the identification of several adaptation strategies, including cultural adaptations, water usage and dynamics, and soil management techniques in viticulture, allowing the definition of several short– and long–term adaptation strategies (Table 3).

The suitability of these strategies and information on the stage of implementation were gathered. This analysis comprised literature revision and the knowledge of the PRIMA VineProtect's experts in each region, obtained by their experience in past works and by direct contacts with local growers and agents related to the grapevine value chain of each country. A score from 1 – *Hardly ever used* to 5 – *Very frequently* used was attributed to the level of their awareness about the frequency of the application of each adaptation strategy in their regions.

2.5 Statistical analysis

Climate data transformation and projections presented in this work, namely the yearly means of the ERA–Interim reanalysis, and the 4–model ensemble for the 1981–2010 and 2041–2070 periods were performed using specifically written Python codes. The historical baseline data,

Table 3 List of adaptation strategies in viticulture to mitigate climate change

Long–term adaptations	References	Short–term adaptations	References
Change in training systems	(Pieri and Gaudillère 2003)	Smart irrigation	(Du et al. 2008; Koech and Langat 2018)
Diminish inter–row length	(Santos et al. 2020)	Conventional irrigation	(Koech and Langat 2018)
Vineyard relocation	(Santos et al. 2020)	Hydrogel application	(Maienza et al. 2017; Uysal et al. 2023)
Use of heat–tolerant grapevine varieties	(Morales-Castilla et al. 2019)	Leaf management	(Molitor et al. 2011; Hed et al. 2015)
Adaptation of vineyard's spatial orientation	(Grifoni et al. 2008)	Anticipate harvesting	(Santos et al. 2020)
Use of more resistant rootstocks	(Frioni et al. 2020)	Sunscreen application	(Dinis et al. 2016; Bernardo et al. 2021)
		Microorganism application	(Vimal et al. 2017)
		Organic compost application	(Novara et al. 2011)
		Mulching	(Helder and João 2018; Burg et al. 2022)
		Use of shadow nets	(Serat and Kulkarni 2013; Basile et al. 2015)
		Use of cover crops	(Gattullo et al. 2020)
		Herbicide use	(Santos et al. 2020)

for the 1981–2010 period, was obtained by calculating an average of the database of each analysed parameter. For the projections, the 4–model ensemble values were calculated by averaging their values for 1981–2010, and the differences to the observed values for the same period were subsequently calculated (bias correction). Then, this same difference was subtracted from the 4–model ensemble of the climatic data projections for the 2041–2070 period. The Principal Component Analysis (PCA) presented in this work was carried out using IBM SPSS Statistics®, version 29.0.0.0.

3 Results

3.1 Climatic historical data of the selected Mediterranean regions

Several climatic parameters for the 1981–2010 period were collected and analysed for the six regions. As shown in Table 4, differences are observed between these regions, including within the same country, namely on both annual precipitation sum and temperature indices, but also in some of the remaining parameters. These climatic differences are shown in the ombrothermic diagrams of Figs. 2, 5, 8, and 11, and in Table 4.

3.2 Portuguese regions

3.2.1 Climatic analysis of the 1981–2010 baseline period

The observed climatic differences between Vila Real and Foz Côa show that, though aggregated to the same demarcated region, grapevine physiology, and the adopted viticultural practices, must be distinguished. Foz Côa, has ~40% less mean precipitation than Vila Real. This is reinforced by CDD, which is 14 days longer in Foz Côa. The analysis highlighted that not only the sum of total precipitation is lower in the Côa Valley, but also the frequency of rainy days, which is also shown by the analysis of VHPD, in which Vila Real has a historical mean of 11.8 days/year, while Foz Côa shows only 3.9 days/year. All these described climatic differences are corroborated by the ombrothermic diagrams in Fig. 1, which shows the average monthly rainfall and temperature data, and where it is observable that Foz Côa (Fig. 2B) has a longer and more prominent dry season, when compared to Vila Real (Fig. 2A).

Furthermore, BEDD indicates that Foz Côa vineyards have a higher accumulated vegetative–growth favourable degrees, meaning that the grapevine vegetative cycle is premature in this area, compared to Vila Real vines. Moreover, the average daily temperature range for the 1981–2010 period is relatively higher in Foz Côa, displaying hotter days (+ 0.53°C) and colder nights (– 0.09°C). The lower mean minimum temperature in the Côa Valley together with the slightly higher number of tropical nights suggests that winter temperatures are more rigorous in Foz Côa. GSL values also show that temperatures in Vila Real are slightly more favourable to the plant vegetative cycle, as it has approximately 5 more days in this parameter than Foz Côa, likely due to the low temperatures that the Côa region normally reaches during winter.

3.2.2 Climatic analysis of the projections for 2041–2070

Climate projections in Foz Côa (Fig. 3) show a clear aggravation of the climatic scenario for the region. On one hand, minimum and maximum temperatures will rise, approximately

Table 4 Average values of different climatic parameters in several important Mediterranean viticulture regions, for the 1981–2010 historical period; Data source: ERA–Interim Reanalysis, Agroclimatic indicators, Copernicus Climate Data Store

Country	Region	AnnP (mm)	MaxT (°C)	MinT (°C)	BEDD (°C)	GSL (days)	CDD (days)	TropNights (days)	VHPD (days)
Portugal	**Vila Real**	1068.2	17.7	7.2	4492.4	346.6	82.1	0.33	11.8
	Foz Côa	656.4	18.2	7.1	4583.8	341.9	96.2	0.57	3.9
Italy	**Verona**	797.9	17.3	8.2	4674.6	277.1	75.2	11.2	7.1
Turkey	**Aegean Sea**	761.9	22.3	11.8	6174.5	363.7	110.2	45.0	9.9
	Alasehir	564.9	21.1	8.6	5394.2	338.4	128.0	5.1	4.0
Morocco	**Marrakech**	250.3	23.5	13.8	7096.3	365.2	184.8	52.3	1.3

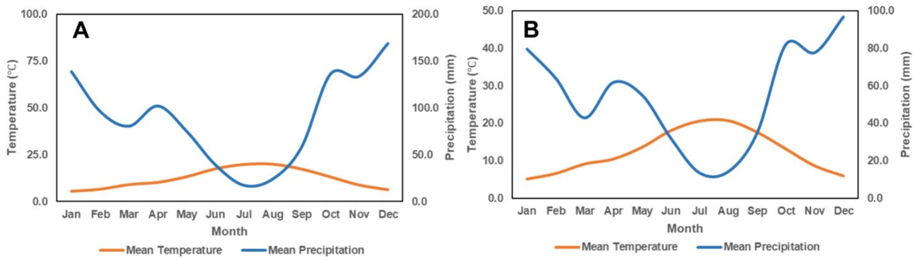

Fig. 2 Ombrothermic diagrams of the historical period 1981–2010; **A** – Vila Real; **B** – Foz Côa; Mean precipitation (mm) – blue line; Mean temperature (°C) – orange line

1.5°C and 2.0°C, respectively, for the RCP4.5 scenario, and 3.0°C and 4.0°C, respectively, for the RCP8.5 scenario. On the other hand, precipitation will decrease at an average of approximately 5% and 10% in the RCP4.5 and the RCP8.5 scenarios, respectively. This decrease in AnnP is also reinforced by CDD, showing an increase in consecutive days without precipitation in both RCPs. These decreases may aggravate the biggest problem in this viticulture region, i.e. the lack of water resources.

Foz Côa region is, therefore, an accurate example of the impacts that climate change will have on the Mediterranean region, with a devastating increase in temperatures, in an already warm *terroir* during summer, and a decrease in precipitation, in an already drought–stressed region. Projections of the other parameters, namely BEDD, TropNights and VHPD, corroborate the aggravation of the climatological conditions in the Côa Valley. Huge increases in BEDD, which could be more than 1200°C by 2070 (+ 27.5%) in the worst–case scenario, as well as in TropNights, from 0.57 to approximately 22, by 2070, in the worst–case scenario, are expected, whilst VHPD remain close to the historical period values.

Vila Real projection dynamics are very similar to those of Foz Côa, being expected a general aggravation of climatic conditions (Fig. 4). It is expected an average increase in MinT and MaxT of 1.9°C and 2.5°C respectively, in the RCP4.5 scenario, and 2.9°C and 3.9°C in the RCP 8.5 scenario. Precipitation projections for Vila Real show a decrease in AnnP for both climate scenarios. The RCP4.5 model estimates a decrease of approximately ~8% in AnnP, which reaches ~11.5% in RCP8.5, for the 2041–2070 period. CDD projection shows an increase in the number of days without precipitation, meaning a decrease in terms of both volume and frequency. Furthermore, projections for the remaining studied parameters show an increase in BEDD, which could reach 20% in the worst–case scenario, but mainly in TropNights, whose change is dramatic, with a possible increase of ~2180% (in RCP8.5). However, in Vila Real, VHPD is expected to remain stable, corroborating the idea that precipitation days will be less frequent, as it will be concentrated on specific days with precipitations above 20mm.

3.3 Italian region of Verona

3.3.1 Climatic analysis of the 1981–2010 baseline period

As observed in Fig. 5, Verona has an interesting temperature amplitude, associated with a stable precipitation throughout the year, as the ombrothermic diagram in Fig. 5 shows that Verona has annual wet seasons.

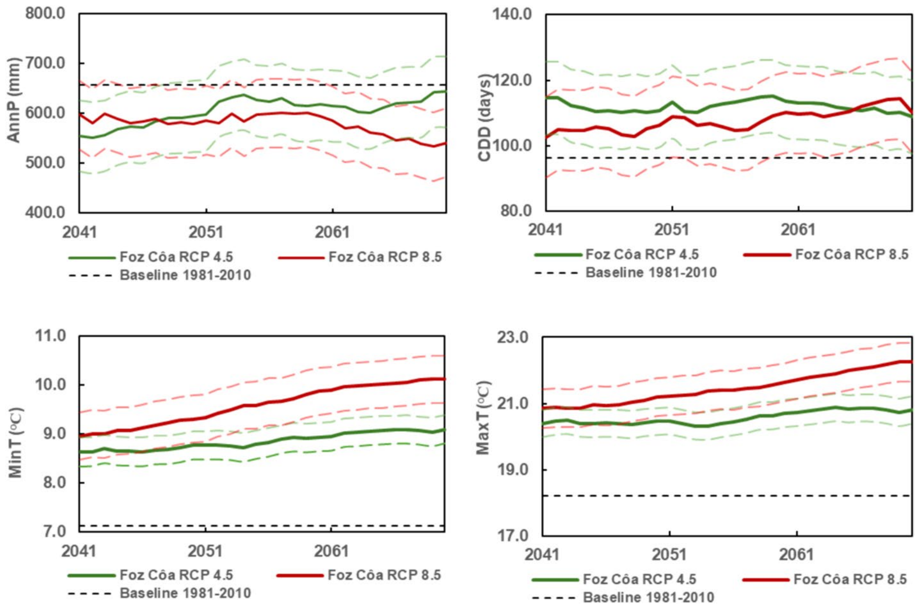

Fig. 3 Climatic parameter projections for Foz Côa, with the bias corrected 4–model ensemble for the 2041–2070 period; MinT: annual mean of minimum temperatures (°C); MaxT: annual mean of maximum temperatures (°C); AnnP: annual precipitation sum (mm); CDD: longest annual period of consecutive days with less than 1mm in precipitation (days); RCP4.5 (green, with standard deviation in dashed green), RCP8.5 (red, with standard deviation in dashed red); Mean value of 1981–2010 period "Baseline" (dashed black line)

Furthermore, Verona's temperate climate is interesting for viticulture, which is shown by the results for BEDD and GSL in the historical period. BEDD in Verona is higher than in both Portuguese regions, mainly due to higher temperatures in summer months. Moreover, mean temperatures in winter months are lower than in the Douro Demarcated Region, which is also positive for the dormancy period of Verona's grapevines. However, annual MinT is higher in Verona, meaning that thermic amplitude is also more prominent throughout the year. The periods without rain are relatively small, as shown by both CDD value and the stability of the mean precipitation in Fig. 5, but the frequency of tropical nights is relevant.

3.3.2 Climatic analysis of the projections for 2041–2070

Climatic projections for Verona indicate an aggravation of the main parameters (Fig. 6).

Climate change is expected to impact mainly on temperatures, according to the significant increases of MinT and MaxT mean values, estimated to be by 2.3–3.0°C and 2.6–3.3°C, respectively, for the 2041–2070 period. Regarding AnnP, projections do not indicate significant variations, while the CDD parameter is expected to increase slightly, likely reaching up to 5 days/year, thus indicating a decrease in the frequency of rainy days. This is further supported by the slight increase in VHPD. On the other hand, BEDD and GSL tend to increase significantly, suggesting an anticipation of the vegetative cycle. TropNights also show dramatic increases, up to 474% in the RCP8.5 scenario.

