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Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment

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Abstract
Air temperatures play a major role on temperate fruit development, and the projected future warming may thereby bring additional threats. The present study aims at analyzing the impacts of climate change on chilling and heat forcing on European vineyards and olive (V&O) orchards. Chilling portions (CP) and growing degree hours (GDH) were computed yearly for the recent past (1989–2005) and the RCP4.5 and RCP8.5 future scenarios (2021–2080), using several regional-global climate models, also considering model uncertainties and biases. Additionally, minimum CP and GDH values found in 90% of all years were also computed. These metrics were then extracted to the current location of V&O in Europe, and CP-GDH delimitations were assessed. For recent past, high CP values are found in north-central European regions, while lower values tend to exist on opposite sides of Europe. Regarding forcing, southern European regions currently show the highest GDH values. Future projections point to an increased warming, particularly under RCP8.5 and for 2041 onwards. A lower/higher CP is projected for south-western/eastern Europe, while most of Europe is projected to have higher GDH. Northern-central European V&O orchards should still have future CP-GDH similar to present values, while most of southern European orchards are expected to have much lower CP and higher GDH, especially under RCP8.5. These changes may bring limitations to some of the world most important V&O producers, such as Spain, Italy and Portugal. The planning of suitable adaptation measures against these threats is critical for the future sustainability of the European V&O sectors.

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1 Introduction

The vineyard and olive orchard (V&O) sector in Europe is of key importance for the regional food industry. Europe comprises some of the world top producers of grapes and olives, along with other temperate climate fruits (Eurostat 2014). Grapevines have a strong socioeconomic and cultural importance, due to the thriving winemaking sector. Vineyard area is of approximately 3 mha, with Spain (33%), France (26%), Italy (23%) and Portugal (6%) being amongst the countries with the highest areas (OIV 2017). The area under olive trees accounts for roughly 4.6 mha in Europe (Eurostat 2014). The olive production is also concentrated in the Mediterranean countries, such as Spain (53%), Italy (24%), Greece (15%) and Portugal (7%).

It is clear that most V&O orchards in Europe are currently located in regions characterized by Mediterranean-type climates. These regions are also classified as climate change hotspots, i.e. "a region for which potential climate change impacts on the environment or different activity sectors can be particularly pronounced" (Giorgi 2006). Therefore, it becomes clear that fruit production may be particularly vulnerable to climatic change (Baldocchi and Wong 2008; Luedeling et al. 2011), particularly in southern Europe (Atkinson et al. 2013). Given the threats to many vulnerable plants in a warmer world, it is imperative to understand the impacts of climate and climate change on these important food crops in Europe.

Temperature is a fundamental factor affecting plant growth and development rates. Many plants have thermal thresholds for adequate growth, physiological development and phenology (Schwartz and Hanes 2010). There are usually two main thermal factors influencing plant development: cold (chilling) and heat (forcing) requirements (Benmoussa et al. 2017; Ruiz et al. 2007). While the onset of vegetative development generally occurs following cold requirements, actual growth and development are driven by heat requirements (Osborne et al. 2000).

Regarding cold requirements, chilling refers to an extended accumulation of cold weather, which enables plant to leave the dormancy stage, allowing plants to properly set buds and produce fruit when warmer temperatures arise. For perennial crops, chilling requirements are usually a strict criterion imperative to break dormancy (Schwartz and Hanes 2010), and development is only active when chilling requirements have been met. Consequently, the non-fulfilment of dormancy requirements slows/stops crop development (Campoy et al. 2011). Following this stage, heat accumulation plays a major role, forcing plant phenological development and growth. A certain accumulation of warm temperatures is indeed necessary for plants to achieve a proper ripening.

Given the high sensitivity of V&O to thermal conditions, it becomes clear that the ongoing global warming may have significant impacts on productivity and fruit quality (Benmoussa et al. 2017; Campoy et al. 2011; Luedeling et al. 2011). Higher winter temperatures may be detrimental, as insufficient chilling may cause delayed budding and foliation, resulting in low fruit set/yields (Campoy et al. 2011). Additionally, increased temperatures during the growing season may result in faster and unbalanced fruit ripening, which may lead to implications in fruit quality, fruit set and yields. However, higher temperatures may have very different implications throughout European grape and olive-producing regions. Therefore, estimating present and future heat and chill conditions is essential for maintaining economically viable V&O orchards or for ensuring that detrimental impacts of climate change can be effectively mitigated.

To quantify plant cold and heat requirements, several modelling approaches have been developed (Benmoussa et al. 2017). The dynamic model (for computing the chilling portions—henceforth CP) (Fishman et al. 1987) is one of the most recent and advanced chilling models, whereas the growing degree hour (GDH) model (Anderson et al. 1986; Gu 2016) has emerged as one of the most skilful forcing models. While several other models have previously been applied to many tree species, such as chilling hours or growing degree days (e.g. Matzneller et al. 2014; Spinoni et al. 2015), they are usually outperformed by CP and GDH, though not being directly comparable (Luedeling and Brown 2011).

The present study aims at analyzing the impacts of climate change on chilling and heat forcing conditions of V&O orchards in Europe. As such, the objectives of the present study are fivefold: (1) to compute recent past thermal conditions over Europe, using state-of-the-art chilling portions and growing degree hours; (2) to link these thermal conditions to the regions where the main V&O orchards are located; (3) to compute future changes of these thermal conditions using a large ensemble of high-resolution climate models and for two future scenarios (RCP4.5 and RCP8.5); (4) to combine chill and heat conditions, allowing to establish the limits of the recent past and future V&O production zones; and (5) to discuss potential adaptation measures.

