European Journal of Agronomy 170 (2025) 127740

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Enhancing climate change impact assessment in viticulture by resolving microclimates

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ARTICLE INFO

Keywords:
Precision agriculture
Sustainability
Crop management
Yield
Vineyards
STICS
NicheMapR
Portugal

ABSTRACT

Climate change poses significant challenges to viticulture, particularly by affecting vineyard phenology, yield, and grape quality. This study highlights the role of microclimate modelling in improving vineyard management, using the climate-water-soil-plant nexus. High-resolution climate downscaled data (10 m spatial resolution) generated by the NicheMapR microclimate model, coupled with the STICS soil-crop model, provide accurate phenological and yield predictions for two Portuguese vineyards: “Quinta do Bomfim” (Douro wine region) and “Herdade do Esporão” (Alentejo wine region). The NicheMapR microclimate model captures fine-scale environmental variables to simulate vineyard-scale parameters under historical (1981–2010) and future (2041–2070 and 2071–2100) climate scenarios. Following Representative Concentration Pathways (RCPs) 4.5 and 8.5, shifts in key phenological stages, such as flowering, fruit filling, maximal leaf area index, physiological maturity, and harvest, along with yield changes, were analysed. Results reveal earlier phenological events, shortened growth periods, and significant yield declines, particularly under the high-emission scenario RCP8.5. The findings highlight the value of microclimate modelling in understanding and adapting to climate-induced changes, providing a framework for precision agriculture and agronomic modelling. This approach significantly reduces climate change risks, sustains vineyard productivity, and fosters a climate-resilient wine sector.

1. Introduction

Recognising climate’s impact on agriculture is crucial as climate change encompasses temperature, precipitation, and other factors that impact productivity and quality (Prada et al., 2024; Santos et al., 2020). This study is centred on downscaling climate data for specific use in agronomic models, particularly in predicting vineyard phenology and yield. This study improves vineyard management by using a precision agriculture approach in viticulture, through the development of microclimate data (Fonseca et al., 2024).

Vineyards are affected by changes in climate, and the timing of grapevine growth stages relies on various environmental factors (Fraga et al., 2016; Ramos and Martínez de Toda, 2020). Grape quality, yield, and vineyard economic viability are influenced by climate-induced changes in phenological timing (Keller, 2010). Understanding phenological stages is vital for vineyard management to decide, e.g. on pruning, fertilisation, irrigation, pest control, and harvest timing (de Cortazar Atauri et al., 2017). The sensitivity of each stage to climate variations highlights the significance of phenological modelling in projecting the potential influence of climate change on vineyard productivity and grape quality. Furthermore, increased extreme weather events can cause heat stress, impact water availability, or lead to frost (Valdés-Gómez et al., 2009), making accurate downscaled climate data crucial for vineyard managers to make informed decisions (Blanco-Ward et al., 2019). To effectively incorporate in situ management and adaptation strategies into impact studies, it is essential to have quantitative information on natural variation and the ability to manage local conditions (Mosedale et al., 2016). Several studies point to the role of local knowledge in determining how vulnerability is defined and understood, both across and within wine-growing regions. Focusing on wine quality,

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https://doi.org/10.1016/j.eja.2025.127740
Received 23 January 2025; Received in revised form 20 May 2025; Accepted 8 June 2025
Available online 11 June 2025

the findings reveal that, local environmental conditions and socioeconomic factors significantly influence levels of exposure and sensitivity. Moreover, even under less favorable climate conditions—winegrowers recognised the need to adapt their viticultural practices. This included re-evaluating management strategies, such as adjusting bud numbers per vine, applying soil amendments, introducing cover cropping, and implementing leaf and crop thinning (Neethling et al., 2017; Santos et al., 2020).

Downscaling with microclimate models can provide precise data for agricultural models like STICS, which simulate the impact of environmental variables on crop growth and yield (Artru et al., 2018; Brisson et al., 2004). Precise growth cycle predictions help vineyard managers optimise practices and reduce risks from extreme weather, promoting sustainable and climate-smart viticulture management, affecting wine production (Rogiers et al., 2022; Van Leeuwen et al., 2019).

STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) (Beaudoin et al., 2023) is a versatile soil-crop model widely used in agronomy to predict plant growth, yield, and water use based on soil, weather, and crop management inputs. By integrating microclimate data, this study enhances the accuracy of vineyard phenology simulation in STICS. Vineyard managers gain valuable insights into vineyard growth and yield predictions and can adjust practices to mitigate climate change impacts, enhance resource use efficiency, ensure sustainable vineyard practices, and improve crop resilience. This approach is particularly important in the context of climate change, as vineyard managers are tasked with mitigating its potential impacts while maintaining economically viable and sustainable solutions (Costa et al., 2022; Mirás-Avalos and Araujo, 2021; Montalvo-Falcón et al., 2023; Palliotti et al., 2014).