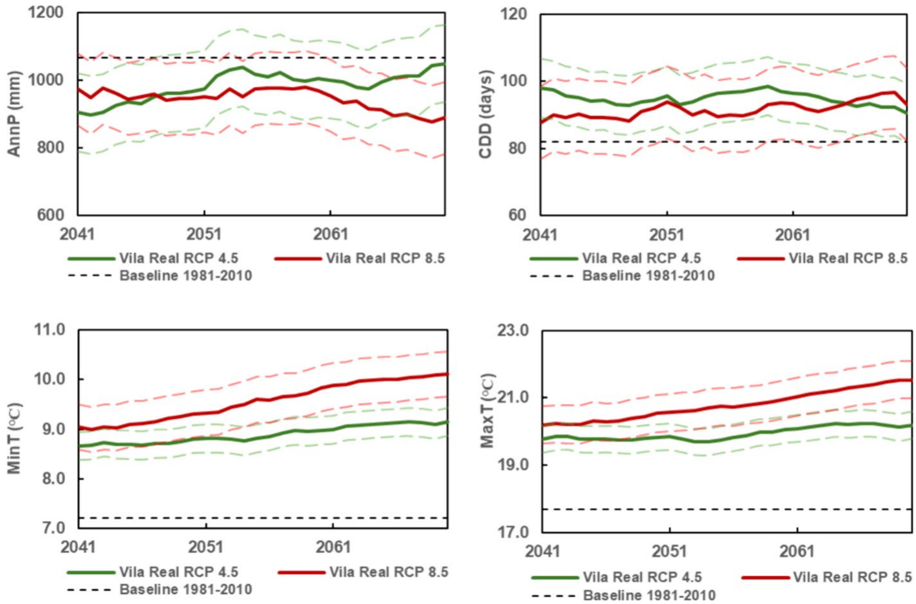

Fig. 4 Climatic parameter projections for Vila Real, with the bias corrected 4–model ensemble for the 2041–2070 period; MinT: annual mean of minimum temperatures (°C); MaxT: annual mean of maximum temperatures (°C); AnnP: annual precipitation sum (mm); CDD: longest annual period of consecutive days with less than 1mm in precipitation (days); RCP4.5 (green, with standard deviation in dashed green), RCP8.5 (red, with standard deviation in dashed red); Mean value of 1981–2010 period "Baseline" (dashed black line)

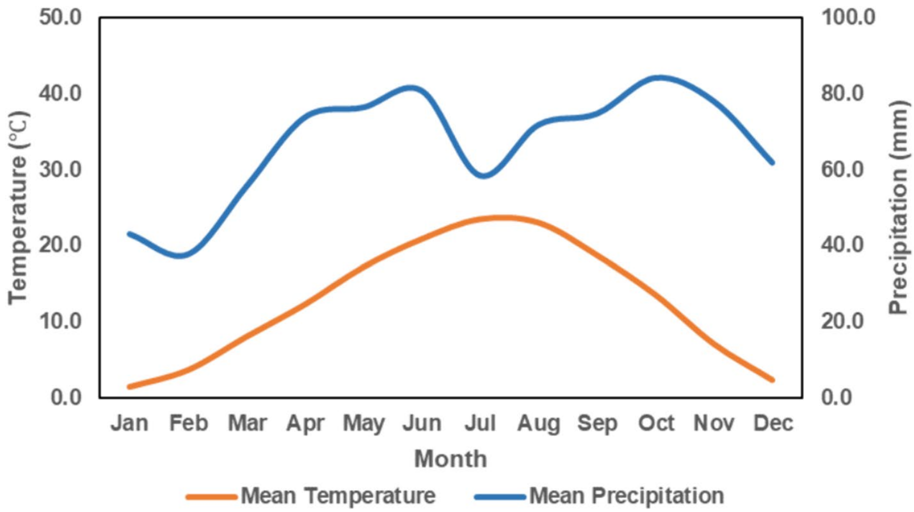

Fig. 5 Ombrothermic diagram of the historical period 1981–2010 in Verona; Mean precipitation (mm) – blue line; Mean temperature (°C) – orange line

3.4 Turkish regions

3.4.1 Climatic analysis of the 1981–2010 baseline period

Since Turkish–selected vineyards are at a considerable distance from each other, although belonging to the Aegean viticulture region, important climatic differences are expected. The Aegean Sea–near area, due to sea proximity, has historically a wetter climate than the Anatolian plateau region, differing in more than 100 mm of precipitation per year. However, in both regions, AnnP is relatively low, which could already raise some concerns about water supply to vineyards. CDD is, therefore, normally higher in Alasehir, with historical mean values 18 days/year higher than in the Aegean Sea–near region. These regions display different temperatures, higher in the Aegean Sea–near region, + 3°C in MinT and + 1.2°C in MaxT, compared to Alasehir. BEDD in the Aegean Sea near region is significantly higher than in Alasehir (6174.5°C and 5394.2°C, respectively).

The above–described data is corroborated by the ombrothermic diagrams of Fig. 7, which show that these two Turkish regions have some variation in their seasonal climatic dynamics, having considerable dry seasons and noticeable wet seasons. However, it is possible to observe that in the Aegean Sea–near region (Fig. 7A) these two seasons have smaller amplitudes, with a softer dry season and a more humid wet season, than Alasehir (Fig. 7B).

GSL is also higher in Aegean Sea–near region, approximately + 30 days/year than in Alasehir, but the main difference, in all analysed parameters, is TropNights, which is much more

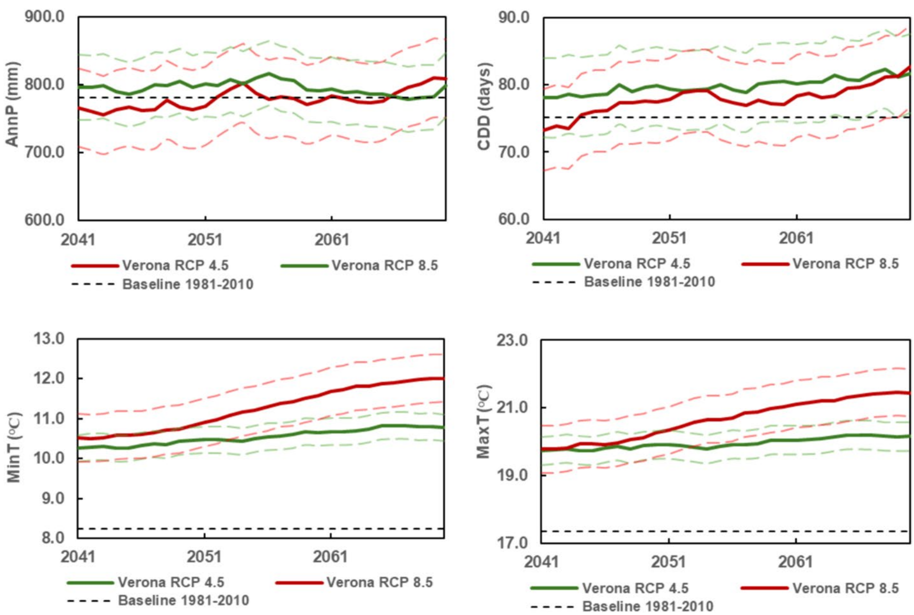

Fig. 6 Climatic parameter projections for Verona, with the bias corrected 4–model ensemble for the 2041–2070 period; MinT: annual mean of minimum temperatures (°C); MaxT: annual mean of maximum temperatures (°C); AnnP: annual precipitation sum (mm); CDD: longest annual period of consecutive days with less than 1mm in precipitation (days); RCP4.5 (green, with standard deviation in dashed green), RCP8.5 (red, with standard deviation in dashed red); Mean value of 1981–2010 period "Baseline" (dashed black line)

frequent in the first (45.0 and 5.1 days/year, respectively). These results indicate that the grapevine vegetative cycle in the Aegean Sea–near region starts and ends earlier than in Alasehir, and grapevines have more available water, meaning that viticulture is more vulnerable in Alasehir.

3.4.2 Climatic analysis of the projections for 2041–2070

Climatic projections for the Aegean Sea–near region are challenging (Fig. 8). The projection for temperature evolution in the region shows an increase in both MinT and MaxT, whose average, for the 2041–2070 period, could be around + 2.0°C to + 2.9°C in MinT, and + 2.5°C to + 3.5°C for MaxT, comparing to the historical baseline average. In fact, in the RCP8.5 model, temperatures could even reach an average of almost 27°C for the last years of the 2060 decade. Moreover, as MinT is expected to increase, so is TropNights, which is expected to, at least, double its annual frequency. GSL should be maintained during the analysed period. This may be explained by the fact that the historical values for this parameter are already close to the maximum (363.7 days/year).

The projection for temperature evolution in the region shows an increase in both MinT and MaxT, whose average, for the 2041–2070 period, could be around + 2.0°C to + 2.9°C in MinT, and + 2.5°C to + 3.5°C for MaxT, comparing to the historical baseline average. In fact, in the RCP8.5 model, temperatures could even reach an average of almost 27°C for the last years of the 2060 decade. Moreover, as MinT is expected to increase, so is TropNights, which is expected to, at least, double its annual frequency. GSL should be maintained during the analysed period. This may be explained by the fact that the historical values for this parameter are already close to the maximum (363.7 days/year). Conversely, BEDD is expected to increase by 12.3–16.5%. These numbers are accompanied by the sustained decrease in AnnP, which is expected to diminish by 10.3–23.3%, and by the reinforcement of the decrease in precipitation frequency, with consecutive dry days increasing by 13.9–18.3 days. However, VHPD is expected to diminish by 6.5–7.0%, which will result in an overall deficit of water supply.

The projections for Alasehir are similar to the ones for the Aegean Sea region, although slightly more concerning (Fig. 9).

Both analysed parameters show an increase in minimum and maximum temperatures for 2041–2070, which vary between +2.0°C and +2.9°C for MinT, and +2.7°C and +3.6°C for MaxT, compared to the 1981–2010 mean values. Furthermore, with the increased MinT, huge increases in TropNights are expected, as the number of nights with temperatures above 20^{0}C will go up by 37.3 days, meaning an increase of 737.1%, in the RCP4.5 model, or even 58.2 days, meaning an increase of 1148% (the historical mean was 5.1 days). BEDD (15–20%), CDD (11.9–17.4%) and GSL (2.3–2.4%) will also increase, while VHPD will remain stable.

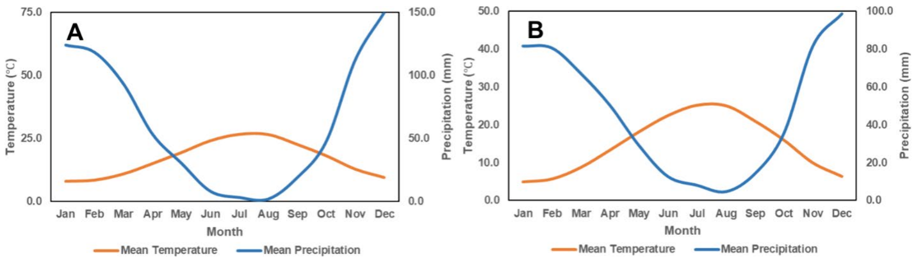

Fig. 7 Ombrothermic diagrams of the historical period 1981–2010; **A** – Aegean Sea–near; **B** – Alasehir; Mean precipitation (mm) – blue line; Mean temperature (°C) – orange line

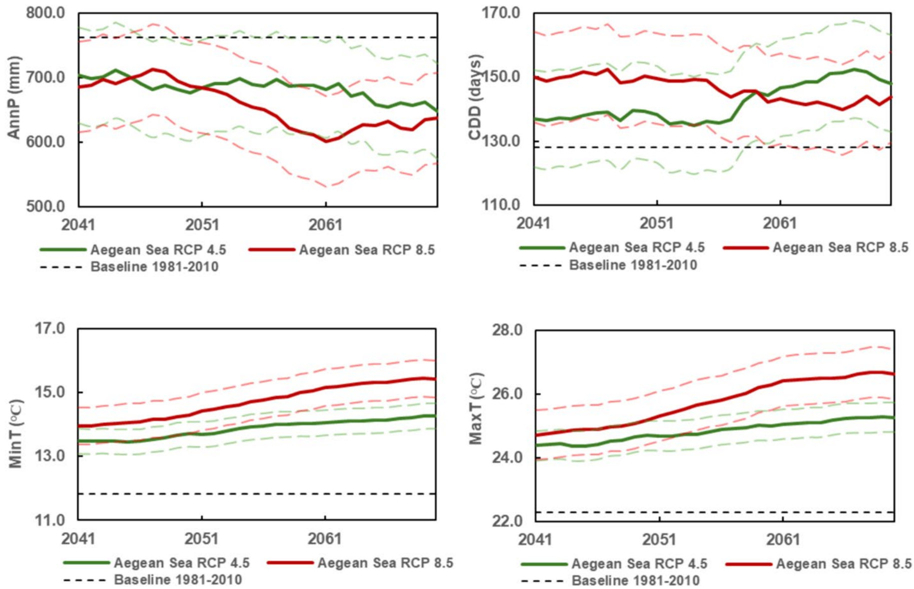

Fig. 8 Climatic parameter projections for the Aegean Sea–near regions, with the bias corrected 4–model ensemble for the 2041–2070 period; MinT: annual mean of minimum temperatures (°C); MaxT: annual mean of maximum temperatures (°C); AnnP: annual precipitation sum (mm); CDD: longest annual period of consecutive days with less than 1mm in precipitation (days); RCP4.5 (green, with standard deviation in dashed green), RCP8.5 (red, with standard deviation in dashed red); Mean value of 1981–2010 period "Baseline" (dashed black line)

3.5 Moroccan region

3.5.1 Climatic analysis of the 1981–2010 baseline period

Marrakech has the highest averages for minimum and maximum temperatures in the historical period 1981–2010, between the analysed locations, being 13.8°C and 23.5°C respectively. These values result in the highest mean values for GSL (365.2 days/year, meaning that temperatures allow grapevines to grow all year round), BEDD (7096.3°C), and TropNights (52.3 days) registered between all the analysed Mediterranean regions. Moreover, the annual precipitation sum average value for the historical period (250.3 mm) is, in fact, the most significant and limiting characteristic of Marrakech's climate. The ombrothermic diagram in Fig. 10 reinforces these data, as the dry season happens almost all year, showing that water availability is hugely scarce.

