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TITLE

Modelling Olive Phenological Phases for Agro-Climate Risk Assessment in a Changing Future Climate over the Euro-Mediterranean Region

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Abstract

Under future changing climate, the Mediterranean is considered a region extremely prone to global warming and intensified climate events which, will possibly change the timing of phenological phases and alter conditions and risks for olive tree`s growth. This situation may restrict olive cultivation which is economically strategic in the Mediterranean countries. Since, the timing and management of agronomic practices (planting, irrigation, fertilization, crop protection, harvesting, etc.) are based on phenological phases and plant growth, accurate phenological projections are essential to assess climate risks and guide optimal management apt to mitigate climate change effects on olive development. Initially, the present investigation aims to introduce an innovative phenological modeling, i.e., Chill, Anti-Chill, and Growing Degree Days combined model (CAC_GDD) applicable in heterogenous areas with limited and scattered observations. Then, we project future changes in olive phenological phases (i.e., sprouting, blooming, and pit hardening) and relevant agro-climate stressors over the Euro-Mediterranean for both early and mid-late budbreak cultivars. For model parametrization and validation, the phenological observations were gathered from nine experimental sites in Italy and temperature timeseries from European Centre for Medium-Range Weather Forecasts, Reanalysis v5. To project the timing of phenological phases and then calculating the agro-climate stressors we used an ensemble of high-resolution climate projections at 0.11° from EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment) repository, for two historical (1976-2005) and future (2036-2065) 30-year periods under three emission scenarios (i.e., RCP2.6, RCP4.5, and RCP8.5). The CAC_GDD modeling showed best performance (RMSE: 4 days) for blooming phase of mid-late cultivars, suiting similarly and in some cases even better than more complex model to our experimental conditions. The spatial phenological projection illustrated that at leat 75% of the Euro-Mediterranean area will experience significant phenological advances for olive crop. Meanwhile, current olive cultivations in the Mediterranean basin may face accelerated climate extremes mainly at blooming and pit hardening stages in the future. Hence, we expect possible future shifts in olive growing areas from the Mediterranean to colder regions with more thermal adaptability for the mid-late cultivars.

Keywords: Phenological modelling, Olive cultivars, CAC_GDD phenological model, Climate change scenarios, The Euro-Mediterranean region, Climate stress assessment.

General Introduction

Olive (Olea europaea L.) is one of the traditional and long-lived evergreen trees in the Mediterranean environment (Caracuta, 2020; Connor, 2005; Petruccelli et. al. 2022). Its origin is identified in the eastern portion of the Mediterranean basin, from which it expanded toward other parts of the Mediterranean basin in southern and southwestern Europe, and northern Africa (Connor, 2005). The countries including Spain, Italy, Greece, Turkey, Tunisia, and Portugal, which are widely characterized by typical Mediterranean climate account overall to more than 95% of the olive oil production worldwide (Diana et al., 2019), embracing approximately 80% of the global olive growing area. However, future climate change scenarios, anticipate negative impacts on olive growth, restricting its cultivations in the Mediterranean basin due to intensified warming (MedECC, 2020).
Olive trees` distribution in the world is significantly confined by several climatic factors, and particularly olive orchards are limited to regions within 30° - 45° in the northern and southern hemispheres because of thermal limitations (Fiorino and Mancuso, 2000; Therios, 2009). An olive tree typically cannot withstand temperatures below -8°C for more than one week, and high summer temperatures may also damage its yield performance (Koubouris et al., 2009). There are also other ecological and pedological parameters affecting suitability of olive growth in different environments, e.g., soil characteristics.

