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Co-designed agro-climate indicators identify different future climate effects for grape and olive across Europe

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HIGHLIGHTS

- Climate change impacts on grapes and olives in Europe are assessed.
- Heat stress and dry conditions are expected to become major issues in the Mediterranean.
- Emerging compound events will become more frequent.
- Production patterns will need to adapt to increasing levels of climate variability.

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ABSTRACT

Co-design processes involving the scientific community, practitioners, end users and stakeholders can efficiently characterize harmful weather events during the growing season that potentially result in losses of crop yield and quality. This study builds on the experience of the EU Horizon 2020 project MED-GOLD for grape and olive. The identified agro-climate indicators are extended from the MED-GOLD regions to the entire ones where grape and olive are currently grown in Europe and Turkey, and used to assess climate change impacts with intrinsic adaptation relevance stemming from the co-design process. Before 2000, only a low fraction of the European grape and olive growing areas was exposed to extreme weather events as revealed by the agro-climate indicators, but this has changed rapidly afterward. Projections show increasingly widespread extreme high temperature events from 2020 to 2080. Approximately one-third of grapevine regions and over half of olive cultivation areas are expected to experience extreme drought conditions. Additionally, the frequency of compound extreme events will increase in the future, especially in the Mediterranean region and under the high-end emission scenario RCP8.5. This outcome calls for a new decision-making mindset that embeds expected levels of climate variability and extremes as the "new normal" for grape and olive in Europe. This will facilitate deployment of the required biophysical, economic and policy adaptation tools.

Practical implications

Grapevine and olive plants critically depend on weather conditions preceding and occurring during the growing season. Quantity and quality of crop yield are negatively affected by unfavorable weather and climate events, such as heat stress, drought and excessive wetness. Increasing temperatures induce changes in climatic suitability for both crops, and it has already become clear

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that farmers need to raise their preparedness to increased occurrence of harmful events (Fraga et al., 2021; Santos et al., 2020; Gambetta et al., 2020; Brito et al., 2019; Haworth et al., 2018).

The EU Horizon 2020 project MED-GOLD (https://doi.org/10.3030/776467) co-developed climate services for three staple crops of the Mediterranean food system, namely grape, olive and durum wheat. The developed services were applied to pilot regions for each of these crops: the Douro region in Portugal for grapes, Andalusia in Spain for olive, and several Italian regions for durum wheat. The co-development process involving scientists, farmers, agronomists and food companies resulted, among the others, in a set of specific agro-climate indicators characterising abiotic stress. This made it possible to achieve an informative and user-oriented integration of climate predictions at different time scales as well as to investigate risks under different climate projections.

Compared to more complex approaches, the use of targeted indicators ease the interpretability and the informed actions to be taken by end users, such as farmers. Furthermore, such an approach is scalable and favours a wider uptake, e.g. by entire continental grapevine and olive sectors. This study builds on that approach by taking a subset of those Med-GOLD developed indicators and applying them to the entire European region where grape and olive crops are currently grown. These indicators can be classified broadly in two categories: temperature and precipitation based. They provide actionable information on which varieties are best suited for a given climate, heat stress and drought/wet stress. The climate change assessment, here performed, provides important insights on the need to adapt varieties to the new climatic conditions, a clear and intuitive way to assess which areas would gain or lose suitability for the production of quality wines and olive oil, and determines the necessary changes to be taken in vineyard and olive stands operations.

The European grape and olive production areas exposed to climate extremes have been relatively low before 2000 but this has changed rapidly after. The projections for temperature-based indicators show that the extreme high temperature events will become increasingly widespread in the production areas from 2020 to 2080. The frequency of analyzed compound events, such as dry/wet spring and hot growing season, is expected to increase in the future, especially in the Mediterranean region and under the high-end emission scenario (RCP8.5). Projected changes will require a dedicated decision-making mindset, able to address with biophysical, economic and policy tools the higher levels of climate mean, variability and extremes in the future.

Data availability

Data will be made available on request.

1. Introduction

Building a resilient and sustainable future of grape and olive production requires the development and implementation of tailored climate change adaptation strategies (Toreti et al., 2022). Co-designed and co-developed climate services can translate state-of-the-art climate data and predictions at different time scales into valuable information for a wide range of end users in the agricultural sector (Ceglar et al., 2020, and references therein). Co-design processes - involving the scientific community (e.g. climate scientists), practitioners (e.g. agronomists), end users (e.g. farmers, food companies) and stakeholders - can efficiently characterize harmful weather and climate events during the growing season that may result in losses of crop yield quality and quantity, as well as the occurrence of diseases and other weather-related problems during the harvest period. A co-design process also increases the possibility of climate information reaching a broader range of end-users (Allis et al., 2019; Jacobs and Street, 2020).

With 45 % of global vineyard areas and 63 % of global wine production, Europe is not only the global wine production leader, but it is also the main market for wine (Dell'Aquila et al., 2023). Wine is an agricultural product with high added-value, with its quality and features depending on several factors and their interactions. Among these factors, there are the characteristics of the production area together with the prevailing local climate conditions during the growing season, but also the farm structure and the processing infrastructure (Santos et al., 2020). A growing body of literature points to the northward shift of agro-climatic zones in Europe (e.g. Ceglar et al., 2019). This is leading to decreasing suitability for grape production in the Mediterranean regions (Sgubin et al., 2023), while northern regions in Europe might gain suitability. Recent warming in Europe has already led to changes in grape phenology (Santos et al., 2020), having notable effects on fruit composition and quality (Sgubin et al., 2023, and references therein). In addition to chronic changes in temperatures, increasing intensity and frequency of climatic extreme events and compound events might further compromise crop productivity (Chenyao et al., 2022; Dinis et al., 2022; Lesk et al., 2022; Fraga et al., 2020; Toreti et al., 2019; Vogel et al., 2019), having implications for yield quality and quantity.

