Mitig Adapt Strateg Glob Change (2025) 30:56
https://doi.org/10.1007/s11027-025-10247-4

ORIGINAL ARTICLE

Future agroclimatic suitability for oliviculture in Portugal based on a new high-resolution climate dataset

Teresa R. Freitas[1] · João A. Santos[1] · António Fernandes[1] · Christoph Menz[2] · Paula Paredes[3] · Helder Fraga[1]

Received: 2 December 2024 / Accepted: 21 July 2025 / Published online: 29 August 2025

Abstract

The Mediterranean-type climates on mainland Portugal generally provide suitable conditions for growing olive trees, though climate change may challenge their long-term sustainability. Historical (1995–2014) and projected future scenarios (2041–2060) of agroclimatic indices are developed herein to guide olive orchard (OR) management. Daily simulations from six Global Circulation Models are processed with the CHELSA method, using bias-adjusted ISIMIP3b climate projections based on CMIP6 simulations. Two Shared Socio-Economic Pathways (SSP) are considered: SSP3-7.0 (regional rivalry) and SSP5-8.5 (fossil-fuelled development). Daily data (~1 km) are used to calculate the following indices: Consecutive Frost Days (CFD), Spring Heat Day (SPR32), Spring Maximum Temperature (SPRTX), Summer Heat Stress Days (SU40), Total rainfall October–May (WINRR). During the historical period, the North and Centre regions experienced a CFD between 0 and 35, whereas a reduction in CFD up to 9 days and 11 days will be expected under SSP3-7.0 and SSP5-8.5, respectively. In 1995–2014, higher SPR32 (3–12 days) and SPRTX (20–24 °C) are recorded in the inner southern regions, increasing to 24 days and 26 °C, respectively, under SSP5-8.5. In these areas, SU40 could reach 24 days in the future. WINRR will decrease by 100–140 mm (7% of the area), particularly in southern regions. The southern regions will be particularly exposed to high temperatures and low rainfall, while phenological timings and yields may be significantly affected. Adaptation measures, i.e., biostimulants implementation and irrigation strategies definition, could be tools to reduce the impact of climate change on OR. These outcomes can be an important tool for climate change adaptation and risk reduction in the Portuguese olive chain sector.

Keywords Olive crop · Agroclimatic zoning · Climate change · Suitability · CHELSA · CMIP6

Extended author information available on the last page of the article

1 Introduction

The olive tree (*Olea europaea* L.) holds considerable social, economic and cultural importance worldwide (Brito et al. 2019; Chou et al. 2023). In particular, the countries in the Mediterranean Basin are a reference for this species' distribution, as well as in the production of table olives and olive oil (Mogollón Hernández et al. 2021). In Portugal, olive trees are widespread throughout the country, although they are scarce in coastal areas due to the negative effects of strong winds and high air moisture (Claro et al. 2023), as well as the possibility of high salt concentrations deposited by sea winds (Sergeeva and Spooner-Hart 2011). Despite the relatively narrow area, Portugal ranks 9th in global olive production and 4th in olive oil production (FAOSTAT 2023). In 2022, Portugal was the leading exporter of olives (41% of global exports) and the 3rd largest global exporter of olive oil (FAOSTAT 2023; Tridge 2024). The olive orchard (OR) area has increased in recent decades, mainly in southern Portugal, where many are intensive and super-intensive (irrigated). In contrast, in northern Portugal, the traditional (rainfed) ORs areas are the most representative (Freitas et al. 2024).

The geographical distribution and yields of olive trees are strongly influenced by climatic conditions (Garrido et al. 2021). Several studies have highlighted the importance of optimal climatic conditions for olive growth, as well as the possible impacts of climate change on its sustainability, particularly concerning traditional rainfed ORs (e.g., Ramos-Román et al. 2019; Orlandi et al. 2020; Gratsea et al. 2022; Honorio et al. 2024). Air temperatures are important because they influence the growth stages (phenophases) of plants and the entire production process. Precipitation is significant in traditional (rainfed) ORs (Bonofiglio et al. 2008; Oteros et al. 2013; Brilli et al. 2016). Rising temperatures, expected in the future, may change their phenological timings (Moriondo et al. 2015), pollen performance (Vuletin Selak et al. 2013), olive fruit growth and yield (Orlandi et al. 2020). Earlier flowering and fruit ripening, and earlier harvest, may be detrimental to fruit quality and ripeness (Nissim et al. 2020; Silveira et al. 2023). Additionally, warm spring temperatures may increase the incidence of pests, such as the anticipation of the activity of the olive fruit fly *(Bactrocera oleae* Gmel.) (Gutierrez et al. 2009). In summer, temperatures above 40 °C may reduce the photosynthetic rates and yields (Fraga et al. 2020a; Silveira et al. 2023).

The olive tree is a drought-tolerant species, commonly found in sub-humid and semi-arid zones, with hot and dry summers (Fraga et al. 2020a). Previous studies indicate drying trends across the Mediterranean, accompanied by more frequent and intense precipitation extremes, like torrential downpours, heavy rainstorms and droughts (Cardell et al. 2020; Seker and Gumus 2022; Arjdal et al. 2023; Essa et al. 2023). The Intergovernmental Panel on Climate Change (IPCC) has identified southern Europe as a climate change hotspot (IPCC 2023). CMIP6 projections suggest that climate change trends already observed in the Mediterranean region are likely to persist, or even worsen, in the foreseeable future (Chou et al. 2023). Furthermore, the uncertainties associated with these trends pose significant risks to crop sustainability, as well as to the olive chain sector (Chou et al. 2023). More specifically, southern Portugal is projected to experience a 90 mm decrease in precipitation, increasing water scarcity and impacting crop yields (Fraga et al. 2020b). Olive tree drought tolerance mechanisms, well-adapted to very specific Mediterranean environments, have played a significant role in their predominance under warm and dry regions (Connor and Fereres 2004; Sofo et al. 2008; Montanaro et al. 2018; Silveira et al. 2022). However, reduced precipitation, combined with higher air temperatures, may undermine their future sustainability (Gratsea et al. 2022), particularly under rainfed conditions. Furthermore, the increasing occurrence of extreme weather events increases uncertainty about the growing conditions and potential production of olive trees (Moriondo et al. 2015).

Agroclimatic indices (AgrIs) are reference parameters for understanding climatic conditions that support species' growth (Freitas et al. 2022). The application of these indices can help identify optimal areas for olive cultivation and growth, supporting decision-making in OR management (Gratsea et al. 2022). These tools are useful for describing climatic changeability and studying the effects of climate change on olive trees (Fraga et al. 2013; Gratsea et al. 2022). Comparing projected and observed AgrI patterns can provide a basis for biodiversity conservation and boosting ecosystem resilience (Silveira et al. 2023; Fierke et al. 2024). Particularly for olive species, certain AgrIs are usually considered, such as the Spring Heat Day (when the maximum temperature exceeds 32 °C), Spring Maximum Temperature and Total rainfall between October and May (Rivas-Martínez et al. 2011; Orlandi et al. 2020; Gratsea et al. 2022; Silveira et al. 2023). These indices can help explain the growth responses of olive trees under different climatic conditions (Silveira et al. 2023). While other studies have applied different AgrIs (Gratsea et al. 2022; Chou et al. 2023; Silveira et al. 2023), there is still a lack of detailed studies in Portugal using high-resolution climate data, in terms of spatial and temporal scales.

A comprehensive climatological analysis is critical to detect and understand the impacts of climate change (Gratsea et al. 2022). The present study is based on AgrIs calculated from high-resolution climate datasets (~1 km). As such, the present study analysed historical AgrIs and projected future climate scenarios to guide OR management. In addition, future climate conditions are evaluated through statistical analysis and adaptation and mitigation measures are proposed to reduce the possible impacts on olive trees. This study should serve as a Decision Support System (DSS) tool to support farmers, stakeholders and organisations involved in the olive sector.

2 Materials and methods

2.1 Study area

The olive trees are widespread in areas with long, warm, and dry summers and rainy winters, typical of Mediterranean countries (Fig. 1a) (Caudullo et al. 2017; Gratsea et al. 2022). In Portugal, the species is widely distributed across the mainland, covering more than 350×10^3 ha, representing 32% of the cultivated area (Rodríguez Sousa et al. 2023). According to the Köppen-Geiger classification (Kottek et al. 2006), *Csb* and *Csa* climates are prevalent over Portugal, which are characterised by warm (*Csb*) or hot summers (*Csa*) and rainy winters (Beck et al. 2018).

The characterisation of these olive-growing areas is based on the digital inventory of the Geographical Institute of Portugal, with the areas referred to as "Olivais" (Fig. 1b) (DGT 2018). The species is mainly found in the country's eastern regions. Traditional rainfed and intermediate orchards are established in the North and Centre regions (NUTII), where the orography is more heterogeneous (Fig. 1c) (Silveira et al. 2022; Fraga et al. 2024). The southern areas (Alentejo agrarian region) consist of intensive and super-intensive orchards

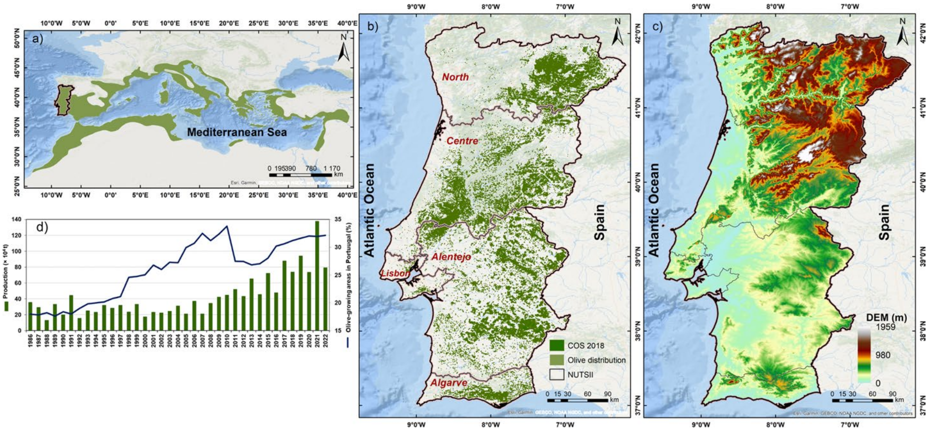

Fig. 1 – Overview of the study area: (**a**) distribution of olive trees across the Mediterranean region (Caudullo et al. 2017); (**b**) distribution of olive-growing areas in mainland Portugal (DGT 2018) and the NUTII illustration (DGT 2023); (**c**) digital elevation model (DEM) (Karger et al. 2017); (**d**) cultivated area in Portugal for olive-growing (%) and yield (t) of olive trees in the country, between 1986–2022 (FAOSTAT 2023; Tridge 2024)

(Guerrero-Casado et al. 2021; DGT 2023). Historical records available (1986–2022) show that the highest production year was 2021 (138×10^4 t), with 32% cultivated area for the olive species. Although 2020 saw the largest harvested area (381×10^3 ha), this did not reflect the highest yield (FAOSTAT 2023). The annual olive yield fluctuation in ORs is often due to the alternate bearing phenomenon typical of these plants (Fig. 1d) (Lavee and Wodner 2004; Gratsea et al. 2022).