- **Temperature and phenological modeling**

Timing of phenological phases mainly correlate to the temperatures (López-Bernal et al., 2020; Fraga et al., 2019; McMaster and Wilhelm, 1997; Cesaraccio et al. 2004; Luedeling et al. 2021; Rojo and Perez-Badia, 2015). Temperature acts as the main driver of olive tree phenology by regulating the release from the endo-dormancy period, after the accumulation of adequate cold units during wintertime (chill units), and then the release from the eco-dormancy period, whose duration is dependent on heating units accumulated from the ending point of endo-dormancy to bud breaking stage (Fraga et al., 2019). Hence, the breaking of winter rest and onset of the pursuant vegetative stages are highly dependent on temperature (López-Bernal et al., 2020). Chilling and heating methods presented different temperature ranges to account for chill and heat accumulation. Indeed, these consider both lower and upper thresholds, beyond which temperature does no longer affect a crop physiologically in terms of growing and rest period. However, divergences and uncertainty lay about the required chill and heat accumulations and the period of time needed to complete phenological phases for different cultivars (Rojo et al., 2020). Flowering dates for olive were modelled (De Melo-Abreu et al., 2004) considering olive development from the beginning of the season (i.e. 1st of February) and temperature sum reaching a defined number of growing degree-days (GDD) for the onset of flowering. On the other hand, GDD accumulation depends highly on the specific olive cultivar and the initial date for heat accumulation. Several authors observed a delay in blooming with increasing latitude and elevation and attributed this trend to the lower heat accumulation in the cooler zones (Galan et al., 2005; Aguilera et al.,2014; Orlandi et al., 2010; Rojo and Pérez-Badia, 2014). According to Aguilera et al. (2014), the earlier blooming dates of olive cultivars grown in southern Mediterranean regions (e.g., Tunisia) result from tree adaptation, a defense mechanism against temperatures above 30-35°C occurring during late spring months. Indeed, it was suggested that high temperatures are detrimental to the development and fertility of flowers (Barranco et al., 2008).

Since there is a high correlation between crop growth, yield, and temperature (Magugu et al., 2016; Porter and Gawit, 1999), phenological models mainly rely on temperature as an input variable (e.g., McMaster and Wilhelm, 1997; Cesaraccio et al. 2004; Luedeling et al. 2021). Temperature variations in different stages of plant development can influence phenological timing and impact on growth and yield. For example, Rojo and Perez-Badia, (2015) studied the relationship between temperature and timing of flowering stage for Cornicabra olive cultivar in central Spain (Toledo province). Their findings showed a positive correlation between temperature rise and phenological postponing, e.g., between temperature and the onset of the dormancy stage. However, a negative correlation between temperature rise and phenological earliness was observed for the early spring flowering stage.

Despite the varietal-specific phenological behavior of several tree species (Nieddu et al., 2002; Cesaraccio et al., 2004; Ruml et al., 2010), still only few papers have proposed and compared phenological models for specific cultivars (De Melo-Abreu et al., 2004; Zouari et al., 2017). Several crop phenological models have already been developed and implemented by investigators in environmental and agricultural sciences to project single phenological stages (Cesaraccio et al., 2004; Moriondo et al., 2015; Moriondo et al.,2019; McMaster and Wilhelm, 1997; Luedeling et al., 2021; Ghersa and Holt, 1995). Previously available studies on olive phenology focused on modelling and estimated mainly early phase in spring time (e.g., bloom). For instance, Rojo et. al. (2020) developed a research to define thermal accumulation to fulfill the chilling and heating requirements for the budbreak stage of olive trees in Toledo, central Spain; Lecce, southeastern Italy; and Chaal, central Tunisia. Considering both chilling and forcing requirements they developed a phenological model which, confirmed the highest performance in Toledo (with an error of about 2 days). Zouari et al. (2017) applied the growing degree day (GDD) model to estimate heating requirements of four olive cultivars for flowering stages in southern Tunisia. They obtained a large inter-annual variation of GDD amounts while comparing differences between cultivars (from 100 to 267 GDD). Orlandi et al., (2010), developed a project study to find linkages between olive flowering and heat accumulation using the GDD model in the Mediterranean regions of Italy and Tunisia. The results confirmed that the olive species showed various heat requirements for flowering, according to the latitudes of the experimental sites. Also, a phenological model was implemented for olive cultivars in Italy with a reverse modelling approach using the developmental rate function, which is built on linear and nonlinear functions, to predict phenological stages from budbreak to complete flowering (Di Paola et al., 2021) for single locations.

The PhenoFlex model (Luedeling et al., 2021) was developed recently to predict phenological stage of deciduous fruit trees in spring (e.g., budburst). It links both the dynamic model (for chill accumulation) and the growing degree hours model (for heat accumulation) with a very large number of parameters that offer high flexibility in simulating dormancy breaking. However, such an extensive parameterization usually requires a high number and years of observations, which are barely available for many sites.

Mainly, the above-mentioned studies were carried out separately at single locations that are characterized by specific environmental conditions and well adapted local cultivars. Using these results, spatial projections of phenological phases and validation over a wide region could have more limitations since they could not meet a comprehensive range of environmental conditions.