2 Material and methods

2.1 Chill and heat conditions

In the present study, to assess chilling and heat forcing, two metrics were computed: the CP (Fishman et al. 1987) and the GDH (Anderson et al. 1986). The dynamic model (Fishman et al. 1987), which computes the CP, assumes that winter chill is accumulated in two steps: (i) firstly, an intermediate chilling product is created, which requires cool temperatures and can be destroyed by high temperatures (Luedeling et al. 2009). (ii) Secondly, when this intermediate product reaches a certain accumulation, it is permanently converted into a CP (Fishman et al. 1987; Luedeling et al. 2009). This model is based on a temperature curve computed on an hourly basis from October to February. This model has been shown to perform better than other conventional chilling models developed for peach, but has now been adopted for other plant species (Ruiz et al. 2007). The dynamic model still offers some advantages for some species (Ruiz et al. 2007), and in climate change assessments (Luedeling et al. 2009).

For GDH, the hourly thermal accumulation from February to October is determined between the base threshold of 4 °C and the critical threshold of 36 °C, with an optimum temperature of 26 °C (Anderson et al. 1986). It should be noted that for temperatures above the critical threshold, GDH stops accumulating. The GDH offers several advantages over the more common growing degree day metric, as the latter is calculated using one temperature per day, lacking accuracy and the temperature ranges of a sub-daily metric (Gu 2016).

For calculating both GDH and CP, the R® package 'chillR' was used (Luedeling et al. 2013). Extended time periods for thermal accumulation (CP: October to February; GDH: February to October) were herein selected to take into account future advances/delays in plant development (Guo et al. 2015). These metrics were computed over several years for the recent past period and for the future periods (explained in the following sections) and were subsequently averaged for each period. Additionally, two other metrics were computed: the safe winter chill (SWC) (Luedeling et al. 2011)—the amount of CP exceeded in 90% of all years—and safe heat forcing (SHF)—the amount of GDH exceeded in 90% of all years (the 10th percentile). These two metrics may prove more useful for growers than average CP and GDH (Luedeling et al. 2011).

2.2 Climatic data

For the recent past (1989–2005), daily gridded maximum and minimum (2 m) air temperatures were retrieved from the observation-based E-OBS dataset (Haylock et al. 2008). Data were retrieved within Europe (10° W to 35° E, 35 to 60° N) at a 0.25° latitude × 0.25° longitude grid (~ 25-km resolution). These data were directly used as input in the chillR package to compute both GDH and CP for all years (from 1989 to 2005).

Regarding future projections for CP and GDH, seven regional climate models (RCM, Table S1) were retrieved from the EURO-CORDEX project (Jacob et al. 2014) at a 0.125° latitude × 0.125° longitude spatial resolution. Climate models were evaluated through their ability to replicate observed patterns over Europe. For this purpose, climate model data, driven by ERA-Interim reanalysis (Dee et al. 2011) for 1989–2005, was used. These reanalysis-driven simulations incorporate observational sources and thus allow a direct comparison to the E-OBS-derived CP and GDH. Results were bilinearly interpolated to the coarser E-OBS grid (0.25° latitude × 0.25° longitude) to allow a grid-to-grid comparison. The CP and GDH 7-RCM ensemble mean (ENSMEAN) were also computed and evaluated.

Upon this primary evaluation, RCM model data forced by five global climate models (GCM, Table S1) were also retrieved for 1989–2005 and 2021–2080 under RCP4.5 and RCP8.5 scenarios. First, the simulated RCM-GCM daily maximum and minimum temperatures were bias-corrected for 1989–2005, using E-OBS as baseline and applying the 'empirical quantile mapping' methodology (Cofiño et al. 2017). This correction was then applied to the future period (2021–2080) and both scenarios. Finally, CP and GDH were computed for each year in the future period using the bias-corrected data as input in chillR (Luedeling et al. 2013). CP and GDH were computed for each GCM-RCM separately, and multi-model ensembles were subsequently computed for each year in the future period and for the two scenarios (RCP4.5 and RCP8.5). Additionally, to assess ensemble mean uncertainty, only the climate change signals consistent for more than 70% of models will be presented (Jacob et al. 2014). Three sub-periods were considered and compared to the baseline period (1989–2005) for climate change assessments, i.e. short term (2021–2040), medium term (2061–2080) and long term (2061–2080).

2.3 CP-GDH analysis over V&O orchards

In order to analyse the spatial distribution of V&O orchards in Europe, the CORINE Land Cover (CLC), v18.5.1, was used. This dataset is derived from satellite imagery and direct mapping of land inventories, providing land cover classes over Europe, despite some missing data in some eastern European countries, namely in Ukraine, Belarus and Moldavia. Regarding the V&O orchard categorization within the CLC, this dataset clearly distinguishes V&O orchards, though varietal information is not available. The V&O orchard fractions of the land cover over Europe were extracted from this dataset for subsequent analysis. Next, CP and GDH values at the corresponding locations of these two groups are assessed and compared. To properly address the non-linear relationships between these two metrics, 2D-scatterplots are computed, indicating the density and limits of CP-GDH grid-to-grid values for each orchard type. The same methodology was then applied to the future periods, identifying the shifts in the CP-GDH values for the current growing regions and the corresponding CP-GDH two-dimensional limits (lowest/highest grid-to-grid CP and GDH values).