This study innovatively combines climate downscaling techniques (quantile mapping), a microclimate model (NicheMapR), and an agricultural-phenological model (STICS) to aid precision agriculture and improve the resiliency of the viticulture-wine value chain. Phenological insights derived from precise climate modeling (10 m spatial resolution) can help managers improve productivity, reduce risks and improve supply chain planning, ensuring wine production's long-term sustainability. It provides a versatile framework applicable to various climate-sensitive crops, advancing precision agriculture, and agronomic modeling.

2. Material and methods

2.1. Study area characterisation

The study focused on two living labs in Portugal, specifically chosen to represent different vineyard parcels (Fig. 1). The first location (Fig. 1b), "Quinta do Bomfim" (QB), is in the Douro wine region, renowned for its complex topography, characterised by an elevation differential of approximately 70 m, with a wide range of degrees of direct sunlight caused by mountain casting shadows at different times of the day. The second vineyard (Fig. 1c) is located in "Herdade Esporão" (HE), in Alentejo, in southern Portugal. The area is defined by comparatively flat terrain with an elevation variation of around 7 m. Two grapevine varieties are considered herein: cv. Touriga Nacional (TN) and cv. Touriga Franca (TF), the second commonly featuring earlier phenology.

2.2. Microclimate model

Microscale climate conditions are governed by several key processes, including heat and mass exchange, air temperature, wind speed, humidity, both short- and long-wavelength radiation, and soil moisture (Kearney and Porter, 2020). To model microscale climate and predict hourly total precipitation and air temperature at the study's vineyard plots, the R package NicheMapR was employed (Kearney and Porter, 2017). NicheMapR builds on a generalised mechanistic model (Porter

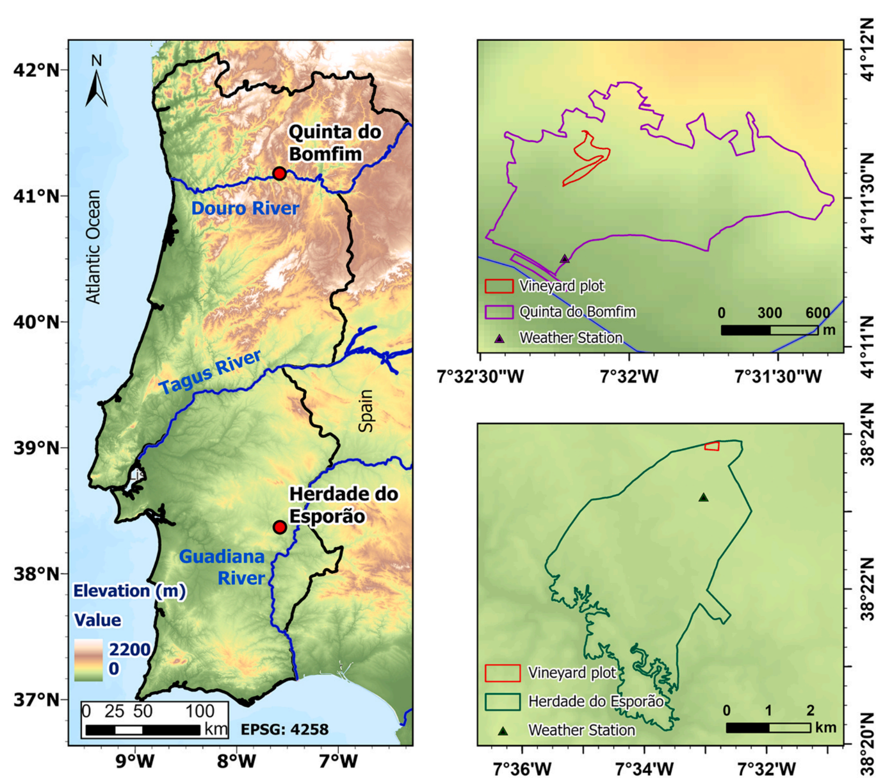

Fig. 1. a) hypsometric map of Portugal's mainland with its major rivers, showing the geographical location of both study areas (Quinta do Bomfim, QB, and Herdade do Esporão, HE); b) quinta do Bomfim with the vineyard plot of cv. Touriga Franca highlighted in red and; c) Herdade do Esporão with the vineyard plot of cv. Touriga Nacional highlighted in red.

et al., 1973) and has been validated across many environmental scenarios (Caldwella et al., 2016; Carter et al., 2015; Enriquez-Urzelai et al., 2020; Gammon et al., 2024; Kearney et al., 2013; Ma et al., 2023; Mitchell et al., 2012; Pincebourde and Woods, 2020; Visintin et al., 2021). Built on a previous Fortran-based model, NicheMapR's core function is to provide hourly predictions of climate variables, including air temperature, relative humidity, wind speed, soil moisture, and temperature. This modelling process incorporates routines such as solar radiation, which account for shading factors like hill shade, canopy, aspect, and slope.