Modelling phenological stages of olive trees at regional or global scales (e.g., Mediterranean basin) is highly challenging due to limited and scattered observations across large and heterogenous environments. Some complex phenology models, qualified for a single phenological stage, e.g. Phenoflex that was built upon many parameters, dependent on long-term phenological observations and hourly temperature time series might be unfit to project comprehensively reliable phenological dates for a mix of experimental conditions. So, a general approach with less parameter demanding structure and flexible projection capability may perform better in modeling successive phenological phases of olive crop over a complex Mediterranean environment, and consequently assist producers, particularly in a changing climate context, with crop cultivation management, planning crop practices in orchards, and mitigating climate-induced risks (Medda et al., 2022).

- **Olive phenological phases under climate change**

There is a high risk that climate change impacts on olive trees would threaten yield quality and quantity (Fraga et al., 2021; Medda et al., 2022). In particular, changing climate conditions might influence olive`s physiological processes (Brito et al., 2019; Petridis et al., 2012) and thus phenological timing (Villalobos et al., 2006; Fraga et al., 2019; Galán et al., 2005). For instance, previous studies showed rising temperatures would affect the timing of olive`s phenological phases, i.e., lengthening the growing season (Pérez-López et al., 2008), and particularly altering the flowering stage (Orlandi et al., 2010; Avolio et al., 2012; Aguilera et al., 2014; Osborne et al., 2000). Olive farming holds significant economic value in numerous Mediterranean countries. Ponti et al. (2014), estimated that smaller private olive farms, and the associated businesses, are likely to face economic losses due to climate change mainly in Italy and Greece, during the upcoming decades.
Earlier studies illustrate climate change impacts on olive from different aspects. For instance, Fraga et al., (2019), used an ensemble of climate models, future scenarios, and dynamic crop models, to calculate agro-climatic indicators over southern Europe, linking their variations to olive productivity changes. Poleward shift in olive growing areas are projected for the future because of increasing temperature and improved climate suitability in northern regions (Moriondo et al., 2013; Tanasijevic et al., 2014). A study developed by Rodríguez Sousa, et al., (2020) estimated a range of temperature increase from 0.8 to 2.3°C along with an annual rainfall decrease of around 200 mm over the Mediterranean region for 2050, which displace olive growing areas towards the more humid and cooler regions (e.g., northern regions and highlands).
Concerning phenological implications, only a few large-scale studies were conducted (Aguilera et al., 2014; Garcia-Mozo et al. 2008; Mariani et al., 2013), and they focused solely on the olive flowering stage. Some studies (e.g., Di Paola et al., 2021) developed a phenological model to predict many phenological phases of olive using observations from different experimental sites to calibrate a statistical inference model. While some resulted in good model performance, the results were not implemented spatially to study future climate model projections over a large area.
Earlier work from Moriondo and Bindi (2007) investigated the impact of increasing temperature on the phenology of Mediterranean crops, including olive trees, by using general and regional circulation models on a broad spatial scale. The results pointed out both changes in growing season length and advanced crop development, which may increase the risk of extreme climate events during some phenological phases, i.e., budbreak and anthesis. de Melo-Abreu et al., (2004) used a combination of temperature-based phenological models and climate projections to predict that olive trees near Cordoba, Spain, would experience earlier flowering phases, from 5.2 to 10 days, in response to applied warming scenarios and models. While some studies showed more remarkable phenological

advancement, for instance, another study in southern Spain used a thermal model (Galan et al., 2005) and demonstrated that global warming projected by regional climate models would result in an advancement of about 1-3 weeks of olive flowering within the mid-elevation inland regions of the study area. A similar study predicted around 10-20 days of potential advance in the flowering phase of olive crops in Southern Italy using projected growing degree days accumulation (Orlandi et al., 2013). Based on a study from Chmielewski and Rotzer (2001) that considers atmospheric circulations, which result from the positive phase of the North Atlantic Oscillation Index (NAO-index) over Europe in late winter and early spring, a plant phenological advancement of about 5-7 days per 1°C temperature rise was projected. The change was attributed to dominant westerly winds and higher temperatures caused by the NAO index.

As shown in the aforementioned examples, warming can alter the timing of olive phenology, which leads to consequential effects on plant development and production. In addition to causing earliness of olive flowering, an investigation by Benloche-González et al. (2018) confirmed that a 4°C temperature increase makes the flowering stage longer and leads to abortion of ovary and reduced final yield. Insufficient chilling units during dormancy prevent olive trees from setting fruit properly (Torres et al., 2017), so decreased chilling under global warming can lead to fruit loss (Fraga et al., 2019; 2022).

