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Invited review article

Using bioclimatic indicators to assess climate change impacts on the Spanish wine sector

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ABSTRACT

Grapevine cultivation is an ancestral practice in Mediterranean regions such as Spain. The current climatic characteristics of this region make it a particularly optimal area for its cultivation, and the climatic changes expected in the coming decades may jeopardise this climatic suitability. Therefore, accurate studies of future projections at a local level are essential.

Local climate change scenarios of six bioclimatic indicators (absolute values together with their categorisation) related to vineyards for the Spanish region based on nine Earth System Models (ESMs) as well as two Representative Concentration Pathways (RCPs) corresponding to the fifth phase of the Coupled Model Intercomparison Project (CMIP5) were generated for the first time. These indicators are the Huglin Index (HI), the Cool Index (CI), the Dryness Index (DI) and the Hidrotermic Index. As a complement, two combined indicators were calculated: the Multicriteria Climatic Classification System (MCC System) and the Composite Index (CompI). The whole territory was analysed as well as the areas involved in the Spanish Denominations of Origin (DOs).

Our results show that Thermal indicators (HI and CI) will tend to increase through the twenty-first century, while water scarcity (DI) will be more pronounced. The trends found do not have the same repercussions throughout the territory. In the south of the peninsula, with HI values exceeding 3500°C and CI above 20°C and DI below −200 mm, the continuity of the wine-growing sector in its current state is seriously endangered, with a decrease in climatically optimal years as shown by the CompI values. On the contrary, the northern peninsula and mountainous areas, despite the expected increases, with HI below 2500°C, cool nights (CI below 15°C) and sufficient water supply (DI above 150 mm) considerably improve their climatic suitability (CompI) although the risk of mildew disease remains due to the increase in temperature and humidity.

1. Introduction

Over the last decades, changes directly related to the heliothermal and hydric requirements that grapevines need for optimal growth have been observed because of climate change. Among others, increases in temperatures, alterations in the precipitation regime, alterations in potential evapotranspiration or increases in CO_2 concentrations are affecting vineyards worldwide (Alonso and O'Neill, 2011; Battaglini et al., 2009; France and Dubourdieu, 2016).

Grapevine is very sensitive to climate (White et al., 2006; Winkler, 1974) and weather conditions over a wide range of time scales (Santos et al., 2020). Changes in the weather/climate patterns due to climate change are causing numerous impacts on the cultivation of grapes (Jones et al., 2005) with economic repercussions, especially in warmer areas such as Spain.

Average climate and climatic variability are the environmental factors that most influence wine quality and production (Santos et al., 2011). The results shown by climate projections seem to show a trend towards stronger and stronger impacts (Meehl et al., 2007) and a shift of the optimal areas for vine cultivation towards the Poles by about 20° by 2050 (Kenny and Harrison, 1993; Tate, 2001). Many studies have highlighted how climate change will alter current wine-growing regions and the need to act accordingly (Jones and Alves, 2012; Lazoglou et al., 2018; Schultz and Stoll, 2010; White et al., 2006, Ollat et al., 2016).

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Europe, as one of the world's major wine-growing regions, is one of the areas most affected by climate change, where extreme events are expected to become more pronounced (Gaitan et al., 2020; Porter and Semenov, 2005). This will lead to increased irrigation demand (Doll, 2002), increased diseases and pests (Alig et al., 2002) and changes in viticultural zoning (Malheiro et al., 2010).

Spain is one of the main wine producers and exporters as well as the world's leading vineyard (with 949,565 ha of vineyards, 13% of the world total, FEV, 2021). Due to its location in southern Europe, it is expected to be one of the regions most affected by climate change, especially rising temperatures and water stress (Gaitan et al., 2019, Gaitan et al., 2020). Indeed, these impacts are detectable today. In Spain, along with the aforementioned impacts, the area of vineyards has decreased in the north-east of the peninsula as a result of water stress (Odo Camps and Ramos, 2012), an increase in the demand for irrigation (Alonso and O'Neill, 2011) and a reduction in the life expectancy of vines by 30% (EXPANSIÓN, 2016). According to a study by the University of La Rioja (EXPANSIÓN, 2019), 90% of professionals associated with a Designation of Origin have felt the effects of climate change and 56% consider that these impacts are affecting them considerably. Among the climatic risks that most affect them are frost, hail, drought and heat waves (Climate change and vineyards in Spain report, 2016). Therefore, determining the relationship between climate and vineyard and assessing its future evolution is of particular interest in regions such as Spain, where the wine sector is not only important in terms of biodiversity but also socio-economic terms.

It is possible to evaluate the relationship between climate/weather and the different factors affecting vines and wine production as a whole by using bioclimatic indices (Fregoni, 2003), which make it possible to determine the climatic suitability of a region for growing vines, the most suitable variety or the possibility of the occurrence of certain pests and/or diseases.

Classical studies use individual indices calculated and derived from temperature and precipitation (Carbonneau and Tonietto, 1998; Tonietto, 1999; Fraga and Santos, 2017) to assess climate-vineyard relationships (Bindi et al., 1996, Jones, 2006) and their impact from different perspectives (Schultz, 2000, Combris et al., 1997).

More recent studies have highlighted the need to work with combined indices as they represent more complete viticultural classification and discrimination and allow wine quality to be characterised (Huglin, 1978; Magalhaes, 2008). This way of working is included in the concept of viticultural zoning and is the first step to evaluate the viticultural potential of a region (Malheiro et al., 2010).

Despite many indications and reports on the effects that climate change has already had on the wine sector, the efforts of the scientific community to identify the relationships between weather variables and vines and the impact of these changes in the future, there are still few studies focused on how wine producers and growers can adapt to these changes (Holland and Smit, 2010).

In addition, most studies use dynamic climate projections (which have not taken into account local climatology), direct outputs from climate models or a limited number of Spanish locations, as they are part of studies covering larger geographical areas. To date, no study assesses the impact of climate change on vineyards in the Ibero-balear Spanish territory using bioclimatic indices calculated based on regionalised climate projections on a local scale with a statistical downscaling technique (considering local climatology) generated from climate models belonging to CMIP5.

Therefore, this study aims to generate local future climate scenarios for the twenty-first century for four individual bioclimatic indices of viticultural impact: Huglin Index (HI), Dryness Index (DI), Cool night Index (CI) and Branas, Bernon and Levadoux Hydrotermal Index (HyI), a combined index (CompI) and a viticultural zonation (MCC System, Tonietto and Carbonneau, 2004) for the Iberian-Peninsular Spanish territory. As a starting point, local daily climate projections generated through a statistical downscaling technique fed with CMIP5 scenarios will be used.

This study will make it possible to assess the suitability of the study area for wine-growing, as well as to determine what areas are going to lose or gain wine-growing potential, which will be very useful information for defining possible adaptation measures and decision making for the wine-growing sector in the face of climate change.

2. Materials and methods

2.1. *Study area*

This study was carried out on the Spanish peninsular territory and the Balearic Islands (Fig. 1) covering an area of 588,294 km^2. Due to its location close to large bodies of water and its complex orography (from sea level to peaks exceeding 3400 km), the Spanish climate is very varied and complex, so that up to 13 climatic regions can be counted according to the Köppen classification (Köppen and Geiger, 1936), and there are multiple local climate. The climate of the Iberian Peninsula depends on its location in the extreme southwest of Europe and its complex orography, while the Balearic Islands are located in the western Mediterranean close to the Iberian Peninsula and are relatively mountainous.

The Spanish mainland and the Balearic Islands have very optimal climatic conditions that favour the cultivation of grapevines, as reflected in the almost 950,000 ha of Spanish territory dedicated to its cultivation.

The Canary Islands have not been included in the study because, due to their climatic characteristics, a consequence of their location in tropical areas, they differ from those of the rest of the Spanish territory and they deserve an individual study that encompasses these differences.

2.2. *Spanish Denominations of Origin (DOs)*

The Spanish DOs are the system used in Spain for the recognition of a differentiated quality, which is the result of specific and distinguishable characteristics due to the geographical environment in which the raw materials are produced and the products are made as well as the influence of the human factor involved. In Spain, there is a wide network of recognised quality according to the Government of Spain (2021): 101 Denominations of Origin (occupying an area of >900.000 ha), 42 Protected Geographical Indications and 26 "Vinos de Pago" (MAPA, 2022 Ministry of Agriculture, Fisheries and Food).

2.3. *Datasets*

2.3.1. *Surface dataset*

The observed data set used in the study consists of a set of time series of daily maximum and minimum temperature and daily precipitation data homogeneously distributed throughout the territory and belonging to the network of observatories of the Spanish Meteorological Agency (AEMET, www.aemet.es).

The selected dataset is the same that has been used in previous studies in the generation of local future climate scenarios for the study area (Gaitan et al., 2019; Gaitan et al., 2020; Gomez-Martinez et al., 2021; Monjo et al., 2016; Ribalaygua et al., 2013b), which have been subjected to strict quality control (p.e. inhomogeneities, gaps and outliers, López et al., 2007).

A total of 1778 observatories with data of both temperature and precipitation were used in the study, covering extensively the entire territory under study (Fig. 1a). For the analysis of the results by Denominations of Origin (DOs), we have chosen those observatories that are located within the territory classified as such (Fig. 1b). In total, there are 789 observatories within 59 DOs located in the iberian-balearic territory (the DOs where no observatories with information of temperature and precipitation simultaneously or with poor meteorological information were found are left out of the present study).

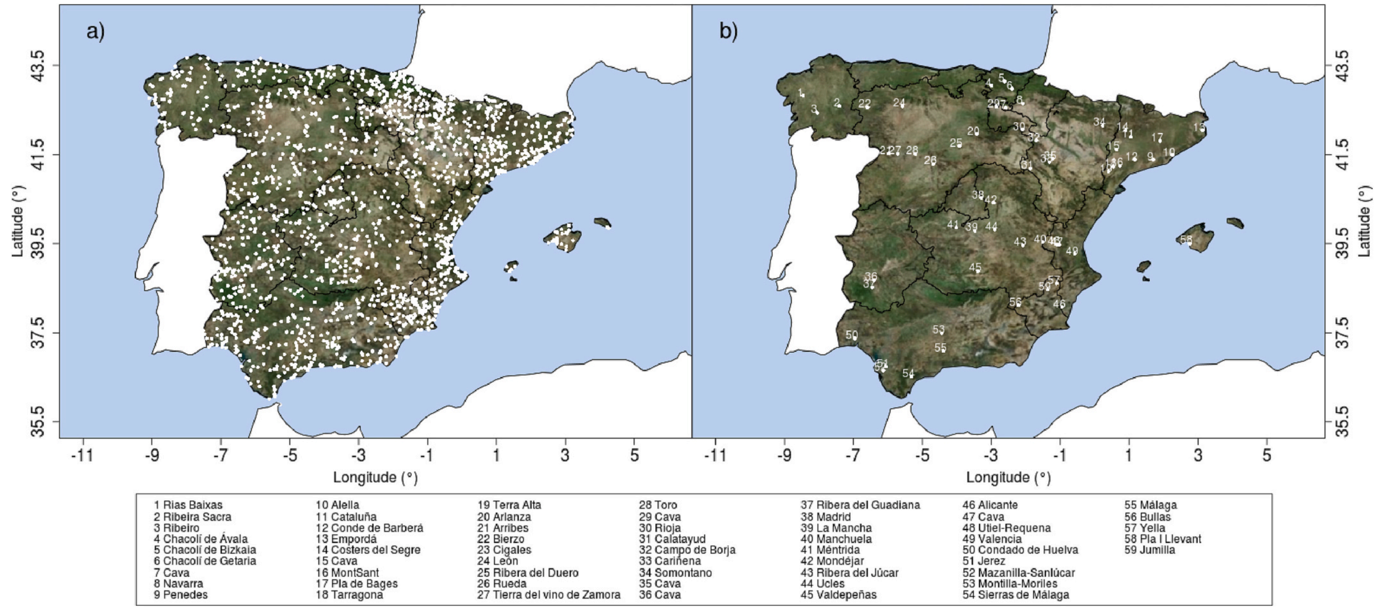

Fig. 1. Location of the study Area. a) Shows the points corresponding to the observatories used in the complete study with available temperature and precipitation data. b) Shows the location of the denominations of origin “(Map source: OpenStreetMap)”.

2.3.2. *Local future climate scenarios*

A set of daily local future climate projections of temperature (maximum and minimum) and precipitation obtained by applying a two-step analogue/regression statistical downscaling methodology developed by the Climate Research Foundation (FIC) was used (Ribalaygua et al., 2013a; Ribalaygua et al., 2013b). This methodology offers some advantages: it is computationally inexpensive, provides local information at observatory scale and allows quantifying the uncertainty associated with the downscaling process (Van der Linden and Mitchell, 2009). Other advantages are the application of future simulations consistent with observations (physically coherent between them) and using local scale (because nearby data points in space are subjected to different climate change conditions) (Ribalaygua et al., 2013b).The generation of daily future climate local scenarios was based on nine global climate models (Table 1), called Earth System Models (ESMs, (Wang et al., 2010), belong to the fifty phase of the Coupled Model Intercomparison Project (CMIP5, Tripathi et al., 2006) and supplied by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archives. This generation of models has contributed to the acquisition of both dynamical and statistical downscaling techniques with less uncertainty in integrating the individual parts of the climate system (atmosphere, ocean, land and sea ice) and the exchange of energy and mass between them (Knutti and Sedlacek, 2013).

This study uses data from two different experiment families of GCMs: the Historical experiment (Taylor et al., 2012), which covers much of the industrial period and can be referred to as “twentieth-century” simulations and the representative concentration pathway (RCP) family (Moss et al., 2010), which corresponds to different possible ranges of radiative forcing reached in the year 2100 for values of the pre-industrial era. This study uses future projections determined by the RCP8.5 ‘high’ scenario and the RCP4.5 ‘intermediate’ scenario.

In total, there is a set of 18 daily climate projections for two emission scenarios, RCP4.5 and RCP8.5 (9 projections for each RCP).