This precipitation deficit is also accompanied by a high CDD (184.8 days), whilst VHPD is considerably low (1.3 days), compared to the remaining Mediterranean regions analysed, showing that water availability all year round in this region is extremely low.

3.5.2 Climatic analysis of the projections for 2041–2070

Marrakech wine region is an important example of a Mediterranean region with severe climatic characteristics for viticulture, and a present model for what other regions could face

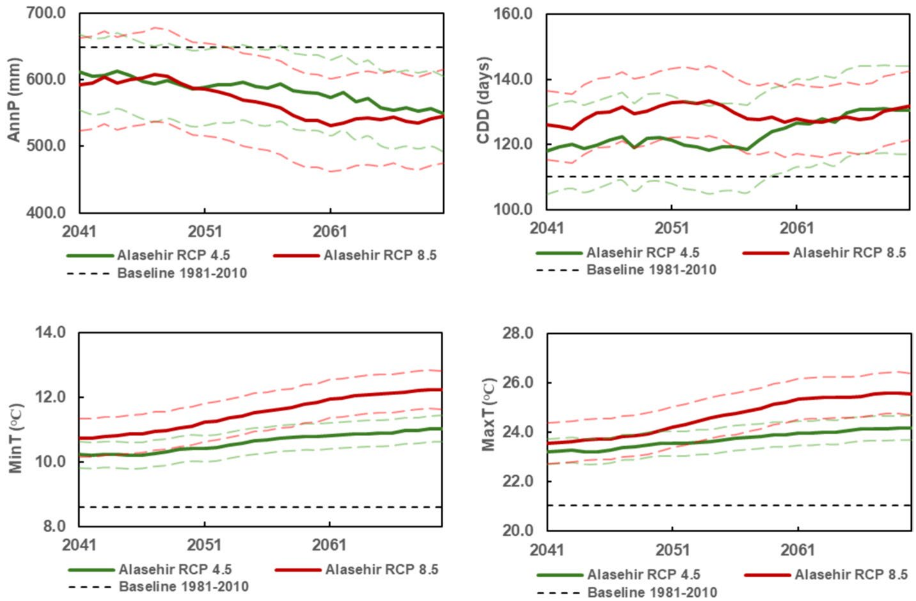

Fig. 9 Climatic parameter projections for Alasehir, with the bias corrected 4–model ensemble for the 2041–2070 period; MinT: annual mean of minimum temperatures (°C); MaxT: annual mean of maximum temperatures (°C); AnnP: annual precipitation sum (mm); CDD: longest annual period of consecutive days with less than 1mm in precipitation (days); RCP4.5 (green, with standard deviation in dashed green), RCP8.5 (red, with standard deviation in dashed red); Mean value of 1981–2010 period "Baseline" (dashed black line)

when climate change takes its course. Although, Marrakech itself has even more problematic projections, as shown in Fig. 11:

These projections show an overall increase in MinT and MaxT, for the 2041–2070 period. In RCP4.5, projections indicate changes of around + 1.7°C and + 2.2°C, for MinT and MaxT, while in RCP8.5 it is observed that temperatures could increase approximately + 2.4°C and + 3.2°C, respectively. In the worst–case scenario, the mean maximum temperature, for 2070, could reach 27.5°C. Also, with this increase in temperatures, BEDD and TropNights will increase by 9.2–12.9% and 76.4–78.5% respectively. Although projections for GSL will not have any differences from the historical period, as mean values for 1981–2010 are already the totality of the days in a year, GSL projected will also be at its maximum limit. Concerning precipitation projections, mean AnnP for the 2041–2070 period will decrease significantly, from 79.9 to 90.8mm/year, and could even reach extremely alarming values by 2070, of 122.6mm/year. With these dramatically low precipitation values, consecutive dry days will increase, from 7.5% to 8.8%, and VHPD will almost become non–existent, with values for both RCPs being less than 1 day/year.

3.6 Data on physiological impacts of climate change in Vitis vinifera varieties

The following Table provides a resume of the literature revision on the state of the art of viticulture and grapevine physiology in response to climate change's impacts, mainly drought and heat stress (Table 5).

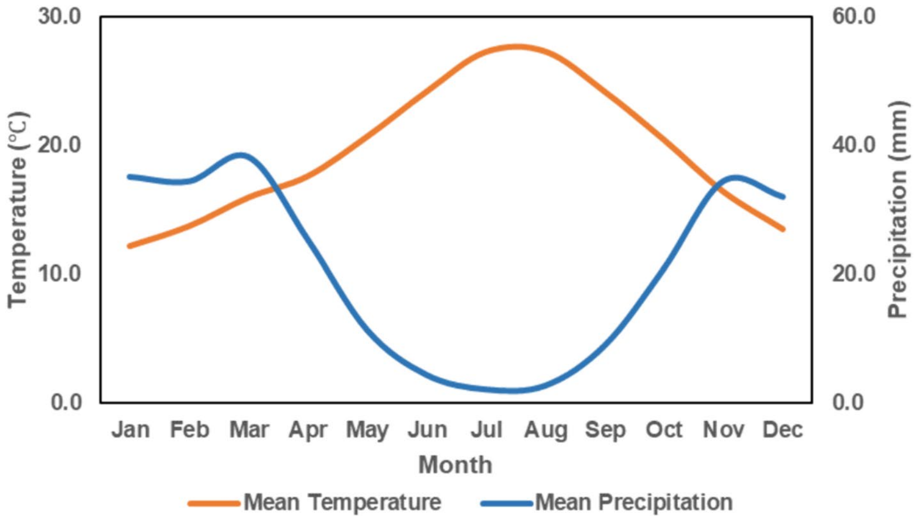

Fig. 10 Ombrothermic diagram of the historical period 1981–2010 for Marrakech; Mean precipitation (mm) – blue line; Mean temperature (°C) – orange line

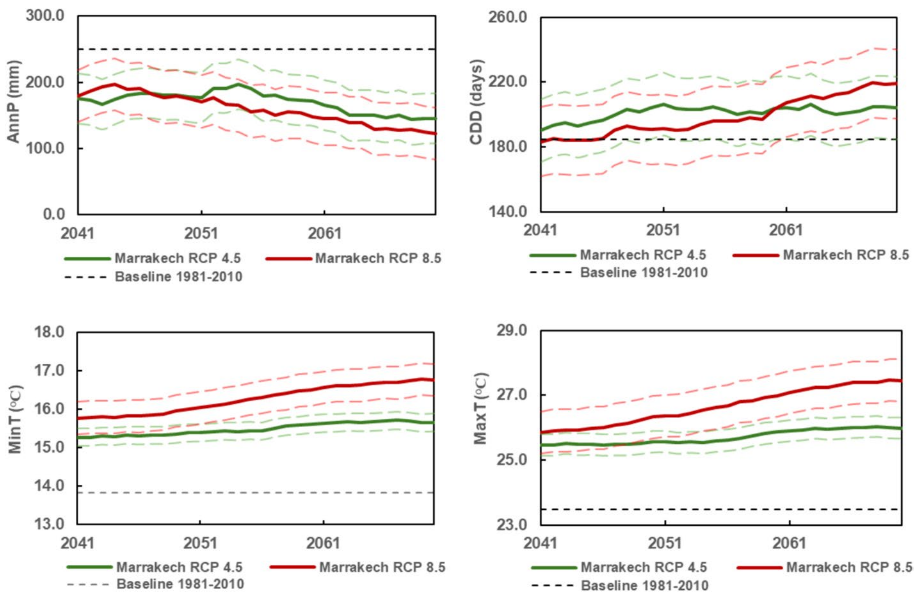

Fig. 11 Climatic parameters' projections for Marrakech, with the bias corrected 4–model ensemble for the 2041–2070 period; MinT: annual mean of minimum temperatures (°C); MaxT: annual mean of maximum temperatures (°C); AnnP: annual precipitation sum (mm); CDD: longest annual period of consecutive days with less than 1mm in precipitation (days); RCP4.5 (green, with standard deviation in dashed green), RCP8.5 (red, with standard deviation in dashed red); Mean value of 1981–2010 period "Baseline" (dashed black line)

3.7 Information collection on adaptation strategies adopted by viticulturists

The information on the stage of adoption of adaptation strategies was collected based on a systematisation approach, carried out by the PRIMA VineProtect consortium (each partner team in their respective region), considering their existing knowledge on the corresponding wine regions acquired throughout previous projects and collaborations with the regional wine sector, literature revision, and direct interaction with local growers of each region. The heatmap of Fig. 12 assembles all adaptative strategies considered in this work, and the respective use frequency, which varies from *Hardly ever* (1 – Red) to *Very frequent* (5 – Green).

The heatmap shows that the most adopted strategy, which is highly common among all analysed regions, is the use of more resistant rootstocks, followed by machine and herbicide use, and then organic compost application. On the contrary, the application of hydrogels/biochar, the implementation of cover crops, or the use of microorganism treatments are yet shortly adopted. It is also noticeable that Turkey's viticulture seems to be the one that adopts a wider range of strategies, whilst Italy seems to adopt fewer.

To further analyse the obtained data, a principal component analysis (PCA) focusing on the adaptative strategies applied by growers, and the countries associated with them, was performed (Fig. 13 and 14).

The PCA of the adaptative strategies shows that there are two major clusters, namely the short–term and the long–term strategies, which appear to be negatively correlated. This negative correlation indicates that farmers either opt for the implementation of a wide package of short–term reactive strategies, or long–term preventive ones. It is noticeable that most of the short–term strategies are highly correlated, such as sunscreen application, herbicide use, the anticipation of harvesting, the implementation of cover crops, or smart irrigation, meaning that, in the cases where farmers opt to use short–term strategies, they use a combination of them, thus being applied in a complementary approach. Moreover, through the PCA of the adaptative strategies, short–term options tend to be applied when long–term ones are not. Long–term strategies, such as the use of heat–tolerant varieties or the diminishing of interrow length, are highly correlated, meaning that these strategies can be complementarily used in a long–term adaptation scenario. Furthermore, the association of the use of more resistant rootstocks with conventional irrigation are negatively correlated with these long–term strategies.

Regarding the PCA for regions' strategies adoption, in Fig. 14, two distinctive approaches can be identified. Douro's (Vila Real and Foz Côa), Turkish, and Verona's approaches are clustered, meaning that they have similar adaptation strategies, which are predominantly short–term ones. On the other hand, Marrakech's strategies are quite different, as long–term strategies are preferred.

4 Discussion

4.1 Grapevines' physiological and phytopathological difficulties in aggravated climatic conditions

The climate scenarios for the 2041 – 2070 period may be challenging for viticulture. The projected temperatures could decrease grapevine yield, as temperatures above 30–35°C lead to heat stress, excessive water loss, and reduced photosynthesis, limiting growth and productivity, diminishing pollen viability, and causing the abortion of inflorescences, or limiting berry fruit set and size (Zsófi et al. 2009; Mira de Orduña

Table 5 Resume of the literature revision on the state of the art for grapevines' susceptibility to climate change–like abiotic conditions

Variety	Treatments	Location	Major impacts	Authors/year
Touriga Nacional	42°C for 4h	Douro Demarcated Region, Portugal	Polen grain viability decrease	(Pereira et al. 2014)
Kékfrankos	AnnP < 650mm and Mean of MaxT 20–25°C	Eger–Kolyukteto and Eger–Nagyeged, Hungary	Decrease in net photosynthesis, lower chlorophyll content, increase in xanthophyll content, lower yield	(Zsófi et al. 2009)
S, Cabernet Franc, Chardonnay	Heated (+0.7 to +1.3°C) and Controlled temperatures	Barossa Valley, Australia	Anticipation of flowering, faster sugar accumulation in berries	(Sadras and Moran 2013)
Baresana, Sprinu, Malvasia, Negroamaro	Higher temperatures during the chilling period	Salento, Italy	Anticipation of bud break, increased risk of bud frosting, decreased number of breaking buds	(Dinu et al. 2021)
Tempranillo	Drought–stressed and irrigated plants	Mallorca, Spain	Stomatal closure and no net CO2 assimilation in non–irrigated grapevines, lower photosynthesis levels	(Flexas et al. 1998)
Pinot Noir	Different irrigation regimes	Leytron, Switzerland	Drought–stressed grapevines had lower vigour, decreased gas exchange, and lower wine–quality	(Zufferey et al. 2017)
Rasheh, Bidane–Sefid	Drought–stressed and irrigated plants	Urma, Iran	Decreased stomatal conductance, net CO2 assimilation, transpiration rate, and chlorophyll a and b concentrations; Increased carotenoids, proline, and total sugars content	(Abdi et al. 2016)

Table 5 (continued)