3 Results

3.1 Current conditions

The mean spatial patterns of both GDH and CP under current conditions (1989–2005) are shown in Fig. 1a, c. Mean chilling accumulation is higher in central and north-western European regions, which are not typical V&O-producing regions. The highest CP values (> 100) are found in the British Isles, northern Iberia, northern France, Belgium and Netherlands. The lowest values (CP < 60) are located in the opposite sides of Europe, such as south-western Iberia and north-eastern Europe. These low values derive from different conditions: in southern Iberia, these low values derive from relatively high temperatures during wintertime, while in north-eastern Europe and the Alps, extremely low temperatures are beyond the range for an effective chill accumulation by plants. This non-linear behaviour was previously found by Luedeling and Brown (2011). Regarding SWC (Fig. 1b), this metric shows a very similar pattern to the mean CP, but obviously with lower overall values across Europe. The highest differences between this metric and mean CP appear on central and northern Europe.

Regarding mean heat forcing, this metric reveals a much more linear behaviour than CP. Despite some exceptions (mainly at high elevations), this metric shows a strong latitudinal gradient, with highest (lowest) values in the southern (northern) regions. The highest GDH values

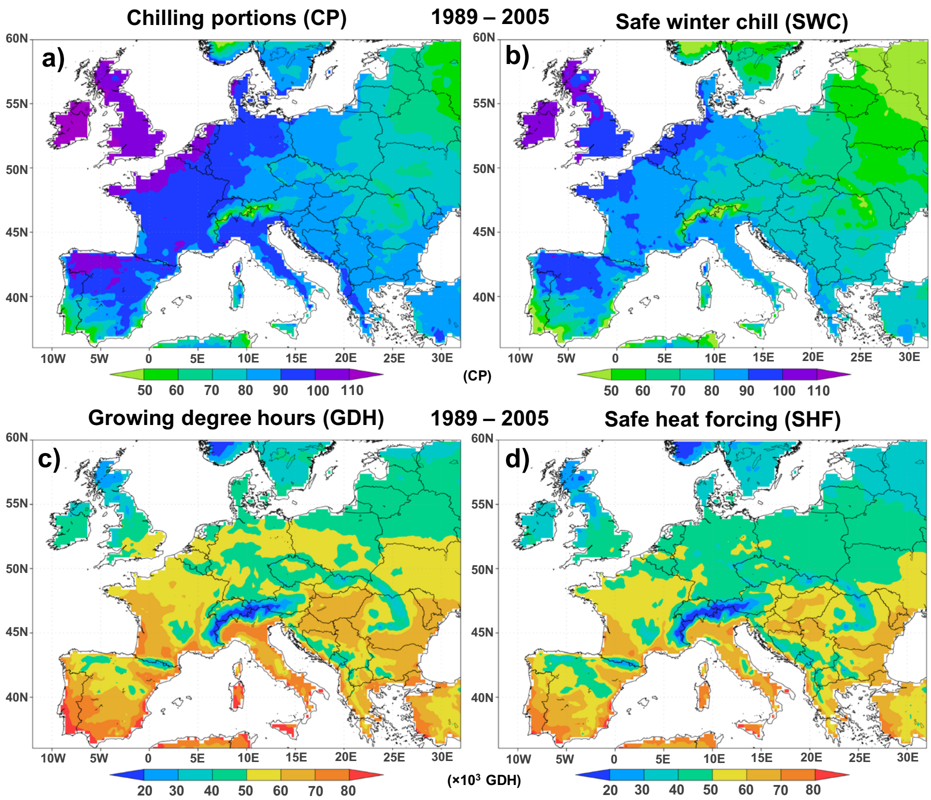


Fig. 1 Mean CP (**a**), SWC (**b**), mean GDH (**c**) and SHF (**d**) patterns over Europe for E-OBS and over the period of 1989–2005

(GDH > 70 × 10^3) are located in southern European regions (Iberia, Italy, southern France), which are some of the world top producers of grapes and olives and have the highest temperatures during the growth stage. Regions above the 52° N parallel tend to show GDH values < 50 × 10^3 GDH. Additionally, high-elevation areas in Europe, such as the Alps and the Pyrenees, show very low heat accumulation (GDH < 30 × 10^3). SHF (Fig. 1d) also shows a very strong similarity with the mean GDH pattern, with overall lower values, especially over Iberia.

3.2 CP and GDH at orchard locations

Figure 2 depicts the locations of the V&O orchards in Europe, along with the respective CP-GDH 2D scatterplots. These diagrams show the thermal conditions associated to vineyards and olive orchards, highlighting the range of thermal conditions in which these crops are currently grown, as well as the non-linear relationship between CP and GDH. Vineyards (Fig. 2a) present highest densities between 75 and 85 CP and 60 and 75 × 10^3 GDH. However, vineyard CP-GDH limits exhibit large ranges. At higher GDH values (GDH > 70 × 10^3), relationships with CP tend to be much more linear, with higher (lower) GDH indicating lower (higher) CP. These values are typical for vineyards in south-eastern Europe (Fig. 1). At lower GDH levels, nevertheless, these relationships become less clear, as vineyards in central (high CP and medium-to-high GDH) and eastern Europe (low-to-medium CP and low-to-medium GDH) are incorporated. Regarding olive orchards (Fig. 2b), the highest densities occur between 75 and 85 CP and 60 and 75 × 10^3 GDH. The limits of the CP-GDH values are much more