2.2 Climate dataset and data processing

The CHELSA method (version 2.1) (Karger et al. 2017, 2021) is a widely used approach for downscaling global climate models, utilising a quasi-mechanistic framework that incorporates physical processes, e.g. orography, temperature stratification, cloud and precipitation formation (Fierke et al. 2024). This method enhances the spatial resolution of climate projections, providing more detailed and physically plausible results. However, despite its advantages, the CHELSA method has some limitations. Specifically, the algorithm is applied to each grid cell and day independently, basically ignoring spatial and temporal correlations of climate parameters at this high scale. Furthermore, it is challenging to evaluate the dataset, as observations are not available at such a high resolution across the entire study domain.

For the present study, we process daily simulations of a six-member ensemble of Global Circulation Models (GCMs), using the CHELSA method. This method is applied to bias-adjusted climate projections from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; 0.5º grid resolution) (Lange 2019, 2021a, b; Frieler et al. 2024), which are based on Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations (Eyring et al. 2016; O'Neill et al. 2016). In contrast to CMIP5, CMIP6 considers a more recent historical period, during which the effects of climate change have already become apparent. This enables researchers to simulate future climate change on the environment and socio-economy (Fernandes et al. 2024).

Two Shared Socio-Economic Pathways (SSP) are considered to represent a wide range of possible future socio-economic development scenarios: SSP3-7.0 (regional rivalry) and SSP5-8.5 (fossil-fuelled development) (Meinshausen et al. 2020; Talebian et al. 2021). SSP3-7.0 is a moderate-to-pessimistic scenario that results in a radiative forcing of 7.0 W/m^2 by 2100 (Brun et al. 2022). SSP5-8.5 is an extreme scenario described by intensive fossil-fuel consumption, leading to a radiative forcing of 8.5 W/m^2 in 2100 (Martinez and Iglesias 2021). The simulations of the six GCMs are available for each pathway (Table 1).

The created dataset, with a resolution of 30 arc-seconds (~1 km), integrates climate observations and model projections of climate variables (Karger et al. 2017, 2021). This high spatial resolution, high data reliability and global coverage enable very detailed assessments of climatic conditions. This level of precision is particularly useful for regions with complex landscapes. This climate dataset has been used for simulating the future environmental and socio-economic impacts of climate change in viticulture (Fernandes et al. 2024).

The AgrIs are calculated from daily data for each model, in the historical baseline period (1995–2014) and the future period (2041–2060), in each scenario. Subsequently, the ensemble mean of the six models is applied for each period and scenario (Freitas et al. 2023). The ensemble mean for each scenario helps to reduce inter-model variability. Ensemble medians are also tested, but the results are very similar (not shown).

2.3 Agroclimatic indices description

AgrIs indices have been used to analyse climate features relevant to the growing conditions and spatial distribution of olive trees, providing predictions about how climate change may affect the crop, thus enabling the development of improved management and adaptation practices (Freitas et al. 2022). In addition, these indices allow for assessing the relationship between yields, climatic variables (e.g., air temperature and precipitation) and water availability (Gratsea et al. 2022). Therefore, this study applies the following AgrIs: Consecutive Frost Days (CFD; day), Spring Heat Day (SPR32; day), Spring Maximum Temperature (SPRTX; ºC), Summer Heat Stress Days (SU40; day) and Total rainfall between October and May (WINRR; mm), which are detailed in Table 2.

Table 1 Ensemble of global climate model (GCM) chains selected for this study and the corresponding Institute that undertook each model experiment

Global Climate Model Abbreviation	Model	Reference
IPSL-CM6A-LR	Institut Pierre-Simon Laplace Earth System Model—Coupled Model version 6 A—Low Resolution	(Lurton et al. 2020)
MPI-ESM1-2-HR	Max Planck Institute Earth System Model Version 1.2—High Resolution	(Gutjahr et al. 2019)
MRI-ESM2-0	Meteorological Research Institute Earth System Model Version 2.0	(Yukimoto et al. 2019)
UKESM1-0-LL	UK Earth System Model 1.0 Low Resolution	(Sellar et al. 2019)
CNRM-CM6-1	Centre National de Recherches Météorologiques — Climate Model Version 6.1	(Voldoire et al. 2019)
MIROC6	Model for Interdisciplinary Research on Climate, version 6	(Tatebe et al. 2019)

Table 2 – Agroclimatic indices characterising the climate conditions for Olive tree cultivation

Agro-climatic Index	Designation	Application	Olive tree impacts	References
Consecutive Frost Days (CFD; day)	CFD by year with minimum temperature (TN; ºC) less than 0 °C.	The determination of CFD helps to understand the impacts of frost on olive growth and fruit yield and may be used as a guide for selecting varieties, optimising and managing irrigation and yields (Fraga et al. 2020a; Silveira et al. 2023).	An increase in the number of frost days may lead to disrupted growth with an impact on phenological stages timing and fruit development. Late frost may also lead to a yield decrease.	(Bartolozzi and Fontanazza 1999; Snyder and Melo-Abreu 2005; Silveira et al. 2023)
Spring Heat Day (SPR32; day)	Total spring days, between 21st April and 21st June, with maximum temperatures (TX; ºC) above 32 °C.	This index is related to early flowering olive trees. It serves as a reference for pre-flowering treatments, irrigation management and yield prediction (Gratsea et al. 2022; Chou et al. 2023).	An increase in these days may lead to earlier flowering, a higher incidence of pests and diseases (e.g., *Prays oleae* Bern. and *Bactrocera oleae* Gmel.), and earlier pollination activity and pollen viability.	(Gratsea et al. 2022; Chou et al. 2023; Silveira et al. 2023)
Spring Maximum Temperature (SPRTX; ºC)	Mean spring (between 1st April and 31st May) of daily mean TX.	SPRTX helps to understand the flowering timings, pollination activity and climatic demand conditions and therefore the tree water requirements. The index is used for guiding pest management, fertilisation, the plant's photosynthetic activity limits and yield forecasting (Chou et al. 2023).	High temperatures can indicate earlier flowering dates and extend the growing season, increasing water stress, particularly in rainfed plantations and potentially affecting pollination periods.	(Pérez-López et al. 2008; Gratsea et al. 2022; Chou et al. 2023; Silveira et al. 2023)
Summer Heat Stress Days (su40; day)	Number of summer days, between 21st June and 21st September, with the daily TX above 40 °C.	This is applied to assess the plant's photosynthetic activity limits under high temperatures. The index is a guide to selecting plant drought-protection methods, pest and irrigation management, predicting fruit quality and selecting drought-tolerant varieties (Gratsea et al. 2022; Chou et al. 2023; Silveira et al. 2023).	An increase in the number of days may lead to greater heat stress or more frequent drought events. High temperatures contribute to earlier fruit ripening and may inhibit photosynthetic and pollinator activity. Furthermore, high temperatures may affect fruit development and oil composition.	(Koubouris et al. 2009a; Haworth et al. 2018; Nissim et al. 2020; Gratsea et al. 2022; Chou et al. 2023; Silveira et al. 2023)

These indices are computed using gridded daily air temperature and precipitation for each model grid point. For each period, the index represents the mean of the corresponding years, followed by the ensemble means of the selected models.

Complementary indices are calculated to support the AgrIs analysis for the olive trees. These included maximum and minimum temperatures and accumulated rainfall over the seasons (winter, summer, spring and autumn). Furthermore, indices related to extreme climate or weather events are also computed, namely the Consecutive Dry Days Index (CDD), the Simple Daily Intensity Index (SDII), and the Precipitation Percentage due to R95p days

Table 2 (continued)

Agro-climatic Index	Designation	Application	Olive tree impacts	References
Total rainfall between October and May (WINRR; mm)	Total accumulative rainfall between October (previous year) and May (following year).	This parameter allows for evaluating the plant's physiological activity and is a reference to irrigation and soil management, as well as for selecting drought-tolerant varieties (Rodrigo-Comino et al. 2021; Gratsea et al. 2022; Silveira et al. 2023). Although this period encompasses a period when the olive trees are less active (i.e. not growing), it plays a key role in the establishment of adequate soil moisture provisioning for the typical summertime hot and dry period in the Mediterranean systems (e.g., Paço et al. 2019; Fraga et al. 2020a; Pereira et al. 2024).	A rise in water deficit between October and May can contribute to a reduction in plant yield, though it may not affect fruit quality. Rainfall below 300 mm is linked to reduced production in rainfed plantations.	(Rodrigo-Comino et al. 2021; Gratsea et al. 2022; Silveira et al. 2023; Moral et al. 2024)

(R95PTOT), described in Table SM1 (Freitas et al. 2022; Schulzweida 2023; Claro et al. 2023). The results are presented in Supplementary Material (Fig. SM1–SM19).

2.4 Model uncertainties and output statistics

To assess uncertainties within ensemble means, the interquartile range (IQR) is applied (Fraga et al. 2013), for each period and AgrI. This method considered the difference between the third quartile (Q_3) and the first quartile (Q_1) at each grid point (Fraga et al. 2013; Shen et al. 2018). The IQR determination allows us to quantify the model uncertainty, with higher values indicating greater variability among models and lower values reflecting greater inter-model consistency. In addition, the Student's *t*-test is applied to assess the significance of the differences between future and historical periods, for each scenario and AgrI (Decremer et al. 2014; Tan et al. 2015), at a significance level of 5%.