The methodology employed for generating temperature and precipitation projections has been used in national and international projects, with good verification (Gaitan et al., 2019; Monjo et al., 2016; Moutahir et al., 2017; Rodriguez et al., 2014; Santiago et al., 2017; Gutierrez et al., 2019; Ribalaygua et al., 2013a, 2013b, 2018) and validation results (Ribalaygua et al., 2013a, 2013b; Gaitan et al., 2019, 2020; Monjo et al., 2016). Verification results (goodness of the methodology used) obtained in the above-mentioned studies showed good results for both, temperatures and precipitation. In the case of the temperature, the average bias achieved was below 0.1°C (which is an error of the simulated climate mean, so it does not accumulate from one

Table 1
Information about the nine climate models belonged to the 5 Coupled Model Intercomparison Project (CMIP5) corresponding to the fifth report of the IPCC. Models were supplied by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archives.°

Climatic model	Spatial /temporal resolution	Research center	References
GFDL-ESM2M	2° x2,5° daily	National Oceanic and Atmospheric Administration (NOAA), E.E.U.U.	Dunne et al. (2013)
CanESM2	2,8° x2,8° daily	Canadian Centre for Climate Modeling and Analysis (CC-CMA), Canadá	Chylek et al. (2011)
CNRM-CM5	1,4° x1,4° daily	CNRM (Centre National de Recherches Meteorologiques), Meteo-France, Francia	Voldoire et al. (2013)
BCC-CSM1–1	1,4°x1,4° daily	Beijing Climate Center (BCC), China Meteorological Administration, China	Xiao-Ge et al. (2013)
HADGEM2-CC	1,87° x1,25° daily	Met Office Hadley Center, United Kingdom	Collins et al. (2008)
MIROC-ESM-CHEM	2,8°x2,8° daily	Japan Agency for marine-Earth Science and Technology (JAMSTEC), Atmosphere and Ocean Research Institute (AORI), and National Institute for Environmental Studies (NIES), Japan	Watanabe et al. (2011)
MPI-ESM-MR	1,8° x1,8° daily	Max-Planck Institute for Meteorology (MPI-M), Germany	Raddatz et al. (2007); Marsland et al. (2003)
MRI-CGCM3	1,2° x1,2° daily	Meteorological Research Institute (MRI), Japan	Yukimoto et al. (2011)
NorESM1-M	2,5° x1,9° daily	Norwegian Climate Centre (NCC), Norway	Bentsen et al. (2013); Iversen et al. (2013)

day to the next) while for precipitation, an error of 10–20% was obtained. The signal of climate change in mean precipitation is always weaker due to natural climate variability but the combination of precipitation and evapotranspiration makes the water balance clearly negative despite these uncertainties. Validation results obtained in the above-mentioned studies for both the maximum and minimum temperatures, showed a bias of around tenths of a degree in all months, so they were very close to zero. The error was not above half of a degree for any of the cases. Therefore, the results showed that the ESMs were capable of adequately simulating both the maximum and the minimum temperatures on annual and seasonal scales. In the case of the precipitation, the results are variable depending on the model and the seasonal period; however, all the models are able to reproduce the annual cycle of precipitation as well as the differences between seasonal periods (maximum values in autumn and spring, followed by winter and summer). The obtained bias and standard deviation are less than ±1 mm/day, which in relative terms supposes a difference of less than or around ±10% in the worst of the cases. Systematic errors (commented in previous paragraphs) have been corrected on a daily scale and do not affect the climate change signal of the bioclimatic indicators.

From the simulated temperature series, future heat and cold wave episodes have been calculated following Gaitan et al., 2019. Heat Waves have been defined at least three consecutive days with a maximum temperature above the 95th percentile of the maximum temperature series calculated between the months of June to September during the period 1971–2000 and at least three consecutive days with a minimum temperature below the fifth percentile of a minimum temperature series and calculated between the months of November to April during the period 1971–2000.

2.4. Bioclimatic indices

A set of four bioclimatic indices (Huglin Index (HI), Dryness Index (DI), Cool night Index (CI) and Branas, Bernon and Levadoux Hydrotermal Index (HyI)) was used to assess the impact that climate change may have on the suitability of a region for growing grapevines and/or certain grape varieties. In addition, two combinations of these indices were analysed: MCC System and CompI. For a complete explanation of indices' definition see Table 2.

The Dryness Index (DI) assesses soil water availability by providing information on water stress conditions. In the absence of information on future land use and other variables, it was decided to use a simplified formula proposed by Tonietto and Carbonneau, 2004 and based on the calculation of the potential evapotranspiration (ETP). According to various studies (Blanco-Ward et al., 2007; Vanderlinden et al., 2004) and specifically Fonseca Conceicao et al., 2012, the Hargraves formula was chosen for the calculation of ETP instead of other more complex formulations.

Table 2
Description of analysed bioclimatic indicators.

Index	Formula	Values or Categories		Interpretation	Description	References
Huglin Index	$\sum_{Abril}^{Sept.}\frac{(\overline{T}-10)(T_{max}-10)}{2}*k$	≤1200	0	—	HI is a thermal index based on degree-days, i.e. on the concept of heat accumulation. This index is used to evaluate the basic thermal and radiative demand of the grapevines during the growing period to guarantee a complete and adequate ripening. Each grape variety requires a certain amount of heat accumulation for optimal ripening to occur	Huglin, 1978
		1200–1500	1	HI-3: Very cool		
		1500–1800	2	HI-2: Cool		
		1800–2100	3	HI-1: Temperate		
		2100–2400	4	HI+1: Temperate warm		
		2400–2700	5	HI+2: Warm		
		2700–3000	6	HI+3: Very warm		
		≥ 3000	7	—		
Dryness Index	$\sum_{April}^{Sept.}(Wo+P-Tv-Es)$	> 150	5	DI-2: Humid	DI assesses soil water availability by providing information on water stress conditions	Riou et al., 1994 Tonietto and Carbonneau, 2004
		150–50	4	DI-1:Sub-humid		
		50–(−100)	3	DI+1:Moderately Dry		
		(−100)–(−200)	2	DI+2: Dry		
		≤ −200	1	DI+3: Very dry		
Cool night Index	$\overline{T}_{\min}$ (sept)	≥25	5	—	CI is a thermal index based on the night temperature during the ripening period (September in the Northern Hemisphere (NH))	Tonietto, 1999
		18–25	4	CI1: Warm nights		
		14–18	3	CI2: Temperate nights		
		12–14	2	CI3: Cool nights		
		6–12	1	CI4: Very cool nights		
		≤6	0	—		
Hydrotermic Index (HyI)	$\sum_{April}^{Aug}(\overline{T}*P)$	< 2500	1	Low risk	HyI is an index that combines the effect of air humidity (through precipitation) and temperature during the growing season to assess the risk of grape exposure to certain diseases such as mildew	Branas et al., 1946, Branas, 1974
		2500–5100	2	Medium risk		
		5100–7500	3	High risk		
		>7500	4	Very high risk		
CompI Index	$\frac{n^{\circ}\ optimum\ years}{n^{\circ}\ years\ for\ a\ period}$ HI ≥ 900 °C DI ≥ −100mm HyI ≤ 7500°C·mm T_{min} > −17 °C (always)	0.0–0.2		% means the percentage of years suitable for viticulture	The CompI is an index to evaluate the climatic suitability for grape growth. The CompI is the percentage of optimum years for vine cultivation for a given period. An optimum year is understood as a year in which critical thresholds of the HI, DI, HyI indices and minimum temperature conditions are reached	Malheiro et al., 2010 Fraga et al., 2013
		0.2–0.4				
		0.4–0.6				
		0.6–0.8				
		0.8–1.0				
MCC System classification	Combination of HI, DI and CI	Most optimal categories: HI-3, HI-2, HI+1 CI+1; CI+2 DI-1, DI+1		Least optimal categories: CI-2, CI-1 DI+2, DI+3	The MCC System is a climatic classification system for grape-growing regions based on the integration of the different classes of the three climatic indices: DI, HI and CI	Tonietto and Carbonneau, 2004

$\overline{T} \equiv mean\ temperature\ (^{\circ}C)$
$T_{max} \equiv maximum\ temperature\ (^{\circ}C)$
$T_{min} \equiv minimum\ temperature$
$P \equiv Precipitation\ (mm)$
$N \equiv n^{\circ}\ days\ per\ month$

$Wo \equiv Initial\ available\ soil\ water\ reserve\ (mm) = 200mm$
$Tv \equiv Potential\ transpitarion\ in\ the\ vineyard\ (mm) = ETP * k$
$Es \equiv Direct\ evaporation\ from\ the\ soil\ (mm) = (ETP/N) * (1-k) * JPm$
$JPm = P/5$
$k(month) = 0, 0, 0,0.1,0.3,0.5,0.5,0.5,0.5,0, 0, 0)$

3. Results

3.1. Observed bioclimatic indices and their verification

The observed (categorised) absolute average values of the indices used in the study (HI, DI, CI, HyI, MCC System and CompI) for the period 1971–2000 can be seen in Fig. 2 and Support Information 1. The results clearly show a north-south and west-east spatial distribution.

Within the Iberian-Balearic territory, we can find HI values (Figs. 2a and S1a) that cover all the categories defined for this index, from 300 to about 3300°C, accumulated in the period from April to September.

Some regions with climatic characteristics not suitable for growing grapes were detected, either because they are too cold with HI < 1000 (Pyrenees) or too warm with HI > 3000 (some points in the Spanish Southwest).

The areas of the northern peninsula as well as most of the valleys of mountainous areas have characteristics of cold climates with HI values between 1500 and 1800 (category 2). In a smaller proportion, there are regions with temperate climates (HI 1800–2100).

In the mountainous regions of the Central System, the Iberian System and Betic System, we find HI values <1500 (category 1, very cold), which places them in the lower thermal limit for grapevine. However, most of the territory of Sierra Morena (the mountain range that runs from east to west in the south of the Iberian Peninsula) presents IH values that oscillate between 2700 and 3000 accumulated degrees (category 6), being areas with very warm climates.

The coastal areas of the Mediterranean and the plateau as well as Cádiz (SW Iberian Peninsula) are characterised by being warm areas (category 5) with a high heliothermic potential (HI between 2400 and 2700).

The values observed for the CI (Figs. 2b and S1b) in the ripening month (average minimum temperature in September) range between 4 and 20°C, which is a great difference between regions within the study area. Most of the northern half of the peninsula and the highest points of the Betic system present very cold CI values below 12°C (category 1). The rest of the northern zone and part of the central plateau present cold CI values between 12 and 14°C (category 2). The Mediterranean coast and the south and west areas of the peninsula, as well as the Balearic Islands, are characterised by mild nights (CI between 14 and 18°C, category 3). Very few areas have high minimum temperatures in

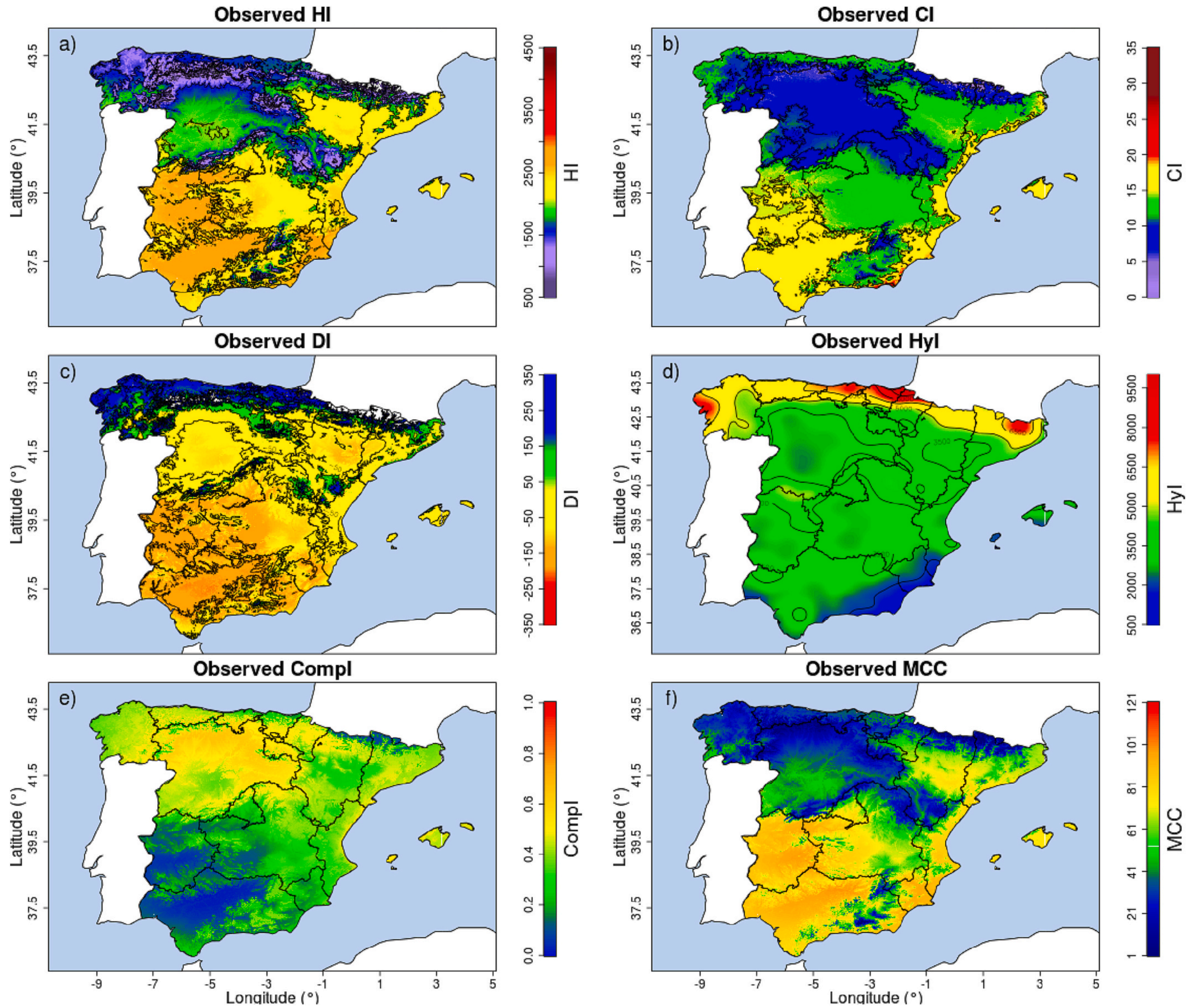

Fig. 2. Geographical representation of the observed values of the a) Huglin Index (HI), b) Cool night Index (CI), c) Dryness Index (DI), d) Branas, Bernon and Levadoux Index (HyI), e) Composite Index (CompI) and f) MCC System for the periods 1971–2000.

September (CI > 18, categories 4 and 5).

The DI values obtained (Figs. 2c and S1c) vary between −260 mm (very dry areas) and 500 mm (super-humid areas). The Cantabrian coast (N) presents the most humid conditions with DI values >150 mm (category 5), while the Cantabrian mountain range presents DI values higher than 50 mm (category 4), which implies humid and sub-humid characteristics with an absence of drought and a high level of water availability. Most of the northern plateau and the Balearic Islands have DI values between 50 to −100 mm (category 3) and are considered moderately dry areas. The rest of the peninsula is characterised by traditionally dry regions (DI between −100 and − 200 mm).

The observed HyI values (Figs. 2d and S1d) show that the southern regions have the lowest risk of incidence of diseases such as mildew (which depend on humidity and temperature to a great extent) and that the risk gradually increases towards the north where the precipitations are more abundant during the period of growth of grapevine.

Considering the aforementioned values, there will be years more suitable from the climatic point of view than others will. Fig. 2f shows the CompI index based on thresholds of some of the commented indices (Tmin, HI, DI, CI and HyI, see Table 2), which reveals that the southwest regions of the peninsula have an optimal percentage of years, climatically speaking, lower than those of the northern half and the Balearic Islands.

By combining these indices, we can establish within which values of the MCC System climatic classification the study area falls, since each of the indices separately is not a guarantee of viticultural climatic suitability. In total, we defined 120 combinations (see Table S1). The northern zone covers the classifications with categories between 1 and 20, the northern plateau belongs to those classifications with categories between 45 and 50, while the Mediterranean and eastern peninsular zones belong to the 70 and90 classes and, finally, the western and southern zones are included in the classes with categories between 90 and 100.