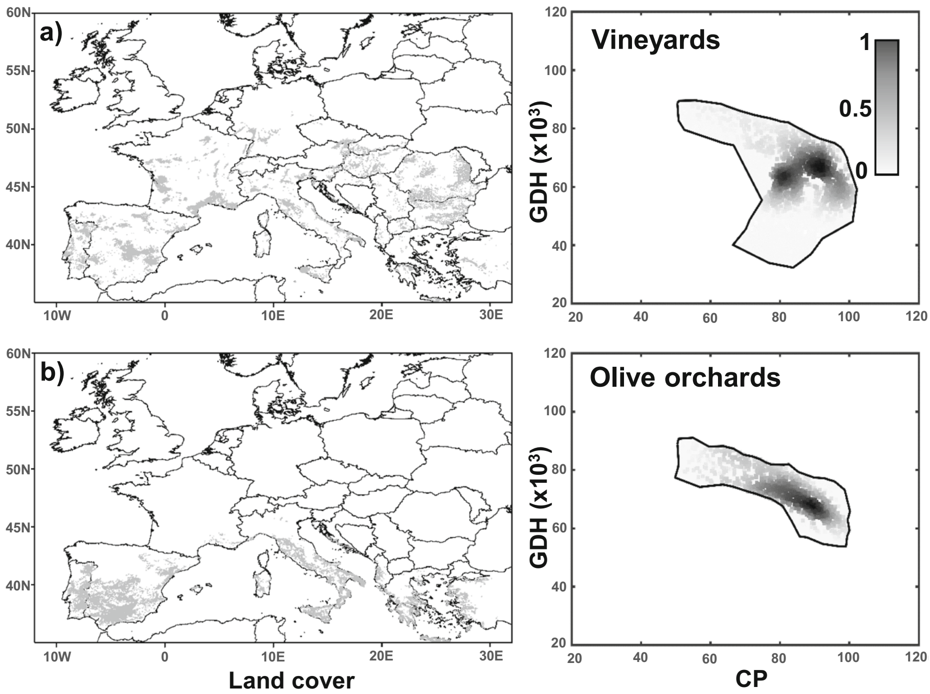


Fig. 2 Spatial distribution of the **a** vineyards and **b** olive orchards in Europe (*left panel*). CP-GDH value limits for **a** vineyards and **b** olive orchards (*right panel*). Point colour gradient corresponds to a scale from the lowest (0) to the highest (1) density of values

linearly delimited than for vineyards, as this crop is prominently established in the Mediterranean countries, where high GDH tends to be related to low CP.

3.3 RCM model skill

The 7-RCM and the corresponding ensemble mean (ENSMEAN) were evaluated for the recent past, by comparison to E-OBS. In order to capture the spatial variability of model performance over Europe, the spatial distribution of the bias in the means (%) was computed separately for each model, i.e. the differences of CP or GDH mean values between model and E-OBS. This evaluation is essential to provide a measure of model skill in the assessment of the non-linear bioclimatic metrics, as they rely heavily on absolute temperature thresholds.

Figure 3 provides an overview of the spatial distribution of the model biases in the CP and GDH means. For CP, it is clear that several models, as well as the ENSMEAN, struggle to depict the correct spatial CP gradient, showing lower CP in south-western Europe and higher values in north-eastern Europe compared to E-OBS. The few exceptions are MPI-CSC-REMO2009 and IPSL-INERIS-WRF331F, which tend to show higher CP throughout Europe. CNRM-ALADIN53 presents the lowest spatial biases across Europe. Nevertheless, if only orchard areas were taken into account, the ENSMEAN tends to outperform single models (Table S2). Regarding GDH, some models (CNRM-ALADIN53, KNMI-RACMO22E and SMHI-RCA4) show lower values throughout Europe, while others (MPI-CSC-REMO2009) show significantly higher values than those from E-OBS. At orchard locations, the ENSMEAN also outperforms single models (Table S2). Given that the ENSMEAN provides

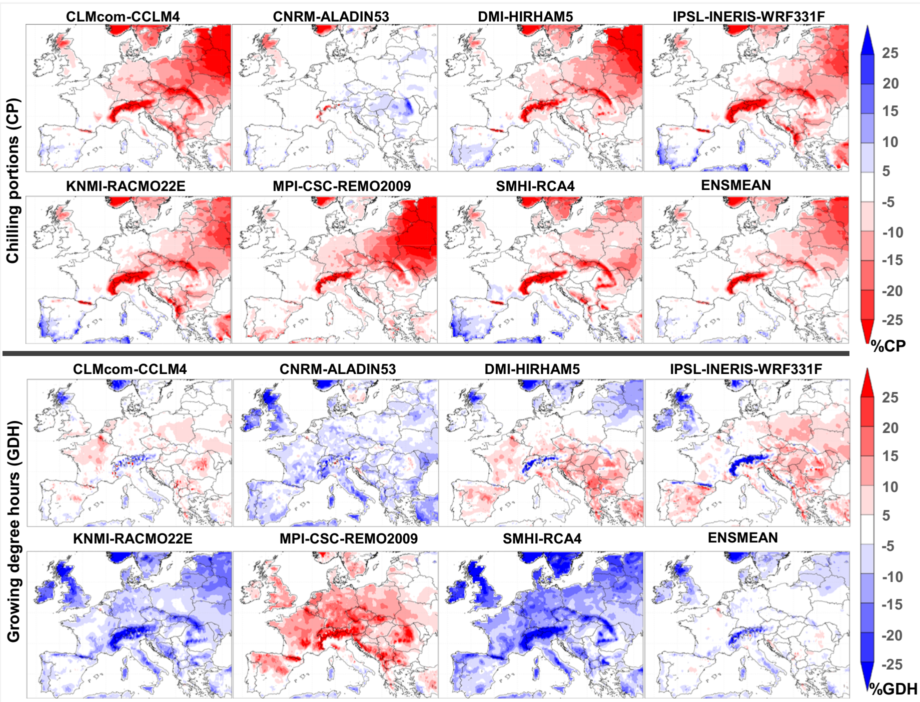


Fig. 3 Spatial distribution of the bias in the means of CP (top panel) and GDH (bottom panel) for each climate model over Europe (w.r.t. E-OBS)