2.5 Temporal variance of the agroclimatic index for Olive oil PDOs

In Portugal, there are six Protected Designation of Origin (PDO) regions: "Trás-os-Montes", "Beira Interior", "Ribatejo", "Norte Alentejano", "Moura", and "Alentejo Interior", for olive oil production (Albuquerque et al. 2019; INE 2021; Freitas et al. 2024). To analyse how the AgrI changes over time, the differences between historical and future periods (Freitas et al. 2022) are computed. The min-max scaler normalisation method is then applied to each index (Amorim et al. 2022). The AgrI values are then extracted based on the ORs' geographical distribution (COS 2018), and the mean values are computed for each PDO. This approach allows us to identify and compare differences between PDOs and highlight which PDO is likely to experience the most significant changes in the future. These results can be particularly useful for suggesting adaptation measures tailored to each specific climatic condition.

3 Results

3.1 Agroclimatic zoning

To analyse the climatic conditions for olive growing, AgrIs are evaluated using the corresponding ensemble means and the IQR. In addition, to assess the climate evolution in future periods, the results of the Student's *t*-test are applied to each index to assess the statistical significance of the differences between the future and historical periods and thereby identify a possible climate change signal.

3.1.1 Consecutive Frost days (CFD)

The ensemble means of historical climatic conditions (Fig. 2a) in the south, centre and north-eastern regions are defined by 0 to 5 CFD, covering 77% of the territory. In contrast, the northeast exhibited greater variability due to its orographic complexity. Low-elevation areas reveal the lowest CFD (0–10), while the highest-elevation regions record the longest periods (15–30 CFD), with the 'Serra da Estrela' mountain range (in central Portugal) reaching up to 35 days of CFD. Although the higher CFD is associated with the higher elevations, as expected, these regions also showed higher model uncertainty (Fig. 2d). Lower elevations show higher model consistency, with the IQR ranging from 0 to 2 days, and covering 92% of the total area.

As increasing temperatures are projected (Fig. SM1 to SM8), the CFD will generally decrease in both scenarios (Fig. 2b, c), particularly at higher elevations. In the "Serra da Estrela" mountain range, a reduction in CFD by up to 9 days (Fig. 3a) is observed under SSP3-7.0, while the reduction reaches 11 days, under SSP5-8.5 (Fig. 3f). In fact, greater variability is expected in the IQR in the north compared to the south (Fig. 2b, c). Overall, model inconsistency is higher in SSP3-7.0 (Fig. 2e) than in SSP5-8.5 (Fig. 2f). The southern

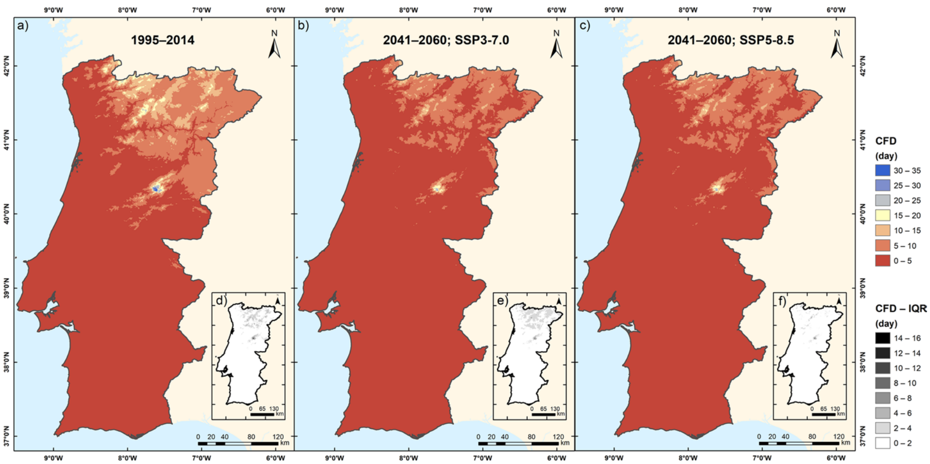

Fig. 2 – Ensemble means of Consecutive Frost Days (CFD; day) for (**a**) the historical period (1995–2014) and future scenarios: SSP3-7.0 (**b**) and SSP5-8.5 (**c**) for 2041–2060. Panels (**d**), (**e**) and (**f**) display the interquartile range (IQR) for the respective historical period and future scenarios

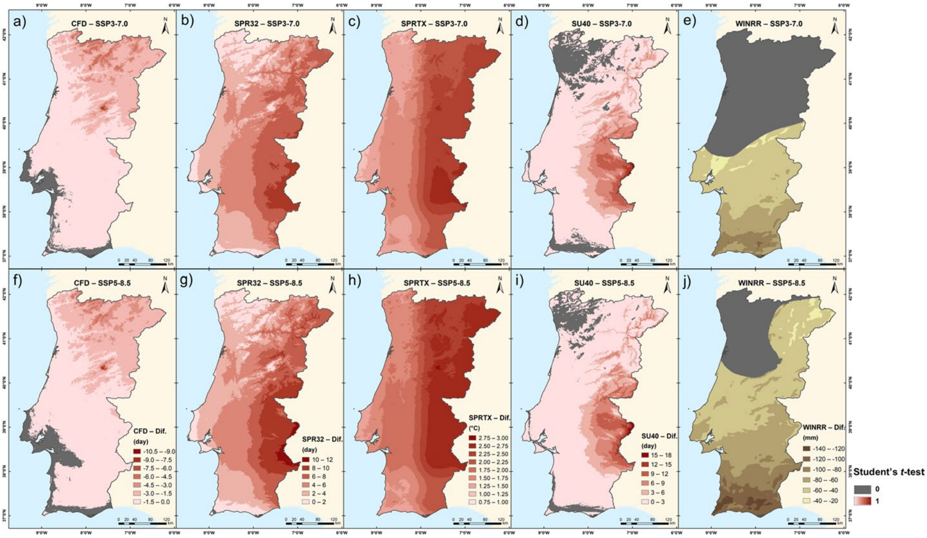

Fig. 3 – Statistical differences between historical and future scenarios according to Student's *t*-test, with a significance level of 0.05. Agroclimatic indices are represented as follows: Consecutive Frost Days (**a**; **f**), Spring Heat Day (**b**; **g**), Spring Maximum Temperature (**c**; **h**), Summer Heat Stress Days (**d**; **i**) and Total rainfall between October and May (**e**, **j**) for scenarios SSP3-7.0 and SSP5-8.5, respectively. Only statistically significant future-historical period differences are represented

coastal region is not expected to show statistically significant differences when compared to the rest of the country, i.e. 7% of the area for SSP3-7.0 and 10% for SSP5-5.8 (Fig. 3a, f).

3.1.2 Spring heat day (SPR32)

Historically, SPR32 is more common in inland Alentejo and southeastern Centre, with 6–12 days (covering 10% of mainland Portugal) (Fig. 4a). In the Alentejo, the Centre and inland

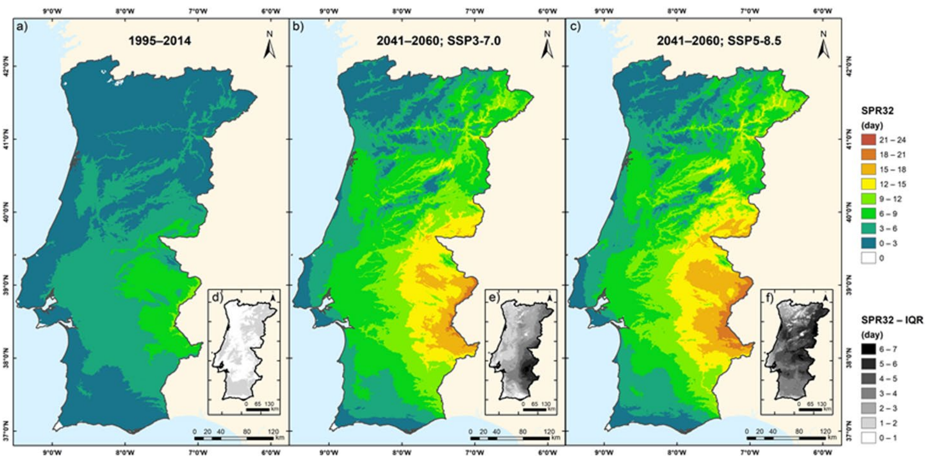

Fig. 4 – Ensemble means of Spring Heat Day (SPR32; day) for (**a**) the historical period (1995–2014) and future scenarios: SSP3-7.0 (**b**) and SSP5-8.5 (**c**) for 2041–2060. Panels (**d**), (**e**) and (**f**) display the interquartile range (IQR) for the respective historical period and future scenarios

North, SPR32 shows 3–6 days (36% of the area). Fewer days (0–3 days) are recorded near the coast, in the Algarve and most of North, covering 53% of the territory, due to the influence of the Atlantic winds and the complex orography in the inland North. The areas with the highest SPR32 correspond to the ORs distribution. During this period, the IQR reached up to 2 days throughout the country (Fig. 4d).

Given the increase in air temperatures in spring and summer (Fig. SM2 and SM3), the number of SPR32 is expected to increase significantly in the future (Fig. 3b, g). Areas near the Atlantic coast present the lowest SPR32, while the number increases as one moves further inland, and is more intense in SSP5-8.5 (Fig. 4c) than in SSP3-7.0 (Fig. 4b). In the inland North, lower elevation areas show higher SPR32 (12–13 days) than higher elevation areas (6–12 days). In SSP3-7.0 (Fig. 4b), 12–21 days are observed in the southeastern Centre and inland Alentejo (15% of the territory). While in SSP5-8.5 (Fig. 4c), a SPR32 of 24 days (0.1% of the area) is observed in inland Alentejo, defined by super-intensive ORs (DGT 2018). Furthermore, in SSP5-8.5, SPR32 intensification is expected to last around 12 days (1.4% of the area) in the inland Alentejo (Fig. 3g). Despite the overall increase, the IQR showed model inconsistencies. In SSP3-7.0, the model variability could reach 6.7 days (1% of the area) (Fig. 4e), with a notable intensification in the inland Alentejo. In the coastal areas, the IQR is lower due to the influence of westerly Atlantic winds (more maritime climates). Under SSP5-8.5 (Fig. 4f), the differences can reach 7 days (3% of the area), with the IQR being larger in the inland mainland Portugal.