Temperature changes during different growth stages of olive trees can cause various biophysiological effects. For instance, Tura et al. (2009) reported that warm conditions during the olive crop maturation phase and sufficient water availability in the autumn and spring seasons improved the volatile compounds and oil quality. A study by Ben-Ari et al. (2021) showed that olive oil quantity and quality depend on temperature solely after the pit hardening stage in the warm months of the year. However, high temperatures commonly impact olive fruit growth throughout its entire development period. Since these effects would differ spatially-temporally, it would be worthwhile to project the successive phenological stages of olive crops over large areas at a yearly scale using different historic and future climate projections. The projections might provide large-scale patterns of olive phenological changes. In addition, they may support olive growers by providing management tools and strategic planning within olive growing areas for a changing climate.

Some crop models' approaches may build upon statistical relationships between relevant variables such as climate, crop development, and final yield, while other process-based phenological models, by integrating chilling and forcing, physiologically predict crop phenological phases using weather data and parameters calibrated with observations (Fraga et al, 2019; Moriondo et al., 2015; Luedeling et al., 2021). Since temperatures impact differently quality and quantity of final yield during any crop phenological stage, the adaptation of the crops to climate change and climate-induced risks through modeling crop phenological stages is fundamental for the evaluation of climate change effects on crop growth and production (Moriondo and Bindi, 2007). Consequently, establishing tools to project the phenological stages of tree crops is crucial for determining management in a changing climate (Luedeling et al., 2021). Considerable research is still needed to predict successive phenological stages scaled up from the local to the regional level.

- **Future climate stressors and olive phenology**

Olive trees indicate remarkable capacity to grow in rough environmental/climatic conditions, e.g., with water scarcity, variant daily-seasonally temperatures, high humidity (Fernández, 2014; Sanzani et al., 2012). However, climatic factors are restricting olive growth worldwide, as in very cold or hot regions olive orchards are unavailable (Fiorino and Mancuso, 2000). During dormancy period temperatures around -7 to -8°C may damage olive growth (Sanzani et al., 2012), but in summer time when temperature exceed 35 to 40°C, heat stress declines the photosynthetic capacity, along with reductions in stomatal conductance of the olive trees (Haworth et al., 2018). Indeed, climate unsuitability and extremes, e.g., frequency of frost or hot days, wet or dry days, windy days, heavy precipitation days, etc. can impose some wrecking effects on olive growth in different phenological phases as well as the final yield. Meanwhile, yearly climate variability can impact olive cultivation system, disease outbreaks, pests and alternating bearing years (Fraga et al., 2021; Ali et al., 2014; Daane and Johnson, 2010; Sofo et al., 2018). Since, the Mediterranean region is considered a climate change hotspot and one of the most prone areas to global warming (Giorgi, 2006; IPCC, 2021), this situation may go on even more harshly under climate change projections over the future period (MedECC, 2020, Hertig et al., 2013, Tanasijevic et al., 2014) by increasing climate extremes and phenological timing advances affecting olive production in the Mediterranean basin (Fraga et al., 2021; Gabaldón-Leal et al., 2017; Mairech et al., 2021).

A research developed by Kaniewski et al., (2023) in the Levant region (a large area in the Eastern Mediterranean region) showed that the climate/environmental extremes during the future decades will challenge olive cultivation in the Mediterranean orchards under changing climate context. Also based on their findings through a paleoclimatic analysis an annual mean temperature of 16.9 ±0.3°C is optimal for olive blooming stage. Mairech et al. (2021) showed under different future climate changes scenarios, olive orchards will be highly impacted especially in dry areas because of rainfall reduction and then deficit irrigation. Although they found variant results over the study area expecting a yield decreases around 28% over the Iberian Peninsula versus 26% of increase in the central Mediterranean region.

In terms of climatic conditions/variables, influential on olive, a research by Mairech et al. (2020) indicated existing of high relationship between climate variability and olive yield. Some other studies more precisely projected that during future period heat and evapotranspiration increase, rainfall deficit, changes in seasonal precipitations along with maximum and minimum temperatures` changes would reduce olive yield over the Mediterranean (Koubouris et al., 2009; Rodriguez Diaz et al., 2007; Moriana et al., 2003; Iniesta et al., 2009; Galan et al., 2008; Rossi et al. 2020). Indeed, the future scenarios project rising temperatures that could lead to olive phenological earliness and also shortening of growth stages (De Melo-Abreu et al., 2004; Gabaldon-Leal et al., 2017, Osborne et al., 2000; Giannakopoulos et al., 2009; Moriondo et al., 2008, 2010; García-Mozo et al., 2010) taking possible climate vulnerabilities on olive growth stages and consequently losses on its final yield.