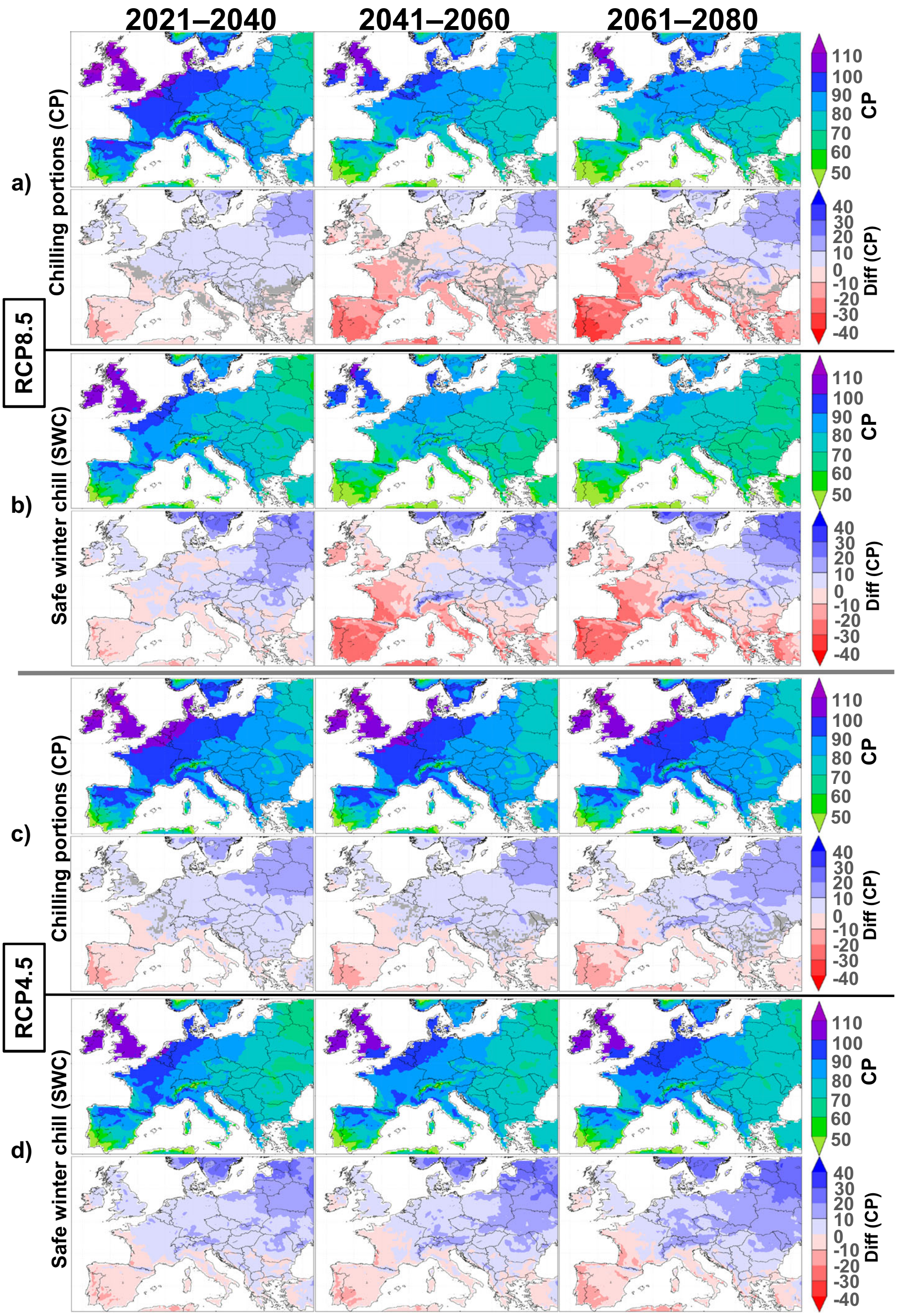


Fig. 4 **a** CP mean patterns under RCP8.5 for 2021–2040, 2041–2060 and 2061–2080, along with the respective differences between these periods and 1989–2005 (future minus recent-past). **b** Same as **a** but for the SWC. **c**, **d** Same as **a** and **b** but for RCP4.5. Gray shading indicates model agreement with the ensemble mean below 70%

the most suitable outputs when compared to observational CP and GDH, and for the sake of succinctness, only the ENSMEAN will be presented hereafter.