3.1.3 Spring maximum temperature (SPRTX)

During the historical period, SPRTX is below 18 °C, mostly in the North region, and covering 10% of the total area (Fig. 5a). Temperatures between 20 and 22 °C are observed in the Centre, Alentejo and Algarve regions (23% of the territory). The highest temperatures (24 °C) are mainly observed in the inland areas of the Alentejo and the Algarve (58% of the

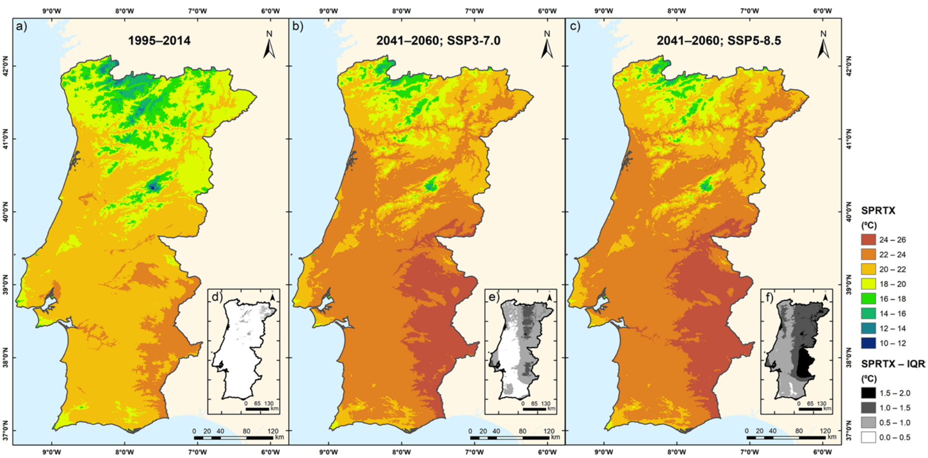

Fig. 5 – Ensemble means of Spring Maximum Temperature (SPRTX; ºC) for (**a**) the historical period (1995–2014) and future scenarios: SSP3-7.0 (**b**) and SSP5-8.5 (**c**) for 2041–2060. Panels (**d**), (**e**) and (**f**) display the interquartile range (IQR) for the respective historical period and future scenarios

area). The IQR (Fig. 5d) is higher in the higher elevation regions (i.e. "Serra da Estrela") and could be up to 1 day.

For future scenarios (Fig. 5b, c), areas with temperatures between 10 and 18 °C are projected to be residual, accounting for only 2.8% of the territory in SSP 3–7.0 and 2.1% in SSP5-8.5. In addition, inland areas temperatures are expected to rise by up to 3 °C as the influence of the sea diminishes. In SSP3-7.0 and SSP5-8.5, temperatures of around 26 °C are frequently reached in the central and southern inland regions, representing 13% of the area affected under SSP3-7.0 and 16% under SSP5-8.5. However, compared to the historical period, the areas with the largest differences are observed in the extreme scenario, especially in the inland regions (Fig. 3c), when compared to the intermediate-to-pessimistic scenario (southern inland) (Fig. 3h). The coastal regions show weaker changes, owing to their more marine climate with air temperature regulation. In SSP3-7.0 (Fig. 5e), the difference between the models could reach 1.5 °C, especially in inland regions (covering 12% of the territory). For SSP5-8.5 (Fig. 5f), there is a model divergence of up to 2 °C in inland Alentejo, as well as in inland North and Centre River basins (12% of the area).

3.1.4 Summer heat stress days (SU40)

Historically (Fig. 6a), no days with temperatures above 40 °C (SU40) are recorded in the northern region and along the coastal areas (16% of the total area), due to the maritime influence. The rest of the continental area records up to 3 days (84% of the area) and 4 days (0.07%) in the inland Alentejo. The IQR reaches between 1 and 2 days in the inland Alentejo (45% of the area), while less than 1 day is observed in the rest of mainland Portugal (Fig. 6d).

In future scenarios (Fig. 6b, c), temperatures above 40 °C may prevail for up to 12 days in the inland North and northeast Centre at low elevations. For SSP3-7.0 (Fig. 3d), no statistically significant differences concerning SU40 (10% of the area) are found in the

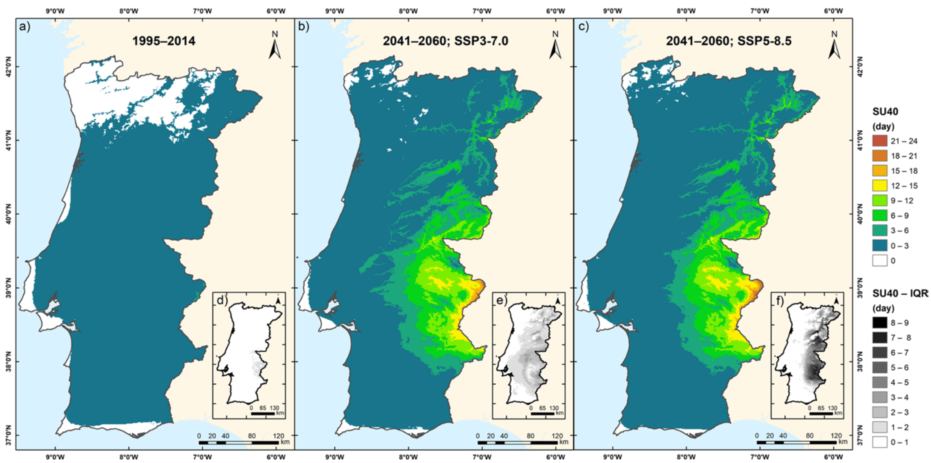

Fig. 6 – Ensemble means of Summer Heat Stress Days (SU40; day) for (**a**) the historical period (1995–2014) and future scenarios: SSP3-7.0 (**b**) and SSP5-8.5 (**c**) for 2041–2060. Panels (**d**), (**e**) and (**f**) display the interquartile range (IQR) for the respective historical period and future scenarios

northwest and coastal areas. However, there will be high variability in SU40, between 3 and 24 days in the southeast Centre and inland Alentejo. SSP5-8.5 (Fig. 6c) shows a larger area with 21–24 days in inland Alentejo (0.2% of the territory). In SSP5-8.5 (Fig. 3i), the areas without statistical differences are smaller but show similar patterns to SSP3-7.0 (15% of the area). The largest differences are observed in the inland Alentejo in both scenarios, with larger impacts in SSP5-8.5 (Fig. 6c). Future projections also show the greatest IQR in inland Portugal (Fig. 6e, f), associated with orographic conditions and the distance from the Atlantic Ocean. The highest IQR (Fig. 6f) is recorded in SSP5-8.5 for the inland Alentejo, reaching up to 9 days.

3.1.5 Total rainfall between October to May (WINRR)

During the period 1995–2014 (Fig. 7a), WINRR generally decreases from the north to the south. The northwestern North region records the most rainfall, with 2% of the area experiencing 1300–1500 mm and 8% recording 1100–1300 mm. However, 46% of the territory, which includes the inland regions of North and Centre, Alentejo and Algarve regions, shows a decrease in WINRR (300–500 mm). The IQR (Fig. 7d) is smaller during this period compared to future projections, with the greatest uncertainties occurring in northwestern Portugal. In addition, the southern regions also show a model divergence of 35–75 mm.

In future scenarios, a decline of the area with 1100–1500 mm is projected for the North and Centre regions, which make up 6% of the territory (Fig. 7b, c). Contrarily, the areas with WINRR of 300–500 mm may expand, particularly in the Alentejo and Algarve (Fig. 3e, j). Under SSP3-7.0, the changes in WINRR will not be statistically significant in North and Centre regions (covering 53% of the area), while in SSP5-8.5 changes in WINRR in coastal North and Centre will not be statistically significant (23%) (Fig. 3j). SSP3-7.0 (Fig. 7e) indicate greater uncertainties in the coastal northern regions (95–195 mm), compared to the southern mainland and northeast North (35–95 mm). Meanwhile, SSP5-8.5 (Fig. 7f) show greater uncertainties in the southern regions, reaching up to 119 mm.

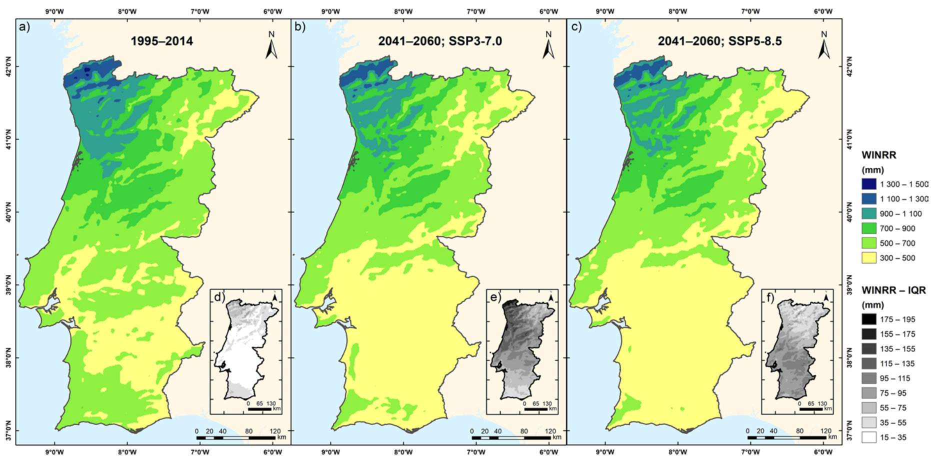

Fig. 7 – Ensemble means of Total rainfall between October and May (WINRR; mm) for (**a**) the historical period (1995–2014) and future scenarios: SSP3-7.0 (**b**) and SSP5-8.5 (**c**) for 2041–2060. Panels (**d**), (**e**) and (**f**) display the interquartile range (IQR) for the respective historical period and future scenarios

The reduction in WINRR follows a consistent pattern across all seasons, which shows a decrease in the annual rainfall (winter, Fig. SM9; spring, Fig. SM10; summer, Fig. SM11; autumn, Fig. SM12). In winter (Fig. SM18a, e), the reduction may be projected to be less statistically significant in future scenarios, particularly in the northern and central regions, compared to other seasons. In summer (Fig. SM18c, d), precipitation is reduced, especially in the North region, and the trend suggests that there will be little to no rainfall in the future. Due to the typical Mediterranean climate, the Alentejo and Algarve regions typically only receive residual rainfall in summer, thus explaining the lower reduction foreseen under future scenarios.