In the verification results (Fig. S2), the indices calculated based on observed data are compared with the indices calculated based on data the downscaled temperature and precipitation series of the ERA40 reanalysis. The verification shows very acceptable bias values for all the indices analysed. In the case of HI the mean Bias is around 104°-day (it supposes at relative error of 4%), for the CI is had been appreciated a mean Bias of 0.16°C (corresponding to a relative error of 1.2%), the DI mean Bias is around −10 mm (with a relative high error of 45% due to the simulation in very aridity places) and finally, the HyI has showed a mean Bias of −10°C *mm (it means a relative error of 0.2%).

3.2. Local future climate scenarios to predict bioclimatic indices

Figs. 3, 5, 7 and 9 show the expected future evolution for HI, CI, DI and HyI, respectively, in absolute terms starting with the historical reference period (1976–2005) and followed by correlative periods of 30 years from 2011 to 2100 as presentation of short, mid and end-century expected values, which have been predicted based on the nine models (see Table 1) and according to the RCP4.5 (top row) and RCP8.5 (bottom row) scenarios.

In addition, the simulated results for the present (Historical period) are displayed to see the expected changes relative to the current state. In the supplementary material, the same information is represented, but in a categorised way (Figs. S3, S5, S7 and S9).

To examine how the different DOs will be affected, Figs. 4, 6, 8 and 10 show the expected future evolution for HI, CI, DI and HyI, respectively, considering exclusively those observatories that are located within some DO (Fig. 1). The DOs have been represented following a geographical order (north at the bottom of the figure-south on the top). The complementary material represents the same information but in a categorised manner (Figs. S4, S6, S8 and S10).

In general, all the indices analysed showed a main north-south spatial distribution and a secondary west-east distribution, which, although it fades, tends to remain throughout the twenty-first century.

The entire Iberian-Balearic territory tends towards warmer climates, so that a large part of the territory will show movements towards increasingly warmer HI categories (Figs. 3 and S3), especially in the last section of the twenty-first century and in the most extreme case of RCP8.5. The highest areas of the territory will go from too-cold climates to optimal climates for any type of grape variety. All DOs show progressive increases in HI throughout the twenty-first century (Figs. 4 and S4) as evidenced by the gradation of the red colours in the graphs. Although in terms of categorisation it seems that the different territories will not undergo heliothermic variations (as is the case of the DO of the southern territories such as Andalusia or Murcia, see Figs. 3 and S3), the absolute values reflect these changes perfectly (see Figs. 4 and S4).

Under the RCP4.5 scenario, the DOs of the País Vasco are those that start with the lowest HI values, remaining at the end of the century with average HI values. It is followed by the DOs of Galicia and Castilla y

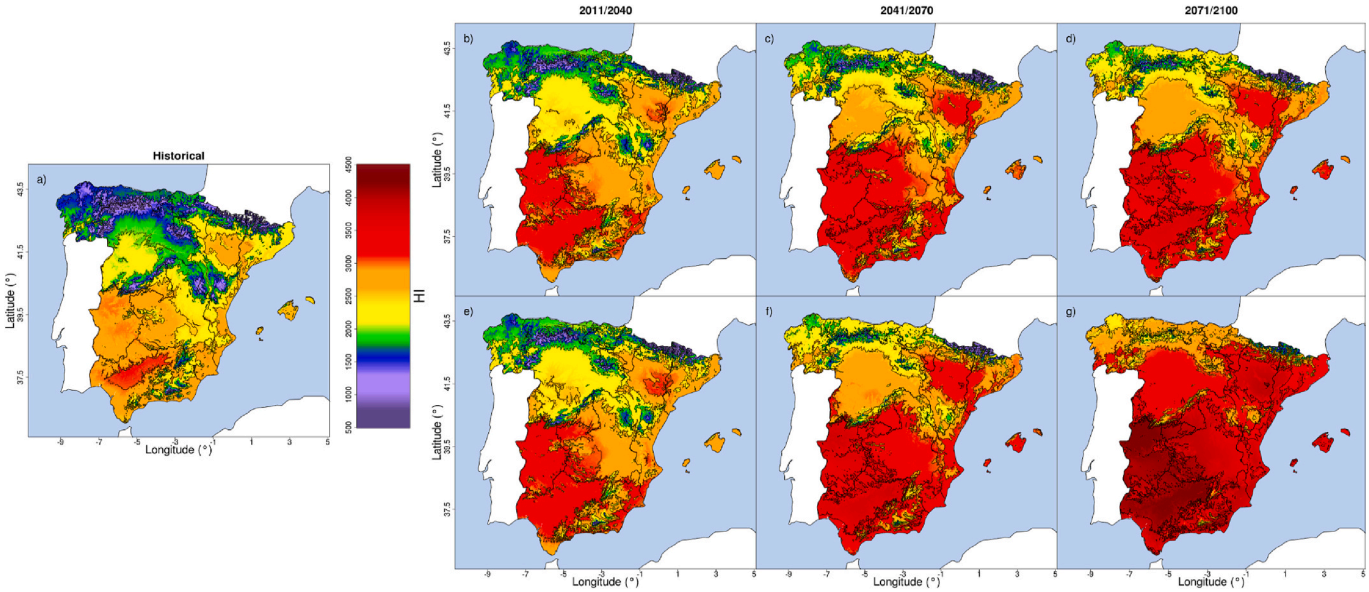

Fig. 3. Geographical representation of the expected values of the Huglin Index (HI) for the periods 2011–2040, 2041–2070 and 2071–2100. Both emissions scenarios are represented: RCP4.5 (figures b, c and d) and RCP8.5 (figures e, f and g). Fig. 3a represents the Historical absolute temperature for the period 1976–2005.

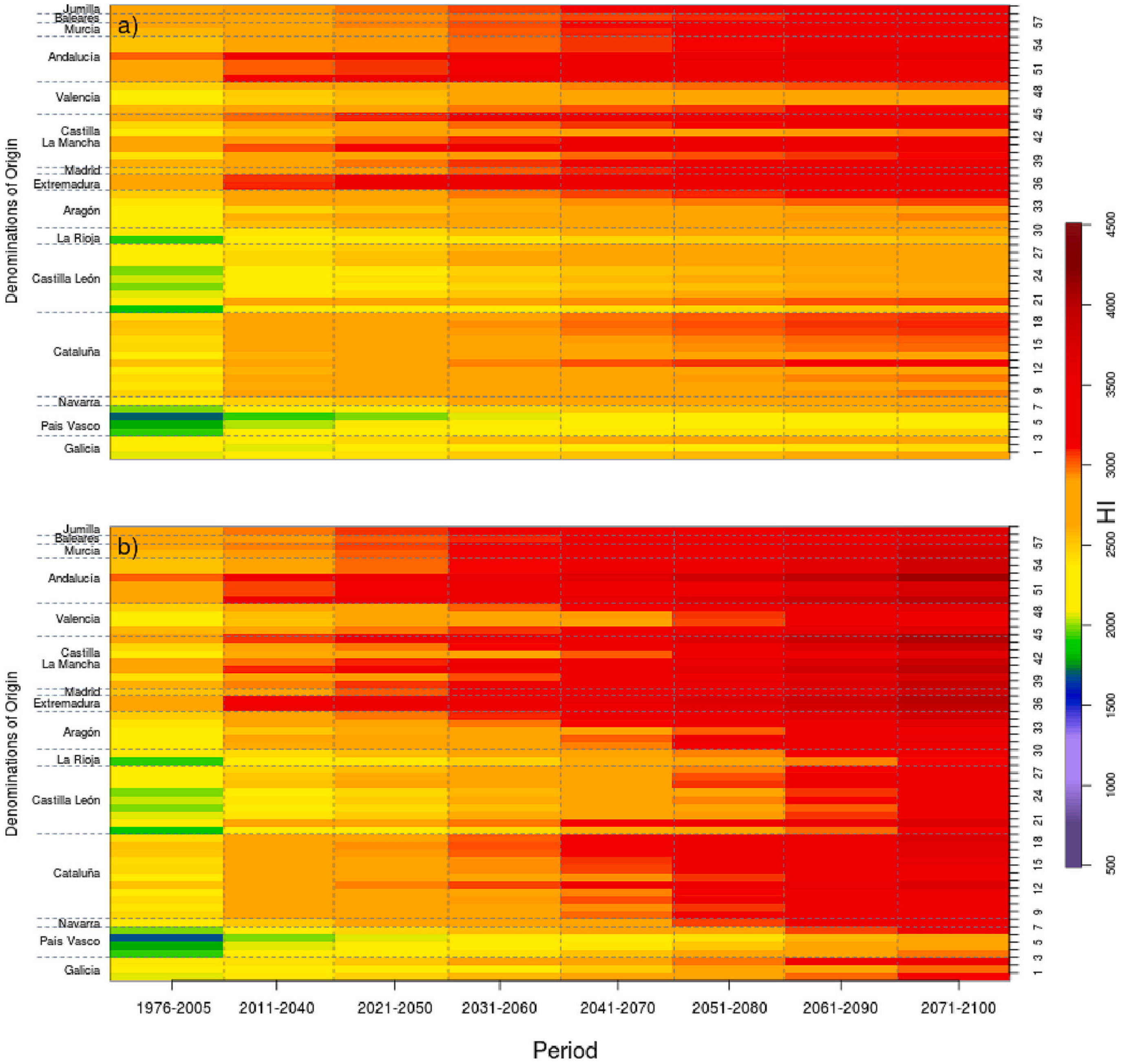

Fig. 4. Evolution of the expected values of the Huglin Index (HI) for the defined Denominations of origin (DOs). Historical period 1976–2005 and 7 correlative periods of 30 years starting on 2011 are showed. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b). Each row represents one DO (see Fig. 1 for number identification) and each column represents a considered period.

León, which gradually become warmer, and they will be the ones that change the most in categorisation throughout the twenty-first century. Under conditions of RCP8.5, the evolutions are much more pronounced, so that almost all DOs will be at the end of the twenty-first century under climates that are too hot, heliothermally speaking, for the cultivation of grapevine.

It is expected that the CI will increase throughout the twenty-first century in the entire territory studied by at least 1°C (Figs. 5 and S5), so that those regions that are at the upper limit of any of the categories pass to be included in the category immediately above. In general, all DOs are expected to vary between 3 and 4°C between current CI values and those expected at the end of the twenty-first century in the RCP4.5 scenario (Figs. 6a and S6b) and between 6 and 8°C under RCP8.5 conditions (Figs. 6b and S6b). The absolute values of the CI show how this index is expected to increase progressively throughout the twenty-first century. Under the conditions of RCP4.5, the DOs of Andalucía, Murcia and Cataluña are those that are expected to have higher CI values. Cooler nights in September are expected on the other side, for Euskadi, Castilla y León and Valencia.

In the future, it is expected that the DI tends to become increasingly dry values because of the increase in temperatures, and therefore of evapotranspiration, and that most of the peninsula and the Balearic Islands are at risk of water stress (Figs. 7 and S7). The northern and Mediterranean areas will be the ones that least accrue these changes, staying in humid or not very dry climates. The expected impact on the water balance (Figs. 8 and S8) shows that only the DO located in the País Vasco will maintain the status of a humid region in the coming decades. Most of the DO will remain at similar hydrological regimens, although

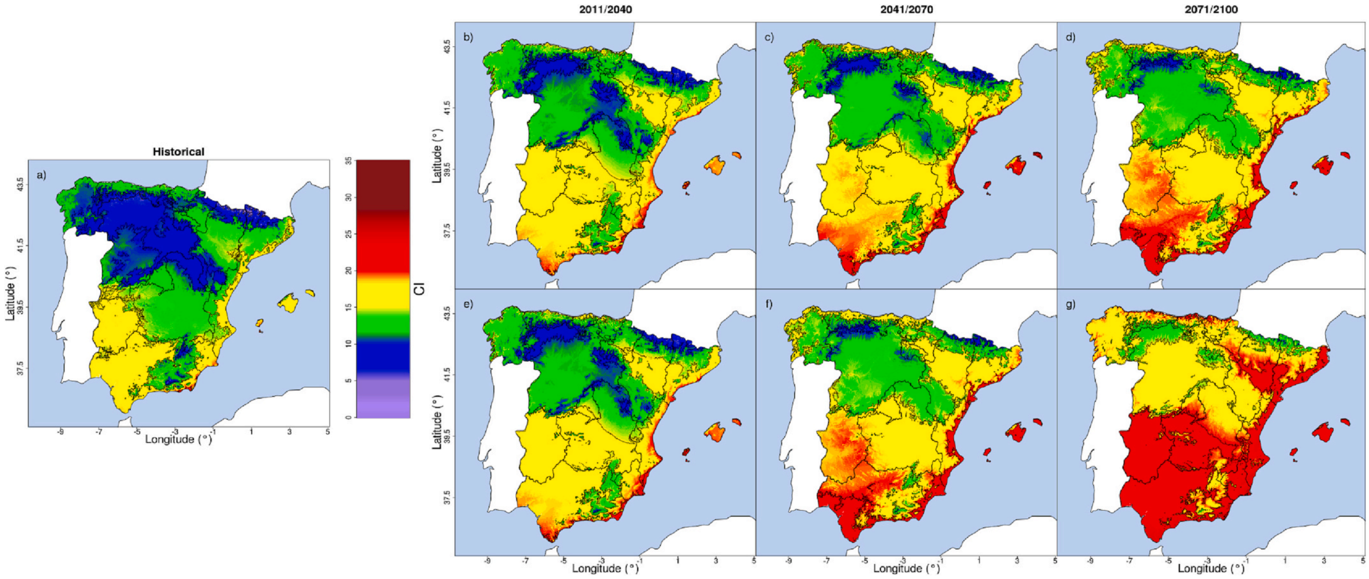

Fig. 5. Geographical representation of the expected values of the Cool Index (CI) for the periods 2011–2040, 2041–2070 and 2071–2100. Both emissions scenarios are represented: RCP4.5 (figures b, c and d) and RCP8.5 (figures e, f and g). Fig. 5a represents the Historical absolute temperature for the period 1976–2005.

the scenarios show a trend towards drier characteristics.

Although the HyI values increase in the coming decades, they remain within the range of medium risk of the presence of diseases such as mildew (Figs. 9 and S9). Most of the DOs (Figs. 10 and S10) will be at a low average risk of mildew presence throughout the twenty-first century. The DOs of Andalucía and Murcia are expected to present a low risk of the presence of mildew since their survival is not favoured due to the low precipitation. The DOs of the País Vasco, mainly, and those of Galicia will have the highest risk of suffering from mildew because of the increase in temperatures combined with the increase in the precipitation regime in these regions.

Finally, it is expected that in the coming decades the percentage of climatically optimal years will decrease throughout the territory (Figs. 11 and 12) a consequence mainly of variations in HyI and DI.

The analysed indices represent the expected changes in climatic characteristics associated with average variables and not with extreme events, such as extreme rainfall, drought or Heat/Cold Waves episodes. The latter, have a strong impact on the vine depending on the phenological stage of the vine at which they occur.