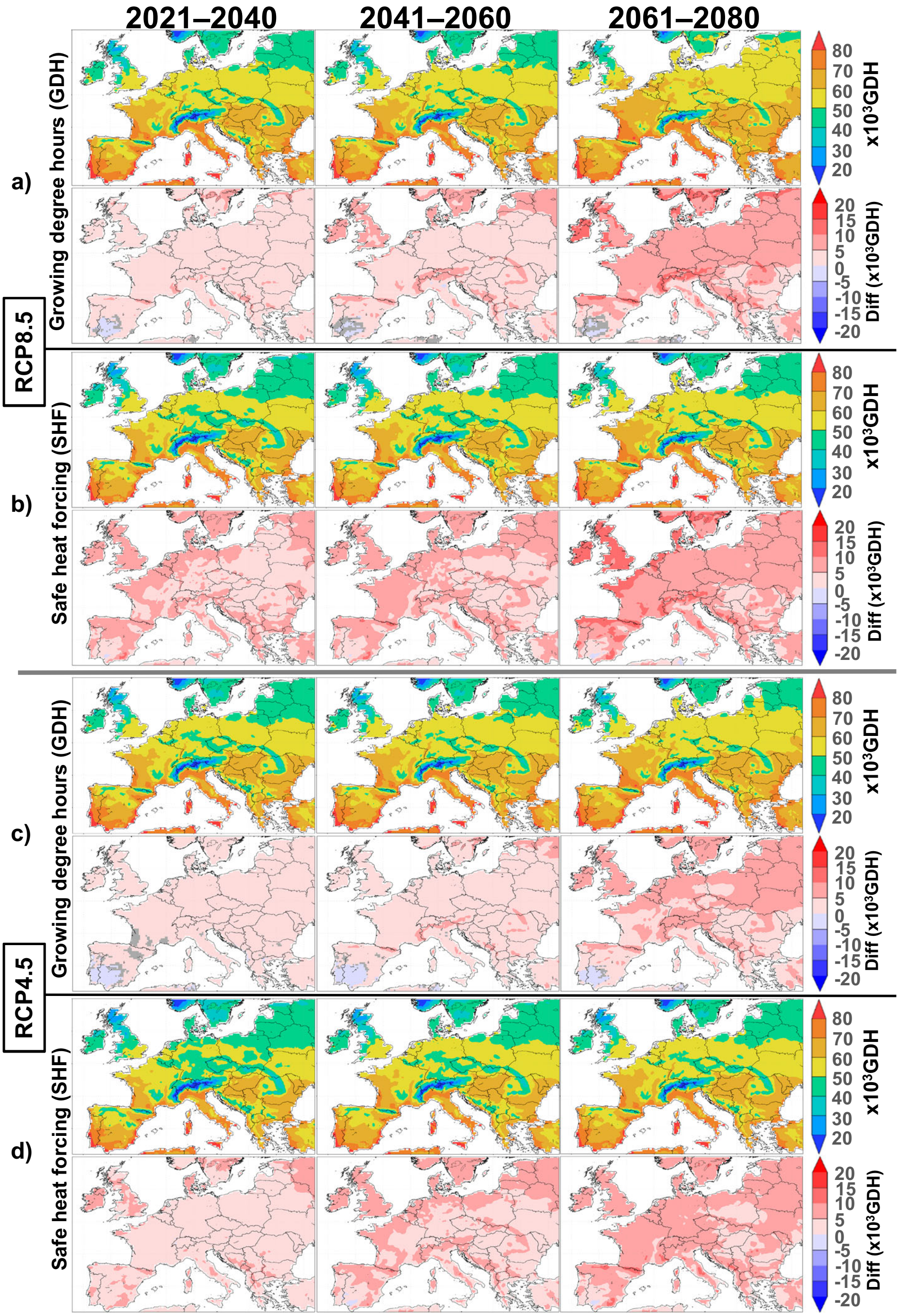


Fig. 5 Same as Fig. 4 but for the GDH and SHF metrics

Fig. 6 Limits of the CP (**a**) and SWC (**b**) for the recent-past and for the future periods under RCP8.5 (2021–2060, 2041–2060 and 2061–2080). **c**, **d** Same as **a** and **b** but for olive orchards (*left panel*). Future zones that show CP-GDH within current values. All colours are overlapped, and the top visible colour corresponds to the last time period that has CP-GDH value within current limits (*right panel*)

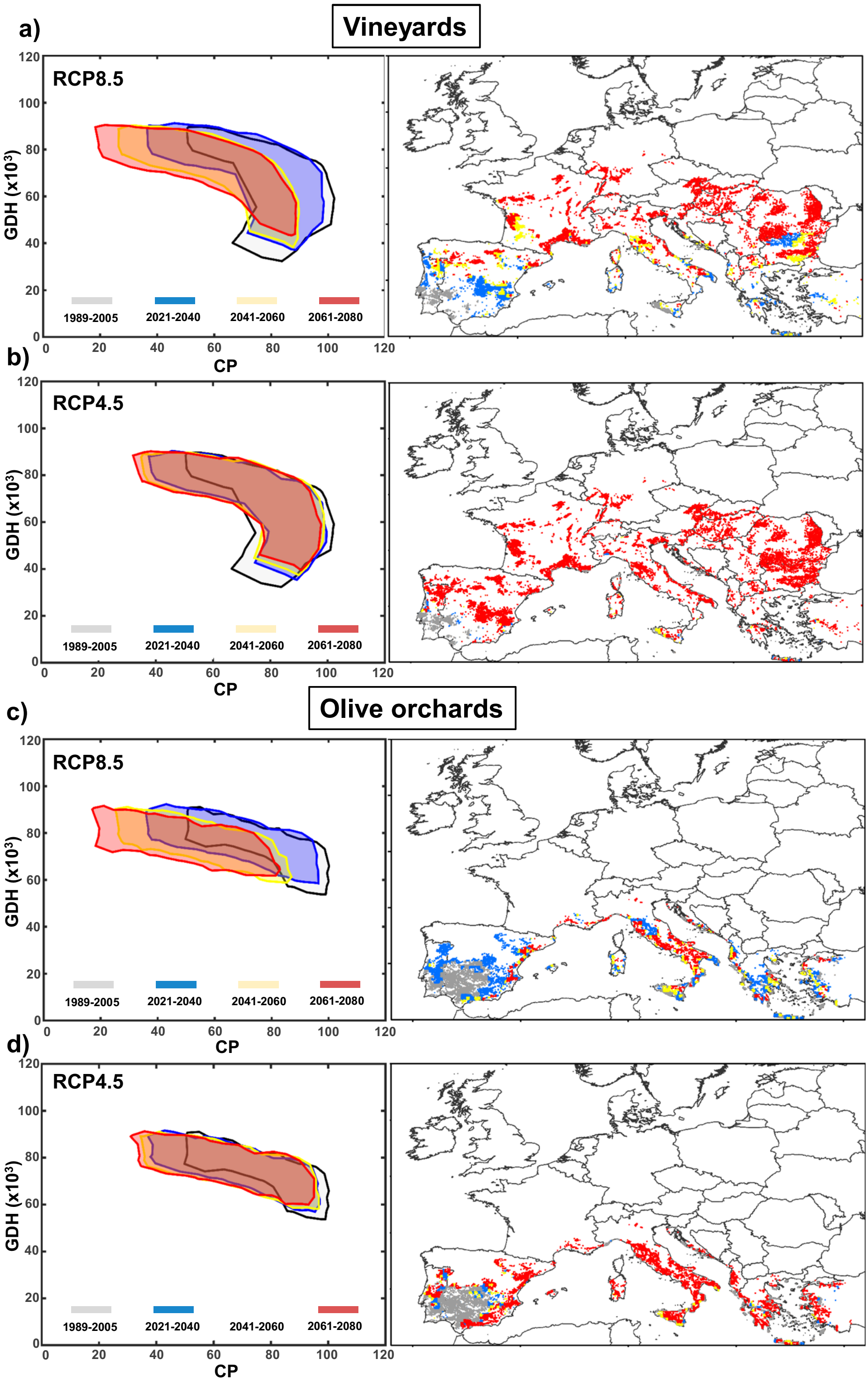
3.4 Future patterns of CP and GDH over Europe