Variety	Treatments	Location	Major impacts	Authors/year
Chardonnay. Xynisteri	Drought–stressed and irrigated plants	Limassol, Cyprus	Decreased stomatal conductance and photosynthetic rate, and increased antioxidant capacity in Xynisteri, leaf damage and increased antioxidant capacity in Chardonnay	(Tzortzakis et al. 2020)
Malvasia, Cabernet Sauvignon, Tempranillo, Grenache	Drought–stressed and irrigated plants	Mallorca, Spain	Decreased total biomass and water consumption, increased non–photosynthetic biomass	(Tomás et al. 2012)
Tempranillo	Heat–stressed and drought–stressed plants	Pamplona, Spain	Decreased biomass and leaf area (only observed in drought–stressed plants), decreased stomatal conductance	(Kizildeniz et al. 2018)

Fig. 12 Heatmap of the adoption of strategies for climate change mitigation in viticulture, in Douro (Vila Real and Foz Côa), Verona, Turkey (Aegean Sea and Alasehir) and Marrakech; Avg– Average of the strategy adoption through the four countries; 1– Hardly ever used; 5– Very frequently used

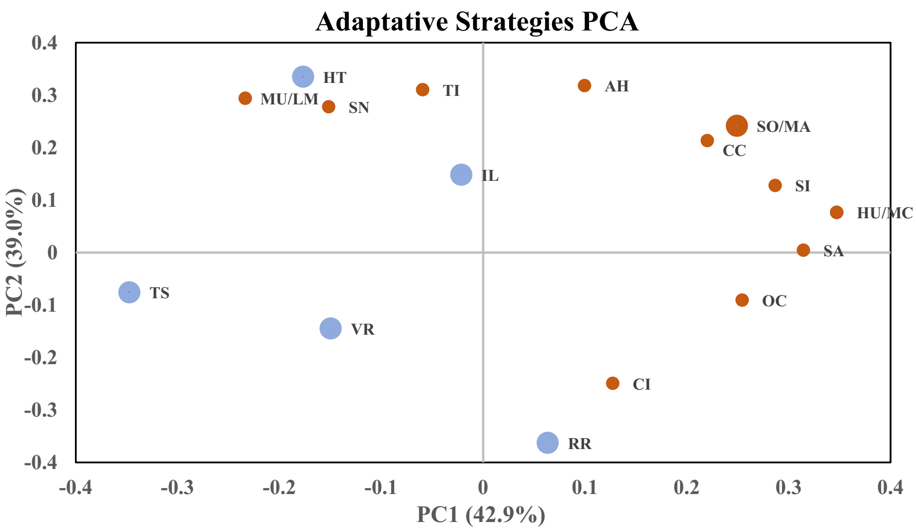

Fig. 13 Principal Component Analysis of the adaptative strategies analyzed. CC– Cover crops; MA– Microorganism application; MU– Mulching application; SI– Smart irrigation; VR– Vineyards relocation; IL– Diminish interrows length; SO– Adaptation of vineyards spatial orientation; SN– Use of shadow nets; CI– Conventional irrigation; HT– Use of heat–tolerant varieties; TS– Change in training systems; LM– Leaf management; SA– Sunscreen application; AH– Anticipate harvesting; TI– Tillage; OC– Organic compost application; HU– Herbicide use; MC– Machine use on cultivation; RR– Use of more resistant rootstocks; Short–term adaptation strategies have small orange dots in the graphic, long–term adaptation strategies have big blue dots in the graphic; SO and MA are overlapped

2010; Pereira et al. 2014), although grapevine vulnerability to heat is partially variety–dependent (Keller 2020). Increased temperatures also manipulate the grapevine vegetative cycle, anticipating their phenological stages, lowering bud break percentage, the yield and the berry quality and aroma (Mori et al. 2005; Duchêne et al. 2010; Ben Mohamed et al. 2010; Parker et al. 2011, 2013, 2020; Franck et al. 2011; Cooke et al.

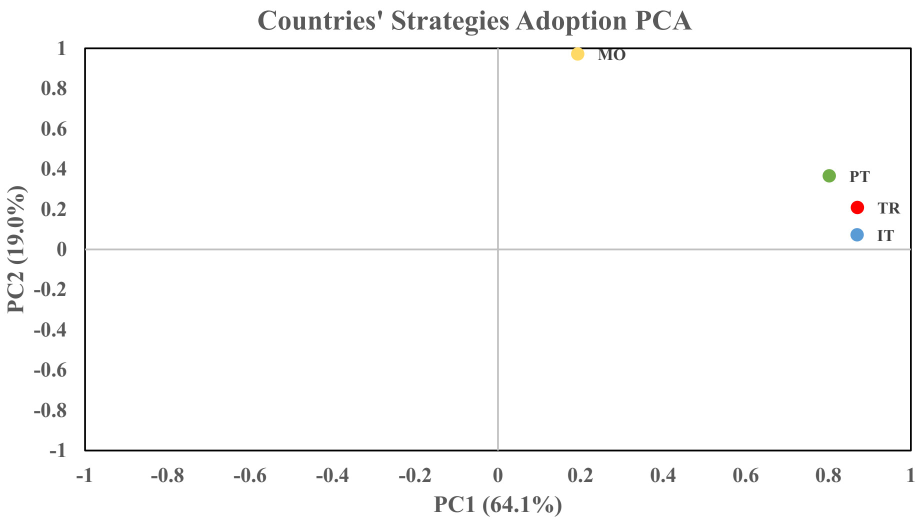

Fig. 14 Principal Component Analysis of the countries' strategies stage of adoption. IT – Verona (blue dot); MO – Marrakech (yellow dot); PT – Douro (Vila Real and Foz Côa) (green dot); TR – Turkey (Aegean Sea and Alasehir) (red dot)

2012; Sadras and Moran 2013). Also, accumulated heat in soils decreases organic matter, carbon storage, and microbiome dynamics (Schultz 2022), and leads to dryness, by increasing vapour pressure deficit, resulting in consecutively smaller water–containing pores, increasing its inaccessibility for grapevines' roots (Watt et al. 2006).

Projections for precipitation show that water availability will decrease. This is a challenging factor as drought–stressed plants tend to close stomata to prevent excessive water loss, thus limiting photosynthesis, and inhibiting plant growth and development (Flexas et al. 1998). Also, predictions for CDD suggest prolonged drought stress, leading to hormonal imbalances, with the increase of abscisic acid (ABA) and the decrease of cytokinin, promoting the biomechanisms associated with fruit ripening, which accelerates the maturity process, promoting ripeness in hotter conditions (decreasing wine quality) and causing leaf senescence and abscission (Zufferey et al. 2017; Pilati et al. 2017). This induced mechanism to limit water loss via evapotranspiration is crucial for their survival (Hochberg et al. 2017; Romero et al. 2017).

Changes in temperature and precipitation also influence the equilibrium of the disease pyramid, impacting the grapevine physiology and yield, and influencing pathogens' reproductive cycles, destabilizing the delicate equilibrium between plants and pathogens, although these imbalances are region–specific. It is estimated that, in humid regions with projected higher temperatures, diseases such as powdery mildew, flavescence dorée, or black rot, can increase their negative influence on grapevine physiology, mainly by modifying photosynthesis and berry composition, which could ultimately impact wine quality (Bocca et al., 2020; Boudon and Maixner, 2007; Ciliberti et al., 2015; Pirrello et al., 2019; Singh et al., 2023; Valdés-Gomez et al., 2011). However, in already warm regions, the increased temperatures could reduce pest/disease incidence (Mira de Orduña 2010).

4.2 General approach to the climate projections and adaptation strategies

Regarding the above, it is mandatory to find adaptation strategies that enhance both the physiological tolerance of vineyards and the sustainability of the winemaking sector (Martins et al. 2021), and these strategies need to be efficient and region–oriented. Adaptation strategies such as delaying the grapevine vegetative cycle, reducing sun exposure, managing/optimizing water consumption, or strategically projecting new vineyards, must be some of the focuses for growers. To achieve it, changes in pruning systems must be considered, such as Guyot or the minimal pruning ones, which can be a good strategy, as they manipulate grapevines, by preventing excessive transpiration, and delaying their vegetative cycles and berry maturity (Bernardo et al. 2018; Malheiro et al., 2020; Molitor et al., 2019). Moreover, the goblet pruning system is one of the most interesting water–saving strategies (Santillán et al. 2020), as it optimises the branches and leaves architecture, reducing berries' sun exposure and water loss through evapotranspiration. However, this pruning system must be carefully planned, as it has a low yield (Deloire et al. 2022).

Leaf area management should also be optimized, as higher leaf area increases water consumption and transpiration, as well as carbon assimilation, leading to excessive water loss, increased sugar content, and an imbalance of wine quality (Santos et al. 2020). However, this strategy must be thoroughly analysed before its use, as in dry and warm areas it may have a negative impact, namely by excessively exposing bunches to direct sunlight, which modifies the organoleptic characteristics of berries (Basile et al. 2015).

The application of sunscreens, namely kaolin, may be an interesting alternative to decrease excessive water loss and leaves and berries scorching on hotter periods, as it lowers leaf temperature and improves water relations (Molitor et al. 2011; Bedrech and Farag 2015; Dinis et al. 2016, 2018). Harvesting anticipation can also help maintain product quality if sugar and acidity levels are monitored to select the best harvesting moment.

Structural changes can also be considered, such as optimising the location and spatial orientation for vineyard implementation, or diminishing the interrow length to reduce sun exposure (although this needs to be thoroughly planned, as diminished interrows will increase water consumption). The implementation of vineyards with more heat/drought–tolerant varieties, such as Cabernet Sauvignon, Malbec, Merlot, Syrah, Victoria, Sigrawn, or Abbou, and/or with more resistant rootstocks, such as the M ones, or the Moroccan Abbou rootstocks, are also fundamental structural strategies (Frioni et al. 2020). In already implemented vineyards, resource strategies such as implementing shadow nets, the application of biostimulants (Gutiérrez-Gamboa et al. 2019), or the application of the abovementioned kaolin, could increase plant tolerance to higher temperatures (Bernardo et al. 2018; Bernardo et al. 2021; Koch and Oehl, 2018; Santos et al. 2020).

Regarding water shortage projections, adaptative strategies such as smart irrigation, the application of hydrogels, and the implementation of mulching should be considered in established vineyards (Medrano et al. 2015; Maienza et al. 2017). Concerning irrigation, it is understood that vineyard production benefits from mild drought stress, as it improves product quality (Plantevin et al. 2022). Therefore, to maximize this optimal balance between drought stress, product quality, and yield, smart irrigation systems, mainly drip irrigation, may be the most effective strategy to maximize water use (Du et al. 2008; Mirás-Avalos et al. 2017; Santos et al. 2020). However, a smart irrigation strategy will depend on the region's possibility to use fresh water as a resource, which will be higher in the cases of Verona or Vila Real, and extremely low in the case of Morocco. Furthermore, as efficient water management is becoming more and more important, the use of irrigation in any way should be considered a last resource in all regions, as growers must prioritize alternative strategies, such as the implementation of hydrogels in grapevines' rhizosphere, as they optimize water usage by plants, namely by their swelling capacity, avoiding excessive water runoff, and by their slow water release, preventing further water losses (Uysal et al. 2023).

Adaptative strategies for soil management should also be considered and should prioritize maintaining/improving soil moisture and nutrient content, enhancing water retention, and promoting soil fauna and microbiome prosperity. Therefore, soil management strategies should include the removal of weeds, mulching and organic compost application, and N_2–fixing cover crops implementation, although the last one should be seasonal – dormancy period – to avoid excessive water competition with grapevines during growing season (Burg et al. 2022; Gattullo et al. 2020; Novara et al. 2011; Schmidt et al. 2018). Also, organic compost application becomes more relevant as VHPD frequency increases, as heavy precipitation increases soil erosion and nutrient runoff (Costa et al. 2023). Tillage and the use of machinery are not recommended, as they negatively impact yield and quality, microbial diversity, and organic matter content, and promote soil erosion (Gómez et al. 2009; Bahar et al. 2019).

Lastly, the application of beneficial microorganisms solutions, combined with extensive soil condition monitorization to promote an increase in microorganism diversity, can increase grapevine development and defences against pathogens and should be considered in all sites (Vimal et al. 2017). The role of plant growth–promoter bacteria (PGPB) could become relevant, as the optimization of the physiological processes and the maximization of the rentability of natural resources is fundamental in climate change mitigation. These PGPBs promote N_2 fixation, PO_4 and K solubilisation, siderophore and auxin production, or S oxidation, improving nutrient availability for plant uptake (de Gannes et al. 2015; Ferreira et al. 2019; Aguilar et al. 2021; Darriaut and Lailheugue 2022). Biological control agents (BCA), such as Trichoderma, are also a microorganism solution to consider, namely due to their capacity to inhibit pathogens' growth and proliferation, being an ecological alternative to the application of commonly used fungicides (Harman et al. 2004; Vimal et al. 2017; Fraceto et al. 2018).

4.3 Current status of the implementation of adaptation strategies

The PCA and the heatmap show that the most innovative adaptation strategies are the least adopted. The necessity to recur to irrigation is obvious, as the heatmap shows that conventional irrigation is commonly used by most countries, except for Portugal (due to government regulations). However, strategies to maximize water use efficiency are rarely adopted, including smart irrigation or the application of hydrogels.

Alternatively, more conventional strategies are the most frequent option by growers, namely organic compost application to correct soil deficiencies, leaf management to reduce water consumption, or the anticipation of harvesting, which are reactive strategies, rather than preventive ones. This analysis shows that, although growers tend to minimize their problems in the short–term, they are not in full control of their vineyards, resulting in decreasing yield, and tend to compensate for the lack of preventive and balanced strategies, such as cover crops, mulching, or microorganism application. However, the most adopted strategy, among the four countries explored, is the use of more resistant rootstocks, which is an important strategy regarding water and nutrient uptake by grapevines.