The increase in maximum temperatures will lead to a greater occurrence of heat wave episodes, as well as an increase in their duration, their average intensity and the maximum intensity reached within each heat wave episode (Figs. S13 and S14).

One of the most affected area will be the Mediterranean coast, where the average duration of a heat wave episode is expected to increase from 9 to 12 days to >18, increasing the average intensity and maximum intensity by 3–4°C. In the northern part of the Iberian Peninsula, although it will also suffer an increase in heat waves, this will be less pronounced than in the rest of the territory, with average increases in duration of 2–3 days and increases in intensity of 1–2°C. In the peninsular plateau and southern zone, the average duration of heat waves is also expected to increase by about 6 days (from 9 to 15 days in duration) with the increase in average and maximum intensity reached during these episodes (between 3 and 5°C) (see supporting information). These results are in line with the conclusions obtained by Molina et al., 2020 in the Mediterranean area, Torres et al., 2021 in the Balearic Islands and by Abaurrea et al., 2018 for the Iberian Peninsula.

The expected increases in minimum temperature will not prevent the occurrence of cold wave episodes (Figs. S15 and S16), although the average duration of cold wave episodes is increasingly shorter.

4. Discussion

This study analyses the evolution of climatic suitability for vine cultivation on the Spanish Mainland and the Balearic Islands based on a set of individual and combined bioclimatic indices using, for the first time, local future climate scenarios based on ESMs from the fifth IPCC report. In addition, the nine climate models available under two RCPs, provide a set of future climate projections of 18 possible future evolutions, which allows taking into account uncertainties, as recommended by various authors (Christensen et al., 2010; Fraga et al., 2014; Weigel et al., 2010).

Moreover, there are strong differences in assessing climate impact at the regional or local level (Santos et al., 2012). Local studies allow us to establish the origin of the main differences between grape types grown in neighbouring regions as suggested by Ramos et al. (2017) and which is evident in the results obtained when considering the future climate scenarios of the bioclimatic indices by DOs. These results reinforce the importance that climatic conditions have on the genuineness and unique character of each designation of origin.

The generation for the first time of future scenarios of bioclimatic indicators of great interest for the wine sector for the 21st century at local scale (considering local climatic characteristics) with a wide set of future climate projections using ESMs from the fifth IPCC report, brings novelty to the studies existing so far in the sector.

Therefore, these results offer one of the best snapshots of future climate change, based on currently available data, and the risks that changes in temperature and precipitation regimes could cause in the way grapevines are cultivated.

4.1. Considerations about the simulation of bioclimatic indices

The future climate scenarios at the local scale used as a basis to generate the future scenarios of bioclimatic indices were developed by the FIC with a two-step analogue methodology (Ribalaygua et al., 2013a), which has been verified and validated in various studies in Spanish territory with very good results (Gaitan et al., 2019; Gaitan et al., 2020; Gutierrez et al., 2019; Monjo et al., 2016; Ribalaygua et al., 2013b). Therefore, the future temperature and precipitation scenarios on which the bioclimatic indicators are obtained are robust and reliable. Moreover, it should be noted that there are studies that reinforce the idea that daily changes in atmospheric conditions play an important role

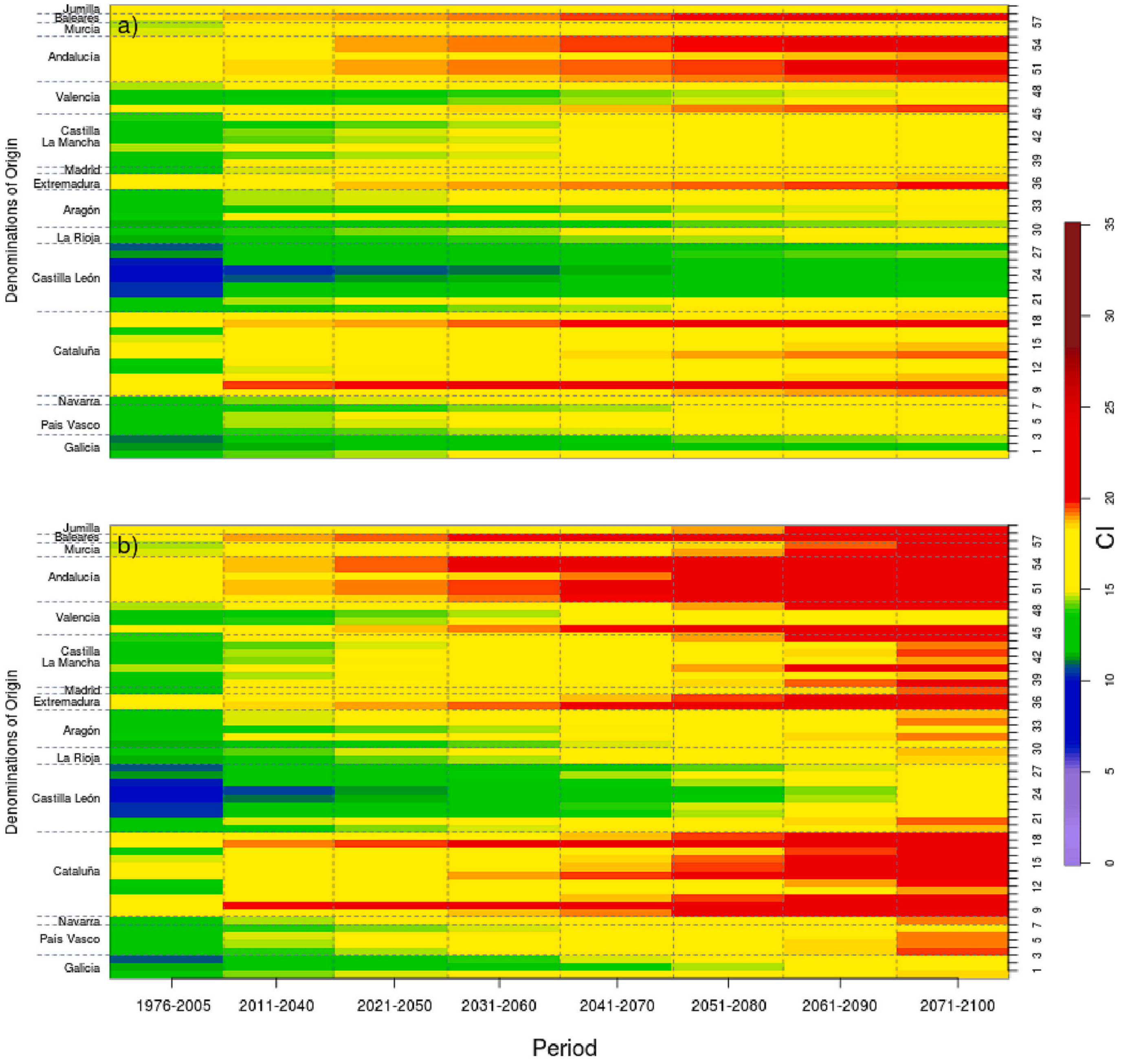

Fig. 6. Evolution of the expected values of the Cool Index (CI) for the defined Denominations of origin (DOs). Historical period 1976–2005 and 7 correlative periods of 30 years starting on 2011 are showed. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b). Each row represents one DO (see Fig. 1 for number identification) and each column represents a considered period.

in plant phenology (Jones and Davis, 2000), and these changes can be more or less significant depending on the region where they occur. These aspects are considered intrinsically in the type of downscaling's methodology used in this study.

Another factor to consider is the benefits that an increase of CO_2 under future climate conditions plays an important role in the development of the vine (Bindi et al., 2001; Goncalves et al., 2009; Moutinho-Pereira et al., 2009) which has only been indirectly considered in this study.

4.2. Local future climate scenarios of bioclimatic indices

In general terms, there is a positive trend in all thermal indicators (HI and CI) and a negative trend in the water index (DI). This reflects the twenty-first century with progressive increases in temperatures, both maximum and minimum, throughout the Iberian Peninsula, while hardly any changes in precipitation patterns are expected. The combination of the expected changes in both variables will have a strong impact on the vineyard. Similar results have been obtained for areas such as Portugal (Fraga et al., 2012), Italy (Bonfante et al., 2017, Bonfante et al., 2018), Germany (Neumann and Matzarakis, 2011; Stock et al., 2004), France(Duchene and Schneider, 2005, Duchene, 2016, García de Cortázar-Atauri et al., 2017) and Spain (Gomez-Gesteira et al., 2011; Ramos, 2017).

Consequently, although the northern regions will see their climatic suitability for growing grapes favoured, certain regions of the south and southwest of the Peninsula as well as the Mediterranean coast, that are at the limits of climatic suitability, may be negatively affected. These

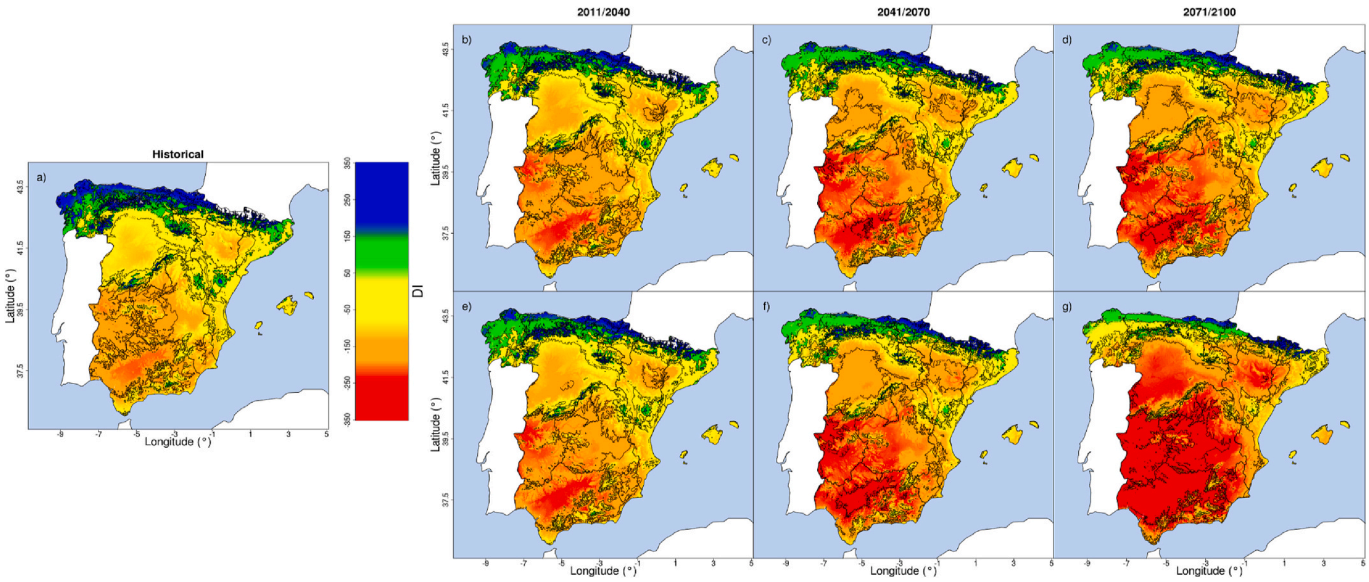

Fig. 7. Geographical representation of the expected values of the Dryness Index (DI) for the periods 2011–2040, 2041–2070 and 2071–2100. Both emissions scenarios are represented: RCP4.5 (figures b, c and d) and RCP8.5 (figures e, f and g). Fig. 7a represents the Historical absolute temperature for the period 1976–2005.

results confirm those obtained by (Fraga et al., 2012; Resco et al., 2016), among others.

The tendency of the HI values to increase is already in itself a determining factor of the variety of grape that can be grown in each zone since they determine the requirements for heat accumulation so that the ripening of the grape occurs optimally. The gradual change of the entire territory towards warmer climates will cause the necessary levels, in terms of heat, for the ripening of the grapes to occur at earlier times, which translates into an advancement of the ripening date (Molitor and Junk, 2019). This can subject vines to heat stress episodes in many regions. In addition, this index has a strong correlation with the different phenological states associated with warm conditions(Bock et al., 2011; Jones et al., 2005; Santos et al., 2012) so its increase would imply overtaking of certain phenological properties, which would alter the phenological cycle of the vine.

In this way, in areas that are too cold (according to our results, the Pyrenees area will be the only one that presents these characteristics), only very early varieties could reach maturity, usually white varieties. These regions should opt for a hybrid or American varieties, more resistant than the *Vitis vinifera*, while in the cool regions (high elevation mountainous regions, (category 3) both white and red can be grown. As the climate becomes more temperate (categories 4 and 5, some regions of the northern Peninsula under RCP4.5 and very few areas of the North under RCP8.5), almost any type of grape such as 'Garnacha' or 'Moscatell' can be grown in the first case and 'Pinot Blanc', 'Pinot Noir' or 'Chardonnay' in the second.

The greatest impact will occur in hot or very hot regions (categories 6 and 7), most of the Peninsular territory and the Balearic Islands, where the minimum requirements that the different grape varieties need to ripen, including those with late-ripening, will be exceeded. In very hot climates, there is a high risk of stress due to heat accumulation that can be detrimental to grapevine (most of the study territory, especially under the RCP8.5 scenario). HI values in the northern peninsular plateau are expected to be lower than those expected under RCP4.5, while the southern plateau and the Balearic Islands will reach very high HI values, regardless of the scenario considered.

In addition, it must be considered that within the same category it may be that each variety has different heat requirements to reach maturity (Tonietto, 1999) and that despite belonging to the same category they could not be cultivated. For example, the 'Cabernet Franc' variety requires an HI of 1800 cumulative degrees while the 'Cabernet Sauvignon' variety requires a HI of 1900 and the 'Ugni Blanc' variety needs a HI of 2000. Although their heliothermic requirements are different, both would be in HI Category 4. Therefore, if we only consider categorised values, we can run the risk of selecting varieties in areas that do not reach the necessary calorific requirements for said variety, hence the need to work with absolute values.

Regarding the CI, the expected increase in minimum temperatures will cause the CI to increase so that in some regions the night coolness necessary for optimal grape ripening will not be achieved. In addition, the advancement of the ripening dates suggests the need to evaluate this index on dates before September (Ramos and Martinez de Toda, 2021).

Changes towards very cold night temperatures can have a positive effect on certain varieties of grapes as long as a sufficient heliothermic contribution is guaranteed to ensure a good level of ripening of the berries. It is not expected that any study region will experience decreases in CI under RCP8.5, but in the case of RCP4.5, areas of the Pyrenees and the Cordillera Cantábrica will remain cold at night throughout the twenty-first century.

In those regions with fresh or medium CI values (such as what is expected to occur in most of the Southern Plateau, according to RCP4.5, and in the Northern Plateau, under both RCPs), the results can be both positive as well as negative depending on the cultivated variety, as the late varieties ripen in colder conditions than the early ones.

Finally, if the CI values are higher than 18°C (as will be the case of the Atlantic and Mediterranean coast and the Balearic Islands if RCP4.5 is considered or of the entire Southern Plateau plus the regions previously mentioned according to RCP8.5), the vines can suffer an excess of heat that affects the colour and aromatic potential of the grape.