Future projections for mean CP and GDH under RCP8.5 and RCP4.5 are shown in Fig. 4a, c, respectively, along with the differences for 2021–2040, 2041–2060 and 2061–2080. Both scenarios depict similar future changes in each metric with differences mostly in the signal intensity and typically for 2041 onwards. Under both future scenarios, the CP shows opposite climate change signals in south-western and north-eastern European regions (Fig. 4a, b). While a decrease is projected for the former, an increase is projected for the latter, a trend that will gradually enhance towards the end of the century. These signals are in agreement with most of the model ensemble members, with minor exceptions in the transition zones between increasing/decreasing values. RCP4.5 tends to show higher CP values than RCP8.5 throughout the full period over all of Europe, with up to + 4 CP in 2021–2040, up to + 12 CP in 2041–2060 and up to + 20 CP in 2061–2080. While in 2021–2040, future changes are restricted to − 20 to + 20 CP for both scenarios; by 2061–2080, these changes will enlarge to − 40 to + 30 CP in RCP8.5. Regarding the SWC future patterns (Fig. 4b, d), it becomes noticeable that the SWF climate change signal undergoes small changes across the different time periods, indicating that minimum chilling should not decline as strongly as the mean chilling.

Regarding mean GDH (Fig. 5a, c), future projections for both scenarios point to higher values throughout Europe, also increasing in time (up to $+ 15 \times 10^3$ GDH) and being more pronounced in the northern regions. The exception to these increases is found in southern Iberia, which tends to show slightly lower GDH values (up to $- 5 \times 10^3$ GDH) associated to extremely high temperature values (> 36 °C, above the upper threshold), though a higher model uncertainty is found in this region (gray-shaded areas in Fig. 5, indicating lower agreement than 70% of the models). Future changes for this metric are very similar across both future scenarios, while still more pronounced in RCP8.5 and for 2061–2080, with up to $+ 5 \times 10^3$ GDH when compared to RCP4.5. SHF future patterns (Fig. 5b, d) point to a similar increase as the mean GDH, although with higher values in the first two time periods, while the GDH decrease zone in southern Iberia is much more limited.

3.5 Implications to current orchard areas

The CP-GDH limits for the recent past and for RCP4.5 and RCP8.5 future periods are shown in Fig. 6 (left panel). Figure 6 (right panel) also maps the last future time periods where V&O will still show CP-GDH values within current-day ranges. At the current locations of European vineyards (Fig. 6a right panel) and olive orchards (Fig. 6c right panel), a clear change in the CP-GDH conditions is projected, especially under RCP8.5. Differences between the two future scenarios are visible mainly at southern European V&O sites. Under RCP8.5, V&O sites are expected to shift outside the present-day CP-GDH value range much sooner than in RCP4.5 (in 2041–2060 under RCP8.5 rather than 2061–2080 under RCP4.5). For V&O under RCP4.5, the CP-GDH conditions are expected to be maintained over the long term (2021–2080), with the exception of regions in inner south Iberia. At these locations, V&O are expected to have future conditions outside of the current CP-GDH range starting from 2021 to 2040 onwards.


a)
Vineyards
RCP8.5
GDH (x10³)
CP
1989-2005
2021-2040
2041-2060
2061-2080
b)
RCP4.5
c)
Olive orchards
d)

A strong warming is anticipated for the southern Iberian V&O orchard areas under both future scenarios, influencing both effective chilling and forcing. For these zones, which already present very high GDH values in the present, future temperatures will also frequently exceed the upper threshold of 36 °C (leading to a reduction in GDH). For central Europe, the most noticeable change is that these regions may have future GDH values similar to current Mediterranean-type regions. This will indeed point to higher heat stress under future climates. Particularly under RCP8.5, these results also clearly indicate a loss of climatic diversity throughout Europe with respect to V&O orchard-growing areas, particularly in the long term. Regarding CP, the limits will shift to lower values, though the full ranges tend to remain similar to current climate. Hence, under future climates, V&O orchards will be challenged by lower effective CP and higher GDH, particularly in regions where GDH is currently lower, such as in north-eastern Europe. Figure 6 (right panel) shows the CP-GDH limits projected over the current V&O orchard areas in Europe. It is clear that southern Europe is projected to gradually have CP-GDH values outside the current limits.