The PCAs show that, although these different degrees of strategy adoption seem equivalent between Italy, Morocco, Portugal, and Turkey, the specific strategies of each country are somehow distinct. Firstly, some strategies seem to be antagonistic. Strategies such as resistant rootstocks or conventional irrigation are most taken when others, such as heat–tolerant varieties, leaf management, or mulching application, are not. This could mean that viticulturists, when conventional irrigation is available and sufficient, prefer to change rootstocks as a first strategy, instead of losing both native products' quality and footprint (granted by varieties in use), and yield (which would be the case in leaf management). Furthermore, as conventional irrigation maintains water status at an adequate point, mulching is not a priority.

Another antagonistic rate of adoption seems to be the preference for a short–term multi–strategy approach, mainly with anticipation of harvesting, irrigation, sunscreen and organic compost application, or cover crops implementation, instead of the more demanding long–term strategy of vineyard relocation. This could be due to the necessity of new vineyard implementation to adopt more structural, long–term strategies, which does not solve the problems in present vineyards. However, it is clear in the analysed data that Morocco is significantly ahead of the remaining countries in the adoption of long–term strategies, suggesting that Moroccan growers are suffering from high temperatures and low precipitation levels for a longer period than Portugal, Italy, or Turkey.

4.4 Adaptation Strategies in Portuguese regions

Regarding the Portuguese regions, results show that they have a very balanced strategy adoption, meaning that a combination of them, which are complementary, is being applied. This adoption of multiple short–term adaptation strategies balances the lack of adoption of long–term ones, meaning that growers are trying to defend the established vineyards, instead of projecting new ones.

The screening of the adaptation strategies in Portuguese regions showed that, regarding cultural adaptations, changes in pruning systems are frequently applied, changing mainly to double Guyot. Leaf area management is also common, especially in locations where natural leaf scorch is less frequent. The most used strategy is the adoption of more resistant rootstocks (namely the 1103P), followed by the anticipation of harvesting. Also, sunscreen (e.g., kaolin) is widely used. Neither shadow nets, interrow space shortening, vineyard relocation with more resistant varieties and rootstocks, nor adaptative measures for water management are being adopted. For soil management, only the application of organic matter and weed removal are frequent.

4.5 Adaptation Strategies in Verona

Regarding Verona, results show a clear focus on their climate change adaptation efforts in two key factors: the use of more resistant rootstocks, and conventional irrigation. This focus, associated with the lack of adoption of heat–tolerant varieties, reinforces the idea that Veronese growers are prioritising their native varieties, valorising their cultural and viticultural inheritance. Nonetheless, grapevine growers in Italy are implementing some other strategies, almost exclusively short–term ones. However, changes in training systems are an option in some cases, normally changing to double Guyot, although pergola veronese, a high water–consuming pruning system, is still frequently used. Despite the use of resistant rootstocks being a constant, strategies such as leaf area management, the anticipation of harvesting, or the adaptation of vineyard orientation and relocation are currently rarely used. Moreover, smart irrigation is rarely seen. Concerning soil management, herbicide is often used, and it is the main strategy to remove weeds, although machinery is also an option. Organic compost application is frequent, whilst mulching, cover crop and microorganism applications are rarely used.

4.6 Adaptation Strategies in Turkish regions

Turkish growers have a different approach, as overall strategies are used at different frequencies and a higher number, compared to the previously analysed locations. As Turkish sites are some of the most climatically endangered ones, and as they already experience very high temperatures and low precipitation levels, these results would be expected. However, it is noticeable the effort to adopt innovative solutions, besides one of the most basic and effective ones, the change in pruning systems, is not being specially adopted.

In the analysed Turkish regions, the most frequently used cultural strategies are the anticipation of harvesting, the use of more resistant rootstocks, and sunscreen application. Furthermore, they are implementing shadow nets, and adapting the spatial orientation of vineyards, in some cases. Changes in pruning systems are rarely an alternative, showing that they prefer to choose alternative strategies before decreasing productivity. Conventional and smart irrigations are common, whilst hydrogel application is never used. Concerning soil management, weeds are removed both mechanically and through herbicide application, and organic composts are frequently applied. The application of microorganisms is already a strategy utilized in some cases. Mulching and cover crops are rarely used.

4.7 Adaptation Strategies in Marrakech

Marrakech's growers have a very different approach regarding the adoption of strategies to mitigate climate change. The option for long–term strategies is more common, which is probably due to the most severe climate conditions for viticulture practice, and to the longer period in which growers are exposed to difficulties in vineyard production. Marrakech's viticulturists focus on managing water, as strategies that are currently applied are directed to reduce water loss. The analysis of the PCA proves exactly that, as Marrakech's main strategies include the change in training systems, the implementation of shadow nets (which also contributes to the reduction of sun exposure, explaining the lack of use of sunscreen) and mulching, and leaf management, to reduce water loss by evapotranspiration. Also, more resistant varieties and rootstocks are often used. Regarding irrigation, conventional irrigation is used in some cases, although carefully managed due to water scarcity, turning out to be short for plants' demands, also due to the high temperatures. Smart irrigation is not used, nor is the application of hydrogels in soil. For soil management, herbicide and machinery use is an option in some cases, whilst the use of cover crops and microorganism application is never an option.

4.8 Are growers making the best decisions?

Regarding adaptative strategies to mitigate climate change impacts, it was observed that growers are adopting different actions. Turkish growers seem more advanced in some strategies, which is understandable, as Turkish regions has higher temperatures and lower precipitation levels than Vila Real, Foz Côa, and Verona. An interesting study conducted in Turkey showed that growers are aware of climate change and its impacts (Uysal et al. 2023), which justifies the higher strategy adoption. However, this is not the case in most of the Mediterranean basin, as most of the taken decisions are not enough to effectively respond to climate change.

Vila Real growers should prioritize their efforts on minimizing water losses through evapotranspiration. The expected increase in temperatures will cause aggravated evapotranspiration losses, lowering soil water availability, meaning that the focus of Vila Real growers should be to minimize water losses, recurring to mulching, as it is effective in retaining water already available in the soil, increasing humidity and decreasing its temperature, while also having a role in weed control and contributing to soil organic matter content (Cabrera-Pérez et al. 2023). Winter cover crops should be considered, as they promote soil biodiversity, increase carbon content, improve water infiltration, increase N–availability, and reduce soil erosion (Abad et al. 2021). Moreover, for water storage in soils and to optimize its use efficiency, hydrogel application should be considered (Dayal Bairwa et al. 2020; Genesio et al. 2015). Other relevant strategies, such as the change in training systems, the application of sunscreen in the hottest summer periods, leaf area management, and the use of more resistant varieties and rootstocks, should be maintained.

Foz Côa has a different scenario. Despite the strategies to reduce evapotranspiration in Vila Real are also suitable for the Côa Valley, as it needs to maximize water management, heat increase should not be undervalued. Here, the decision should be to continue the implementation of new vineyards with more resistant varieties, as well as more resistant rootstocks, such as the M4, which proved to be more efficient than the currently used 1103P in water use and in improving leaf gas exchanges (Frioni et al. 2020). Also, plant management, mainly pruning and leaf area, should be optimized, limiting plant growth and focusing on product quality. The implementation of shade nets should be seriously considered, as they lower leaf temperature and reduce sunburn incidence, promote plant growth, and delay harvesting periods, which is one of the main concerns in the region (Serat and Kulkarni 2013). Interrow length and vineyard spatial orientation in new vineyards should also be optimized to defend plants from excessive solar exposure (although it should be planned carefully, as the shortening of the interrow length could lead to excessive plant competition for resources). Weed control should also be well addressed, to minimize water and nutrient losses, in which mulching could also play an important role (Burg et al. 2022). Microorganism solutions, combined with the already application of organic compost to correct soil imbalances, could be an interesting strategy to maximize plant nutrient uptake, mainly in poor soils, such as the ones in Foz Côa.

The region of Verona is also worrying about the changes that climate change may cause to viticulture. Although water availability is expected to be stable, it is less abundant than in Vila Real, whilst expected temperatures are similar to the Portuguese region. Therefore, grapevine growers should prioritize their efforts to maximize water usage, through hydrogel and mulching application, whilst opting for a less water–demanding pruning system, such as the double Guyot. These strategies should be considered, as others are already being taken, mainly the use of more resistant rootstocks, changes in pruning systems, and kaolin use. Microorganism applications should also be considered, mainly BCAs, due to the possible increase in pathogen incidence, as temperatures will be higher and precipitation levels maintained.

Turkish regions are more alarming, as climatic conditions are expected to worsen, meaning that grapevine growers must take several measures to reduce its impact. Some are already being taken, such as the use of shade nets, the spatial adaptation of vineyards to reduce sun exposure, and microorganism application. Leaf area management, harvesting anticipation, sunscreen application, the use of more resistant rootstocks, and organic compost application, are also implemented strategies. More resistant varieties are sometimes used by growers, although the use of local and international varieties is preferred (i.e. Kalecik Karasi), despite their low heat/drought tolerance. Moreover, conventional and smart irrigation are also being used. However, strategies such as the change in pruning systems, mulching, cover crops, and hydrogel application, are rarely or never used, and should be the points to improve, as it seems that growers, due to their use of irrigation, are not adopting strategies that preserve water availability in soils, which should be the focus, as water availability is expected to decrease.

Marrakech's viticulture is extremely endangered by climate change and, although some strategies are being adopted, there is much more to do, so that viticulture is sustained. As annual precipitation is extremely low, irrigation would be fundamental for a healthy vegetative cycle. However, as water is extremely scarce, irrigation should be the ultimate resource, meaning that water loss containment and maximizing water availability in soil is a priority. Therefore, hydrogel integration in grapevines' rhizosphere, and mulching application, are mandatory. Although the use of shadow nets is an important strategy to reduce sun exposure, complementary actions, such as the management of the vineyard spatial orientation and the approximation of interrow should be considered.

5 Conclusions

Climate change in the Mediterranean basin is more and more impactful, as heat and drought waves, extreme events, and changes in climate dynamics are more frequent. Climate projections for the region show that these events will be more frequent, and that temperature and precipitation will continue its' aggravation tendency, to values that are considered challenging for viticulture, its products, and the socioeconomy associated with it. The influence on viticulture is already being observed, as grapevine growers are challenged to solve issues on their productions, which are sometimes softened or delayed by their interventions. Even though some efforts are starting to be made by growers, these impacts tend to be more and more severe and are starting to threaten productivity, product quality, and even the characteristics that define the *terroir*, which attributes to each production site its uniqueness and value. Nonetheless, most of the efforts made by growers are based on the use of reactive strategies, and not preventive ones, meaning that growers are not fully informed of the real impacts of climate change on their vineyards, or that they do not yet attribute the adequate importance to the issue, which postpone the implementation of the best actions to reduce them.

The differentiation among the subregions in the Mediterranean area allows the understanding of region–specific climate dynamics, promoting optimized and oriented decision–making regarding adaptative strategies. This site–specific analysis showed that different regions need different strategies and have different priorities. Portuguese, Italian, and Turkish growers have distinct urges from Morocco ones, as the African country already is experiencing a direct threat to viticulture itself. However, Portuguese, Italian, and Turkish viticulture could be exposed, in the next decades, to more similar difficulties to Morocco, and a closer look at how Morocco adapted their vineyards to climate change can be important to anticipate major physiological, economic, and sociocultural problems. Regarding the projections presented in this work, Morocco should be thoroughly analysed, and be considered a role model in some adaptation strategies to the European countries under the ongoing warming and drying trends. This work also showed that growers are still using, in much higher frequencies, “conventional” strategies, that have been known for some decades, instead of applying innovative, more efficient ones. Furthermore, as some strategies can be very cost demanding and questionable regarding their ecological impacts, it is of crucial importance to adopt, as much as possible, an integrated production system (IPS), in which biodiversity with authoctonous species is promoted. In this case, the IPS approach would be considered a multi-strategy one, in which it could be possible to, for instance, reconsider the use of shade nets in some cases, by prioritizing the growth of olive trees, which would also promote soil management, water conservation, whilst maintaining the natural landscape (Costantini and Barbetti 2008). Therefore, it is crucial to accelerate scientific communication with growers, enhancing their capacity to understand the problems ahead and sustainably make the best decisions.