Various R libraries were installed as dependencies: MCERA5 (Klinges et al., 2022), ECMWFR (Hufkens et al., 2019), LUBRIDATE (Spinu et al., 2018), DPLYR (Wickham et al., 2018), TIDYNC (Sumner, 2021) and ELEVATR (Hollister et al., 2017). Integrating these packages enables the manipulation of climate data and local orographic factors (i.e. aspect and slope). This process downscales the ERA5-Land 10 km hourly 2 m meteorological data to an approximate spatial resolution of 10 m. The methodology is further explained by Fonseca et al. (2024).

2.3. Climate data

In this study, three periods were chosen: 1981–2010 as a historical baseline, and two future periods, 2041–2070 and 2071–2100, analysed under two Representative Concentration Pathways RCP4.5 and RCP8.5 (Jacob et al., 2014). Historical climate data for each living lab was retrieved from ERA5-Land (European Climate Reanalysis version 5, accessed on 29 November 2024) through the Copernicus Climate Change Service, with a spatial resolution of approximately 10 km (Muñoz Sabater, 2021). Hourly precipitation and temperature data were collected from local stations for both QB and HE, from 2000 to 2019. This observational data was used to correct potential biases in ERA5-Land data using quantile mapping through the R package 'qmap' (Gudmundsson, 2012). Bias-corrected, daily temperature and total precipitation, data for the historical and future periods were generated using the quantile mapping technique. The bias corrected data was used as input to the NicheMapR model. The study sourced future climate data from the EURO-CORDEX project, using a 3-member ensemble of Regional Climate Model (RCM) – Global Climate Model (GCM) chains to account for inter-model uncertainty (Table S1), for RCP4.5 and RCP8.5.

2.4. Quantile mapping

The R package 'qmap' was selected to perform two bias corrections of climate data: 1) adjusting ERA5-Land to local weather station data, and 2) EURO-CORDEX model outputs to the generated microclimate data. The main operations are 'fitQmap' and 'doQmap'. The first defines the parameters for various quantile mapping techniques, while the second applies quantile mapping with the previously defined parameters. This study employed four quantile mapping methods to adjust model data distributions to fit observations: parametric transformations, smoothing splines, non-parametric robust empirical quantiles, and empirical quantiles. Each method fits a transformation function to align model distribution with the observed distribution. Based on the corresponding performance metrics, the smoothing spline method was ultimately chosen as the preferred approach (Fonseca et al., 2024). A version of the script can be found in the supplementary material.

2.5. STICS, multidisciplinary simulator for standard crops

The STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) (Beaudoin et al., 2023) crop model was selected for this study due to its integration of soil–plant–atmosphere processes, which are central to our research objectives. STICS offers robust support for simulating a wide range of crops, specifically grapevines, inter-cropping systems, and management scenarios, making it well-suited for diverse agro-environmental conditions. Furthermore, its widespread use in Europe ensures a base of validated applications and, crop calibrations. Its accessibility and compatibility with R-based tools also facilitated model setup, and reproducibility within the scope of this work. A comparison between several crop models is available in supplementary material (Table S5). It can model processes like photosynthesis, transpiration, nitrogen uptake, and yield formation. The model's diverse inputs are valuable for assessing crop productivity, environmental impact, and resource optimisation. Thus, researchers and farmers can study how factors like climate change, soil management, and agricultural practices may influence crop growth and sustainability. The STICS calibration results and the main parameterisation values (Moriondo et al., 2015) for both living labs are shown as supplementary material (Fig. S1, Tables S2–4). While a formal uncertainty analysis was not conducted, the calibration procedure was carried out following the guidelines presented in Yang et al. (2021). These guidelines informed the selection of parameters, the calibration strategy, and the evaluation of model performance using the STICS model. This approach allowed for methodological consistency with established practices for addressing model uncertainty, despite not explicitly quantifying it.

3. Results

3.1. Microclimate data

The microclimate data (10-m spatial resolution) for both vineyard plots (Fig. 2) reveals distinct spatial patterns of precipitation and temperature gradients, with temperature mainly influenced by elevation, geographic location, and aspect. Due to the small size of the study area, the spatial variability of precipitation is negligible, 1–2 mm, thus minimising any observed differences in precipitation across the vineyard plots. The spatial variation of mean, maximum, and minimum temperature is higher in QB (0.5–0.6 °C) than in HE (< 0.1 °C). This is due to temperature having significant elevation-dependent trends, and HE vineyard plot has a slight elevation gradient (12 m) when compared to the QB plot (150 m).