The majority of olive groves are located in the Mediterranean region. Spain, Italy and Greece alone account for around 73 % of global production. In the Mediterranean region, farmers perceive climate as a major risk factor, likely due to the broad spectrum of possible adverse climate impacts and the uncontrolled aspects of extreme weather events (Lai Nguyen et al., 2016; Battaglini et al., 2009). Regions where olives are predominantly grown are also exposed to water scarcity, further increasing future vulnerability due to climate change. Like grapevines, the olive crop is also affected by climate change, especially temperature increase, reduction of rainfall and change in seasonal weather patterns (e.g. Grillakis et al., 2022; Caselli and Petacchi, 2021; Fraga et al., 2020; Ponti et al., 2014).

Bio-climatic indicators serve as invaluable tools in assessing the impacts of climate change on ecosystems, biodiversity, and species distribution, including crops. By analysing these indicators, we can gain insights in climate change, variability, extremes and their impacts on crops, allowing us to anticipate and respond to shifts in climatic conditions, such as heat stress, drought and excessive wetness (Pérez-Zanón et al., 2023). Bio-climatic indicators are adapted to specific needs and/or application. In our study, we aim to capture the impact of climate conditions on olive trees and vineyards. The developed bio-climatic indicators are a result of the co-development process involving scientists, farmers, agronomists and food companies. A co-development process is an important step in achieving an informative and user-oriented integration of climate data such as predictions at different time scales, and investigating risks under different climate projections (Terrado et al., 2023).

The EU Horizon 2020 project MED-GOLD co-developed climate services for three staple Mediterranean crops, namely grape, olive and durum wheat. The developed pilot services were applied to several key regions for each of these crops: the Douro region in Portugal for grape, Andalusia in Spain for olive, and several Italian regions for durum wheat. Ceglar and Toreti (2021b) extended the climate service developed for durum wheat to the entire European wheat sector by generalising the specific indicators co-developed with Italian wheat farmers and agronomists. The objective of this study is to extend a subset of MED-GOLD indicators, co-developed for grape and olive, to the entire region where these crops are currently grown in Europe, and to use these indicators to assess climate change impacts on olives and wine growing regions under the mid-range (RCP4.5) and high-end (RCP8.5) emission scenarios.

2. Data and methods

The bio-climatic indicators have been co-designed by climate scientists, agronomical experts and farmers (olive and grapevine producers).

2.1. Grape indicators

The indicators for the wine sector are presented in Table 1. Growing Season Temperature (GST) is the average daily mean temperature between the 1st of April and the 31st of October (Northern Hemisphere). GST provides information on which varieties are best suited for a given climate. Climate change assessment of GST provides an important indication for introducing varieties adapted to the new climatic conditions. This indicator provides a clear and intuitive way to assess which areas would gain or lose suitability for the production of quality wines. Growing Degree Days (GDD) is an indicator summing the degree days (base temperature of 10 °C) during the growing season, and can thus as well be used as an indicator for suitability (Fontes et al., 2016; Jones and Alves, 2012).

The number of days with daily maximum 2-m air temperature higher than 35 °C (SU35) between the 1st of April and 31st of October (Northern Hemisphere) is an indicator of heat stress (Venios et al., 2020). Temperatures above 35 °C induce stomatal closures and significantly reduce photosynthesis. This indicator is therefore associated with the level of sugar, polyphenol and aroma precursor concentrations in berries, all essential for the quality of wine. The higher the value of this indicator the lower the quality of the berry and its characteristics to produce quality wine (Costa et al., 2020).

Total spring precipitation (SPRr), a cumulative amount between the 21st of April and the 21st of June, is an indicator used to characterize the level of moisture, associated with higher vigour and fungal disease risk. This indicator is therefore useful for determining the number of protective treatments and vineyard operations, such as canopy management, tipping or leaf thinning. Dry springs tend to delay vegetative growth and reduce vigour and leaf area index, causing disease pressure to remain low. On the other hand, wet springs promote greater vigour, increase the risk of fungal diseases and may disrupt vineyard operations by creating muddy soils incompatible with mechanized equipment and thus increasing the production costs for farmers (van Leeuwen et al., 2009; van Leeuwen et al., 2019; Santos et al., 2020).

Warm Spell Duration Index (WSDI) is defined as the 7-month count of days on which the daily maximum 2-m air temperature exceeds its 90th percentile for at least 6 consecutive days between 1st April and 31st October. It is an indicator of extreme persistent heat, i.e. warm spells and heatwaves, that can increase additional losses due to flowering disruption, water stress and dehydration of berries and leaves (Fraga et al., 2020).

2.2. Olive indicators

A subset of developed olive agro-climate indicators is presented in Table 2. The higher number of cold winter days (SAT1) can lead to a decrease in the quality of the olive harvested (Fraga et al., 2020). The number of spring heat days (SAT2) characterizes the earliness of flowering, and can thus be related to the level of risks of pests and diseases. According to the agronomists participating in the co-design process, this indicator can be related to decisions on plant treatment and irrigation (Gratsea et al., 2022). The cumulative number of dry days (DRY) during the entire year is an indicator of water availability, a driving factor in plant physiological activity. The threshold for dry days (precipitation below 2 mm) has been selected during the co-development process with farmers.

Table 1
Calculated grape indicators in the MEDGOLD project.

Indicator	Description
SU35	Number of heat stress days (annual count of days with daily maximum 2-m air temperatures exceeding 35 °C)
SPRr	Spring total precipitation (total precipitation from April 21st to June 21st)
GST	average of daily average temperatures between April 1st and October 31st (Northern Hemisphere)
GDD	summation of daily differences between daily temperature averages and 10 °C (vegetative growth minimum temperature) between April 1st and October 31st (Northern Hemisphere)
WSDI	Annual count of days with daily maximum temperature exceeding its 90th percentile for at least 6 consecutive days.

Table 2
Calculated olive indicators in the MED-GOLD project.