Furthermore, additional indices of extreme precipitation, which are not directly related to olive tree growing conditions but are also informative of future climatic conditions, hint at decreasing precipitation and increases in the frequency and intensity of extreme events in the future (Supplemental Material). The Consecutive Dry Days (CDD) show more days in the southern than northern regions (Fig. SM13), and the differences may be higher in the centre of Portugal (Fig. SM19a, e), thus highlighting longer dry periods in future climates. The Simple Daily Intensity Index (SDII) patterns in the future may be similar to those of the historical period, being more intense in the northwest than in the other regions (Figs. SM14 and SM19b, f). According to the Precipitation Percentage due to R95p days (R95PTOT), i.e. the contribution of days with precipitation above the 95th percentile to total precipitation, extreme rainfall events may become more intense in the southeast country, with their contribution to total precipitation reaching 48% (Figs. SM15 and SM19c, g).

3.2 Temporal variance of the agroclimatic index for olive oil PDOs

To understand the vulnerability of each PDO, the normalised (from 0 to 1) variation of all indices (difference between future and historical), for each PDO, is presented in Fig. 8.

In the "Trás-os-Montes" (Fig. 8a), the largest differences can be seen in SPR32 and SPRTX. In SSP3-7.0, an increase of 0.49 and 0.67 in these indices is expected, while in SSP5-8.5, the increase will be 0.54 and 0.80, respectively. CFD and WINRR are projected to decrease by around 0.28 and 0.09 in SSP3-7.0 and by 0.28 and 0.21 in SSP5-8.5. SU40 may increase by 0.13 in both scenarios.

In the "Beira interior" (Fig. 8b), the largest changes also occur in SPR32 and SPRTX, with increases of 0.58 and 0.70 under SSP3-7.0, and 0.65 and 0.80 under SSP5-8.5. CFD may decrease by 0.17, and SU40 may increase by 0.27 in both scenarios. The WINRR reduction is more pronounced under SSP5-8.5, with a decrease of 0.27, compared to 0.19 under SSP3-7.0.

The ORs from "Ribatejo" (Fig. 8c) experience smaller changes in SPR32, SPRTX, and SU40 compared to other PDOs, though this does not mean that the ORs experience lower absolute values. CFD and WINRR reduce in future scenarios, with reductions of 0.07 and 0.17, respectively, in SSP3-7.0, and for the SSP5-8.5, a reduction of 0.06 and 0.27 is observed.

"Norte Alentejo" (Fig. 8d), the ORs are exposed to the largest changes in SPR32, SPRTX, and SU40 compared to other PDOs. SPR32 is projected to increase by 0.68 in SSP3-7.0 and 0.78 in SSP5-8.5, while SPRTX is expected to rise by 0.80 and 0.88, respectively. SU40 is increased by 0.47 in both scenarios. CFD is expected to decrease by 0.11 under SSP3-7.0 and by 0.10 under SSP5-8.5, while WINRR drops by 0.39 under SSP5-8.5 and by 0.27 under SSP3-7.0.

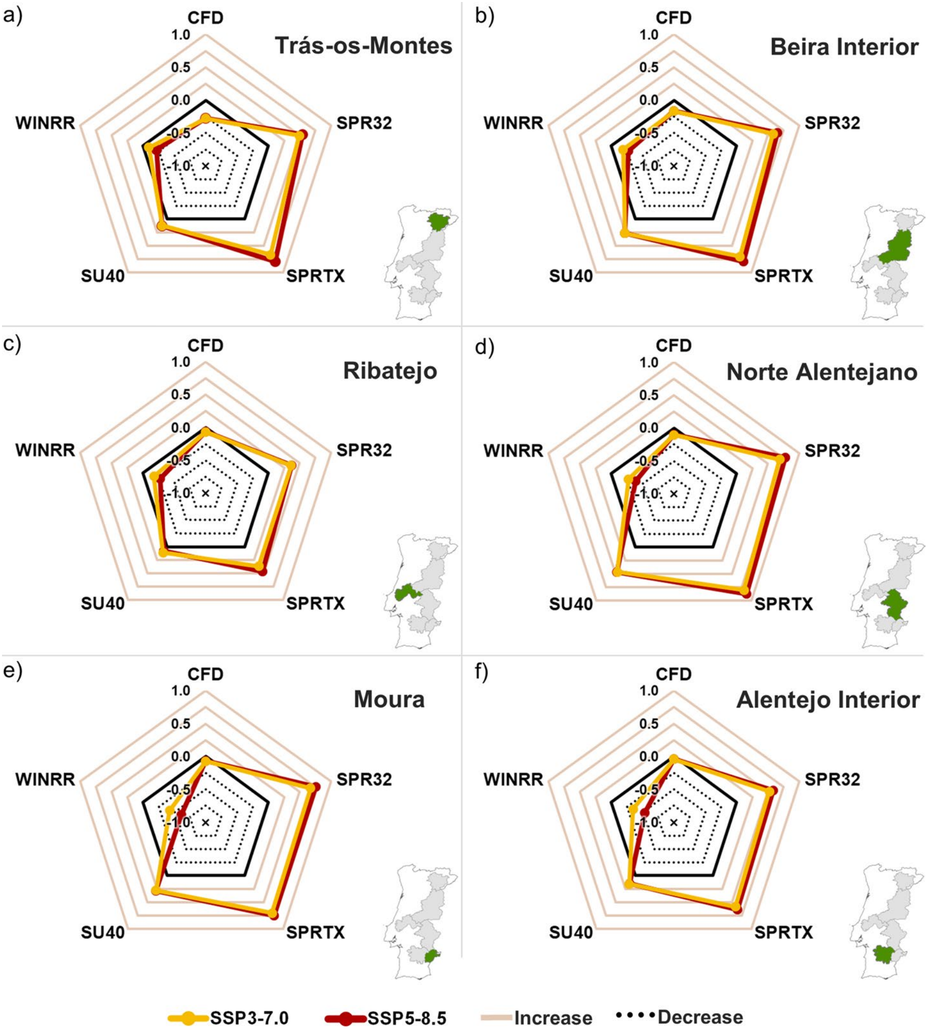

Fig. 8 – Spatial variance of the normalised agroclimatic index between historical and future periods for olive orchards distributed in each Protected Denomination of Origin (PDO) region: "Trás-os-Montes" (**a**), "Beira Interior" (**b**), "Ribatejo" (**c**), "Norte Alentejano" (**d**), "Moura" (**e**), and "Alentejo Interior" (**f**). The scale ranges from −1 to 1, where values between 0 (black line) and 1 indicate an increase (brown line), and values between 0 and −1 indicate a decrease (dotted black line)

The ORs' "Moura" (Fig. 8e), located in the Alentejo region, will experience less rainfall compared to the other PDOs, with differences of 0.43 and 0.61 in SSP3-7.0 and SSP5-8.5, respectively. In both scenarios, SU40 is expected to have the same difference of 0.28. CFD has smaller changes compared to other indices, decreasing by 0.07 in SSP3-7.0 and 0.06 in SSP5-8.5. SPR32 and SPRTX increase by 0.67 and 0.71 in SSP3-7.0, and by 0.75 and 0.76 in SSP5-8.5.

In "Alentejo Interior" (Fig. 8f), the ORs experience the smallest decrease in CFD compared to other PDOs, with decreases of 0.04 in SSP3-7.0 and 0.03 in SSP5-8.5. The largest changes are observed in SPR32, SPRTX, and WINRR, with increases of 0.52, 0.58, and 0.35 in SSP3-7.0, and 0.58, 0.64, and 0.53 in SSP5-8.5, respectively. SU40 is expected to increase by approximately 0.16 and 0.15 in SSP3-7.0 and SSP5-8.5, respectively.

ORs from all PDOs are expected to be significantly affected by higher spring temperatures, leading to the anticipation of flowering and increasing water stress, particularly in the rainfed orchards, as shown by the increases in SPR32 and SPRTX. Conversely, "Ribatejo" will be the least affected. "Norte Alentejo" ORs experience the greatest impact from higher summer temperatures (SU40), as they can affect fruit development and the plant's photosynthetic activity. The "Alentejo Interior" and "Moura" ORs may be most affected by the reduction in WINRR, particularly during fruit ripening, harvest, and dormancy. The "Trás-os-Montes" and "Beira Interior" ORs may be affected by a decrease in frost days (CFD), which may not have a negative impact on the phenological stages and fruit development. To complement the results obtained, future studies should include the simulation of the phenological states of the olive tree, considering climate projections. This study could contribute to a more detailed analysis of the impact of climate on the plant.

4 Discussion

Mainland Portugal's Mediterranean climate (Beck et al. 2018) is favourable for olive growth. Westerly and maritime winds play a role in olive distribution, with the most favourable regions located inland. In the northern region, the traditional (rainfed) and intermediate ORs systems dominate, constrained by the very complex orography (Silveira et al. 2022), while the irrigated intensive and super-intensive systems prevail in the southern regions. In the south, most ORs are irrigated due to lower rainfall (Gratsea et al. 2022; Fraga et al. 2024).

Future projections indicate that summers are expected to become longer, warmer and drier, as observed by Cardoso et al. (2019), disrupting the usual seasonal patterns, which could affect the phenological timing of olive trees (Ahmad et al. 2021; Silveira et al. 2023). In winter, an increase in air temperature can anticipate the phenological stages (Engelen et al. 2023) (Figs. SM1–SM8). Higher temperatures can cause early break in dormancy, advancing key developmental events, such as bud break, flowering, fruit maturation and harvesting. This shift can negatively affect both the plant and overall production, increasing the likelihood of damage from late frosts, disrupting ecological interactions (e.g., with pollinators), and resulting in reduced fruit set, lower yields, and decreased fruit quality (Freitas et al. 2023). Precipitation is expected to decrease markedly in Spring and Autumn (Figs. SM9–SM12). The increase in the occurrence and intensity of the extreme events will be one of the main challenges for farmers, with impacts on fruit development and ORs suitability, namely in Alentejo and Algarve (Mairech et al. 2021; Gratsea et al. 2022; Silveira et al. 2023) (Fig. SM15).