The projected changes in mean annual precipitation and mean, maximum and minimum annual temperature, under historical and future scenarios derived from Representative Concentration Pathways (RCPs) are shown in Fig. 3. The boxplots show a visual evaluation of the annual variability, central tendency, and range of the climate variables, highlighting the differences between regions in response to climate change scenarios. For both regions, the temperature metrics show a consistent warming trend for all scenarios, with a steeper increase under RCP 8.5. Precipitation shows a slight decrease in median values under future scenarios and a higher potential shift in variability in QB than HE.

3.2. Yield and phenology characteristics

The results presented show the impacts of climate scenarios on TF (in QB) and TN (in HE) yields (Fig. 4a) and key phenological stages (Fig. 4b–f), comparing a historical baseline (1981–2010) with projections under RCP4.5 and RCP8.5, for two future periods (2041–2070 and 2071–2100). The figure comprises box plots displaying data distributions for yield and the day of year (DOY) of flowering (FLO), the beginning of fruit filling (DRP), maximum leaf area index (LAX), physiological maturity (MAT), and harvest (REC). Each phenological stage is summarised below concerning historical and projected future conditions.

3.2.1. Yield

In Fig. 4a, QB (HE henceforth within brackets), the vineyard yield shows a decline in future periods, in both RCP4.5 and RCP8.5, compared to the historical period. The median yield under historical conditions is notably higher, 4899 (8336) kg ha^{-1}, whereas in both future periods under RCP4.5 (2041–2070 and 2071–2100), yields decrease slightly, 3500 (5875) and 3900 (5840) kg ha^{-1}, respectively. The more extreme