Indicator	Description
SAT1	Number of cold winter days (cumulative number (count) of days with daily minimum 2-m air temperature (Tmin) below −7 °C in November, December, and January)
SAT2	Number of spring heat days (cumulative number (count) of days with daily maximum 2-m air temperature (Tmax) above 28 °C in April, May and June)
DRY	Annual number of dry days (cumulative number (count) of days with total precipitation below 2 mm)

2.3. Compound events

Different compound events are considered for this study. The results are presented as changes in the probability (P) of an event. The probability of an event is calculated empirically for each model individually before calculating the multi-model median, using the quotient of the total number (N) of events in the study period and the length of the study period in days (n): $\mathrm{PR} = 1/P = N/n$.

The following compound events are considered for grapes:

(i) Warm growing season and dry spring (GDD-SPRr), the event is recorded every time GDD (Table 1) is above the 90th percentile and SPRr is below the 10th percentile, each calculated as grid-specific thresholds for the reference period between 1981 and 2010. Additionally, a compound event with GDD and SPRr both exceeding 90th percentile values, is calculated as well. It indicates conditions associated with the warm season and moist spring conditions, favourable for increased pressure of fungal diseases in grapes (Costa et al., 2020).

(ii) Warm growing season with heat stress (GDD-SU35), the event is recorded when GDD and SU35 (Table 1) are both above the 90th percentile grid-specific values. This indicator characterizes seasons with accelerated phenological development and incident heat stress conditions.

(iii) Another compound event to characterize a warm growing season with heat stress is GDD-WSDI. The event is recorded each time GDD and WSDI (Table 1) are both above the 90th percentile of their grid-specific values. This indicator characterizes seasons with accelerated phenological development and the occurrence of prolonged period(s) with heat stress; this can amplify yield losses due to co-occurrence of advanced phenological stages and heat stress during the sensitive stages of growth (Santos et al., 2020).

One compound event is considered for olives, namely compounding hot spring and dry growing season (SAT2-DRY). The event is recorded each time when SAT2 and DRY are above the 90th percentile of grid-specific values. This indicator characterizes the compounding effects of accelerated phenology due to hot spring conditions and scarce rainfall water availability (Fraga et al., 2020).

2.4. Climate change impact assessment

Observational reference datasets on temperature and precipitation from E-OBS (version v17, Cornes et al., 2018) are here used to calculate the reference set of indicators for the period between 1980 and 2019, on spatial resolution of 0.1°.

Climate projections from 11 high-resolution (0.11° as spatial resolution) EURO-CORDEX experiments (Jacob et al., 2014) are used to simulate future changes in indicator values for both sectors. A parametric and univariate bias adjustment, based on cumulative distribution transfer functions, is applied to each of the EURO-CORDEX runs (for more details see Dosio, 2016). Mid-range (RCP4.5) and high-end (RCP8.5) emission scenarios are considered here. Bias adjustment is applied to daily precipitation, minimum and maximum temperatures. Table 3 shows all simulations including the regional climate models (RCMs) and the driving global climate models (GCMs) used in this study.

WSDI indicators projections are calculated taking into account the 90th percentile of daily maximum temperatures from the reference period (1981–2010) for each model separately using its bias-adjusted historical realization.

The assessment of the impact of extreme climate events on the grape and olive production areas in the European Union and Turkey is based on estimating the proportion of total area affected. Extreme climate events are defined by surpassing percentile-based thresholds for various agro-climate indicators. Specifically, events such as extreme SU35, GST, GDD, WSDI, SAT2, and DRY occur whenever the respective indicator exceeds the 90th percentile of its values of the reference period. Conversely, extreme SPRr and SAT1 events take place whenever the indicator's value falls below the 10th percentile of the reference period. The area for the reference period is computed using the E-OBS data. For the scenario period (2020–2080), annual average multi-model areas are calculated, spanning 10 years before and after each year to encompass a 20-year multi-model area average. To address uncertainty, the multi-model interquartile range (between the 10th and 90th percentiles) is considered for the scenario period.

3. Results

3.1. Spatial distribution of climate change effects

Figs. 1 and 2 illustrate the projected mean climate change effects, along with the associated changes in the inter-annual variability (Figs. S1 and S2) for main grapevine regions in the European Union and Turkey. For the current production area of both grape and olive, the results consistently show a higher magnitude of changes projected in RCP8.5 than in RCP4.5 for all indicators, particularly towards the end of the century (2071–2100; Figs. 1 and 2).

For the current grape production area, the two climate suitability indicators, GST (growing season average temperature) and GDD (growing degree days), have mean values of about 5–20 °C and 1000–4000 degree days over the reference period, respectively (Fig. 1a). These values are projected to have an increase by up to 3 °C and up to 600 degree days for two studied future periods in RCP4.5 (Fig. 1b), while a substantial increase beyond 6 °C and 1400 degree days is respectively projected over 2071–2100 under RCP8.5, with the largest increase detected in Spain and Turkey (Fig. 1c). For the two heat stress indicators, represented by SU35 (hot days that significantly reduce grape photosynthesis) and WSDI (heat waves causing disruption of grape flowering and fruiting), the average values of the reference period vary from up to 10 days to 40 days and about 2 to 10 days respectively (Fig. 1a). In RCP4.5, the average increases of SU35 and WSDI for both near and far future periods are generally less than 10 and 40 days/year, respectively (Fig. 1b). In contrast, significant increases of up to 60 and 200 days/year are projected for SU35 and WSDI, respectively, over 2071–2100 under RCP8.5, with the largest increases in Spain and Turkey (Fig. 1c). Regarding spring precipitation, SPRr has mean values ranging from up to 50 mm (e.g. Sicily and Crete) to over 350 mm in central European regions during the reference period (Fig. 1a). Under climate projections, an overall decrease is found for most regions, with higher magnitude in RCP8.5 (up to 50 %) than in RCP4.5 and in a far (2071–2100) than in a near future period (2031–2060; Fig. 1b). Conversely, a small to moderate increase (up to 16 % in 2031–2060 and 23 % in 2071–2100) is constantly found in some Central European countries (e.g. Germany, Hungary, Romania and Serbia; Fig. 1c).