The changes in the expected DI values condition the region's water supply and, therefore, determine the decisions to be made regarding irrigation. In the entire Iberian-peninsular territory except for the Cantabrian coast and the Pyrenees, regardless of the RCP considered, the DI values will decrease to the lower limit of 50 mm, so these territories will be at the lower limit of water supply, which may give rise to certain restrictions, especially in the summer months. If DI values < -100 mm, the region will be excessively dry, requiring an extra water supply.

On the contrary, values higher than 150 mm (as could occur in the areas of the Pyrenees or the Bay of Biscay) can reduce the quality of the wines and have higher quality grapes in wet years.

Intermediate DI values (between 50 and $-$ 100 mm) that are expected in regions such as Galicia or Asturias, will suffer certain periods

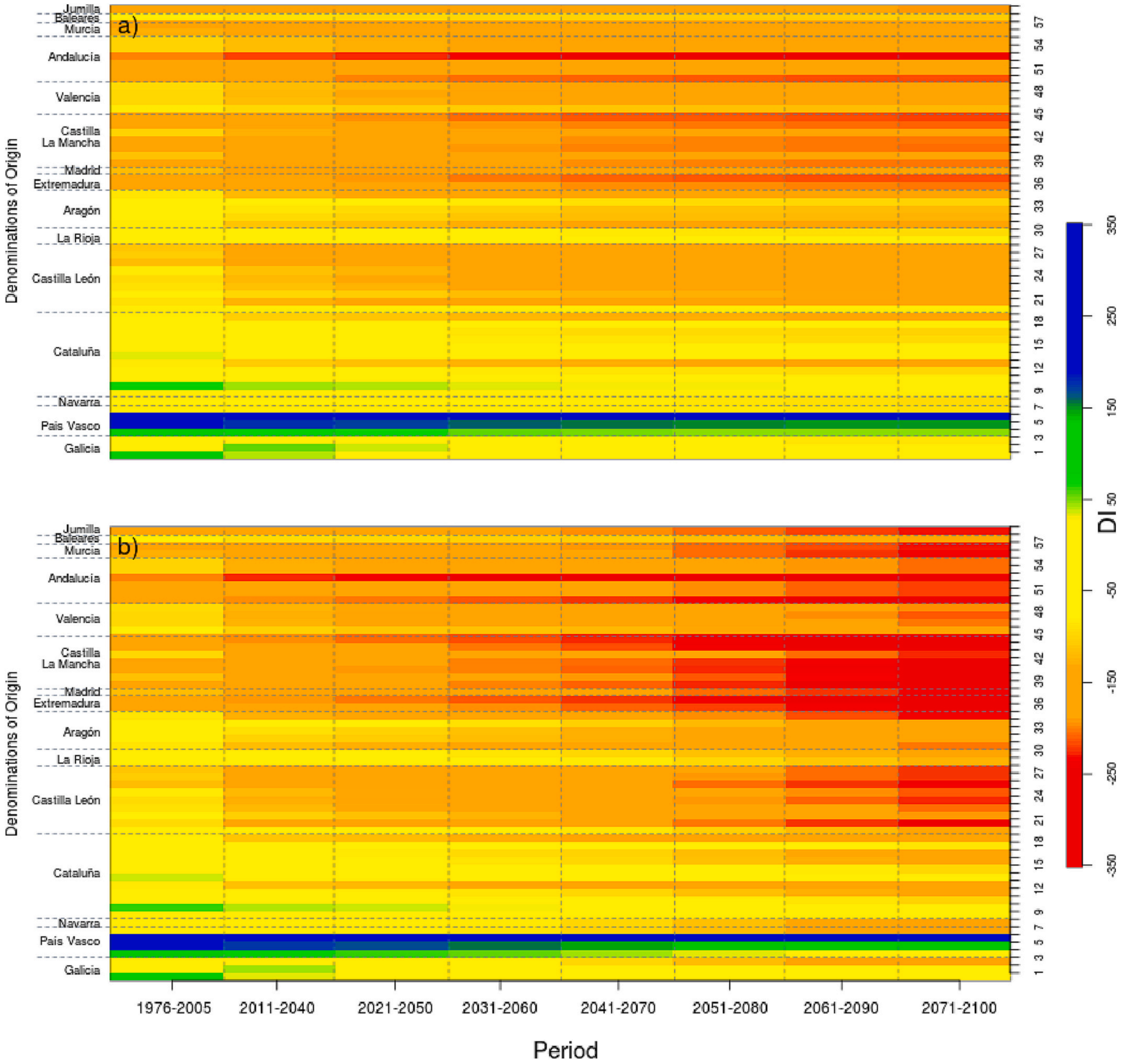

Fig. 8. Evolution of the expected values of the Dryness Index (DI) for the defined Denominations of origin (DOs). Historical period 1976–2005 and 7 correlative periods of 30 years starting on 2011 are showed. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b). Each row represents one DO (see Fig. 1 for number identification) and each column represents a considered period.

of drought that can become favourable during ripening.

The joint assessment of these indices through the MCC System allows establishing a more complete climatic vision of the suitability of the region. Of all the possible combinations, those that are more suitable for grapevine cultivation are those that combine HI values (categories HI-3, HI-2, HI + 1), CI (categories, CI + 1; CI +2) and DI (categories DI-1, DI + 1). While the least optimal have turned out to be those with CI (categories CI-2, CI-1) and DI (categories DI + 2, DI + 3). In the particular case of this study, it is expected that the optimal regions under this criterion will be found in the north of the peninsula, such as the Cantabrian Mountains and the Pyrenees, as well as in almost the entire Northern Plateau (according to both RCPs in the middle of the century). However, the Northern Plateau will only maintain these conditions under RCP4.5. These results are in line with those obtained by other authors (Fraga et al., 2013; Resco et al., 2016).

The combination of moderately low night temperatures with high daytime temperatures in these areas will favour the production of high-quality wines since the synthesis of some phenological components is favoured.

Regarding Hyl, no major changes are expected in the risk of certain diseases such as mildew, but there may be many differences between regions with very different precipitation patterns. The southern regions have a lower risk, which gradually rises to the north where precipitation will be more abundant during the vine growing season, similar to what other authors found (Fraga et al., 2013; Lazoglou et al., 2018).

The results obtained in the CompI index may seem contradictory since the largest Spanish wine-growing regions, such as Andalusia and Castilla-La Mancha, have a very low percentage of optimal years for

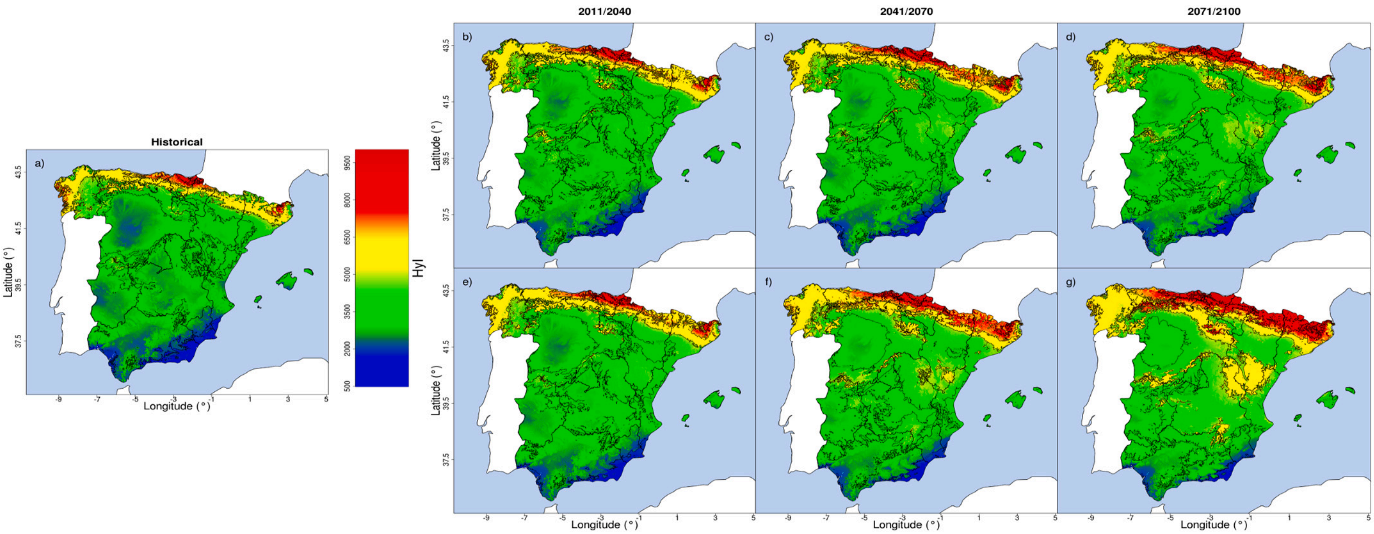

Fig. 9. Geographical representation of the expected values of the Branas, Bernon and Levadoux Index (HyI) for the periods 2011–2040, 2041–2070 and 2071–2100. Both emissions scenarios are represented: RCP4.5 (figures b, c and d) and RCP8.5 (figures e, f and g). Fig. 9a represents the Historical absolute temperature for the period 1976–2005.

growing vines. Similar situations have been found in other studies (Guido, 2015). This is because they are dry regions or with strong periods of drought with DI values < -100 mm, while one of the conditions to consider a climatically optimal year is that the DI > -100 mm. The results of this index must be interpreted in the light of multiple socio-economic factors that determine the success of a vineyard plantation beyond the climatic conditions. For example, in these regions, this situation is solved by viticultural producers through different management strategies and water management, which allow solving this “climatic problem” and taking full advantage of the rest of the climatic characteristics that favour grapevine. Other factors such as the type of cutting used, the orientation of the vineyard, the field management tasks, the type of soil, among others, will be keys to adapting to the challenges posed by climate change (Aleixandre et al., 2013).

It should also be kept in mind that rising temperatures due to climate change may have indirect effects on these crops, as they are expected to cause an increase in tropospheric ozone concentrations and are also likely to affect the chemistry of ozone precursors (NOx, CO, CH_4, NMHC) (Isaksen and Wang, 2002). This modification of atmospheric pollutant generation can be very detrimental to vineyards. For example, it has been suggested that ozone can cause a loss of productivity and a reduction in the sugar content of grapes (Ascenso et al., 2021). Increased exposure to SO_2, NO_2 can cause a severe reduction in photosynthetic rate, transpiration and stomatal conductance in shoot growth (Popescu et al., 2012).

To all these effects must be added the impact of extreme phenomena, especially heat waves. Heat waves (see Figs. S13 and S14) combined with summer drought will be the most common abiotic stress combination in the Mediterranean area (Hannah et al., 2013). The response of grapevines to increased temperatures (acceleration of their key phenological stages affecting grape quality and the properties of grape organoleptic components, such as sugar accumulation, pH, acidity, colour, aroma and flavor) (Ramos et al., 2008, Leolini et al., 2019), is likely to increase with heat waves and will also depend on its coincidence with grape ripening (Sgubin et al., 2018).

In more humid areas, as the northern part of the Peninsula, new growing areas may become viable, for example in areas of higher altitude (Ramos and Martinez de Toda, 2021) or closer to the coast (Santos et al., 2020), while low elevation areas would probably be suitable for lower quality varieties, producing wines of high alcohol content (Moriondo et al., 2007).

In almost all the territory (where a significant intensification of heat wave episodes is expected, see support information) all adaptation options must be considered if current crops are to be maintained, such as water application, row orientation or canopy cover. Water availability is the factor, along with high temperatures, that most affects vine development (Fraga et al., 2018; Fraga et al., 2019). In these areas where irrigation water is not available or is too warm, such as the Guadalquivir Valley or Extremadura, it will not be possible for the vines to mature normally, so it will be necessary to make substitutions towards varieties more tolerant to the new climatic conditions (Ramos et al., 2008). The search for adapted grapevine (*Vitis vinifera* L.) varieties will be a priority in the coming years, either through germplasm collections or genetic improvement processes (Duchene et al., 2010).

At the other extreme, cold wave episodes can be especially damaging to primary buds (Gu et al., 2002), although there are not expected to be considerable variations in the average and/or maximum intensities of such episodes in Spain (Figs. S15 and S16).

Finally, an adaptive evolution with physiological modifications of the wineyard could be expected (Ramos and Martinez de Toda, 2021) especially in those areas where climatic extremes are not so intense or so frequent, as in the northern part of the Peninsula. The adaptation of each variety under the same climatic conditions depends on the peculiarities of each genotype to heat, light or water deficit and the temperature and humidity conditions needed for ripening. The varieties with earlier phenology will be probably the most affected as was described for the Spanish variety “Tempranillo” (Ramos and Martinez de Toda, 2020).

The literature highlights different biochemical, physiological and molecular acclimation mechanisms that grapevine is able to develop in order to adapt to climatic stresses. Changes in photosynthetic efficiency and in the control of electrolyte loss through stomata appear to be frequent mechanisms of adaptation (Zha et al., 2018). For example, adjustment of photosynthesis to elevated temperature has been detected in some cases (Gallo et al., 2021; Kizildeniz et al., 2021). Site-specific stomata and vein traits modulation have been suggested as an acclimation strategy that may influence photosynthetic yield (Damiano et al., 2022). Increasing the heat dissipation capacity by changing the response of its stomata has also been proposed as an adaptation to warmer climatic conditions, since keeping them open allows heat dissipation by evaporative cooling (Costa et al., 2012). Significant changes in the expression pattern of metabolic pathways related to metabolism and hormones have also been detected (Duchene et al., 2010; Kovaleski and Londo, 2019). This opens up opportunities to identify the genetic and physiological traits that make a variety more or less resistant and select