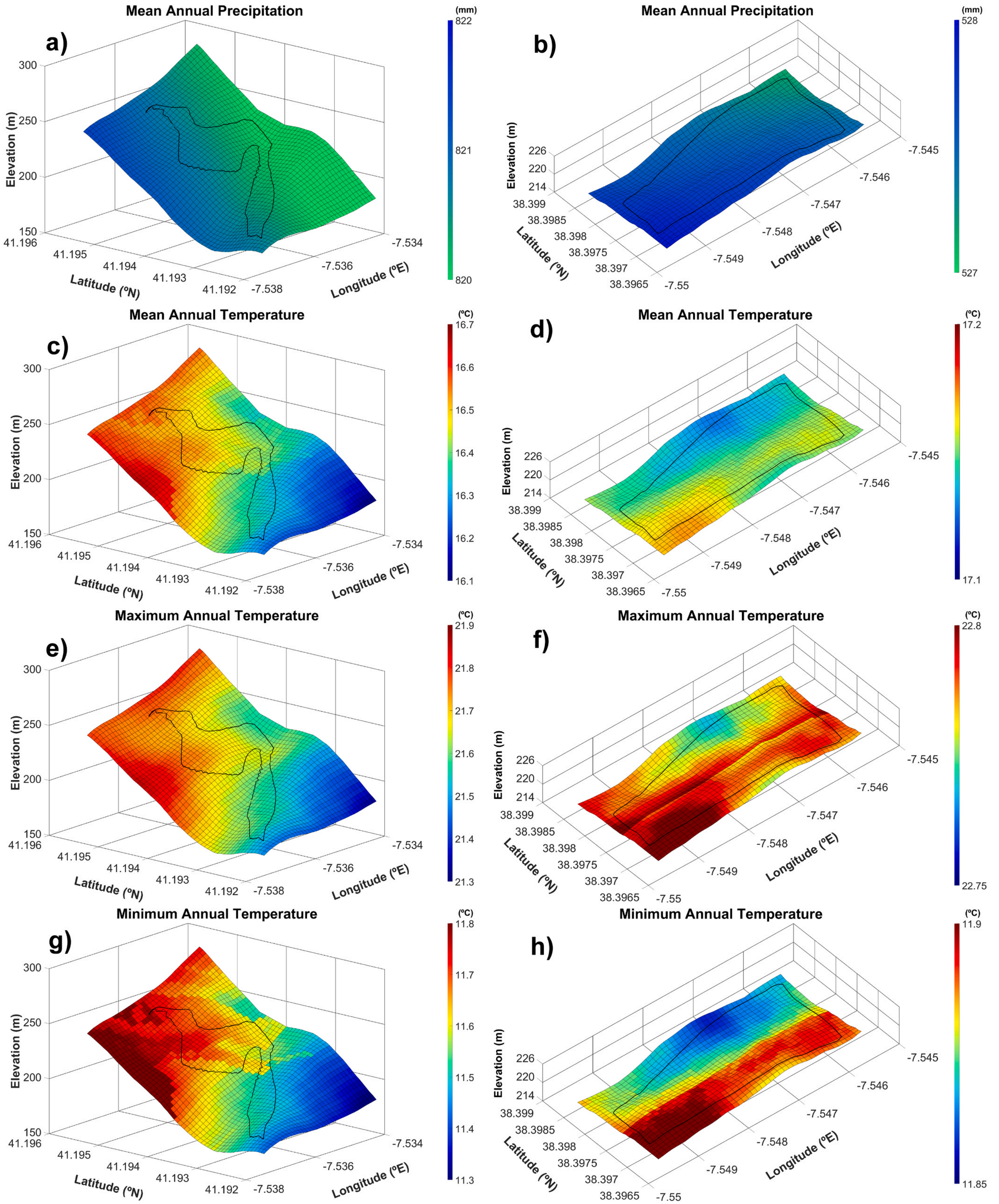

Fig. 2. Spatial variation of (a, b) mean annual precipitation, (c, d) mean, (e, f) maximum and (g, h) minimum, annual temperature, historical period (1981–2010) for (a, c, e, g) quinta do Bomfim (QB) and (b, d, f, g) Herdade do Esporão (HE) vineyard plots.

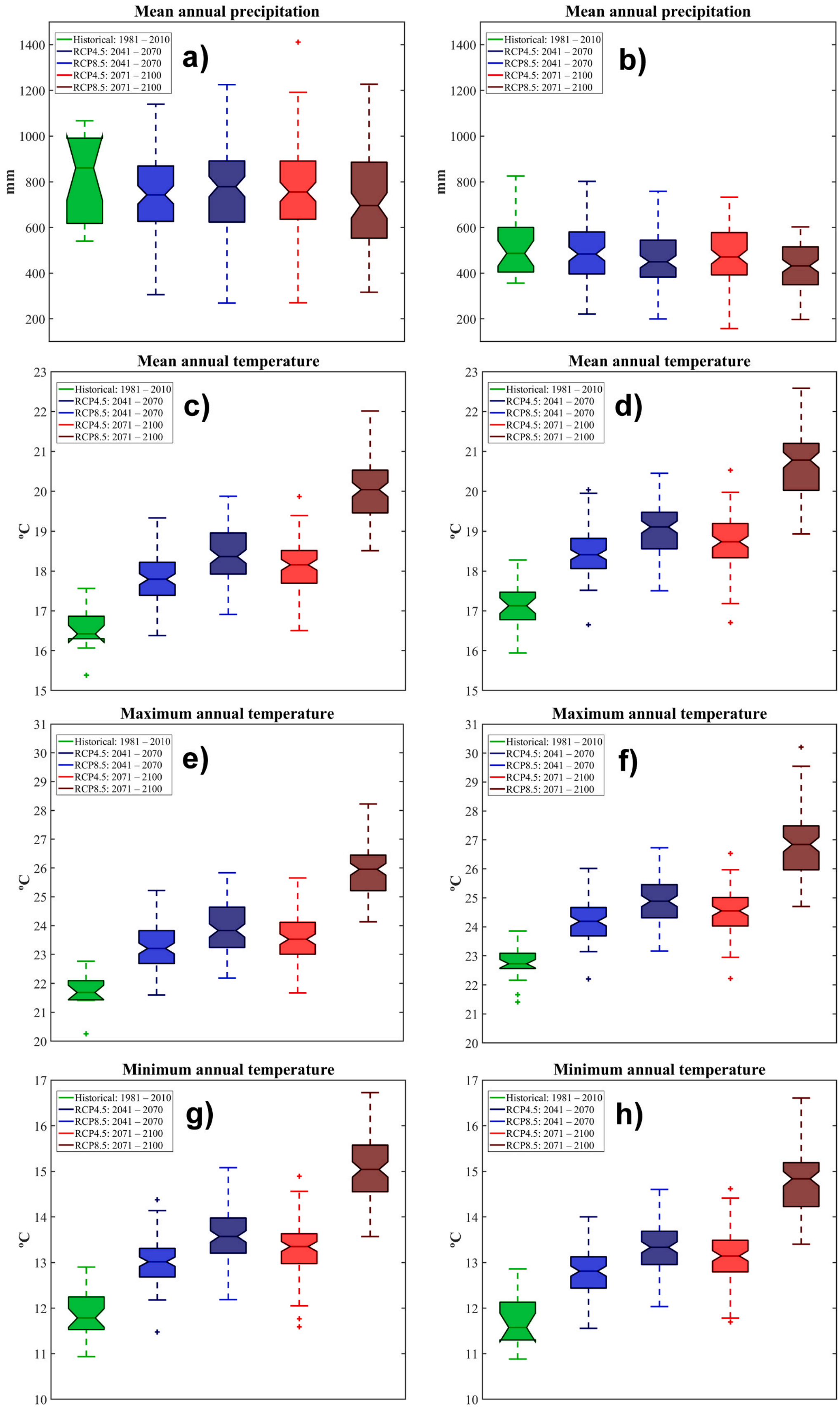

Fig. 3. Boxplots of (a, b) mean annual precipitation, (c, d) mean, (e, f) maximum and (g, h) minimum, annual temperature, with outliers (+ signals) for the historical (1981–2010) and future periods (2041–2070 and 2071–2100) for (a, c, e, g) quinta do Bomfim (QB) and (b, d, f, g) Herdade do Esporão (HE) vineyard plots for two representative concentration pathway scenarios (RCP4.5 and RCP8.5).