With the exception of SPRr (spring rainfall that can increase disease risk), the variability of grape indicators will largely increase in future, especially under the RCP8.5 scenario (Fig. S1). To illustrate, the variability of SU35 is projected to increase by up to 13 days by the end of the century, specifically under the RCP8.5 scenario. Notably, the increase in variability for temperature-related indicators is more pronounced in southeastern Europe. Projections indicate a decrease in the variability of SPRr in Mediterranean regions, aligning with a reduction in spring rainfall. In contrast, a slight increase in variability is anticipated in northern and eastern grape-growing regions. For instance, grapevine regions in Germany, Slovakia, Hungary, and north-western Romania could witness an increase in spring rainfall variability of up to 40 % by the century's end, particularly under the RCP8.5 scenario. Conversely, regions in southern Spain and Portugal, Sicily, and southern Turkey might experience at least 50 % reduction in rainfall variability compared to the reference period.

For the current olive production area, SAT1 (number of cold winter days that can decrease the quality of the olive harvested) is on average below 5 days throughout the reference period, which is projected to undergo a marginal mean decrease by less than 5 days irrespective of both scenarios and periods (Fig. 2a–c). For SAT2 (number of hot spring days indicating earliness of flowering), it is generally below 20 days in the reference period (with higher values in the Iberian Peninsula; Fig. 2a). Climate projections show a moderate increase by 5–15 days under RCP4.5 (Fig. 2b), whereas a substantial increase by up to 30 days is projected in a distant future period under RCP8.5 (Fig. 2c). The average DRY (annual number of dry days, affecting plant physiological activity) varies from 200 to 300 days in the reference period (Fig. 2a). Projections show enhanced dryness, where an increase of less than 10 days is projected for both periods in RCP4.5 (Fig. 2b) or up to 20 days in a far future period in RCP8.5 (Fig. 2b).

The variability of SAT1 and DRY will decrease under both RCP4.5 and RCP8.5 scenarios. While, the variability of SAT2 is projected to increase (most pronouncedly in Italy).

3.2. Increasing grape and olive growth area under the influence of climate extremes

In the historical period, the European grapevine production area has seen a steady low proportion (well below 20 %) of land exposed to extreme events of studied agro-climate indicators before 2000, but this has changed rapidly from 2000 to 2019 (Fig. 3). The projections for temperature-based indicators (GST, GDD, SU35 and WSDI) show that the extreme high temperature events will become increasingly widespread within the production area from 2020 to 2080 under both scenarios (Fig. 3). The multi-model median projections for the suitability

Table 3
List EURO-CORDEX model runs used in this study. Jacob et al. (2014) provides a full description of each model setup. Each of the EURO-CORDEX runs was bias corrected (Dosio, 2016).

Institute	RCM	Driving GCM
CLMCOM	CCLM4.8–17	CNRM-CERFACS-CNRM-CM5
		ICHEC-EC-EARTH
		MPI-M-MPI-ESM-LR
DMI	HIRHAM5	ICHEC-EC-EARTH
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR
KNMI	RACMO22E	ICHEC-EC-EARTH
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5
		ICHEC-EC-EARTH
		IPSL-IPSL-CM5A-MR
		MOHC-HadGEM2-ES
		MPI-M-MPI-ESM-LR