The AgrIs that described the optimal ORs climate conditions revealed significant differences between the future and historical, which may affect the sustainability of olive trees. Several studies (e.g., Lodolini et al. 2016; Mougiou et al. 2020; Rodrigues et al. 2022; Silveira et al. 2023) have shown that the olive tree is susceptible to winter temperatures below 0 °C, resulting in negative impacts on fruit quality, including shoot necrosis, leaf fall, and even tree death (Mougiou et al. 2020; Rodrigues et al. 2022). However, the expected reduction in CFD (up to 10 days) (Fig. 2), particularly in the North and Centre, may be less damaging to the species, as they prefer higher temperatures (Montanaro et al. 2018). Nevertheless, it is essential to ensure that chilling requirements are met so as not to affect the dormancy/rest period (Fraga et al. 2020a).

The historical period showed similar results for the SPR32 (Fig. 4) of up to 12 days inland Alentejo. These results are comparable to the findings reported by Chou et al. (2023). Under SSP5-8.5, an increase of up to 12 days in SPR32 is anticipated for this region, resulting in a total of 12–24 days. This change could contribute to reduced pollinator activity and an earlier flowering stage, shortening this period (Silveira et al. 2023), as well as a decrease in pollen viability (Koubouris et al. 2009b). This may also impact fruit development and ripening (Benlloch-González et al. 2019). In addition, higher temperatures can increase the risk of pests and diseases (Pérez-López et al. 2008). In the Spanish region of Andalusia, near the Alentejo and Algarve regions, an increase of up to 5 days is projected by 2060, under RCP8.5 (Gratsea et al. 2022). The SPRTX (Fig. 5) is closely linked to SPR32. This index shows higher temperatures (up to 24 °C) in inland Alentejo over the historical period, which is consistent with the observations of Chou et al. (2023). The projected increase in temperatures in the future (potentially reaching up to 26 °C) could intensify the impacts associated with SPR32 (e.g., earlier flowering) (Orlandi et al. 2010; Gabaldón-Leal et al. 2017). At this stage, temperatures above 25 °C have a negative impact on pollen tube growth (Benlloch-González et al. 2019; Dareioti et al. 2023), and may reduce yield and fruit quality (Orlandi et al. 2020). In regions where 2–4 °C increase in temperature is expected, flowering may be anticipated by 6–26 days (Grillakis et al. 2022; Gratsea et al. 2022).

Inland Portugal will experience an increase in SU40 (Fig. 6), ranging from 3 to 24 days. This increase suggests a higher frequency of extreme weather events (e.g., heat waves) (Gratsea et al. 2022; Chou et al. 2023). Temperatures above 40 °C lead to a decline in the photosynthetic capacity, reducing stomatal conductance (Haworth et al. 2018), and anticipate ripening, affecting both fruit quality and weight (Silveira et al. 2023). In addition, these high temperatures can cause visible leaf abscission, symptoms of sunburn, and growth inhibition in plants (Nissim et al. 2020). Furthermore, increased water deficit during plant development highlights the need for additional irrigation (Gratsea et al. 2022). However, some olive varieties show greater resilience than others, due to their genotype (Koubouris et al. 2019; Nissim et al. 2020).

Most of the ORs were located in regions where the WINRR ranged 300–900 mm. Currently, in the southern Iberian Peninsula, 50% of the olive-growing area records less rainfall than is considered sufficient for optimal growth (Honorio et al. 2024) when under rainfed conditions, leading to an increase in irrigation requirements (Gratsea et al. 2022). The Alentejo and Algarve will be expected to be the most affected, with reductions of up to 140 mm (7% of the total area). This could have a significant impact on olive yield as the available water may not meet the plants' demand (Moral et al. 2024). Therefore, southern Portugal, where intensive and super-intensive ORs are located, will be most affected by climate change (Freitas et al. 2024).

As mentioned in several studies (Montanaro et al. 2018; Fraga et al. 2020a; Sobreiro et al. 2023), these indices are an essential tool for OR management, particularly to determine the mitigation and adaptation measures, reducing the impacts of climate change on olive trees. The use of plant conditioners such as antitranspirants, kaolin, salicylic and silicon compounds has been one of the measures applied to reduce the effects of rising temperatures and protect plants from extreme heat events (Michael Glenn et al. 2002; Cirillo et al. 2021). These compounds increase the reflection of solar radiation, decreasing the impacts of sunburn. Additionally, kaolin offers protection against pests and diseases (Fraga et al. 2020a). Biostimulants derived from glycine betaine and algae improve eco-physiological and vegetative functions under high temperature and water stress (Graziani et al. 2022). Furthermore, selecting heat-tolerant varieties is an adaptation measure to cope with the impact of rising temperatures (Koubouris et al. 2009b). Some varieties also show resistance to diseases, which is a crucial factor in varietal and clonal selection (Fraga et al. 2020a). Irrigation strategies, e.g., sustained deficit irrigation (SDI), regulated deficit irrigation (RDI), and partial root-zone drying (PRD), are viable options for decreasing water use (Ibba et al. 2023; Sobreiro et al. 2023). Effectively, deficit irrigation, particularly during pit hardening, has been confirmed to be effective in enhancing olive fruit quality (Goldhamer et al. 1994; Moriana et al. 2003). To further reduce water use in irrigation, practices such as inter-row cover cropping, no-tillage, and recycling of pruning residues can be complementary options (Montanaro et al. 2018; Sobreiro et al. 2023). At the same time, these measures also serve as mitigation strategies to promote carbon sequestration caused by climate change.

The AgrIs presented in this study serve as a Decision Support System (DSS) tool for managing ORs in Portugal and for predicting the threats to the species, helping to develop mitigation strategies tailored to the needs of each region and each OR. Public services and stakeholders related to the olive sector can also use this document as a resource for management and creating advanced adaptation strategies (Chou et al. 2023), thereby contributing to greater awareness of climate change in OR management. However, future research should consider other factors for plant growth and crop sustainability, e.g., soil characteristics, varieties of olive trees, and the physiological response of the plants. Identifying potential threats or advantages will help promote better management practices and resilience to future climate change.

5 Conclusions

The application of AgrIs for olive trees allows us to understand climate evolution and its potential impacts on the sustainability of ORs. The expected challenges will test the resilience and adaptability of current olive species, as well as the knowledge, management capacity, and adaptability of producers, stakeholders, and olive sector representatives. In addition, socio-economic and environmental challenges may arise.

In Portugal, climate change will have significant impacts, especially in the inland Alentejo. This region is characterised by intensive and super-intensive ORs, which can amplify the effects of climate change. Therefore, mitigation and adaptation measures (i.e., selecting heat-tolerant varieties, applying bioestimulants, defining irrigation strategies) will be crucial to maintain sustainable systems and reduce the vulnerability of these ORs. Each OR should implement strategies considering its characteristics (e.g., dimension, agricultural practices, and varieties) and its short- and long-term objectives.

Complementary studies should be carried out, including assessments of the chilling and heat conditions for the species' development and the adaptability of olive varieties to climate change. It is also recommended to extend the current study to other regions worldwide and to foster collaboration between academia and the agricultural sector, to obtain a direct understanding of the needs of stakeholders and ORs. This collaboration will improve knowledge sharing, help understand challenges and find solutions for more resilient and sustainable olive yield systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11027-025-10247-4.

Acknowledgements This work was financed by the WaterQB "Integrated web-based platform for supporting irrigation management aiming at coping with climate variability and changes" project (2022.04553.PTDC, https://doi.org/10.54499/2022.04553.PTDC) financed by National Funds by the Portuguese Foundation for Science and Technology (FCT). Authors also thank FCT for projects UIDB/04033/2023 https://doi.org/10.54499/UIDB/04033/2020: Centre for the Research and Technology of Agro-Environmental and Biological Sciences, LA/P/0126/2020 (https://doi.org/10.54499/LA/P/0126/2020), UIDB/04129/2020 (https://doi.org/10.54499/UIDB/04129/2020) and 2022.02317.CEECIND (https://doi.org/10.54499/2022.02317.CEECIND/CP1749/CT0002). Authors thank the additional support, provided by the MONTEVITIS project "Integrating a comprehensive European approach for climate change mitigation and adaptation in Montenegro viticulture", funded by the European Union's Horizon Europe—the Framework Programme for Research and Innovation (2021–2027)—under grant agreement nº 101059461 (https://doi.org/10.3030/101059461).

Author contributions All authors contributed to the study's conception and design. Conceptualisation, T.R.F., J.A.S. and H.F.; methodology, T.R.F., J.A.S., and H.F.; software, T.R.F., A.F. and C.M; validation, T.R.F., A.F. and C.M.; data curation, T.R.F., A.F and C.M.; writing—original draft preparation, T.R.F.; writing—review and editing, J.A.S., A.F., C.M., P.P. and H.F.; visualisation, T.R.F.; supervision, J.A.S and H.F.; project administration, P.P. and H.F. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by FCT|FCCN (b-on). This work is supported by National Funds by FCT – Portuguese Foundation for Science and Technology, under the projects UID/04033/2023: Centre for the Research and Technology of Agro-Environmental and Biological Sciences and LA/P/0126/2020 (https://doi.org/10.54499/LA/P/0126/2020).

Data availability Not applicable.

Declarations

Competing Interests All authors declare that there is no conflict of interest in the publication of this study.