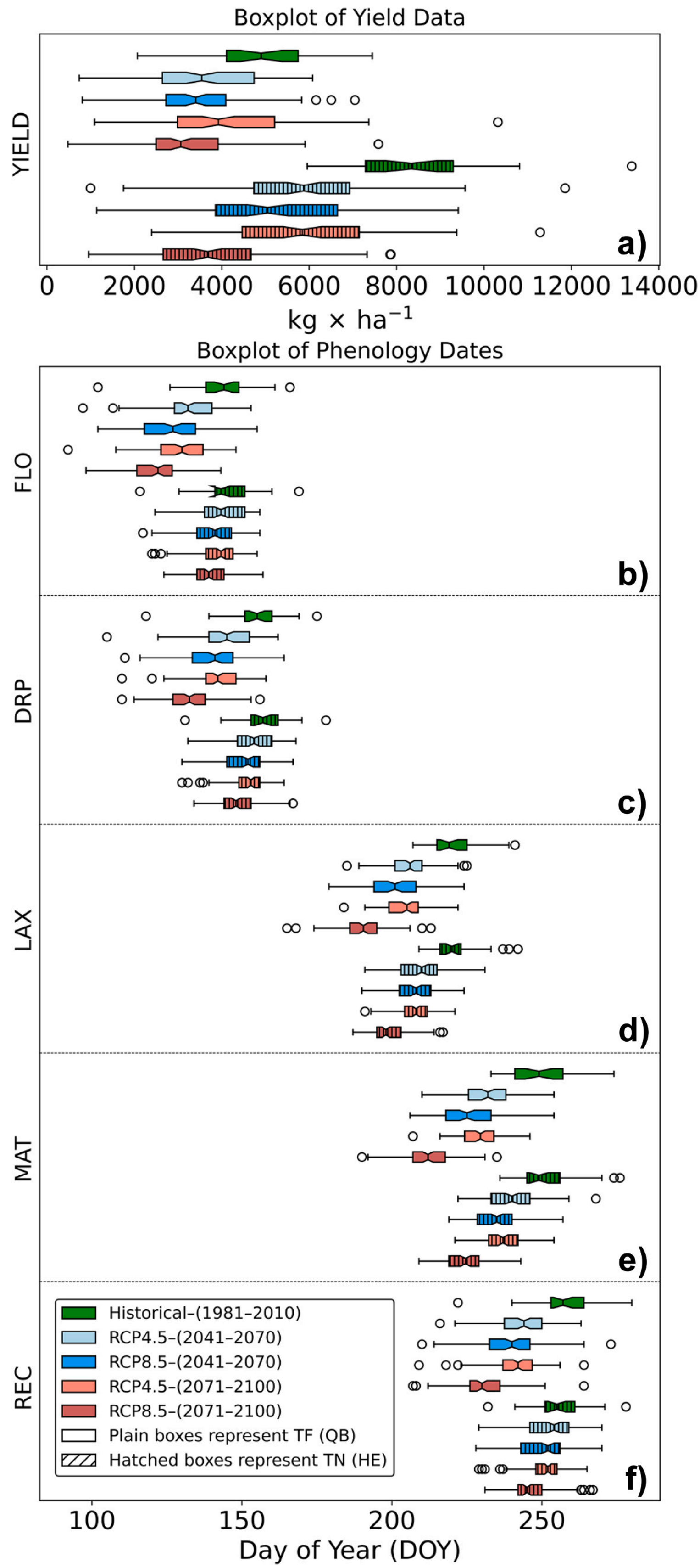

Fig. 4. a) yield (kg × ha^{-1}) and vineyard phenology stages: b) flowering (FLO), c) beginning of fruit filling (DRP), d) maximal leaf area index (LAX), e) physiological maturity (MAT) and f) harvest (REC) dates, according to the day of year (DOY). for the historical period (1981–2010) and future periods (2041–2070, 2071–2100) under RCP 4.5 and 8.5, for Touriga Franca, TF, "Quinta do Bomfim", QB (plain boxes), and Touriga Nacional, TN, "Herdade do Esporão", HE (hatched boxes).