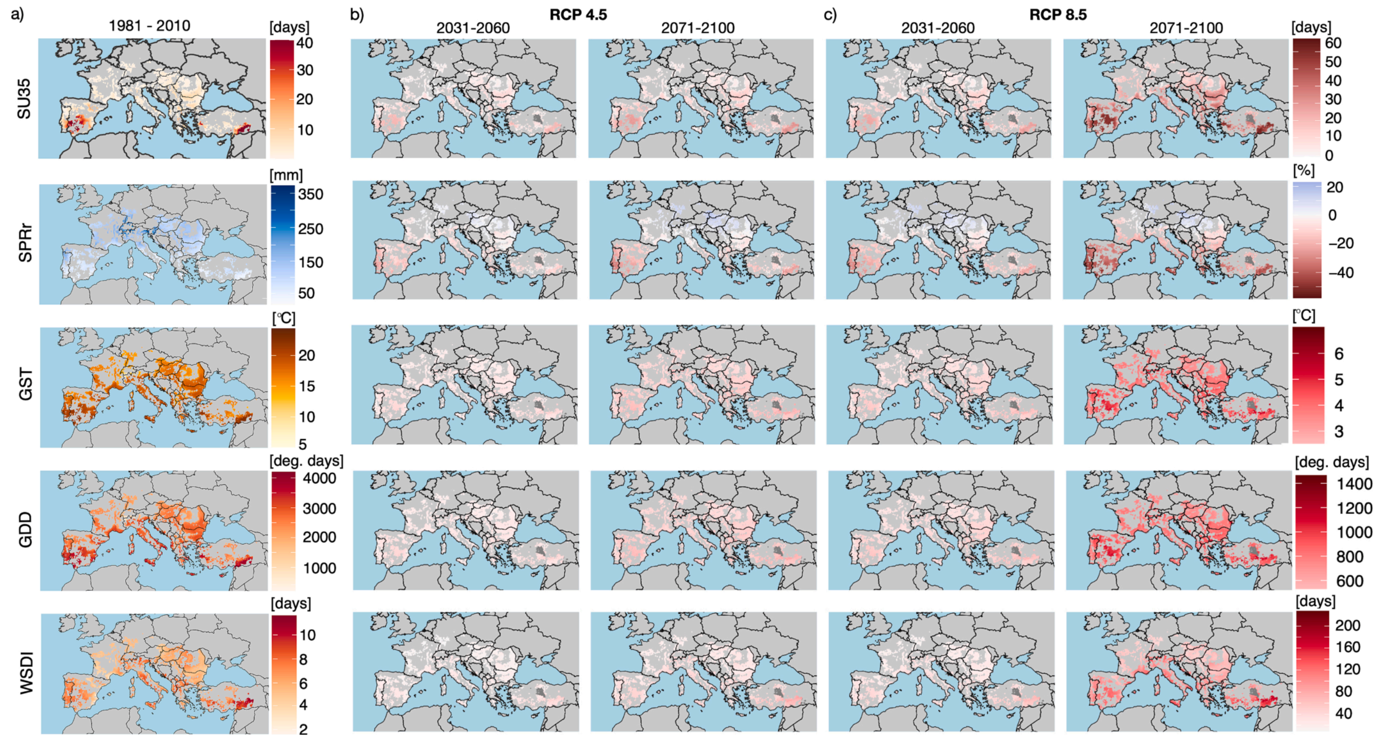

Fig. 1. Reference historical (1981–2010) average values of grape-related indicators (a). Changes in average values of grapevine indicators under two different future periods and two representative concentration pathways: RCP4.5 (b) and RCP8.5 (c). Changes are calculated as climate model ensemble averages of differences between future and reference periods. The legends on the right side are applicable to both b) and c).

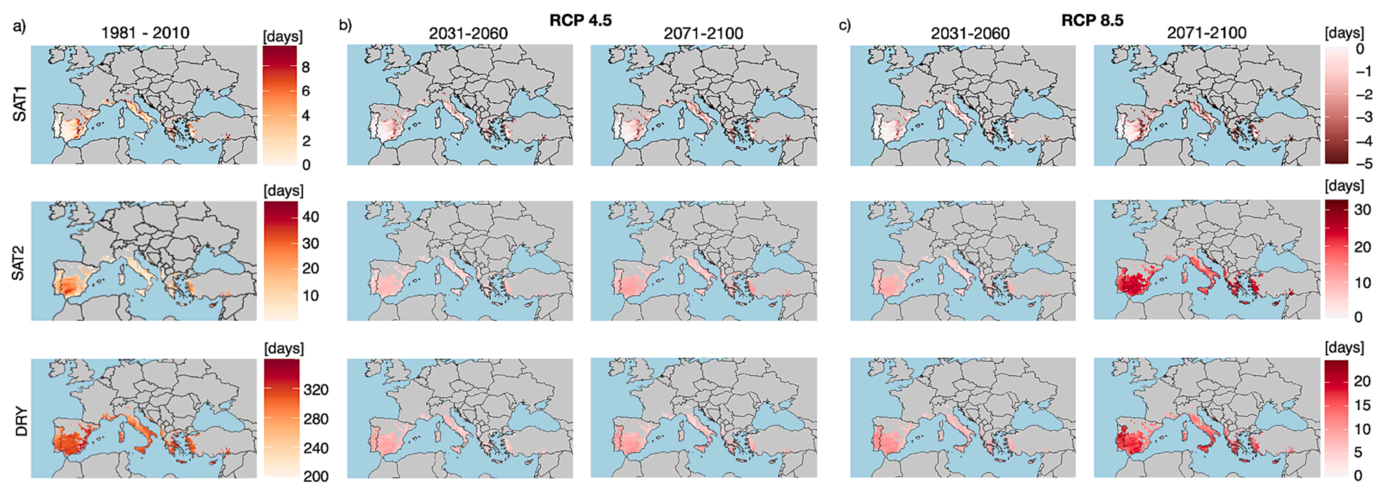

Fig. 2. Reference historical (1981–2010) average values of olive-related indicators (a). Changes in average values of olive indicators under two different future periods and two representative concentration pathways: RCP4.5 (b) and RCP8.5 (c). Changes are calculated as climate model ensemble averages of differences between future and reference periods. The legends on the right side are applicable to both b) and c).

indicators GST and GDD show a nearly identical pattern, with the affected area increasing from 30 % (RCP4.5) and 38 % (RCP8.5) in 2020 to approximately 80 % (RCP4.5) and 95 % (RCP8.5) in 2080 (Fig. 3). For the two heat stress indicators, the affected area for SU35 is expected to increase from 20 % (RCP4.5) and 28 % (RCP8.5) in 2020 to around 58 % (RCP4.5) and 89 % (RCP8.5) in 2080, while for WSDI these are 40 % (RCP4.5) and 45 % (RCP8.5) in 2020 to around 80 % (RCP4.5) and 95 % (RCP8.5) in 2080 (Fig. 3). The spread among models gradually decreases from the 2060 s and nearly all models predict that almost the entire wine production area could experience historically extreme values of GST, GDD, and WSDI around 2080 in RCP8.5 (Fig. 3). For SPRr projections, there is relatively low uncertainty, with the median values being steadily below 20 % in RCP4.5 and 30 % in RCP8.5 until 2080 (Fig. 3).

As for European olive production, the areas historically affected by a high number of cold days (SAT1) and hot days (SAT2) have respectively seen a gradual decline (increase), in the reference period up to 2019 (Fig. 4). The affected area by extreme SAT1 is projected to be less than 10 % over 2020–2080 for both RCP4.5 and RCP8.5 (Fig. 4). However, the affected SAT2 area is projected to increase from approximately 20 % in 2020 in both scenarios to about 42 % (RCP4.5) and 78 % (RCP8.5) in 2080 (Fig. 4). The areas affected by extreme dry conditions remain low (less than 10 %) in the reference period and undergo a stable development (below 20 %) in RCP4.5 or a moderate increase of up to 35 % in RCP8.5 until 2080 (Fig. 4). The projections for RCP8.5 have higher