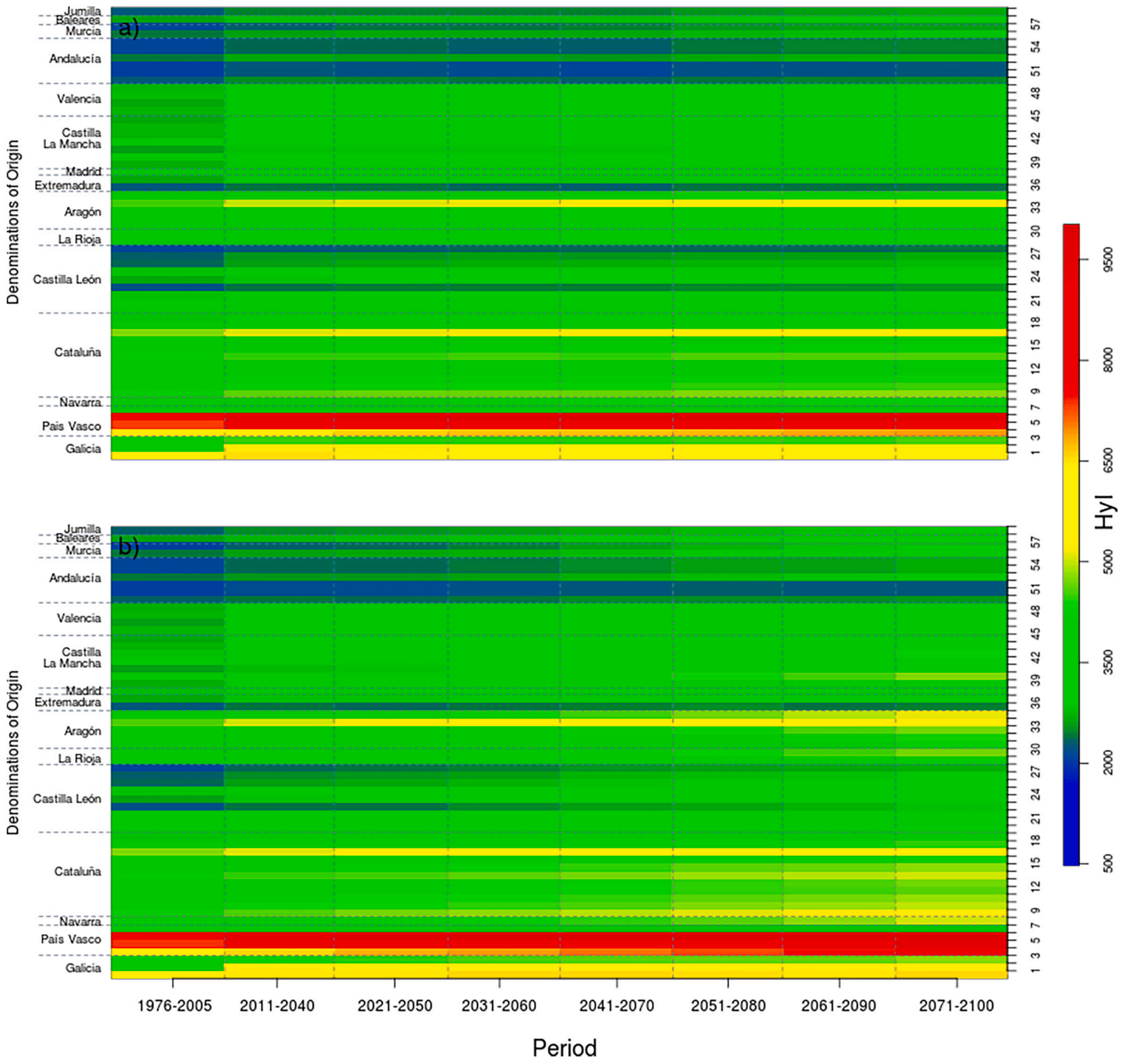

Fig. 10. Evolution of the expected values of the Branas, Bernon and Levadoux Index (HyI) for the defined Denominations of origin (DOs). Historical period 1976–2005 and 7 correlative periods of 30 years starting on 2011 are showed. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b). Each row represents one DO (see Fig. 1 for number identification) and each column represents a considered period.

varieties which would be suitable to replace the more sensitive ones even in the most affected areas such as those in the south or in the central zone of the country. In Ronda (Málaga, South of the Spain), Petit Verdot (originally from Bordeaux), whose long phenological cycle is perfectly adapted to warm climates, is producing good results in recent experiences. In Extremadura (Southwest of the Spain), Portuguese varieties such as Trincadeira or Touriga Nacional are also being successfully cultivated. In Ribera del Duero (central area of Spain) there is a growing interest in growing Malbec (traditionally grown in areas of Castilla-La Mancha and Castilla y León above 1000 m) to accompany Tempranillo (traditionally accompanied by Cabernet).

Another option is to include new sub-varieties within a variety rooted in the area, as is the case in the region of Murcia (South of the Spain), where the cultivation of four new Monastrell grape varieties (Gebas, Myrtia, Calnegre and Calblanque), which are more resistant to the new climatic conditions, has recently been approved.

It is also worth mentioning the efforts being made in Spain to recover local varieties. These vines have adaptive characteristics to the area where they have been cultivated for hundreds of years, so they can be more resilient to climate change at the local level. A recent ambitious project (Munoz-Organero et al., 2022) has studied the phenological characteristics of 53 Spanish minority grape varieties, mostly from the vine collection of El Encín (Alcalá de Henares, Madrid) to determine their possible adaptation to climate change conditions, concluding that many white (Planta nova, Zurieles, Albana, Hebén, Tortozón, and Aúrea among others) and red varieties (Cornifesto, Negreda, Benedicto, among others) present characteristics for a greater chance of success under more extreme climatic conditions.

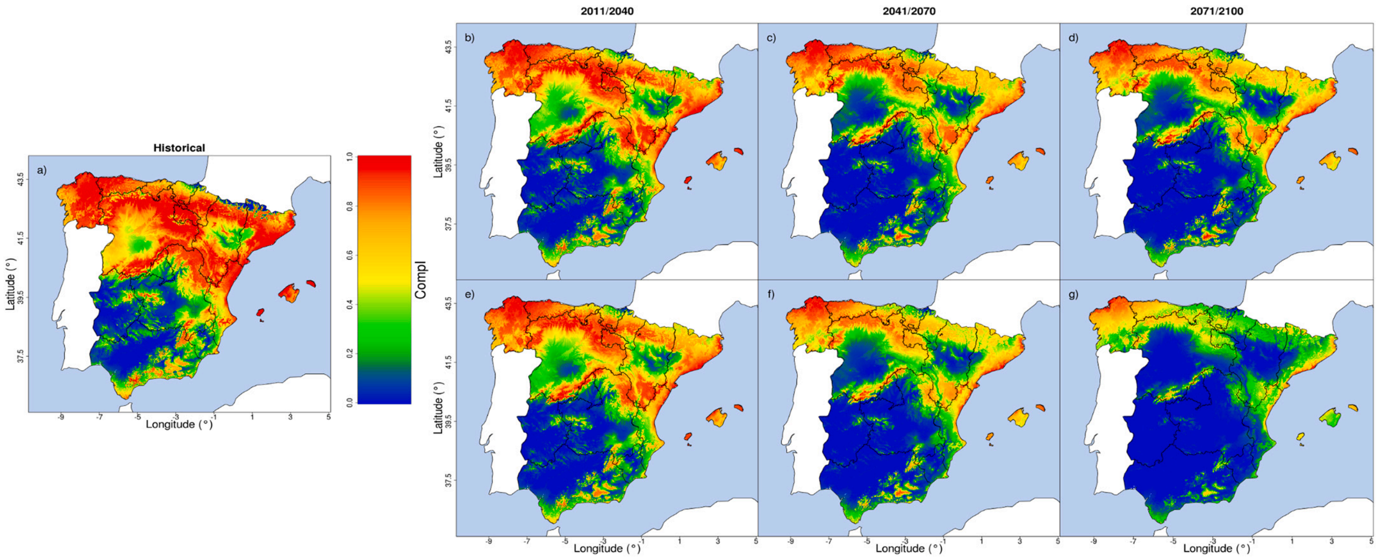

Fig. 11. Geographical representation of the expected values of the Composite Index (CompI) for the periods 2011–2040, 2041–2070 and 2071–2100. Both emissions scenarios are represented: RCP4.5 (figures b, c and d) and RCP8.5 (figures e, f and g). Fig. 11a represents the Historical absolute temperature for the period 1976–2005.

Other studies describe the local red grapevine Pasera (PAS), a variety from northern Spain (Navarra), as a potential candidate to be exploited under climate change, as it can maintain wine quality under warming and increased CO_2 (Goicoechea et al., 2021). Other local minor Mediterranean grapevine varieties (Alicante, Spain) such as Arcos and Forcallat have been studied for their ability to withstand water stress and show higher intrinsic water use efficiency (Gisbert et al., 2022).

Encouraging the cultivation of these local varieties can contribute to the adaptation of vines to climate change, but also to the local economy and to avoid the loss of genetic diversity.

However, the process of incorporating new varieties is complex, not only because it depends strongly on local characteristics (to the meteorological-climatic context must be added the type of soil, orientation, slope of the land and investments in irrigation or other adaptive technologies, among others), but also because it is subject to the legislation in force in each area and the long process involved in incorporating a new variety in a region from which it does not originate.

A final aspect that may play an additional role in the adaptation of the grapevine crop to stress generated by increased temperatures, drought or increased CO_2 and, perhaps less studied, is the protective role of soil microflora and, in particular, of mycorrhiza, a plant-fungus symbiosis (Trouvelot et al., 2015). Increasing heat tolerance by inoculating the plant with endophytic microorganisms, such as arbuscular mycorrhizal fungi (AMF), may be a new strategy to overcome the impact of high temperatures on grapevines(Fraga et al., 2016). In fact, there are already experiences that show that AMF inoculation could also help sustain grape growth under thermal stress conditions, especially after heat shocks(Nogales et al., 2020). AMF also increase the tolerance to water stress improving water uptake(Kohler et al., 2008). It seems that during periods of water stress, grapevines compensate for a lower density of fine roots by stimulating the colonization of arbuscular mycorrhizal fungi (Schreiner et al., 2007) which allow the plant to absorb water more efficiently, enabling the grapevine to cope with water stress. The grapevines inoculated with mycorrhiza not only improved leaf water status, but also photosynthetic capacity, stomatal conductance, and transpiration rate and decreased the intercellular CO_2 concentration making the plant more resistant to abiotic stresses(Ye et al., 2022).

4.3. Relevance of the results

The results obtained in this study show how the Iberian peninsular territory is one of the wine-growing regions most sensitive to the impact of climate change, not only because of the significant variations in the values obtained in the study, especially in those dependent thermal indices, but also because these variations place the region within the optimal thermal limits for growing vines. Other European regions such as France and Italy are also expected to suffer variations in their climatic conditions with implications for the vineyard, but the expected impact is not estimated to be as marked (Fraga et al., 2013), and the regions in Northern Europe will even benefit from the expected climate changes (Hannah et al., 2013).

Alterations in climatic requirements (heliothermic and hydric) have a strong impact on the final organoleptic characteristics (sugar, acidity, colour, etc.) of the grape and the characteristics of the wine. Spain has a long viticultural tradition, its wines being recognised worldwide precisely for the characteristics of the wines belonging to each DO, maintaining those own characteristics is of vital importance to guarantee the continuity of the DOs.

Currently, there is a shortage of agricultural models for grapevine (Bindi et al., 1996) or for the quality of grapevine (Webb et al., 2008) as well as tools to support decision-making (Iglesias et al., 2012; Santos et al., 2012). There are some soil suitability models (Escariz et al., 2007) and cereal modeling (STICS, BRIN, WANG04) that combined with a good observed phenological database (Mosedale et al., 2016) and climate projections such as those presented in this study, which would considerably facilitate the adaptation of the wine sector to climate change.

The results obtained can be a starting point to review and update certain factors that under new climatic conditions may be altered. As an example, currently in Spain, only those varieties that are in the register of Commercial Varieties of the Vine of Spain can be cultivated and for the control of plantations the List of Authorised, Recommended and Plant Conservation Varieties is used, both listings could be altered due to new climatic conditions.

The results of this study should be complemented with other limiting factors (White et al., 2006) such as orientation, latitude, longitude, altitude, topography and proximity to water areas as well as orientation and exposure; characteristics that, together with the properties of the soil, the management practices and the iterations between all the factors that make up the system provide grapevine and wine with unique qualities that differentiate them, even within the same DO where different grape varieties, soil types, and field characteristics may coexist.

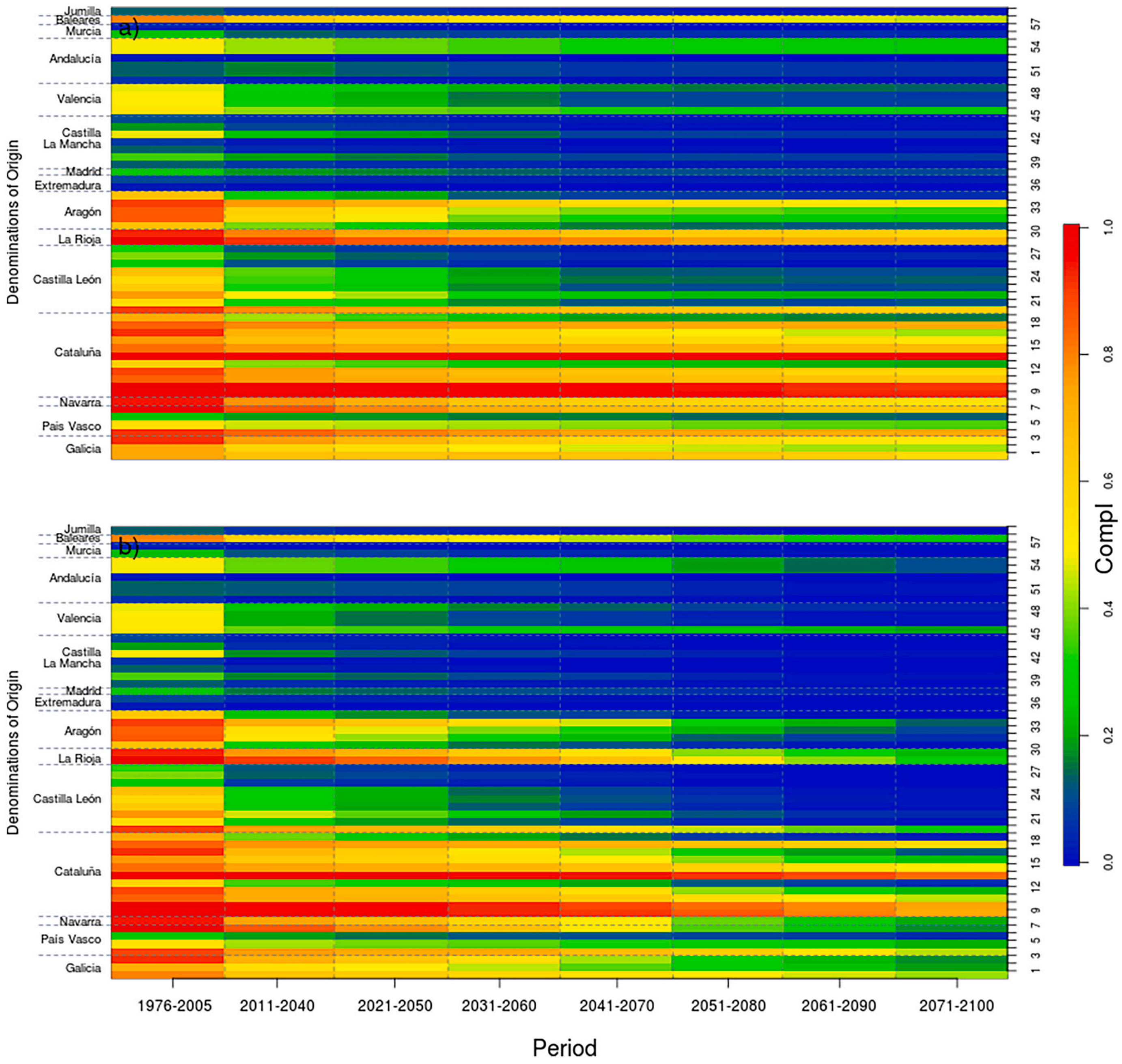

Fig. 12. Evolution of the expected values of the CompI Index (CompI) for the defined Denominations of origin (DOs). Historical period 1976–2005 and 7 correlative periods of 30 years starting on 2011 are showed. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b). Each row represents one DO and each column represents a considered period.