RCP8.5 scenario shows a steeper decrease, with the 2071–2100 period having the lowest yields among all groups, 3060 (3670) kg ha^{-1}. The decreasing trend hints at a potential adverse impact of climate change on productivity, especially under high-emission scenarios.

3.2.2. Flowering (FLO)

Flowering (Fig. 4b,c) reveals a clear trend towards earlier flowering dates, with a median DOY of 144 (143). Under RCP4.5 and RCP8.5, flowering occurs progressively earlier in both future periods, with the median shifting to 122 (139) DOY by 2071–2100 in RCP8.5. This trend towards earlier flowering suggests that rising temperatures or changes in seasonal patterns may accelerate vineyard development.

3.2.3. Beginning of fruit filling (DRP)

The beginning of fruit filling, displayed in Fig. 4c, also shows an earlier advancement under both future scenarios. The historical median DOY for fruit filling is 155 (157). In future scenarios, particularly under RCP8.5, the onset of fruit filling shifts earlier, with the median reaching 132 (148) by 2071–2100. This shift aligns with the pattern observed in flowering, suggesting that climate change may shorten the grapevine's vegetative and reproductive phases, eventually affecting yield and crop quality.

3.2.4. Maximal leaf area index (LAX)

The maximal leaf area index (Fig. 4d) follows a similar trend. Historically, the median maximal leaf area index occurs at 219 (220) DOY. However, under both RCP4.5 and RCP8.5, the maximal leaf area index is reached earlier, with RCP8.5 in 2071–2100 showing the earliest median at 190 (198) DOY. This shift may show faster crop growth cycles under warmer future conditions, affecting photosynthetic capacity and yield potential if growth phases are shortened.

3.2.5. Physiological maturity (MAT)

The physiological maturity stage (Fig. 4e) also displays an advancement across future scenarios. The historical median is 249 (249) DOY, while under RCP4.5 and RCP8.5, physiological maturity occurs earlier, particularly under RCP8.5 in the late-century period (2071–2100), where the median is 212 (224) DOY. This accelerated maturity under higher temperatures could contribute to the observed reduction in yield.

3.2.6. Harvest (REC)

The harvest date (Fig. 4f) further confirms the trend of accelerated crop cycles under future climate scenarios. Historically, the median harvest date is approximately 257 (255) DOY. In future projections, particularly under RCP8.5, the harvest date shifts earlier, with the median around 230 (245) DOY by 2071–2100. This shift to earlier harvests aligns with the changes observed in other phenological stages, illustrating an overall reduction in the vineyard growth period under climate change, which could reduce overall biomass and yield.

4. Discussion

The innovative use of microclimate modelling, particularly through the NicheMapR framework, enabled the development of climate data (10 m spatial resolution) for each vineyard's unique environmental conditions. This approach provides an improvement over traditional climate modelling methods, which often lack the spatial resolution for accurate vineyard analysis. The microclimate model allowed for capturing critical local variations, enabling tools for the identification of biotic/abiotic stresses (Caffarra et al., 2012; Santos et al., 2020). Existing methods usually assess phenology based on local weather station data or on a coarser climate spatial resolution (~1 km or even ~10 km) not capturing the microclimates of the vineyard plots (Cameron et al., 2021; Rafique et al., 2024). Thus, assessing phenology data with low spatial resolution such as a specific watershed, a wine region or a denominated protected area of origin. Further, microclimate modelling offers a cost-efficient and scalable option, that serves as an alternative or complement to drone and sensor technologies. It is particularly advantageous for strategic planning, historical analysis, and large-area assessments, where direct measurement is impractical or too costly.

Combining detailed microclimate data and the STICS model allowed simulating specific phenological stages and yield projections. The results show accelerated phenological development, under both moderate (RCP 4.5) and high-emission (RCP 8.5) scenarios with potential implications for grape quality and yield. As shown in the results, the advancement in key phenological stages—such as flowering, fruit filling, and physiological maturity—suggests that the crop's growth cycle will become shorter in future climate conditions. Notably, significant yield reductions under the high-emission scenario (RCP8.5) raise concerns regarding the long-term sustainability of the value chain, particularly in traditionally warm wine-growing regions, where adaptation strategies may be essential for maintaining production levels.

These insights are crucial for vineyard managers, as they reveal how local climate variations, combined with broader climate trends, can impact grape quality and productivity (Gonçalves et al., 2022), namely for terroir-specific crops like wine grapes, where quality is intricately tied to local environmental conditions. For instance, areas within a vineyard that experience higher heat accumulation may benefit from interventions such as the use of shade nets, adjusted row orientation, or increased canopy density to reduce sun exposure and prevent heat stress (Martinez-Luscher et al., 2017). Conversely, cooler or more humid zones might require leaf thinning to enhance airflow and reduce disease risk (McDonald et al., 2013). In zones prone to faster soil moisture loss due to higher temperatures or wind exposure, targeted irrigation or soil mulching could be implemented to conserve water and maintain vine health (Romero et al., 2022a). Additionally, variation in frost risk or budburst timing across the plot could inform differential pruning strategies or the selection of cultivars better suited to specific areas (Poni et al., 2022).