4 Discussion and conclusions

The objectives of the present study were to quantify the impacts of climate change on the main V&O orchards in Europe. Chilling and forcing for plants were computed using bias-corrected data from several RCM-GCM model chains. Given the results for future CP and GDH in European V&O orchards, it is evident that climate change may have important implications for these food crops. Regarding forcing, for both future scenarios, the ensemble projections indicate that most of Europe will experience increased warming during plant development, with a very high agreement amongst the seven GCM-RCM models. Regarding chilling, the currently warmer V&O growing regions in Western Europe will undergo strong declines in winter chilling. Conversely, the cooler regions in north-eastern Europe may experience increased chilling, due to more suitable thermal ranges in the future (Luedeling et al. 2011). However, the intensity of the climate change signal depends of the choice of the projected future scenario. Under RCP4.5, most of European V&O are still expected to maintain current CP-GDH values. Nonetheless, under RCP8.5 future scenario, this warming is strengthened, bringing additional problems to southern European V&O-growing regions, particularly over the long-term period (2061–2080). The exception to this is V&O located in inner south Iberia, which is expected to be outside current CP-GDH limits by 2021–2040.

These outcomes may bring implications to the suitability of a given region to grow a specific crop, and the impacts will be specifically tied to the regions that produce a certain type of fruit (Atkinson et al. 2013). Future V&O production might be particularly vulnerable in southern Europe (Baldocchi and Wong 2008; Luedeling et al. 2011), which currently has some of the most important producing countries worldwide. For V&O orchards in southern Europe, increased warming may bring additionally challenges, especially during summertime. Increased heat stress during this season may heavily impact on the productivity of V&O. The decrease in SWC and increase in SHF are also important for V&O-growing regions, which should have impacts on crop sustainability.

For grapevines, thermal forcing is the main driver of crop development, as grapevines are not a high chill-demanding crop (Dokoozlian 1999) and very low CP is commonly required to break dormancy (Santos et al. 2018). Under future climates, most of the current European viticultural regions are still projected to achieve these minimum CP thresholds, thus triggering normal budbreak. Still, these requirements are varietal related, and some varieties may struggle more than others (Fila et al. 2012; Fraga et al. 2016; García de Cortázar-Atauri et al. 2017). Regarding the higher GDH projected for the future, this warming will likely lead to an advance of the phenological stages (Jones et al. 2005), with implications on grapevine yield and quality attributes. Nonetheless, given that for many southern European viticultural regions, GDH values are projected to only increase slightly in the future, days with temperatures above the maximum threshold (36 °C) are expected to increase, enhancing the heat stress and respective detrimental impacts on this crop.

For olive trees, chilling plays an important role for flowering and fruit set (Orlandi et al. 2005), and is a major yield determinant (Ramos et al. 2018). Although olive trees exposed to insufficient chilling may indeed flower, it tends to result in low fruit set percentage (Ramos et al. 2018). Given that the current olive orchard areas are mostly located in the Mediterranean-climate countries, the projected reductions in CP may threaten this crop. Under lower CP in the future, flowering and fruit set may be reduced due to insufficient chilling (Torres et al. 2017). The higher GDH at olive orchards may also lead to advances in the timing of each phenological stage, affecting fruit yields and quality attributes (Bonofiglio et al. 2009; Garcia-Mozo et al. 2008; Osborne et al. 2000). It is important to note that future impacts on these two important crops are also variety-dependent. Certain varieties, of either grapevines or olive trees, are more resilient to the negative impacts of the changes in heat and chill conditions, particularity regarding phenological timings (De Melo-Abreu et al. 2004).

The present study outcomes suggest the loss of suitable V&O areas owing to lower chilling during autumn-winter and warming during spring-summer, particularly in southern Europe. The magnitude of the negative impacts of climate change is deeply tied to the projected future scenario. Under RCP8.5, impacts on chilling and forcing should be significantly more pronounced than in RCP4.5. Additionally, it is important to note that V&O may still thrive outside the current suitability ranges, as these two species have a strong climatic resilience. However, a timely planning of suitable adaptation measures may help mitigating future yield/quality losses and warrant the future sustainability of this sector. Crop relocation, while possible, is a long-term measure and is far from being an ideal solution. Hence, to deal with climate change in these regions, it becomes crucial to develop and adopt suitable cultural practices aimed at specific climate change threats. As examples of adaptation measures, regarding the future lower chilling, the development of practices to artificially break dormancy may be considered (Luedeling et al. 2011). Other cultural practices, such as defoliation or adoption of appropriate scion-rootstock combinations, may also potentially reduce chilling requirements (Ghrab et al. 2014). The adoption of other less chill-demanding varieties may also be planed. In order to cope with excessive heat during spring-summer, more focus should be given to plant thermal stress, by, e.g. heat/radiation reduction systems (e.g. sun screens and shading) and/or adopting smart irrigation strategies, which may influence orchard microclimates. Furthermore, intra- and inter-varietal heat tolerance should also be envisioned. Nonetheless, the adoption of these measures requires further research and planning to ensure the future economic sustainability of V&O orchards in Europe.

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