Although these factors play an essential role in the wine creation process, they do not pose as great a challenge as the climate (Van Leeuwen et al., 2004), an aspect on which this study was focused.

Finally, the great variety of grape types that are grown in Spain because of the great climatic diversity of the territory, and its long viticultural tradition makes it possible for the studies to be replicated in other regions with very similar climates.

This study has focused on presenting the average climatic conditions that the wine sector will face in the coming decades, allowing winegrowers to have a snapshot of the new changes they will have to face. Therefore, the impacts that some extreme events (such as extreme rainfall, hail, droughts, among others) may have on the sector in the coming decades have not been included. Following this study, it is necessary to go a step further by assessing the impact of extreme events as well as the impact on the phenological stages of the vine through relationships between these and meteorological variables.

On the other hand, future studies should be carried out in the small parts of the island territory not included in this study, such as some iberian-balearic DOs as well as the Canary Islands.

4.4. Conclusions

Our results offer a precise and rigorous picture of the impacts that climate change will cause on the grapevine crop in the Iberian Peninsula based on currently available data applying a set of six bioclimatic indices and using, for the first time, local future climate scenarios based on ESMs from the fifth IPCC report and working locally.

The Iberian-peninsular territory will be the wine-growing region most sensitive to the impact of climate change in the twenty-first century as reflected by the results obtained for the different indices, especially those dependent on thermal and hydric conditions. Progressive increases in temperatures are expected, both maximum and minimum, as indicated by the thermal indicators (HI and CI), while the water shortage (DI) will be more pronounced. The combination of the expected changes of both variables will have a strong impact on the vineyard, modifying the final organoleptic characteristics in the best of cases, but also leaving a large part of the Iberian Peninsula within the optimal thermal limits for growing vines, which it may have dramatic results for grapevine growing.

The northern and mountainous areas of the peninsula, having climatic characteristics colder and wetter than in the south, are expected to benefit from climatic variations that will allow them to adapt to climate change in a positive way, either by changing the grape variety or by regulating the water supply, among other measures. The central and southern areas of the peninsula (with strong periods of water scarcity and high temperatures) will have problems in maintaining certain types of grape and tillage techniques. They will not reach the minimum water requirements and will exceed the thermal requirements that the different grape varieties need to ripen. Therefore, these territories will be forced to rethink vineyard management techniques that allow them to counteract these negative effects or assess the economic viability of continuing to cultivate vineyards in the same regions.

These results provide valuable information for decision making in this sector to develop adaptation measures to climate change at the local scale.

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CRediT authorship contribution statement

Emma Gaitán: Conceptualization, Formal analysis, Methodology, Investigation, Writing – original draft. **Mª. Rosa Pino-Otín:** Conceptualization, Formal analysis, Investigation, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2023.106660.

References

Abaurrea, J., Asín, J., Cebrián, A.C., 2018. Modelling the occurrence of heat waves in maximum and minimum temperatures over Spain and projections for the period 2031-60. Glob. Planet. Chang. 161, 244–260. ISSN 0921-8181,. https://doi.org/10.1016/j.gloplacha.2017.11.015.

Aleixandre, J.L., Giner, J.F., Aleixandre–Tudó, J.L., 2013. Evaluación del efecto terroir sobre la calidad de la uva y el vino. Enoviticultura N20.

Alig, R.J., Adams, D.M., McCarl, B.A., 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. For. Ecol. Manag. 169, 3–14.

Alonso, A.D., O'Neill, M.A., 2011. Climate change from the perspective of Spanish wine growers: a three-region study. Br. Food J. 113, 205–221.

Ascenso, A., Gama, C., Blanco-Ward, D., Monteiro, A., Silveira, C., Viceto, C., et al., 2021. Assessing Douro vineyards exposure to tropospheric ozone. Atmosphere 12.

Battaglini, A., Barbeau, G., Bindi, M., Badeck, F.-W., 2009. European winegrowers' perceptions of climate change impact and options for adaptation. Reg. Environ. Chang. 9, 61–73.

Bentsen, M., Bethke, I., Debernard, J.B., Iversen, T., Kirkevag, A., Seland, O., et al., 2013. The Norwegian earth system model, NorESM1-M - part 1: description and basic evaluation of the physical climate. Geosci. Model Dev. 6, 687–720.

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., Miglietta, F., 1996. Modelling the impact of future climate scenarios on yield and yield variability of grapevine. Clim. Res. 7, 213–224.

Bindi, M., Fibbi, L., Lanini, M., Miglietta, F., 2001. Free air CO_2 enrichment (FACE) of grapevine (*Vitis vinifera* L.): I. Development and testing of the system for CO_2 enrichment. Eur. J. Agron. 14, 135–143.

Blanco-Ward, D., Garcia Queijeiro, J.M., Jones, G.V., 2007. Spatial climate variability and viticulture in the Mino River Valley of Spain. Vitis 46, 63–70.

Bock, A., Sparks, T., Estrella, N., Menzel, A., 2011. Changes in the phenology and composition of wine from Franconia, Germany. Clim. Res. 50, 69–81.

Bonfante, A., Alfieri, S.M., Albrizio, R., Basile, A., De Mascellis, R., Gambuti, A., Giorio, P., Langella, G., Manna, P., Monaco, E., et al., 2017. Evaluation of the effects of future climate change on grape quality through a physically based model application: a case study for the Aglianico grapevine in Campania region, Italy. Agric. Syst. 152, 100–109.

Bonfante, A., Monaco, E., Langella, G., Mercogliano, P., Bucchignani, E., Manna, P., Terribile, F., 2018. A dynamic viticultural zoning to explore the resilience of terroir concept under climate change. Sci. Total Environ. 624, 294–308.

Branas, J., 1974. Viticulture générale. Dehan, Montpellier, p. 990.

Branas, J., Bernon, G., Levadoux, L., 1946. eléments de viticulture générale.

Carbonneau, A., Tonietto, J., 1998. La géoviticulture: de la géographie viticole aux évolutions climatiques et technologiques à l'échelle mondiale. Rev. Oenol. Tech. Vitivin. Oenol. 87, 16–18.

Christensen, J.H., Kjellstrom, E., Giorgi, F., Lenderink, G., Rummukainen, M., 2010. Weight assignment in regional climate models. Clim. Res. 44, 179–194.

Chylek, P., Li, J., Dubey, M.K., Wang, M., Lesins, G., 2011. Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2. Atmos. Chem. Phys. Discuss. 11, 22893–22907.

Collins, W.J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Hinton, T., Jone, C.D., Liddicoat, S., Martin, G., O`Connor, F., Rae, J., Senior, C., Totterdell, I., Woodward, S., Reichler, T., Kim, J., Halloran, P., 2008. Evaluation of the HadGEM2 Model. Hadley Centre Technical Note HCTN. Met Office Hadley Centre, Exeter, UK, p. 74.

Combris, P., Lecocq, S., Visser, M., 1997. Estimation of a hedonic price equation for Bordeaux wine: does quality matter? Econ. J. 1997 (107), 3–390.

Costa, J.M., Ortuño, M.F., Lopes, C.M., Chaves, M.M., 2012. Grapevine varieties exhibiting differences in stomatal response to water deficit. Funct. Plant Biol. 39, 179–189.

Damiano, N., Arena, C., Bonfante, A., Caputo, R., Erbaggio, A., Cirillo, C., et al., 2022. How leaf vein and stomata traits are related with photosynthetic efficiency in Falanghina grapevine in different pedoclimatic conditions. Plants-Basel 11.

Doll, P., 2002. Impact of climate change and variability on irrigation requirements: a global perspective. Clim. Chang. 54, 269–293.

Duchene, E., 2016. How can grapevine genetics contribute to the adaptation to climate change? OENO One 50.

Duchene, E., Schneider, C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. Agron. Sustain. Dev. 25, 93–99.

Duchene, E., Huard, F., Dumas, V., Schneider, C., Merdinoglu, D., 2010. The challenge of adapting grapevine varieties to climate change. Clim. Res. 41, 193–204.

Dunne, J.P., John, J.G., Shevliakova, E., Stouffer, R.J., Krasting, J.P., Malyshev, S.L., et al., 2013. GFDL's ESM2 global coupled climate-carbon earth system models. Part II: Carbon system formulation and baseline simulation characteristics. J. Clim. 26, 2247–2267.

Escariz, A., Blanco, J., Miranda, D., Crecente, R., 2007. Zonificación y metodología para la delimitación de comarcas vitícolas. Aplicación a la ampliación de vino de la tierra de Betanzos. In: XI congreso internacional de Ingenieria de proyectos Lugo.

EXPANSIÓN, 2016. https://www.expansion.com/economia/2019/12/16/5df6afff468aebed0c8b467f.html.

EXPANSIÓN, 2019. https://www.researchgate.net/publication/345973796_Impacto_adaptacion_y_percepcion_del_cambio_climatico_en_la_DOCa_Rioja.

FEV, 2021. https://www.expansion.com/economia/2019/12/16/5df6afff468aebed0c8b467f.html.

Fonseca Conceicao, M.A., Tonietto, J., Fialho, F.B., 2012. Using temperature to calculate the dryness index of grape production regions. Rev. Bras. Frutic. 34, 175–182.

Fraga, H., Santos, J.A., 2017. Daily prediction of seasonal grapevine production in the Douro wine region based on favourable meteorological conditions. Aust. J. Grape Wine Res.

Fraga, H., Santos, J.A., Malheiro, A.C., Moutinho-Pereira, J., 2012. Climate change projections for the portuguese viticulture using a multi-model ensemble. Cienc. Tec. Vitivinic. 27, 39–48.

Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Santos, J.A., 2013. Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. Int. J. Biometeorol. 57, 909–925.

Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Jones, G.V., Alves, F., Pinto, J.G., et al., 2014. Very high resolution bioclimatic zoning of Portuguese wine regions: present and future scenarios. Reg. Environ. Chang. 14, 295–306.

Fraga, H., Santos, J.A., Malheiro, A.C., Oliveira, A.A., Moutinho-Pereira, J., Jones, G.V., 2016. Climatic suitability of Portuguese grapevine varieties and climate change adaptation. Int. J. Climatol. 36, 1–12.

Fraga, H., de Cortázar, García, Atauri, I., Santos, J.A., 2018. Viticultural irrigation demands under climate change scenarios in Portugal. Agric. Water Manag. 196, 66–74.

Fraga, H., Pinto, J.G., Santos, J.A., 2019. Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment. Clim. Chang. 152, 179–193.

France, I., Dubourdieu, A.D., 2016. Climate change: field reports from leading winemakers. J. Wine Econ. 11, 5–47.

Fregoni, M., 2003. L'indice bioclimatico di qualitá Fregoni. Terroir, Zonazione Viticoltura 2003, 115–127.

Gaitan, E., Monjo, R., Portoles, J., Rosa, Pino-Otin M., 2019. Projection of temperatures and heat and cold waves for Aragon (Spain) using a two-step statistical downscaling of CMIP5 model outputs. Sci. Total Environ. 650, 2778–2795.

Gaitan, E., Monjo, R., Portoles, J., Rosa, Pino-Otin M., 2020. Impact of climate change on drought in Aragon (NE Spain). Sci. Total Environ. 740.

Gallo, A.E., Perez Pena, J.E., Prieto, J.A., 2021. Mechanisms underlying photosynthetic acclimation to high temperature are different between *Vitis vinifera* cv. Syrah and Grenache. Funct. Plant Biol. 48, 342–357.

García de Cortázar-Atauri, I., Duchêne, E., Destrac-Irvine, A., Barbeau, G., de Rességuier, L., Lacombe, T., Parker, A.K., Saurin, N., van Leeuwen, C., 2017. Grapevine phenology in France: from past observations to future evolutions in the context of climate change. OENO One 51.

Gisbert, C., Soler, J.X., Fos, M., Intrigliolo, D.S., Yuste, A., Pico, B., et al., 2022. Characterization of local Mediterranean grapevine varieties for their resilience to semi-arid conditions under a rain-fed regime. Agronomy-Basel 12.

Goicoechea, N., Jimenez, L., Prieto, E., Gogorcena, Y., Pascual, I., Irigoyen, J.J., et al., 2021. Assessment of nutritional and quality properties of leaves and musts in three local Spanish grapevine varieties undergoing controlled climate change scenarios. Plants-Basel 10.

Gomez-Gesteira, M., Gimeno, L., deCastro, M., Lorenzo, M.N., Alvarez, I., Nieto, R., et al., 2011. The state of climate in NW Iberia. Clim. Res. 48, 109–144.

Gomez-Martinez, G., Galiano, L., Rubio, T., Prado-Lopez, C., Redolat, D., Blazquez, C.P., et al., 2021. Effects of climate change on water quality in the Jucar River Basin (Spain). Water 13.

Goncalves, B., Falco, V., Moutinho-Pereira, J., Bacelar, E., Peixoto, F., Correia, C., 2009. Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): volatile composition, phenolic content, and in vitro antioxidant activity of red wine. J. Agric. Food Chem. 57, 265–273.

Gu, S., Ding, P., Howard, S., 2002. Effect of temperature and exposure time on cold hardiness of primary buds during the dormant season in 'Concord', 'Norton', 'Vignoles' and 'St. Vincent' grapevines. J. Hortic. Sci. Biotechnol. 77, 635–639. https://doi.org/10.1080/14620316.2002.11511550.

Guido, V., 2015. Impact of climate change on *Vitis Vinifera* L. over Mediterranean area. In: Tesi di Dottorato in Agrometeorologia ed Ecofisiologia dei Sistemi Agrari e Forestali. Università degli Studi di Sassari.

Gutierrez, J.M., Maraun, D., Widmann, M., Huth, R., Hertig, E., Benestad, R., et al., 2019. An intercomparison of a large ensemble of statistical downscaling methods over Europe: results from the VALUE perfect predictor cross-validation experiment. Int. J. Climatol. 39, 3750–3785.

Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Shaw, M.R., Tabor, G., et al., 2013. Climate change, wine, and conservation. Proc. Natl. Acad. Sci. U. S. A. 110, 6907–6912.

Holland, T., Smit, B., 2010. Climate change and the wine industry: current research themes and new directions. J. Wine Res. 21, 125–136.

Huglin, P., 1978. Nouveau Mode d'Évaluation des Possibilités Héliothermiques d'un Milieu Viticole. C. R. Acad. Agr. France 1117–1126.

Iglesias, A., Quiroga, S., Moneo, M., Garrote, L., 2012. From climate change impacts to the development of adaptation strategies: challenges for agriculture in Europe. Clim. Chang. 112, 143–168.

Isaksen, I.S.A., Wang, W.C., 2002. Atmospheric ozone and climate change. In: 3rd International Symposium on Non-CO_2 Greenhouse Gases, Maastricht, Netherlands, pp. 319–330.

Iversen, T., Bentsen, M., Bethke, I., Debernard, J.B., Kirkevag, A., Seland, O., et al., 2013. The Norwegian earth system model, NorESM1-M - part 2: climate response and scenario projections. Geosci. Model Dev. 6, 389–415.