The outcomes highlight that the projected acceleration of phenological stages, particularly under high-emission scenarios, may reduce the accumulation of key compounds like sugars, acids, and phenolics, compromising grape quality and altering the flavour profiles that are critical to regional wine identities (Jones and Davis, 2000; Monteiro et al., 2024). The results also show that phenological stages may be significantly delayed (whiskers of the boxplots), resulting from e.g. extreme weather events, such as heatwaves, which can cause development stoppages in grapevines, leading to higher uncertainties for growers. Earlier harvest dates further require adjustments in vineyard management, challenging producers to maintain consistent wine quality. To mitigate these risks, adaptive management strategies are critical. The microclimate data developed in this study provides a robust foundation for developing targeted interventions. These include adjusting pruning schedules and harvest timing to align with earlier phenological stages, as well as selecting rootstock-variety-clone combinations better suited to warmer conditions. Additionally, smart water management practices can be implemented to mitigate heat and water stress, while shade management techniques (e.g. from agroecological or agroforestry approaches) and optimised vineyard location, elevation, and solar exposure can help reduce the impact of extreme temperatures (Costa et al., 2019; Fonseca et al., 2023; Mirás-Avalos and Araujo, 2021; Romero et al., 2022b).

Using the NicheMapR microclimate model as an input for the STICS crop model is a promising approach to integrating fine-scale environmental data into crop simulations. However, this coupled integration also comes with several limitations such as: bias in simulated microclimate, the introduction of bias due to aggregation and resampling of data from hourly (NicheMapR) to daily (STICS) data; lack of dynamic coupling between microclimate and crop growth, microclimate estimates based on light (shade and canopy) may not reflect crop-specific canopy development, affecting STICS accuracy for transpiration, photosynthesis or thermal stress, since NicheMapR treats vegetation as static over time; uncertainty propagation, assumptions in NicheMapR are not explicitly propagated in STICS results, thus yield and phenology are subject to unquantified uncertainty.

5. Conclusion

This study model's grapevine responses using the climate-water-soil-plant nexus and at very high spatial resolutions. It highlights the role of microclimate data in addressing the impacts of climate change on vineyards. By integrating microclimate data into the STICS crop model, we provide a comprehensive analysis of how climate change may affect the phenological stages of vineyards. In summary, the results reveal that, under future climate scenarios, both vineyards plots may experience accelerated phenological development, earlier harvest dates, and yield reductions, particularly under high-emission scenarios. Adapting to these shifts will be crucial for vineyard sustainability, highlighting the need for ongoing research and innovation in climate resilience strategies for the wine industry.

These coupled models enable data-driven decision-making that can help vineyard managers adapt to climate change while preserving the economic viability of the vineyard operations. The methodologies developed in this study not only support sustainable vineyard practices but also offer a framework for broader application to other regions worldwide and other climate-sensitive crops. While the framework was developed within a viticultural context, its core components such as: using microclimate modelling data as input to a crop model, are broadly applicable to other crops and regions. By adapting input data (e.g., crop-specific thermal thresholds, phenological stages), the approach can support targeted decision-making in a variety of agricultural systems, including orchards, arable crops, or other perennial plantations where microclimatic variability significantly influences productivity and risk.

The current approach will be integrated into a decision support tool for stakeholders, i.e. a GIS-based platform with a high technology readiness level. By contributing to the resilience of the global wine industry, this research highlights the potential of precision agriculture to address challenges arising from a changing climate.

CRediT authorship contribution statement

Carina Neto: Writing – review & editing, Visualization, Resources. **Rui Flores:** Writing – review & editing, Visualization, Resources. **João A. Santos:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Helder Fraga:** Writing – review & editing, Visualization, Validation. **Cristina Andrade:** Writing – review & editing, Validation, Investigation. **Joana Valente:** Writing – review & editing, Visualization, Resources. **Fernando Alves:** Writing – review & editing, Validation, Resources. **André Fonseca:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José Cruz:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Data curation.

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.

Acknowledgments

This research was funded by Vine & Wine Portugal—Driving Sustainable Growth Through Smart Innovation, PRR & NextGeneration EU, Agendas Mobilizadoras para a Reindustrialização, Contract Nb. C644866286-011. This work is supported by National Funds by FCT – Portuguese Foundation for Science and Technology, under the project UIDB/04033 (https://doi.org/10.54499/UIDB/04033/2020) and LA/P/0126/2020 (https://doi.org/10.54499/LA/P/0126/2020).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127740.

Data availability

Data will be made available on request.

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