Appendix

Graphics of the remaining climatic parameters analysed in the study

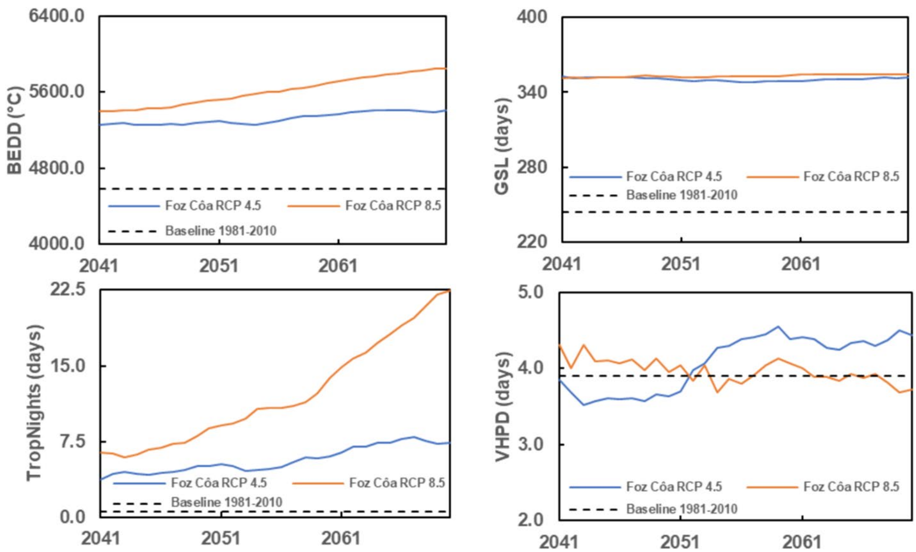

Fig. 15 Climatic parameters’ projections for Foz Côa, 2041–2070 period; BEDD: sum of yearly biological effective degree days (°C); GSL: Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after 1st July of at least 6 consecutive days with mean temperature < 5°C); TropNights: number of days with minimum temperature > 20°C; VHPD: number of days of precipitation above 20mm; RCP4.5 (blue), RCP8.5 (orange); Mean value of 1981–2010 period "Baseline" (dashed line)

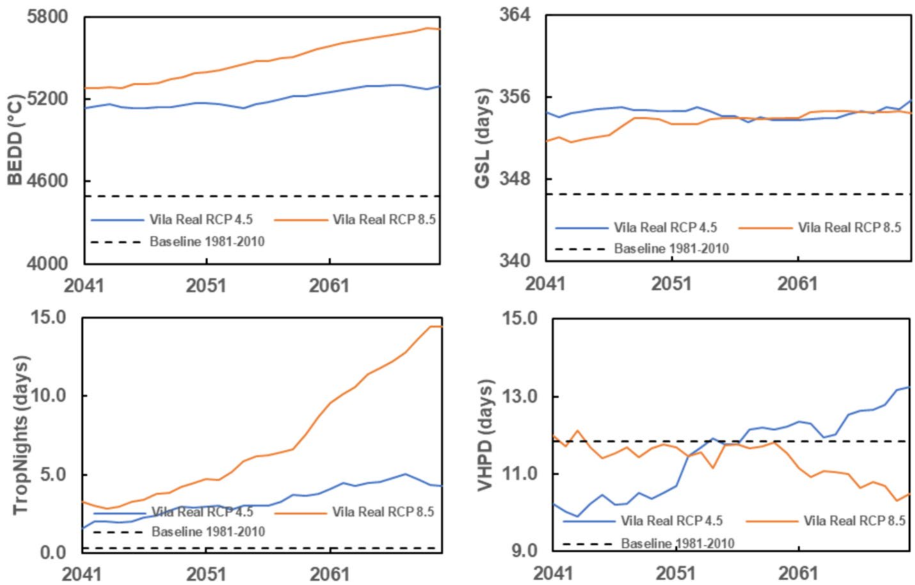

Fig. 16 Climatic parameters' projections for Vila Real 2041–2070 period; BEDD: sum of yearly biological effective degree days (°C); GSL: Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after 1st July of at least 6 consecutive days with mean temperature < 5°C); TropNights: number of days with minimum temperature > 20°C; VHPD: number of days of precipitation above 20mm; RCP4.5 (blue), RCP8.5 (orange); Mean value of 1981–2010 period "Baseline" (dashed line)

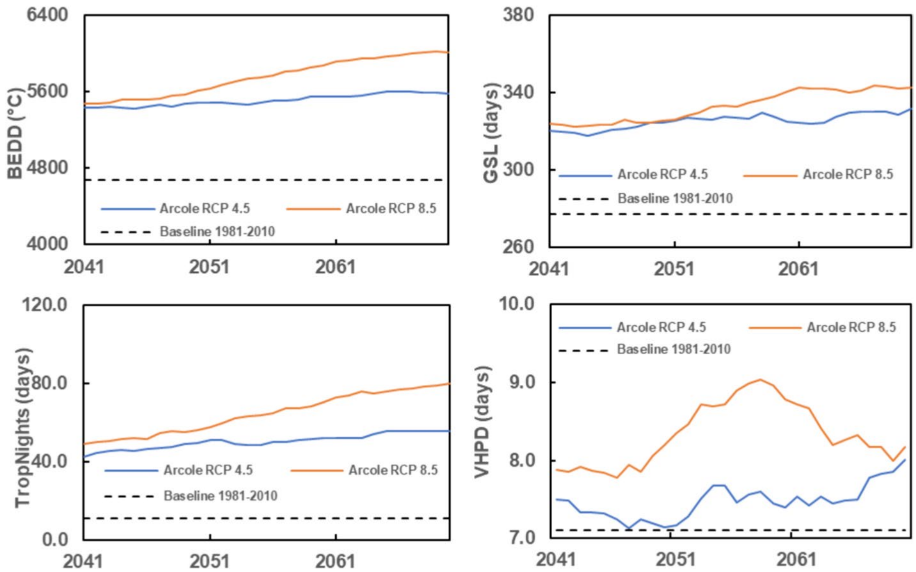

Fig. 17 Climatic parameters' projections for Verona 2041–2070 period; BEDD: sum of yearly biological effective degree days (°C); GSL: Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after 1st July of at least 6 consecutive days with mean temperature < 5°C); TropNights: number of days with minimum temperature > 20°C; VHPD: number of days of precipitation above 20mm; RCP4.5 (blue), RCP8.5 (orange); Mean value of 1981–2010 period "Baseline" (dashed line)

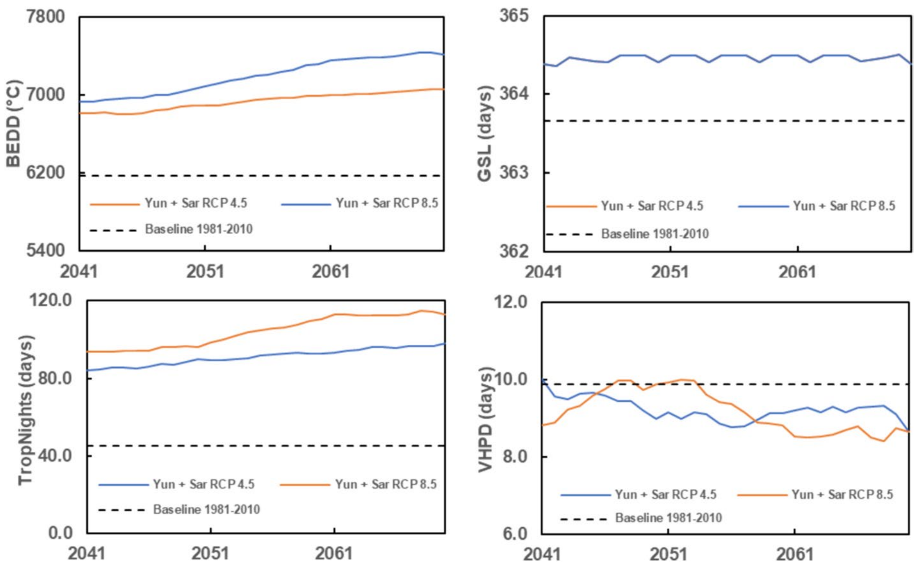

Fig. 18 Climatic parameters' projections for Yun + Sar 2041–2070 period; BEDD: sum of yearly biological effective degree days (°C); GSL: Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after 1st July of at least 6 consecutive days with mean temperature < 5°C); TropNights: number of days with minimum temperature > 20°C; VHPD: number of days of precipitation above 20mm; RCP4.5 (blue), RCP8.5 (orange); Mean value of 1981–2010 period "Baseline" (dashed line)

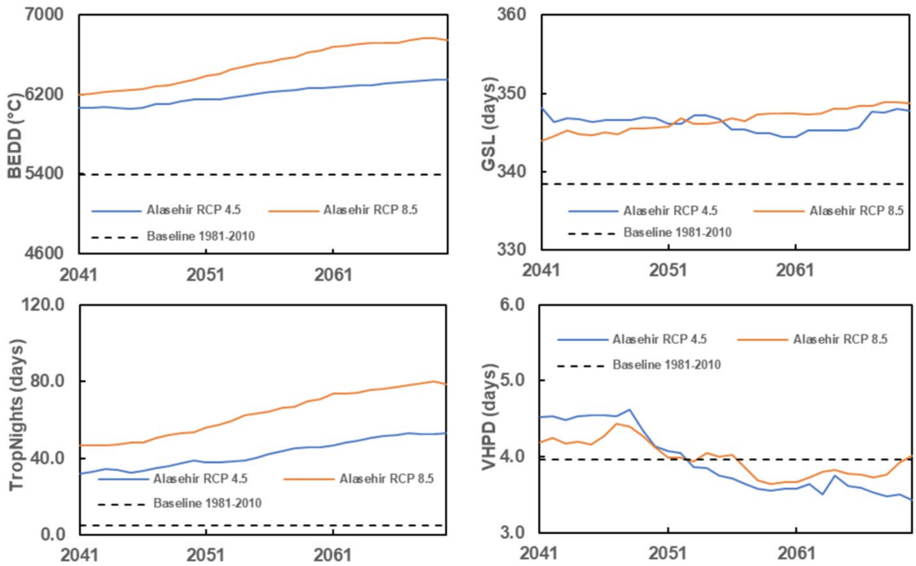

Fig. 19 Climatic parameters' projections for Alasehir 2041–2070 period; BEDD: sum of yearly biological effective degree days (°C); GSL: Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after 1st July of at least 6 consecutive days with mean temperature < 5°C); TropNights: number of days with minimum temperature > 20°C; VHPD: number of days of precipitation above 20mm; RCP4.5 (blue), RCP8.5 (orange); Mean value of 1981–2010 period "Baseline" (dashed line)

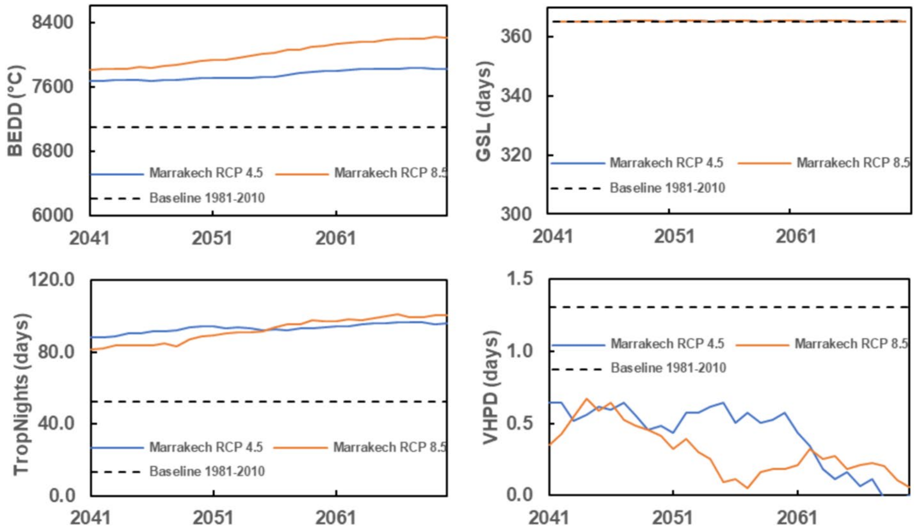

Fig. 20 Climatic parameters' projections for Marrakech 2041–2070 period; BEDD: sum of yearly biological effective degree days (°C); GSL: Number of days between the first occurrence of at least 6 consecutive days with mean temperature > 5°C and the first occurrence after 1st July of at least 6 consecutive days with mean temperature < 5°C); TropNights: number of days with minimum temperature > 20°C; VHPD: number of days of precipitation above 20mm; RCP4.5 (blue), RCP8.5 (orange); Mean value of 1981–2010 period "Baseline" (dashed line)

Table 6 Frequency of application of the adaptation strategies per country

	CLIMATE CHANGE ADAPTATION STRATEGIES	Portugal	Italy	Turkey	Morocco
Long–term strategies	Vineyards relocation	1	2	1	2
	Diminish interrow length	1	1	2	2
	Adaptation of the vineyard spacial orientation	2	2	3	2
	Use of shadow nets	1	1	3	4
	Use of heat–tolerant vine varieties	3	1	3	4
	Change in training systems	3	3	2	4
	Use of more resistant rootstocks	4	5	4	4
Short–term strategies	Hydrogel/Biochar application	1	1	1	1
	Sap flow variation analysis	1	1	1	1
	Trunk diameter variation analysis	1	1	1	1
	Cover crops	2	1	2	1
	Microorganism application	1	1	3	1
	Mulching application	2	1	2	3
	Smart irrigation	1	2	4	1
	Conventional irrigation	1	5	3	2
	Leaf management	3	2	3	4
	Sunscreen application	4	3	4	1
	Anticipate harvesting	4	2	4	3
	Tillage	3	3	4	4
	Organic compost application	5	4	4	2
	Herbicide use	4	4	5	3
	Machine use in cultivation	4	4	5	3
	Sum of points in frequency of adopted strategies	**52**	**50**	**64**	**53**

Acknowledgements This work is supported by National Funds by FCT - Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020. The authors are grateful for all the conditions made available by the Foundation for Science and Technology (FCT, Portugal) and European Fund for Regional Development (FEDER) under Programme PT2020 for the financial support to the Centre for the Research and Technology of Agro–Environmental and Biological Sciences (CITAB, UIDB/04033/2020). Also, the authors are grateful for the conditions that the Partnership for Research and Innovation in the Mediterranean Area (PRIMA), the Ministry of University and Research (Italy), the Ministry of Higher Education, Research and Innovation (Morocco), the Scientific and Technological Research Council of Turkiye (Turkey), and the European Union provided in the development of the VineProtect project (PRIMA/0011/2021), and for the support of the Associated Laboratory for Green Chemistry (LAQV) of the Network of Chemistry and Technology (REQUIMTE). This work is part of the PhD scholarship of João Prada, also funded by FCT, with the reference PRT/BD/153394/2021.