References

Ahmad M, Waraich EA, Skalicky M et al (2021) Adaptation strategies to improve the resistance of oilseed crops to heat stress under a changing climate: an overview. Front Plant Sci. https://doi.org/10.3389/fpls.2021.767150

Albuquerque TG, Costa HS, Oliveira MBPP (2019) An overview of Portuguese Olive oils and table olives with protected designation of origin. Eur J Lipid Sci Technol. https://doi.org/10.1002/ejlt.201800129

Amorim LBV, Cavalcanti GDC, Cruz RMO (2022) The choice of scaling technique matters for classification performance. https://doi.org/10.1016/j.asoc.2022.109924

Arjdal K, Driouech F, Vignon É et al (2023) Future of land surface water availability over the Mediterranean Basin and North Africa: analysis and synthesis from the CMIP6 exercise. Atmos Sci Lett. https://doi.org/10.1002/asl.1180

Bartolozzi F, Fontanazza G (1999) Assessment of frost tolerance in olive (*Olea europaea* L). Sci Hortic 81:309–319

Beck HE, Zimmermann NE, McVicar TR et al (2018) Present and future Köppen-geiger climate classification maps at 1-km resolution. Sci Data. https://doi.org/10.1038/sdata.2018.214

Benlloch-González M, Sánchez-Lucas R, Bejaoui MA et al (2019) Global warming effects on yield and fruit maturation of olive trees growing under field conditions. Sci Hortic 249:162–167. https://doi.org/10.1016/j.scienta.2019.01.046

Bonofiglio T, Orlandi F, Sgromo C et al (2008) Influence of temperature and rainfall on timing of olive (*Olea europaea*) flowering in Southern Italy. N Z J Crop Hortic Sci 36:59–69. https://doi.org/10.1080/01140670809510221

Brilli L, Gioli B, Toscano P et al (2016) Rainfall regimes control C-exchange of Mediterranean Olive orchard. Agric Ecosyst Environ 233:147–157. https://doi.org/10.1016/j.agee.2016.09.006

Brito C, Dinis LT, Moutinho-Pereira J, Correia CM (2019) Drought stress effects and olive tree acclimation under a changing climate. Plants. https://doi.org/10.3390/plants8070232

Brun P, Zimmermann NE, Hari C et al (2022) Global climate-related predictors at kilometer resolution for the past and future. Earth Syst Sci Data 14:5573–5603. https://doi.org/10.5194/essd-14-5573-2022

Cardell MF, Amengual A, Romero R, Ramis C (2020) Future extremes of temperature and precipitation in Europe derived from a combination of dynamical and statistical approaches. Int J Climatol 40:4800–4827. https://doi.org/10.1002/joc.6490

Cardoso RM, Soares PMM, Lima DCA, Miranda PMA (2019) Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate high-resolution projections for Portugal. Clim Dyn 52:129–157. https://doi.org/10.1007/s00382-018-4124-4

Caudullo G, Welk E, San-Miguel-Ayanz J (2017) Chorological maps for the main European woody species. Data Brief 12:662–666. https://doi.org/10.1016/j.dib.2017.05.007

Chou C, Marcos-Matamoros R, López-Nevado J et al (2023) Comparison of five strategies for seasonal prediction of bioclimatic indicators in the olive sector. Clim Serv. https://doi.org/10.1016/j.cliser.2023.100345

Cirillo A, Conti S, Graziani G et al (2021) Mitigation of high-temperature damage by application of Kaolin and Pinolene on young olive trees (*Olea europaea* l.): a preliminary experiment to assess biometric, eco-physiological and nutraceutical parameters. Agronomy. https://doi.org/10.3390/agronomy11091884

Claro AM, Fonseca A, Fraga H, Santos JA (2023) Susceptibility of Iberia to extreme precipitation and aridity: a new high-resolution analysis over an extended historical period. Water. https://doi.org/10.3390/w15213840

Connor DJ, Fereres E (2004) The physiology of adaptation and yield expression in Olive. Horticultural reviews. Wiley, pp 155–229

Decremer D, Chung CE, Ekman AML, Brandefelt J (2014) Which significance test performs the best in climate simulations? Tellus A Dyn Meteorol Oceanogr 66:23139. https://doi.org/10.3402/tellusa.v66.23139

DGT (2018) Carta de Uso e Ocupação do Solo de Portugal Continental— COS 2018. https://www.dgterritorio.gov.pt/. Accessed 3 Sep 2024

DGT (2023) CAOP - Carta Administrativa Oficial de Portugal. https://dados.gov.pt/en/datasets/carta-administrativa-oficial-de-portugal-caop2023-continente/. Accessed 23 Sep 2024

Engelen C, Wechsler T, Bakhshian O et al (2023) Studying parameters affecting accumulation of chilling units required for olive winter flower induction. Plants. https://doi.org/10.3390/plants12081714

Essa YH, Hirschi M, Thiery W et al (2023) Drought characteristics in mediterranean under future climate change. NPJ Clim Atmos Sci. https://doi.org/10.1038/s41612-023-00458-4

Eyring V, Bony S, Meehl GA et al (2016) Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 9:1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

FAOSTAT (2023) Crops and livestock products. In: Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL. Accessed 28 Jun 2024

Fernandes A, Kovač N, Fraga H et al (2024) Challenges to viticulture in Montenegro under climate change. ISPRS Int J Geo-Inf 13(8):270. https://doi.org/10.3390/ijgi13080270

Fierke J, Joelson NZ, Loguercio GA et al (2024) Assessing uncertainty in bioclimatic modelling: a comparison of two high-resolution climate datasets in Northern Patagonia. Reg Environ Change. https://doi.org/10.1007/s10113-024-02278-5

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2013) Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. Int J Biometeorol 57:909–925. https://doi.org/10.1007/s00484-012-0617-8

Fraga H, Moriondo M, Leolini L, Santos JA (2020a) Mediterranean olive orchards under climate change: a review of future impacts and adaptation strategies. Agronomy 11:56. https://doi.org/10.3390/agronomy11010056

Fraga H, Pinto JG, Santos JA (2020b) Olive tree irrigation as a climate change adaptation measure in Alentejo, Portugal. Agric Water Manag 237:106193. https://doi.org/10.1016/j.agwat.2020.106193

Fraga H, Freitas T, Guimarães N, Santos JA (2024) Perma_crops_PT: a geolocated dataset for permanent crops in Portugal. Data Brief 110971. https://doi.org/10.1016/j.dib.2024.110971

Freitas TR, Santos A, Silva AP et al (2022) Climate change projections for bioclimatic distribution of *castanea sativa* in Portugal. Agronomy. https://doi.org/10.3390/agronomy12051137

Freitas TR, Santos JA, Silva AP et al (2023) Evaluation of historical and future thermal conditions for almond trees in North Eastern Portugal. Clim Change 176:1–22. https://doi.org/10.1007/s10584-023-03569-2

Freitas TR, Santos JA, Paredes P, Fraga H (2024) Future aridity and drought risk for traditional and super-intensive olive orchards in Portugal. Clim Change 177:155. https://doi.org/10.1007/s10584-024-03813-3

Frieler K, Volkholz J, Lange S et al (2024) Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the inter-sectoral impact model intercomparison project (ISIMIP3a). Geosci Model Dev 17:1–51. https://doi.org/10.5194/gmd-17-1-2024

Gabaldón-Leal C, Ruiz-Ramos M, de la Rosa R et al (2017) Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in Southern Spain. Int J Climatol 37(S1):940–957. https://doi.org/10.1002/joc.5048

Garrido A, Fernández-González M, Vázquez-Ruiz RA et al (2021) Reproductive biology of Olive trees (Arbequina cultivar) at the Northern limit of their distribution areas. Forests 12:1–16. https://doi.org/10.3390/f12020204

Goldhamer DA, Dunai J, Ferguson LF, IRRIGATION REQUIREMENTS OF OLIVE TREES AND RESPONSES TO SUSTAINED DEFICIT IRRIGATION (1994) Acta Hortic 172–175. https://doi.org/10.17660/ActaHortic.1994.356.36

Gratsea M, Varotsos KV, López-Nevado J et al (2022) Assessing the long-term impact of climate change on Olive crops and Olive fly in Andalusia, Spain, through climate indices and return period analysis. Clim Serv. https://doi.org/10.1016/j.cliser.2022.100325

Graziani G, Cirillo A, Giannini P et al (2022) Biostimulants improve plant growth and bioactive compounds of young Olive trees under abiotic stress conditions. Agric (Switzerland) 12. https://doi.org/10.3390/agriculture12020227

Grillakis MG, Kapetanakis EG, Goumenaki E (2022) Climate change implications for Olive flowering in Crete, Greece: projections based on historical data. Clim Change. https://doi.org/10.1007/s10584-022-03462-4

Guerrero-Casado J, Carpio AJ, Tortosa FS, Villanueva AJ (2021) Environmental challenges of intensive woody crops: the case of super high-density olive groves. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.149212

Gutierrez AP, Ponti L, Cossu QA (2009) Effects of climate warming on olive and olive fly (*Bactrocera oleae* (Gmelin)) in California and Italy. Clim Change 95:195–217. https://doi.org/10.1007/s10584-008-9528-4

Gutjahr O, Putrasahan D, Lohmann K et al (2019) Max Planck Institute Earth system model (MPI-ESM1.2) for the High-Resolution model intercomparison project (HighResMIP). Geosci Model Dev 12:3241–3281. https://doi.org/10.5194/gmd-12-3241-2019

Haworth M, Marino G, Brunetti C et al (2018) The impact of heat stress and water deficit on the photosynthetic and stomatal physiology of olive (*Olea europaea* L.)—a case study of the 2017 heat wave. Plants 7:76. https://doi.org/10.3390/plants7040076

Honorio F, Aguirado C, Paniagua LL et al (2024) Exploring the climate and topography of olive orchards in Extremadura, Southwestern Spain. Land. https://doi.org/10.3390/land13040495

Ibba K, Kassout J, Boselli V et al (2023) Assessing the impact of deficit irrigation strategies on agronomic and productive parameters of Menara Olive cultivar: implications for operational water management. Front Environ Sci. https://doi.org/10.3389/fenvs.2023.1100552

INE (2021) Recenseamento Agrícola - Análise dos principais resultados – 2019. Lisbon, pp 1–165

IPCC (2023) Climate Change 2023: Synthesis Report

Karger DN, Conrad O, Böhner J et al (2017) Climatologies at high resolution for the earth's land surface areas. Sci Data. https://doi.org/10.1038/sdata.2017.122. 4:

Karger DN, Wilson AM, Mahony C et al (2021) Global daily 1 km land surface precipitation based on cloud cover-informed downscaling. Sci Data. https://doi.org/10.1038/s41597-021-01084-6

Kottek M, Grieser J, Beck C et al (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130

Koubouris GC, Metzidakis IT, Vasilakakis MD (2009a) Impact of temperature on olive (*Olea europaea* L.) pollen performance in relation to relative humidity and genotype. Environ Exp Bot 67:209–214. https://doi.org/10.1016/j.envexpbot.2009.06.002

Koubouris GC, Metzidakis IT, Vasilakakis MD (2009b) Impact of temperature on olive (*Olea europaea* L.) pollen performance in relation to relative humidity and genotype. Environ Exp Bot 67:209–214. https://doi.org/10.1016/j.envexpbot.2009.06.002

Koubouris G, Limperaki I, Darioti M, Sergentani C (2019) Effects of various winter chilling regimes on flowering quality indicatorsof Greek olive cultivars. Biol Plant 63:504–510. https://doi.org/10.32615/bp.2019.065