Jones, G.V., 2006. Climate and Terroir: Impacts of Climate Variability and Change on Win, in Fine Wine and Terroir - The Geoscience Perspective. In: Macqueen, R.W., Meinert, L.D. (Eds.), Geoscience Canada Reprint Series Number 9. Geological Association of Canada, St. John's, Newfoundland, p. 247.

Jones, G.V., Alves, F., 2012. Impact of climate change on wine production: a global overview and regional assessment in the Douro Valley of Portugal. Int. J. Glob. Warm. 4, 383–406.

Jones, G.V., Davis, R.E., 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. 51, 249–261.

Jones, G.V., White, M.A., Cooper, O.R., Storchmann, K., 2005. Climate change and global wine quality. Clim. Chang. 73, 319–343.

Kenny, G.H., Harrison, P.A., 1993. The effects of climatic variability and change on grape suitability in Europe. J. Wine Res. 4, 163–183.

Kizildeniz, T., Pascual, I., Irigoyen, J.J., Morales, F., 2021. Future CO_2, warming and water deficit impact white and red Tempranillo grapevine: photosynthetic acclimation to elevated CO_2 and biomass allocation. Physiol. Plant. 172, 1779–1794.

Knutti, R., Sedlacek, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nat. Clim. Chang. 3, 369–373.

Kohler, J., Hernandez, J.A., Caravaca, F., Roldan, A., 2008. Plant-growth-promoting rhizobacteria and arbuscular mycorrhizal fungi modify alleviation biochemical mechanisms in water-stressed plants. Funct. Plant Biol. 35, 141–151.

Köppen, W., Geiger, R., 1936. Das geographische System der Klimate.

Kovaleski, A.P., Londo, J.P., 2019. Tempo of gene regulation in wild and cultivated *Vitis* species shows coordination between cold deacclimation and budbreak. Plant Sci. 287.

Lazoglou, G., Anagnostopoulou, C., Koundouras, S., 2018. Climate change projections for Greek viticulture as simulated by a regional climate model. Theor. Appl. Climatol. 133, 551–567.

Leolini, L., Moriondo, M., Romboli, Y., Gardiman, M., Costafreda-Aumedes, S., de Cortazar-Atauri, I.G., Bindi, M., Granchi, L., Brilli, L., 2019. Modelling sugar and acid content in Sangiovese grapes under future climates: an Italian case study. Clim. Res. 78, 211–224.

López, F., Cabrera, M., Cuadrat, J.M., 2007. Atlas Climático de Aragón, First ed. J. Factory, Spain.

Magalhaes, N., 2008. Tratado de viticultura: a videira, a vinha e o terroir. Chaves Ferreira Publicacoes, Lisboa, Portugal.

Malheiro, A.C., Santos, J.A., Fraga, H., Pinto, J.G., 2010. Climate change scenarios applied to viticultural zoning in Europe. Clim. Res. 43, 163–177.

Marsland, S.J., Haak, H., Jungclaus, J.H., Latif, M., Roske, F., 2003. The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates. Ocean Model. 5, 91–127.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., et al., 2007. Global Climate Projections 2007: The Physical Science Basis, pp. 747–845.

Molina, M.O., Sánchez, E., Gutiérrez, C., 2020. Future heat waves over the Mediterranean from an Euro-CORDEX regional climate model ensemble. Sci. Rep. 10, 8801. https://doi.org/10.1038/s41598-020-65663-0.

Molitor, D., Junk, J., 2019. Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the Luxembourgish grapegrowing region. OENO One 53, 409–422.

Monjo, R., Gaitan, E., Portoles, J., Ribalaygua, J., Torres, L., 2016. Changes in extreme precipitation over Spain using statistical downscaling of CMIP5 projections. Int. J. Climatol. 36, 757–769.

Moriondo, M., Maselli, F., Bindi, M., 2007. A simple model of regional wheat yield based on NDVI data. Eur. J. Agron. 26, 266–274.

Mosedale, J.R., Abernethy, K.E., Smart, R.E., Wilson, R.J., Maclean, I.M.D., 2016. Climate change impacts and adaptive strategies: lessons from the grapevine. Glob. Chang. Biol. 22, 3814–3828.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Moutahir, H., Bellot, P., Monjo, R., Bellot, J., Garcia, M., Touhami, I., 2017. Likely effects of climate change on groundwater availability in a Mediterranean region of Southeastern Spain. Hydrol. Process. 31, 161–176.

Moutinho-Pereira, J., Goncalves, B., Bacelar, E., Cunha, J.B., Coutinho, J., Correia, C.M., 2009. Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): physiological and yield attributes. Vitis 48, 159–165.

Munoz-Organero, G., Espinosa, F.E., Cabello, F., Zamorano, J.P., Urbanos, M.A., Puertas, B., et al., 2022. Phenological study of 53 Spanish minority grape varieties to search for adaptation of vitiviniculture to climate change conditions. Horticulturae 8.

Neumann, P.A., Matzarakis, A., 2011. Viticulture in Southwest Germany under climate change conditions. Clim. Res. 47, 161–169.

Nogales, A., Ribeiro, H., Nogales-Bueno, J., Hansen, L.D., Goncalves, E.F., Coito, J.L., et al., 2020. Response of mycorrhizal 'touriga nacional' variety grapevines to high temperatures measured by calorespirometry and near-infrared spectroscopy. Plants-Basel 9.

Odo Camps, J., Ramos, M.C., 2012. Grape harvest and yield responses to inter-annual changes in temperature and precipitation in an area of north-East Spain with a Mediterranean climate. Int. J. Biometeorol. 56, 853–864.

Ollat, N., Touzard, J.M., van Leeuwen, C., 2016. Climate change impacts and adaptations: new challenges for the wine industry. J. Wine Econ. 11, 139–149.

Popescu, Simona, Popa, Aurel, Gavrilescu, Elena, Marius, Gruia, 2012. The effects of air pollution on the main physiological processes of the grapevine grown in the vicinity of a power plant. Carpathian J. Earth Environ. Sci. 7, 61–70.

Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B Biol. Sci. 360, 2021–2035.

Raddatz, T.J., Reick, C.H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., et al., 2007. Will the tropical land biosphere dominate the climate-carbon cycle feedback during the twenty-first century? Clim. Dyn. 29, 565–574.

Ramos, M.C., 2017. Projection of phenology response to climate change in rainfed vineyards in north-East Spain. Agric. For. Meteorol. 247, 104–115.

Ramos, M.C., Martinez de Toda, F., 2020. Variability in the potential effects of climate change on phenology and on grape composition of Tempranillo in three zones of the Rioja DOCa (Spain). Eur. J. Agron. 115.

Ramos, M.C., Martinez de Toda, F., 2021. Interannual and spatial variability of grape composition in the Rioja DOCa show better resilience of cv. Graciano than cv. Tempranillo under a warming scenario. Oeno One 55, 85–100.

Ramos, M.C., Jones, G.V., Martinez-Casasnovas, J.A., 2008. Structure and trends in climate parameters affecting winegrape production in Northeast Spain. Clim. Res. 38, 1–15.

Ramos, M.C., Jones, G.V., Yuste, J., 2017. Variability of Tempranillo grape quality within the Ribera del Duero do (Spain) and relationships with climatic characteristics. J. Vitic. Enol. N 12/1.

Resco, P., Iglesias, A., Bardaji, I., Sotes, V., 2016. Exploring adaptation choices for grapevine regions in Spain. Reg. Environ. Chang. 16, 979–993.

Ribalaygua, J., Rosa Pino, M., Portoles, J., Roldan, E., Gaitan, E., Chinarro, D., et al., 2013a. Climate change scenarios for temperature and precipitation in Aragon (Spain). Sci. Total Environ. 463, 1015–1030.

Ribalaygua, J., Torres, L., Portoles, J., Monjo, R., Gaitan, E., Pino, M.R., 2013b. Description and validation of a two-step analogue/regression downscaling method. Theor. Appl. Climatol. 114, 253–269.

Ribalaygua, J., Gaitan, E., Portoles, J., Monjo, R., 2018. Climatic change on the Gulf of Fonseca (Central America) using two-step statistical downscaling of CMIP5 model outputs. Theor. Appl. Climatol. 132, 867–883.

Riou, C.H., Becker, N., Sotes Ruiz, V., Gomez-Miguel, V., Carbonneau, A., Panagiotou, M., Calo, A., Costacurta, A., Castro de, R., Pinto, A., Lopes, C., Carneiro, L., Climaco, P., 1994. Le déterminisme climatique de la maturation du raisin: application au zonage de la teneur em sucre dans la communauté européenne. Office des Publications Officielles des Communautés Européennes, Luxembourg, p. 322.

Rodriguez, R., Navarro, X., Casas, M.C., Ribalaygua, J., Russo, B., Pouget, L., et al., 2014. Influence of climate change on IDF curves for the metropolitan area of Barcelona (Spain). Int. J. Climatol. 34, 643–654.

Santiago, J.M., Munoz-Mas, R., Solana-Gutierrez, J., de Jalon, D.G., Alonso, C., MartinezCapel, F., et al., 2017. Waning habitats due to climate change: the effects of changes in streamflow and temperature at the rear edge of the distribution of a cold-water fish. Hydrol. Earth Syst. Sci. 21.

Santos, J.A., Malheiro, A.C., Karremann, M.K., Pinto, J.G., 2011. Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. Int. J. Biometeorol. 55, 119–131.

Santos, J.A., Malheiro, A.C., Pinto, J.G., Jones, G.V., 2012. Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. Clim. Res. 51, 89–103.

Santos, M., Fonseca, A., Fraga, H., Jones, G.V., Santos, J.A., 2020. Bioclimatic conditions of the Portuguese wine denominations of origin under changing climates. Int. J. Climatol. 40, 927–941.

Schreiner, R.P., Tarara, J.M., Smithyman, R.P., 2007. Deficit irrigation promotes arbuscular colonization of fine roots by mycorrhizal fungi in grapevines (*Vitis vinifera* L.) in an arid climate. Mycorrhiza 17, 551–562.

Schultz, H.R., 2000. Climate change and viticulture: a European perspective on climatology, carbon dioxide and UV-B effects. Aust. J. Grape Wine Res. 6, 2–12.

Schultz, H.R., Stoll, M., 2010. Some critical issues in environmental physiology of grapevines: future challenges and current limitations. Aust. J. Grape Wine Res. 16, 4–24.

Sgubin, G., Swingedouw, D., Dayon, G., Garcia de Cortazar-Atauri, I., Ollat, N., Pagé, C., Van Leeuwen, C., 2018. The risk of tardive frost damage in French vineyards in a changing climate. Agric. For. Meteorol. 250–251, 226–242.

Stock, M., Gerstengarbe, F.W., Kartschall, T., Werner, P.C., 2004. Reliability of climate change impact assessments for viticulture. In: 7th International Symposium on Grapevine Physiology and Biotechnology, Davis, CA, pp. 29–39.

Tate, A.B., 2001. Global warming's impact on wine. J. Wine Res. 12, 95–109.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93, 485–498.

Tonietto, J., 1999. Les Macroclimats Viticoles Mondiaux et l'Influence du Mésoclimat sur la Typicité de la Syrah et du Muscat de Hambourg dans le Sud de la France: Méthodologie de Carátérisation. Thèse Doctorat. Ecole Nationale Supérieure Agronomique, Montpellier.

Tonietto, J., Carbonneau, A., 2004. A multicriteria climatic classification system for grape-growing regions worldwide. Agric. For. Meteorol. 124, 81–97.

Torres, C., Jordà, G., de Vílchez, P., Vaquer-Sunyer, R., Rita, J., Canals, V., Cladera, A., Escalona, J.M., Miranda, M.Á., 2021. Climate change and their impacts in the Balearic Islands: a guide for policy design in Mediterranean regions. Reg. Environ. Change 21 (4), 107. https://doi.org/10.1007/s10113-021-01810-1. Epub 2021 Oct 23. 34720740. PMC8536903.

Tripathi, S., Srinivas, V.V., Nanjundiah, R.S., 2006. Dowinscaling of precipitation for climate change scenarios: a support vector machine approach. J. Hydrol. 330, 621–640.

Trouvelot, S., Bonneau, L., Redecker, D., van Tuinen, D., Adrian, M., Wipf, D., 2015. Arbuscular mycorrhiza symbiosis in viticulture: a review. Agron. Sustain. Dev. 35, 1449–1467.

ENSEMBLES: climate change and its impacts. In: Van der Linden, P., Mitchell, J. (Eds.), 2009. Summary of Research and Results from the ENSEMBLES Project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK, p. 160.

Van Leeuwen, C., Friant, P., Chone, X., Tregoat, O., Koundouras, S., Dubourdieu, D., 2004. Influence of climate, soil, and cultivar on terroir. Am. J. Enol. Vitic. 55, 207–217.

Vanderlinden, K., Giraldez, J.V., Van Meirvenne, M., 2004. Assessing reference evapotranspiration by the Hargreaves method in southern Spain. J. Irrig. Drain. Eng. 130, 184–191.

Voldoire, A., Sanchez-Gomez, E., Salas y Melia, D., Decharme, B., Cassou, C., Senesi, S., et al., 2013. The CNRM-CM5.1 global climate model: description and basic evaluation. Clim. Dyn. 40, 2091–2121.

Wang, B., Zhou, T., Yu, Y., 2010. A view of earth system model development (vol 23, pg 1, 2009). Acta Meteorol. Sin. 24, 547.

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., et al., 2011. MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. Geosci. Model Dev. 4, 845–872.

Webb, L.B., Whetton, P.H., Barlow, E.W.R., 2008. Modelling the relationship between climate, winegrape price and winegrape quality in Australia. Clim. Res. 36, 89–98.

Weigel, A.P., Knutti, R., Liniger, M.A., Appenzeller, C., 2010. Risks of model weighting in multimodel climate projections. J. Clim. 23, 4175–4191.

White, M.A., Diffenbaugh, N.S., Jones, G.V., Pal, J.S., Giorgi, F., 2006. Extreme heat reduces and shifts United States premium wine production in the 21st century. Proc. Natl. Acad. Sci. U. S. A. 103, 11217–11222.

Winkler, A.J., 1974. General Viticulture. University of California Press, CA.

Xiao-Ge, X., Tong-Wen, W., Jie, Z., 2013. Introduction of CMIP5 experiments carried out with the climate system models of Beijing climate Center. Adv. Clim. Chang. Res. 4, 41–49. https://doi.org/10.3724/SP.J.1248.2013.041.

Ye, Q., Wang, H., Li, H., 2022. Arbuscular mycorrhizal fungi improve growth, photosynthetic activity, and chlorophyll fluorescence of *Vitis vinifera* L. cv. ecolly under drought stress. Agronomy-Basel 12.

Yukimoto, S., Yoshimura, H., Hosaka, M., Sakami, T., Tsujino, H., Hirabara, M., Tanaka, T.Y., Deushi, M., Obata, A., Nakano, H., Adachi, Y., Shindo, E., Yabu, S., Ose, T., Kitoh, A., 2011. Meteorological Research Institute- Earth System Model v1 (MRI-ESM1)— Model Description. Technical Report of MRI, p. 64.

Zha, Q, Xi, X, He, Y, Jiang, A, 2018. Comprehensive evaluation of heat resistance in 68 Vitis germplasm resources. Vitis 57, 75–81.