Funding Open access funding provided by FCT|FCCN (b-on).

Data availability The datasets generated during and/or analysed during the current study are available in ECMFW's Copernicus Climate Data Store repository, https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis–agroclimatic–indicators?tab=overview.

Declarations

Competing interests The authors declare no competing interests.

References

Abad J, Hermoso De Mendoza I, Marín D et al (2021) Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard. Oeno One 55:295–312

Abdi S, Abbaspur N, Avestan S, Barker AV (2016) Physiological responses of two grapevine (Vitis vinifera L.) cultivars to cycocel^{TM} treatment during drought. J Hort Sci Biotech 91:211–219. https://doi.org/10.1080/14620316.2015.1123405

Agriculture and Rural Development EC (2021) The common agricultural policy: 2023–27

Aguilar MO, Alvarez F, Medeot D et al (2021) Screening of epiphytic rhizosphere–associated bacteria in argentinian malbec and cabernet–sauvignon vineyards for potential use as biological fertilisers and pathogen–control agents. Oeno One 55:145–157. https://doi.org/10.20870/oeno-one.2021.55.4.4655

Bahar E, Semih A, Asin Y (2019) The yield and berry quality under different soil tillage and clusters thinning treatments in grape (Vitis vinifera L.) cv. Cabernet–Sauvignon. Afr J Agr Res 5:2986–2993

Basile B, Caccavello G, Giaccone M, Forlani M (2015) Effects of early shading and defoliation on bunch compactness, yield components, and berry composition of aglianico grapevines under warm climate conditions. Am J Enol Vitic 66:234–243. https://doi.org/10.5344/ajev.2014.14066

Bedrech SA, Farag SG (2015) Usage of some sunscreens to protect the Thompson Seedless and Crimson Seedless grapevines growing in hot climates from sunburn. Nat Sci (East Lansing) 13. https://doi.org/10.7537/marsnsj131215.05

Ben Mohamed H, Vadel AM, Geuns JMC, Khemira H (2010) Biochemical changes in dormant grapevine shoot tissues in response to chilling: Possible role in dormancy release. Sci Hortic 124:440–447. https://doi.org/10.1016/j.scienta.2010.01.029

Bernardo S, Dinis LT, Machado N, Moutinho-Pereira J (2018) Grapevine abiotic stress assessment and search for sustainable adaptation strategies in Mediterranean–like climates. A review. Agron Sustain Dev 38. https://doi.org/10.1007/s13593-018-0544-0

Bernardo S, Luzio A, Machado N et al (2021) Kaolin application modulates grapevine photochemistry and defence responses in distinct mediterranean–type climate vineyards. Agronomy 11. https://doi.org/10.3390/agronomy11030477

Blotevogel S, Schreck E, Laplanche C et al (2019) Soil chemistry and meteorological conditions influence the elemental profiles of West European wines. Food Chem 298. https://doi.org/10.1016/j.foodchem.2019.125033

Bocca FM, Picciau L, Alma A (2020) New insights on scaphoideus titanus biology and their implications for integrated pest management. Entomo Gen 40:337–349. https://doi.org/10.1127/entomologia/2020/0977

Boudon E, Maixner M (2007) Potential effects of climate change on distribution and activity of insect vectors of grapevine pathogens. International and multi-disciplinary "Global warming, which potential impacts on the vineyards?". Beaune, France. ffhal-02758434

Bove A, Ounissi R (2022) Morocco climate change development report. World Bank

Burg P, Čížková A, Mašán V et al (2022) The Effect of Mulch Materials on Selected Soil Properties, Yield and Grape Quality in Vineyards under Central European Conditions. Agronomy 12. https://doi.org/10.3390/agronomy12081862

Cabrera-Pérez C, Llorens J, Escolà A et al (2023) Organic mulches as an alternative for under–vine weed management in Mediterranean irrigated vineyards: Impact on agronomic performance. Euro J Agron:145. https://doi.org/10.1016/j.eja.2023.126798

Caldas RJ, Guedes A (2015) AlmaTourism Journal of Tourism, Culture and Territorial Development The Douro Region: Wine and Tourism. 11. DOI: https://doi.org/10.6092/issn.2036-5195/4647

Ciliberti N, Fermaud M, Roudet J, Rossi V (2015) Environmental conditions affect Botrytis cinerea infection of mature grape berries more than the strain or transposon genotype. Phyto 105:1090–1096. https://doi.org/10.1094/PHYTO-10-14-0264-R

Climate Nexus (2019) RCP 8.5: Business–as–usual or a worst–case scenario? https://climatenexus.org/climate–change–news/rcp–8–5–business–as–usual–or–a–worst–case–scenario/. Accessed 4 May 2023

Cooke JEK, Eriksson ME, Junttila O (2012) The dynamic nature of bud dormancy in trees: Environmental control and molecular mechanisms. Plant Cell Environ 35:1707–1728. https://doi.org/10.1111/j.1365-3040.2012.02552.x

Costa JM, Egipto R, Aguiar FC et al (2023) The role of soil temperature in mediterranean vineyards in a climate change context. Front Plant Sci 14. https://doi.org/10.3389/fpls.2023.1145137

Costantini EAC, Barbetti R (2008) Environmental and visual impact analysis of viticulture and olive tree cultivation in the province of Siena (Italy). Euro J Agron 28:412–426. https://doi.org/10.1016/j.eja.2007.11.012

Czigány S, Novák TJ, Pirkhoffer E et al (2020) Application of a topographic pedosequence in the villány hills for terroir characterization. Hung Geo Bull 69:245–261. https://doi.org/10.15201/hungeobull.69.3.2

Darriaut R, Lailheugue V, Masneuf–Pomarède I, et al (2022) Grapevine rootstock and soil microbiome interactions: Keys for a resilient viticulture. Hortic Res 9 DOI: https://doi.org/10.1093/hr/uhac019

Dayal Bairwa D, Singh Prajapat B, Kadam SS (2020) Hydrogel: the best option for saving irrigation water. Vigyan Varta 1(8):63–66

de Gannes V, Eudoxie G, Bekele I, Hickey WJ (2015) Relations of microbiome characteristics to edaphic properties of tropical soils from Trinidad. Front Microbiol 6. https://doi.org/10.3389/fmicb.2015.01045

del Pozo A, Brunel-Saldias N, Engler A et al (2019) Climate change impacts and adaptation strategies of agriculture in Mediterranean–climate regions (MCRs). Sustain (Switzerland) 11. https://doi.org/10.3390/su11102769

Deloire A, Rogiers S, Baeza Trujillo P (2022) What could be the architectural forms of future vines adapted to climate change: a new challenge! Let's discuss the Gobelet (Bush Vine). IVES Technical Reviews, vine and wine. DOI: https://doi.org/10.20870/ives-tr.2022.5384

Deluc LG, Grimplet J, Wheatley MD et al (2007) Transcriptomic and metabolite analyses of Cabernet Sauvignon grape berry development. BMC Genomics 8. https://doi.org/10.1186/1471-2164-8-429

Dinis LT, Ferreira H, Pinto G et al (2016) Kaolin–based, foliar reflective film protects photosystem II structure and function in grapevine leaves exposed to heat and high solar radiation. Photosynthetica 54:47–55. https://doi.org/10.1007/s11099-015-0156-8

Dinis LT, Malheiro AC, Luzio A et al (2018) Improvement of grapevine physiology and yield under summer stress by kaolin–foliar application: water relations, photosynthesis and oxidative damage. Photosynthetica 56:641–651. https://doi.org/10.1007/s11099-017-0714-3

Dinu DG, Ricciardi V, Demarco C et al (2021) Climate change impacts on plant phenology: Grapevine (vitis vinifera) bud break in wintertime in southern italy. Foods 10. https://doi.org/10.3390/foods10112769

Droulia F, Charalampopoulos I (2021) Future climate change impacts on european viticulture: A review on recent scientific advances. Atmosphere (Basel) 12. https://doi.org/10.3390/atmos12040495

Droulia F, Charalampopoulos I (2022) A Review on the Observed Climate Change in Europe and Its Impacts on Viticulture. Atmosphere (Basel):13. https://doi.org/10.3390/atmos13050837

Drori E, Munitz S, Pinkus A et al (2022) The effect of irrigation-initiation timing on the phenolic composition and overall quality of cabernet sauvignon wines grown in a semi-arid climate. Foods 11. https://doi.org/10.3390/foods11050770

Du T, Kang S, Zhang J et al (2008) Water use efficiency and fruit quality of table grape under alternate partial root–zone drip irrigation. Agric Water Manag 95:659–668. https://doi.org/10.1016/j.agwat.2008.01.017

Duchêne E, Huard F, Dumas V et al (2010) The challenge of adapting grapevine varieties to climate change. Clim Res 41:193–204. https://doi.org/10.3354/cr00850

Ferreira CMH, Soares HMVM, Soares EV (2019) Promising bacterial genera for agricultural practices: An insight on plant growth–promoting properties and microbial safety aspects. Sci Total Environ 682:779–799

Flexas J, Escalona JM, Medrano H (1998) Down–regulation of photosynthesis by drought under field conditions in grapevine leaves. Aust J Plant Physiol 25:893–900. https://doi.org/10.1071/PP98054

Fraceto LF, Maruyama CR, Guilger M et al (2018) Trichoderma harzianum–based novel formulations: potential applications for management of Next–Gen agricultural challenges. J Chem Technol Biotechnol 93:2056–2063

Fraga H, Malheiro AC, Moutinho-Pereira J et al (2014) Integrated analysis of climate, soil, topography and vegetative growth in iberian viticultural regions. PLoS One 9. https://doi.org/10.1371/journal.pone.0108078
Franck N, Morales JP, Arancibia-Avendaño D et al (2011) Seasonal fluctuations in Vitis vinifera root respiration in the field. New Phytologist. 192:939–951. https://doi.org/10.1111/j.1469-8137.2011.03860.x
Frioni T, Biagioni A, Squeri C et al (2020) Grafting cv. grechetto gentile vines to new m4 rootstock improves leaf gas exchange and water status as compared to commercial 1103p rootstock. Agronomy 10. https://doi.org/10.3390/agronomy10050708
Gattullo CE, Mezzapesa GN, Stellacci AM et al (2020) Cover crop for a sustainable viticulture: Effects on soil properties and table grape production. Agronomy 10. https://doi.org/10.3390/agronomy10091334
Genesio L, Miglietta F, Baronti S, Vaccari FP (2015) Biochar increases vineyard productivity without affecting grape quality: Results from a four years field experiment in Tuscany. Agric Ecosyst Environ 201:20–25. https://doi.org/10.1016/j.agee.2014.11.021
Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Glob Planet Change 63:90–104. https://doi.org/10.1016/j.gloplacha.2007.09.005
Gómez JA, Guzmán MG, Giráldez JV, Fereres E (2009) The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil Tillage Res 106:137–144. https://doi.org/10.1016/j.still.2009.04.008
Grasso M, Feola G (2012) Mediterranean agriculture under climate change: Adaptive capacity, adaptation, and ethics. Reg Environ Change 12:607–618. https://doi.org/10.1007/s10113-011-0274-1
Grifoni D, Carreras G, Zipoli G et al (2008) Row orientation effect on UV–B, UV–A and PAR solar irradiation components in vineyards at Tuscany, Italy. Int J Biometeorol 52:755–763. https://doi.org/10.1007/s00484-008-0168-1
Gutiérrez-Gamboa G, Romanazzi G, Garde-Cerdán T, Pérez-Álvarez EP (2019) A review of the use of biostimulants in the vineyard for improved grape and wine quality: effects on prevention of grapevine diseases. J Sci Food Agric 99:1001–1009
Harman GE, Howell CR, Viterbo A et al (2004) Trichoderma species – Opportunistic, avirulent plant symbionts. Nat Rev Microbiol 2:43–56. https://doi.org/10.1038/nrmicro797
Hed B, Ngugi HK, Travis JW (2015) Short– and long–term effects of leaf removal and gibberellin on Chardonnay grapes in the Lake Erie region of Pennsylvania. Am J Enol Vitic 66:22–29. https://doi.org/10.5344/ajev.2014.14034
Helder F, João AS (2018) Vineyard mulching as a climate change adaptation measure: Future simulations for Alentejo, Portugal. Agric Syst 164:107–115. https://doi.org/10.1016/j.agsy.2018.04.006
Hochberg U, Windt CW, Ponomarenko A et al (2017) Stomatal closure, basal leaf embolism, and shedding protect the hydraulic integrity of grape stems. Plant Physiol 174:764–775. https://doi.org/10.1104/pp.16.01816
Instituto dos Vinhos do Douro e do Porto (2024) Região Demarcada do Douro. In: https://www.ivdp.pt/pt
Italian Wine Central (2023) Wine Production by Region. In: https://italianwinecentral.com/wine-production-in-italy-by-region/
Keller M (2020) The Science of Grapevines
Kizildeniz T, Irigoyen JJ, Pascual I, Morales F (2018) Simulating the impact of climate change (elevated CO2 and temperature, and water deficit) on the growth of red and white Tempranillo grapevine in three consecutive growing seasons (2013–2015). Agric Water Manag 202:220–230. https://doi.org/10.1016/j.agwat.2018.02.006
Koch B, Oehl F (2018) Climate change favors grapevine production in temperate zones. Agric Sci 09:247–263. https://doi.org/10.4236/as.2018.93019
Koech R, Langat P (2018) Improving irrigation water use efficiency: A review of advances, challenges and opportunities in the Australian context. Water (Switzerland) 10. https://doi.org/10.3390/w10121771
Lionello P, Scarascia L (2018) The relation between climate change in the Mediterranean region and global warming. Reg Environ Change 18:1481–1493. https://doi.org/10.1007/s10113-018-1290-1
Maienza A, Baronti S, Cincinelli A et al (2017) Biochar improves the fertility of a Mediterranean vineyard without toxic impact on the microbial community. Agron Sustain Dev 37. https://doi.org/10.1007/s13593-017-0458-2
Malheiro AC, Pires M, Conceição N et al (2020) Linking sap flow and trunk diameter measurements to assess water dynamics of touriga-nacional grapevines trained in cordon and guyot systems. Agric (Switzerland) 10:1–15. https://doi.org/10.3390/agriculture10080315
Martínez-Bracero M, González-Fernández E, Wójcik M et al (2020) Airborne fungal phytopathological spore assessment in three European vineyards from different bioclimatic areas. Aerobiologia (Bologna) 36:715–729. https://doi.org/10.1007/s10453-020-09664-6