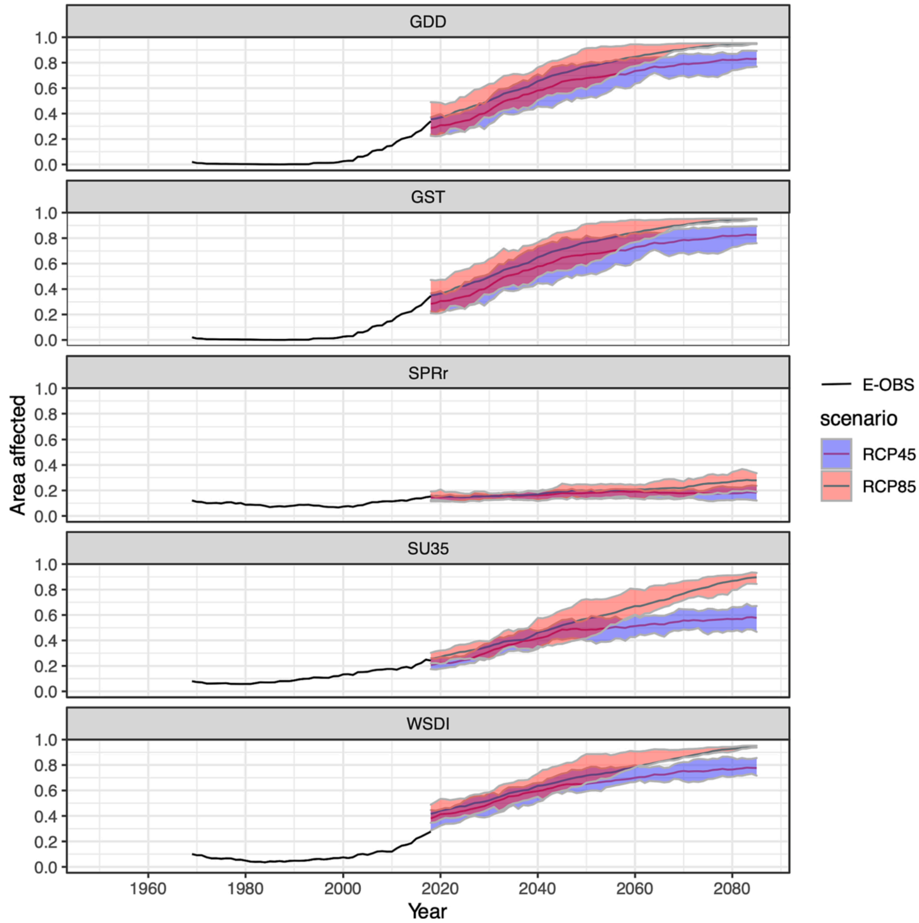

Fig. 3. Proportion of European grape production area affected by extreme climate events defined by exceeding the 90th percentile threshold (calculated using the reference period 1981–2010) for temperature related indicators (GDD, GST, SU35, WSDI), and by being lower than 10th percentile for spring rainfall (SPRr).

uncertainties than for RCP4.5 (Fig. 4).

3.3. Compound events

In this section, we examine the frequency of occurrence and the projected changes in extreme compound climate events (see Section 3.2) that affect the current wine-growing regions in Europe (Fig. 5). The main findings reveal that an extremely warm growing season with a dry spring (as measured by GDD-SPRr) is a rare event (<8%) during the reference period between 1981 and 2010 (Fig. 5a). The frequency of this compound event is projected to remain largely unchanged for the two studied time horizons under RCP4.5 (Fig. 5b), but a moderate increase in its occurrence probability (<20 %) is predicted for 2071–2100 under RCP8.5 (Fig. 5c). The combination of an extremely warm season and wet spring is even rarer (<2%) during the reference period, and remains mostly unchanged under climate projections, except for a moderate increase <20 % in the far future period under RCP8.5 for some Central European grapevine regions (Fig. S3). Similarly, the occurrence of an extremely warm season with high levels of heat stress (as measured by GDD-SU35 and GDD-WSDI) is also rare (<10 %) during the reference period (Fig. 5a). However, projections indicate that both compound events are likely to become more frequent in the near-future period under RCP4.5 (up to 50 % increase in probability in southern and 20 % in central Europe) and RCP8.5 (up to 70 % increase in probability in southern Europe and 50 % in central Europe), with a high likelihood of becoming normal events in the far future period, particularly under RCP8.5 (i.e. more than 80 % increase in probability of occurrence) where they may occur almost every year (Fig. 5b-c).

For the current olive growing regions in Europe, the extreme compound event with spring heat stress and seasonal dryness (as measured by SAT2-DRY) is a rare event (<8%) during the reference period (Fig. 6a). However, projections indicate that this compound event is likely to become more frequent in the future. In RCP4.5, a moderate increase of less than 20 % in the occurrence probability is projected for the two future time horizons (Fig. 6b). In contrast, under RCP8.5, a substantial increase of between 30 % and 40 % is expected over a far future period (Fig. 6b).

4. Discussion and conclusions

Using co-developed agro-climate indicators provide a robust approach to assess the potential impacts of climate change on grapes and olives in the near and far future. This approach has some advantages with respect to more complex assessments regarding the information usability in decision-making processes thanks to the robustness of the co-developed indicators, their scalability and ease of interpretation by a range of end-users. Its main advantage, however, is the ability to integrate climate predictions at different time scales, going from seasonal-to-decadal as well as climate projections.