Lange S (2019) Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). Geosci Model Dev 12:3055–3070. https://doi.org/10.5194/gmd-12-3055-2019

Lange S (2021a) ISIMIP3b bias adjustment fact sheet

Lange S (2021b) ISIMIP3BASD. Zenodo. https://doi.org/10.5281/zenodo.4686991

Lavee S, Wodner M (2004) The effect of yield, harvest time and fruit size on the oil content in fruits of irrigated olive trees (*Olea europaea*), cvs. Barnea and Manzanillo. Sci Hortic 99:267–277. https://doi.org/10.1016/S0304-4238(03)00100-6

Lodolini EM, Alfei B, Santinelli A et al (2016) Frost tolerance of 24 Olive cultivars and subsequent vegetative re-sprouting as indication of recovery ability. Scientia Hortic 211:152–157. https://doi.org/10.1016/j.scienta.2016.08.025

Lurton T, Balkanski Y, Bastrikov V et al (2020) Implementation of the CMIP6 forcing data in the IPSL-CM6A-LR model. J Adv Model Earth Syst. https://doi.org/10.1029/2019MS001940

Mairech H, López-Bernal Á, Moriondo M et al (2021) Sustainability of olive growing in the mediterranean area under future climate scenarios: exploring the effects of intensification and deficit irrigation. Eur J Agron. https://doi.org/10.1016/j.eja.2021.126319

Martinez A, Iglesias G (2021) Wind resource evolution in Europe under different scenarios of climate change characterised by the novel shared socioeconomic pathways. Energy Convers Manage 234:113961. https://doi.org/10.1016/j.enconman.2021.113961

Meinshausen M, Nicholls ZRJ, Lewis J et al (2020) The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci Model Dev 13:3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Michael Glenn D, Prado E, Erez A et al (2002) A reflective, Processed-Kaolin particle film affects fruit temperature. Radiation Reflection, and Solar Injury in Apple

Mogollón Hernández J, Clemente E, Cerro Campón A, Fernández Folgado J (2021) Olive oil tourism in the Euro-Mediterranean area. Int J Euro-Mediterranean Stud 14

Montanaro G, Nuzzo V, Xiloyannis C, Dichio B (2018) Climate change mitigation and adaptation in agriculture: the case of the olive. J Water Clim Change 9:633–642. https://doi.org/10.2166/wcc.2018.023

Moral FJ, Rebollo FJ, García-Martín A et al (2024) Spatial and Temporal analysis of water resources in the Olive-Growing areas of Extremadura. Southwest Spain. https://doi.org/10.20944/preprints202407.1563.v1

Moriana A, Orgaz F, Pastor M, Fereres E (2003) Yield responses of a mature olive orchard to water deficits. J Am Soc Hortic Sci 128:425–431. https://doi.org/10.21273/JASHS.128.3.0425

Moriondo M, Ferrise R, Trombi G et al (2015) Modelling olive trees and grapevines in a changing climate. Environ Model Softw 72:387–401. https://doi.org/10.1016/j.envsoft.2014.12.016

Mougiou N, Baalbaki B, Doupis G et al (2020) The effect of low temperature on physiological, biochemical and flowering functions of Olive tree in relation to genotype. Sustain (Switzerland) 12:1–14. https://doi.org/10.3390/su122310065

Nissim Y, Shloberg M, Biton I et al (2020) High temperature environment reduces olive oil yield and quality. PLoS One. https://doi.org/10.1371/journal.pone.0231956

O'Neill BC, Tebaldi C, Van Vuuren DP et al (2016) The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev 9:3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Orlandi F, Sgromo C, Bonofiglio T et al (2010) Spring influences on olive flowering and threshold temperatures related to reproductive structure formation. HortScience 45:1052–1057. https://doi.org/10.21273/HORTSCI.45.7.1052

Orlandi F, Rojo J, Picornell A et al (2020) Impact of climate change on Olive crop production in Italy. Atmos (Basel) 11. https://doi.org/10.3390/atmos11060595

Oteros J, García-Mozo H, Vázquez L et al (2013) Modelling olive phenological response to weather and topography. Agric Ecosyst Environ 179:62–68. https://doi.org/10.1016/j.agee.2013.07.008

Paço TA, Paredes P, Pereira LS et al (2019) Crop coefficients and transpiration of a super intensive arbequina Olive orchard using the dual Kc approach and the Kcb computation with the fraction of ground cover and height. Water (Basel) 11:383. https://doi.org/10.3390/w11020383

Pereira LS, Paredes P, Oliveira CM et al (2024) Single and basal crop coefficients for estimation of water use of tree and vine woody crops with consideration of fraction of ground cover, height, and training system for mediterranean and warm temperate fruit and leaf crops. Irrig Sci 42:1019–1058. https://doi.org/10.1007/s00271-023-00901-7

Pérez-López D, Ribas F, Moriana A et al (2008) Influence of temperature on the growth and development of olive (*Olea europaea* L.) trees. J Hortic Sci Biotechnol 83:171–176. https://doi.org/10.1080/14620316.2008.11512366

Ramos-Román MJ, Jiménez-Moreno G, Anderson RS et al (2019) Climate controlled historic Olive tree occurrences and Olive oil production in southern Spain. Glob Planet Change. https://doi.org/10.1016/j.gloplacha.2019.102996

Rivas-Martínez S, Rivas Sáenz S, Penas A et al (2011) Worldwide bioclimatic classification system. Global Geobotany 1–634. https://doi.org/10.5616/gg

Rodrigo-Comino J, Senciales-González JM, Yu Y et al (2021) Long-term changes in rainfed olive production, rainfall and farmer's income in Bailén (Jaén, Spain). EuroMediterr J Environ Integr. https://doi.org/10.1007/s41207-021-00268-1

Rodrigues N, Casal S, Rodrigues AI et al (2022) Impact of Frost on the Morphology and Chemical Composition of cv. Santulhana Olives. Applied Sciences (Switzerland) 12:. https://doi.org/10.3390/app12031222

Rodríguez Sousa AA, Muñoz-Rojas J, Brígido C, Prats SA (2023) Impacts of agricultural intensification on soil erosion and sustainability of Olive groves in Alentejo (Portugal). Landsc Ecol 38:3479–3498. https://doi.org/10.1007/s10980-023-01682-2

Schulzweida U (2023) CDO user guide. https://doi.org/10.5281/zenodo.10020800

Seker M, Gumus V (2022) Projection of temperature and precipitation in the Mediterranean region through multi-model ensemble from CMIP6. Atmos Res. https://doi.org/10.1016/j.atmosres.2022.106440

Sellar AA, Jones CG, Mulcahy JP et al (2019) UKESM1: description and evaluation of the U.K. Earth system model. J Adv Model Earth Syst 11:4513–4558. https://doi.org/10.1029/2019MS001739

Sergeeva V, Spooner-Hart R (2011) Diseases and disorders associated with environmental stress in sustainable Olive orchards in Australia. Acta horticulturae. International Society for Horticultural Science, pp 145–150

Shen M, Chen J, Zhuan M et al (2018) Estimating uncertainty and its temporal variation related to global climate models in quantifying climate change impacts on hydrology. J Hydrol 556:10–24. https://doi.org/10.1016/j.jhydrol.2017.11.004

Silveira C, Almeida A, Ribeiro AC (2022) Technological innovation in the traditional olive orchard management: advances and opportunities to the Northeastern region of Portugal. Water. https://doi.org/10.3390/w14244081

Silveira C, Almeida A, Ribeiro AC (2023) How can a changing climate influence the productivity of traditional Olive orchards?? Regression analysis applied to a local case study in Portugal. https://doi.org/10.3390/cli11060123. Climate 11:

Snyder RL, de Melo-Abreu JP (2005) Frost protection: fundamentals, practice and economics. Food and Agriculture Organization of the United Nations

Sobreiro J, Patanita MI, Patanita M, Tomaz A (2023) Sustainability of high-density olive orchards: hints for irrigation management and agroecological approaches. Water. https://doi.org/10.3390/w15132486

Sofo A, Manfreda S, Fiorentino M et al (2008) The Olive tree: a paradigm for drought tolerance in Mediterranean climates. Hydrol Earth Syst Sci 12:293–301. https://doi.org/10.5194/hess-12-293-2008

Tan ML, Ibrahim AL, Duan Z et al (2015) Evaluation of six high-resolution satellite and ground-based precipitation products over Malaysia. Remote Sens 7:1504–1528. https://doi.org/10.3390/rs70201504

Tatebe H, Ogura T, Nitta T et al (2019) Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. Geosci Model Dev 12:2727–2765. https://doi.org/10.5194/gmd-12-2727-2019

Tridge (2024) Overview of Olive Market in Portugal. https://www.tridge.com/intelligences/olive/PT. Accessed 1 Aug 2024

Voldoire A, Saint-Martin D, Sénési S et al (2019) Evaluation of CMIP6 DECK experiments with CNRM-CM6-1. J Adv Model Earth Syst 11:2177–2213. https://doi.org/10.1029/2019MS001683

Vuletin Selak G, Perica S, Goreta Ban S, Poljak M (2013) The effect of temperature and genotype on pollen performance in olive (*Olea europaea* L). Sci Hortic 156:38–46. https://doi.org/10.1016/j.scienta.2013.03.029

Yukimoto S, Kawai H, Koshiro T et al (2019) The meteorological research institute earth system model version 2.0, MRI-ESM2.0: description and basic evaluation of the physical component. Journal of the Meteorological Society of Japan. Ser. II 97:931–965. https://doi.org/10.2151/jmsj.2019-051

Authors and Affiliations

Teresa R. Freitas[1] · João A. Santos[1] · António Fernandes[1] · Christoph Menz[2] · Paula Paredes[3] · Helder Fraga[1]

✉ Teresa R. Freitas
trfreitas@utad.pt

1 Centre for the Research and Technology of Agro-Environmental and Biological Sciences, CITAB, Inov4Agro, University of Trás-os-Montes e Alto Douro, UTAD, Quinta de Prados, P.O. Box 1013, Vila Real 5000–801, Portugal

2 Potsdam Institute for Climate Impact Research e. V, PIK, Telegrafenberg A 31, Potsdam 14473, Germany

3 Linking Landscape, Environment, Agriculture and Food Research Center, LEAF, Associated Laboratory TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, Lisboa 1349–017, Portugal