Martins J, Fraga H, Fonseca A, Santos JA (2021) Climate projections for precipitation and temperature indicators in the douro wine region: The importance of bias correction. Agronomy 11. https://doi.org/10.3390/agronomy11050990
Medrano H, Tomás M, Martorell S et al (2015) Improving water use efficiency of vineyards in semi–arid regions. A review. Agron Sustain Dev 35:499–517. https://doi.org/10.1007/s13593-014-0280-z
Mira de Orduña R (2010) Climate change associated effects on grape and wine quality and production. Food Res Int 43:1844–1855. https://doi.org/10.1016/j.foodres.2010.05.001
Mirás-Avalos JM, Fandiño M, Trigo-Córdoba E (2017) Effects of surface and subsurface drip irrigation on physiology and yield of "Godello" grapevines grown in Galicia, NW Spain. Cienc Tec Vitivinic 32(et al):42–52. https://doi.org/10.1051/ctv/20173201042
Molitor D, Schultz M, Mannes R et al (2019) Semi-minimal pruned hedge: a potential climate change adaptation strategy in viticulture. Agron 9. https://doi.org/10.3390/agronomy9040173
Molitor D, Behr M, Fischer S et al (2011) Timing of cluster-zone leaf removal and its impact on canopy morphology, cluster structure and bunch rot susceptibility of grapes. Oeno One 45. https://doi.org/10.20870/oeno-one.2011.45.3.1495
Morales-Castilla I, De Cortázarcortćortázar-Atauri G, Cook BI et al (2019) Diversity buffers winegrowing regions from climate change losses. https://doi.org/10.1073/pnas.1906731117/-/DCSupplemental.y
Mori K, Saito H, Goto-Yamamoto N et al (2005) Effects of abscisic acid treatment and night temperatures on anthocyanin composition in Pinot noir grapes. Vitis:44. https://doi.org/10.5073/vitis.2005.44.161-165
Nobakht M, Beavis P, O'Hara S, Hutjes R, Supit I (2019) Agroclimatic indicators from 1951 to 2099 derived from climate projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.dad6e055
Novara A, Gristina L, Saladino SS et al (2011) Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. Soil Tillage Res 117:140–147. https://doi.org/10.1016/j.still.2011.09.007
Onofri L, Bianchin F, Boatto V et al (2018) What Is the Future of the Wine–Grape Industry in Veneto? Evidence from a Micro–Macro Prediction Model. J Wine Econ 13:384–393. https://doi.org/10.1017/jwe.2018.39
Parker A, de Cortázar-Atauri IG, Chuine I et al (2013) Classification of varieties for their timing of flowering and veraison using a modelling approach: A case study for the grapevine species Vitis vinifera L. Agric For Meteorol 180:249–264. https://doi.org/10.1016/j.agrformet.2013.06.005
Parker AK, De Cortázar-Atauri IG, Van Leeuwen C, Chuine I (2011) General phenological model to characterise the timing of flowering and veraison of Vitis vinifera L. Aust J Grape Wine Res 17:206–216. https://doi.org/10.1111/j.1755-0238.2011.00140.x
Parker AK, García de Cortázar-Atauri I, Gény L et al (2020) Temperature–based grapevine sugar ripeness modelling for a wide range of Vitis vinifera L. cultivars. Agric For Meteorol:285–286. https://doi.org/10.1016/j.agrformet.2020.107902
Pereira HS, Delgado M, Avó AP et al (2014) Pollen grain development is highly sensitive to temperature stress in Vitis vinifera. Aust J Grape Wine Res 20:474–484. https://doi.org/10.1111/ajgw.12105
Pieri P, Gaudillère JP (2003) Sensitivity to training system parameters and soil surface albedo of solar radiation intercepted by vine rows. Vitis 42:77–82. https://doi.org/10.5073/vitis.2003.42.77-82
Pilati S, Bagagli G, Sonego P et al (2017) Abscisic acid is a major regulator of grape berry ripening onset: New insights into ABA signaling network. Front Plant Sci 8. https://doi.org/10.3389/fpls.2017.01093
Pirrello C, Mizzotti C, Tomazetti TC et al (2019) Emergent ascomycetes in viticulture: an interdisciplinary overview. Front Plant Sci 10
Plantevin M, Gowdy M, Destrac-Irvine A et al (2022) Using δ13C and hydroscapes for discriminating cultivar specific drought responses. Oeno One 56:239–250. https://doi.org/10.20870/oeno-one.2022.56.2.5434
Reynolds A, Naylor A (1994) 'Pinot noir' and 'riesling' grapevines respond to water stress duration and soil water-holding capacity. Hort Sci 29:1505–1510. https://doi.org/10.21273/HORTSCI.29.12.1505
Ricardo-Rodrigues S, Laranjo M, Coelho R et al (2019) Terroir influence on quality of 'Crimson' table grapes. Sci Hortic 245:244–249. https://doi.org/10.1016/j.scienta.2018.10.035
Romero P, Botía P, Keller M (2017) Hydraulics and gas exchange recover more rapidly from severe drought stress in small pot–grown grapevines than in field–grown plants. J Plant Physiol 216:58–73. https://doi.org/10.1016/j.jplph.2017.05.008
Sadras VO, Moran MA (2013) Nonlinear effects of elevated temperature on grapevine phenology. Agric For Meteorol 173:107–115. https://doi.org/10.1016/j.agrformet.2012.10.003

Santillán D, Garrote L, Iglesias A, Sotes V (2020) Climate change risks and adaptation: new indicators for Mediterranean viticulture. Mitig Adapt Strateg Glob Chang 25:881–899. https://doi.org/10.1007/s11027-019-09899-w

Santillán D, Iglesias A, La Jeunesse I et al (2019) Vineyards in transition: A global assessment of the adaptation needs of grape producing regions under climate change. Sci Total Environ 657:839–852. https://doi.org/10.1016/j.scitotenv.2018.12.079

Santos JA, Fraga H, Malheiro AC et al (2020) A review of the potential climate change impacts and adaptation options for European viticulture. Appl Sci (Switzerland) 10:3092. https://doi.org/10.3390/app10093092

Savoi S, Wong DCJ, Arapitsas P et al (2016) Transcriptome and metabolite profiling reveals that prolonged drought modulates the phenylpropanoid and terpenoid pathway in white grapes (Vitis vinifera L.). BMC Plant Biol 16. https://doi.org/10.1186/s12870-016-0760-1

Schmidt R, Gravuer K, Bossange AV et al (2018) Long–term use of cover crops and no–till shift soil microbial community life strategies in agricultural soil. PLoS One 13. https://doi.org/10.1371/journal.pone.0192953

Schultz HR (2022) Soil, vine, climate change; the challenge of predicting soil carbon changes and greenhouse gas emissions in vineyards and is the 4 per 1000 goal realistic? Oeno One 56:251–263. https://doi.org/10.20870/oeno-one.2022.56.2.5447

Science On a Sphere (2013) Climate Model: Temperature Change (RCP 4.5) – 2006 – 2100. https://sos.noaa.gov/catalog/datasets/climate–model–temperature–change–rcp–45–2006–2100/. Accessed 4 May 2023

Seager R, Osborn TJ, Kushnir Y et al (2019) Climate variability and change of mediterranean–type climates. J Clim 32:2887–2915. https://doi.org/10.1175/JCLI-D-18-0472.1

Serat B, Kulkarni SS (2013) Effect of Shade Net on Yield and Quality of Grapes cv. Thompson Seedless. IJSR 4:1841–1844

Singh BK, Delgado-Baquerizo M, Egidi E et al (2023) Climate change impacts on plant pathogens, food security and paths forward. Nat Rev Microbiol 21:640–656

Tomás M, Medrano H, Pou A et al (2012) Water–use efficiency in grapevine cultivars grown under controlled conditions: Effects of water stress at the leaf and whole–plant level. Aust J Grape Wine Res 18:164–172. https://doi.org/10.1111/j.1755-0238.2012.00184.x

Tzortzakis N, Chrysargyris A, Aziz A (2020) Adaptive response of a native mediterranean grapevine cultivar upon short–term exposure to drought and heat stress in the context of climate change. Agronomy 10. https://doi.org/10.3390/agronomy10020249

Uysal Y, Doğaroğlu ZG, Çaylali Z, Makas MN (2023) Evaluation of swelling properties of different biochar–doped hydrogels. J Soils Sediments 23:3787–3805. https://doi.org/10.1007/s11368-023-03594-9

Valdés-Gómez H, Gary C, Cartolaro P et al (2011) Powdery mildew development is positively influenced by grapevine vegetative growth induced by different soil management strategies. Crop Prot 30:1168–1177. https://doi.org/10.1016/j.cropro.2011.05.014

Vimal SR, Singh JS, Arora NK, Singh S (2017) Soil–Plant–Microbe Interactions in Stressed Agriculture Management: A Review. Pedosphere 27:177–192. https://doi.org/10.1016/S1002-0160(17)60309-6

Watt M, Silk WK, Passioura JB (2006) Rates of root and organism growth, soil conditions, and temporal and spatial development of the rhizosphere. Ann Bot 97:839–855. https://doi.org/10.1093/aob/mcl028

wein.plus (2022) Morocco. In: https://glossary.wein.plus/morocco

Wine–Searcher (2021) Aegean Wine. In: https://www.wine-searcher.com/regions–aegean

Zsófi Z, Váradi G, Bálo B et al (2009) Heat acclimation of grapevine leaf photosynthesis: Mezo– and macroclimatic aspects. Funct Plant Biol 36:310–322. https://doi.org/10.1071/FP08200

Zufferey V, Spring JL, Verdenal T et al (2017) Influence of water stress on plant hydraulics, gas exchange, berry composition and quality of pinot noir wines in Switzerland. Oeno One 51:37–57. https://doi.org/10.20870/oeno-one.2017.51.1.1314

Authors and Affiliations

João Prada[1,2,3,4,5] · Lia-Tânia Dinis[1,2,6] · Elia Soriato[7] · Elodie Vandelle[7] · Oğuzhan Soletkin[8] · Şener Uysal[9] · Abdelhi Dihazi[10] · Conceição Santos[3,4] · João A. Santos[1,2,6]

✉ João Prada
joao.prada@fc.up.pt

1 Universidade de Trás-os-Montes e Alto Douro Escola de Ciências Agrárias e Veterinárias, UTAD, Quinta de Prados, 5000-801 Vila Real, Portugal

2 Centre for the Research and Technology of Agroenvironmental and Biological Sciences, CITAB, University of Trás-os-Montes and Alto Douro, UTAD, Quinta de Prados, 5000-801 Vila Real, Portugal

3 LAQV-REQUIMTE, Faculdade de Ciências da Universidade do Porto, Porto, Portugal

4 iB2, Departamento de Biologia, Faculdade de Ciências da Universidade do Porto, Porto, Portugal

5 Fundação Côa Parque, Rua do Museu, 5150-620, Vila Nova de Foz Côa, Guarda, Portugal

6 Inov4Agro - Institute for Innovation, Capacity Building and Sustainability of Agri-Food Production, University of Trás-os-Montes and Alto Douro (UTAD), Quinta de Prados, 5000-801 Vila Real, Portugal

7 Dipartimento di Biotecnologie, Università degli Studi di Verona, Strada Le Grazie, 15, 37 134 Verona, Italy

8 Viticulture Research Institute, Department of Agronomy, Yunusemre, 45125 Manisa, Turkey

9 Viticulture Research Institute, Department of Agricultural Economics, Yunusemre, 45125 Manisa, Turkey

10 Agrobiotechnology and Bioengineering Center, Faculty of Sciences and Technology, Cadi Ayyad University, Marrakech, Morocco