Our results focus on the current growing regions rather than delineating potential new growing regions. The latter would require a more holistic assessment, including soil characteristics, geographical denominations and other socio-economic factors. The sustainability of grape and olive production depends on many drivers, such as climate change, economic conditions (demand and supply), and competitiveness in the global marketplace. While climate indicators used in this study do not address the production sustainability entirely, they do provide robust information on the important emerging climate extremes

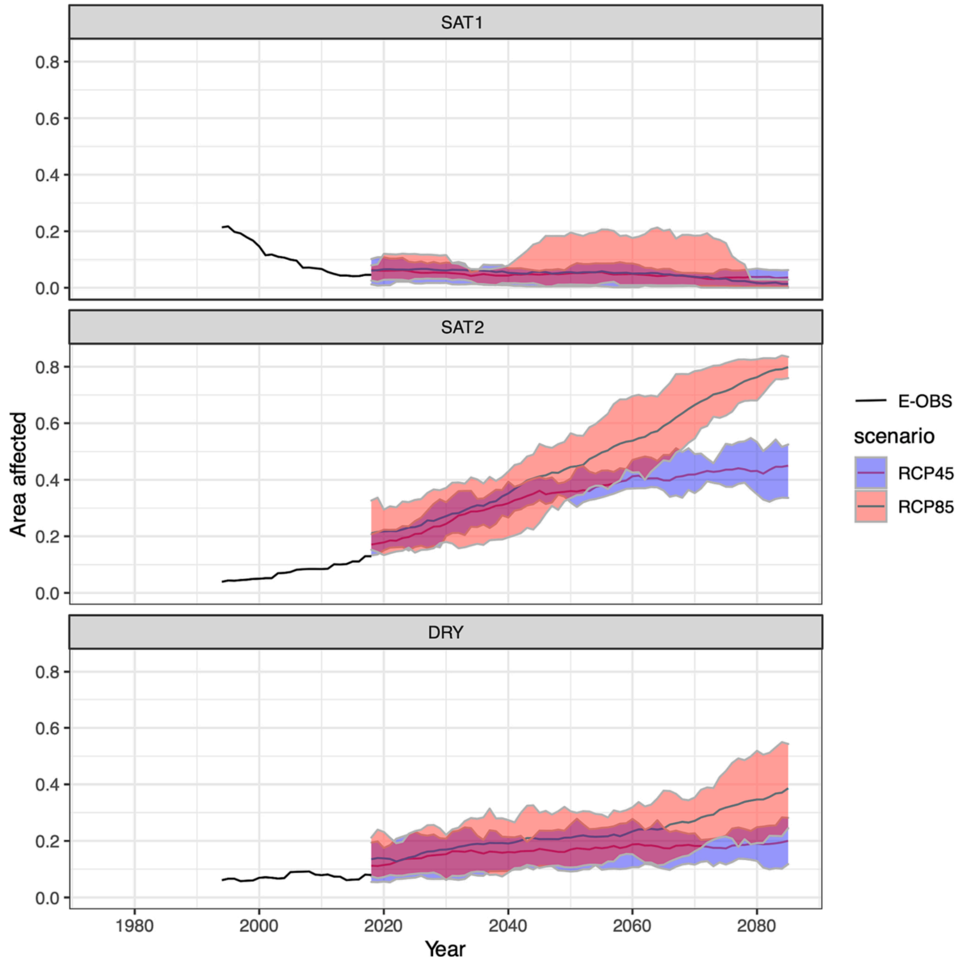

Fig. 4. Proportion of European olive production area affected by extreme climate events defined by exceeding the 90th percentile threshold (calculated using the reference period 1981–2010) for SAT2 and DRY, and by being lower than the 10th percentile for SAT1.

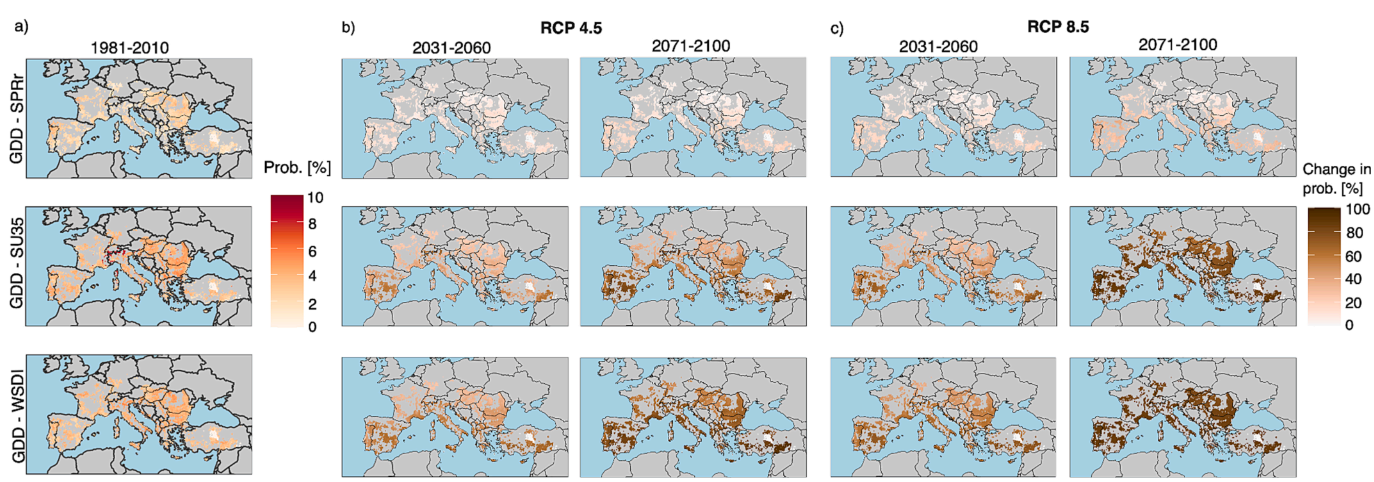

Fig. 5. The probability of compound climate events occurring over the European wine-growing areas. Three pairs of compound events have been identified here, based on: growing degree days and spring rainfall (GDD-SPRr), growing degree days and number of summer days with maximum daily temperature exceeding 35 °C (GDD-SU35) and growing degree days with WSDI (GDD-WSDI). Compound events occur when both indicators exceed pre-defined threshold values (90th percentile for temperature-based indicators), or fall below (10th percentile for spring rainfall) during the same growing season. Historical probability is shown on the left (a), while changes in the probability of occurrence under two different time horizons and emission scenarios are shown on (b) for RCP4.5 and (c) for RCP8.5. The legends on the right side are applicable to both b) and c).

relevant to grape and olive production across Europe. Our findings highlight a growing influence of climate extremes on viticulture in Europe, supporting the evidence of a non-linear decline in climatically suitable wine regions across the continent (Sgubin et al., 2023).

A comparable study focused on viticulture in Greece utilized various pertinent agro-climatic indicators to assess the temperature effects on

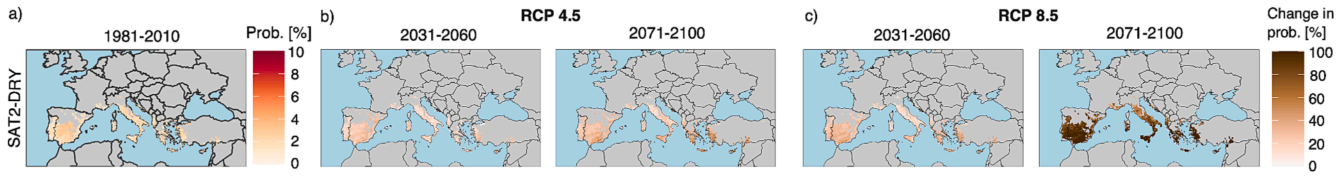

Fig. 6. The probability of compound climate events occurring over European OLIVE growing areas. One pair of compound events has been identified here based on SAT2 and DRY. Compound events occur when both indicators exceed pre-defined threshold values (90th percentile for SAT2), or fall below (10th percentile for DRY) during the same growing season. Historical probability is shown on the left (a), while changes in the probability of occurrence under two different time horizons and emission scenarios are shown on (b) for RCP4.5 and (c) for RCP8.5. The legend on the right side is applicable to both b) and c).

grapevine growth and production from 1974 to 2019 (Koufos et al., 2014). In alignment with the findings presented in this study, their results reveal a discernible trend toward a progressively warmer climate characterized by elevated nighttime temperatures and extended periods of drought. Notably, the study identifies that high-temperature events during critical developmental stages have lasting impacts on vine production in the subsequent year (Koufos et al., 2014). Mavromatis et al. (2022) assessed the climate change impacts over Greece during 2071–2100 under RCP8.5, showing increased spring hot days by up to 11 days (maximum temperature above 30 °C), accompanied by decline in wet days by up to 9 days in spring and summer. Our results show SAT2 and DRY can increase by up to 30 and 20 days, respectively, in a distant future period under RCP8.5 (Fig. 2). Notably, SAT2 employs a lower threshold for the indicator (maximum temperature above 28 °C), and the definition of DRY differs from that of wet days.

Changes in average climate conditions suggest that northward expansion and variety adaptation might come as an obvious solution; however, increasing variability and the higher occurrence of extreme conditions will pose an additional level of risk for crop failure on a year-to-year basis. Maintaining or even increasing the current growing areas for both crops under increasing future demand will therefore rely not only on exploitation of emerging suitable areas (Sgubin et al., 2023), but also on the implementation of effective sustainable adaptation strategies in the current growing region. The latter will require consideration of a full spectrum of economic factors, including sustainable changes in value chains (FAO, 2019) due to interlinkages between natural resources and agriculture, local economies and development patterns in agriculture (Ceglar et al., 2021a).

Mean and variability of high-temperature indicators, largely projected to increase in the future for both grape and olive production regions, call for a dedicated decision-making mindset, able to address with biophysical, economic and policy tools the higher levels of variability. Co-designed and co-developed agro-climate services, based on the indicators presented in this study, can provide an effective way to enhance farmers' resilience, especially with respect to increasing inter-annual variability. The possibility to integrate climate predictions on different time scales enables decision-makers to plan and implement agro-management actions using seasonal forecasts (Ceglar and Toreti, 2021b) or varietal selection and infrastructure development using decadal climate predictions (Solaraju-Murali et al., 2021). The flexibility of integrating climate information on different time scales makes such a climate service a robust tool to adapt to increasing climate variability in the future.

Our analysis shows that high temperatures will become extreme (especially in the case of RCP8.5) over the entire olive production area. For olive, extreme spring heat seems to be a major issue that becomes widespread towards the end of the century. However, extreme winter cold might remain a problem for approximately one fifth of the olive production area well into the century, with extreme drought increasing and affecting about half of the olive growing area towards the end of the century.

Compound events represent an emerging issue with severe impacts on crop yield quality and quantity, potentially non-linearly amplified as compared to the impacts of single climate extremes (e.g. Zscheischler et al., 2018; Toreti et al., 2019). The frequency of compound events analysed in our study will increase in the future, especially under the RCP8.5 scenario. The risk associated with the analysed compound events is expected to increase over a major proportion of grape production areas, with the most notable increase of compound events characterized by warm season and dry spring in the Mediterranean region. Mostly due to an increase in spring rainfall variability, an increase of the opposite type of compound event, warm seasons and wet spring conditions, is expected in grape producing regions of central and southeastern Europe. These conditions can lead to issues related to the occurrence of diseases and pests. Olive stands are projected to be affected by more severe events with hot springs and drier conditions during the growing season, further amplifying issues related to limited plant water availability, and pointing to the higher irrigation requirements. Even though the identified compound events carry the potential to significantly reduce the quality and quantity of yields, their impact remains to be quantified in future studies.

CRediT authorship contribution statement

Andrej Ceglar: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Chenyao Yang:** Writing – review & editing, Writing – original draft. **Andrea Toreti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **João A. Santos:** Writing – review & editing, Writing – original draft. **Massimiliano Pasqui:** Writing – original draft, Project administration, Investigation. **Luigi Ponti:** Writing – original draft, Investigation, Funding acquisition. **Alessandro Dell'Aquila:** Writing – original draft, Project administration, Investigation, Funding acquisition. **António Graça:** Writing – review & editing, Writing – original draft, Project administration, Methodology.

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.cliser.2024.100454.

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