A research developed by Tanasijevic et al. (2014), also illustrated significant reduction of precipitation and increase of evapotranspiration demand over future, which can threat rainfed olive cultivations in the Mediterranean orchards. Some previous researches indicated that under future climate change the most vulnerable variables relevant to agricultural/horticultural crops, e.g., olive, would be biomass growth, crop evapotranspiration, phenological stages` duration, water need and the final yield (Osborne et al., 2000; Pereira and De Melo-Abreu, 2009; Quiroga and Iglesias, 2009).

To assess climate risk or suitability for olive crop growth, calculation of agro-climatic indicators preferably for single phenological phases are needed. The agro-climatic suitability models work also based on agro-climatic/ ecoclimatic indicators to evaluate how the climatic conditions are favorable/unfavorable for a particular plant development process or they possibly barricade cultural practices during certain phenological stages (Caubel et al. 2015). For instance, increased frequency of dry days in olive sprouting stage more likely decreases shoot development (Chartzoulakis et al. 2000; Xilayannis et al. 1999; Pierantozzi et al. 2013; Rapoport et al. 2012), and from pit hardening stage onward because of water stress the fruit production rate will be diminished significantly (Beede and Goldhamer, 1994; Varol and Ayaz, 2012). Different temperature thresholds also effect bio-physiologically olive growth: e.g., higher than 30°C, photosynthesis rate decreases; higher than 35°C, closing stomata, followed by limited gases exchange for photosynthesis, will lead to restrict olive crop growth; and higher than 40°C, photosynthesis process will be pulled in completely (Rallo and Cuevas, 2008; Benlloch-González et al. 2016; Ayaz and Varol, 2015). On the other hand, low temperatures e.g., frost days can damage olive tree`s shoot tip, foliation and branches bark respectively, depending on freezing intensities (Gucci and Cantini, 2001). Olive tree also can be more subjected to frost events in late winter, when cold hardiness after a limited exposure to higher temperatures may return suddenly (Kozlowski and Pallardy, 1997). Freezing temperature in early spring likely damages olive`s young vegetation and bloom (Proietti and Regni, 2018). Windiness also impacts olive growth, as extreme winds can drop olive fruits and blooms and break shoots and young vegetation (Proietti and Regni, 2018). However, during all phenological phases of olive wind speed higher than 2m/s (Barranco navero, et. al., 2017) can disturb pesticide spray treatments, and harvesting process. Intense rainfall during summer would barricade olive growth, but increase olive fly population (Di Paola et al. 2023). A research developed in north west of Arabi Saudi indicated that heavy rainfall events (on December 22, 1993, January 1, 1994, and October 17, 1997) damaged olive trees by sudden defoliation, destroying of young trees, and shoot tip burning (Naser et la. 2018). The impacts of climate extremes on olive crop can originate from abiotic (e.g., temperature, water availability, and weather extremes) and biotic (e.g., pests and diseases) parameters reducing yield quantity and quality (Sanzani et al., 2012; Fraga et al., 2021; Ponti et al., 2014; Bosso et al., 2016). Meanwhile, under future climate scenarios the aforementioned climate indicators/extremes are expected to be more intensified damaging increasingly olive crop (Moriana et al., 2003; Iniesta et al., 2009; Koubouris et al., 2009; Leolini et al., 2018; Rossi et al., 2020; Mairech et al., 2020 and 2021) in the Mediterranean orchards.

- **Problem definition and objectives**

Previous studies mainly focused on modeling the flowering stage of olive trees in Mediterranean areas (Orlandi et al., 2010; Avolio et al., 2012; Aguilera et al., 2014; Osborne et al., 2000; De Melo-Abreu et al., 2004; Galan et al., 2005; Orlandi et al., 2013), considering ongoing and future climate change effects for single olive growing locations with limited scaling up to a larger area (e.g., Fernández, 2014; Di Paola et al. 2023; Kaniewski et al. 2023). Thus, developing a phenological-based study for different growth stages of olive cultivars based on a generalized modelling approach but still effectively representative a large spectrum of biogeographic zones, such as the Euro-Meiterranean region, would be crucial for spatial analysis of olive cultivation and agronomic practices under future changing climate.

Regarding the phenological data restrictions in the study area we consider only three principal and consecutive phenological phases for modelling as follows:

1) Sprouting (or emergence of the spring bud), which begins usually at late winter. Plants` growth occurs from the appearance of the buds. During this phase both vegetative buds and flower buds emerge, which form floral clusters;
2) Blooming (or flowering). This phenological phase is the key stage, through which the olive tree traverses into its annual cycle. In this stage the olive tree, shows a great number of flowers whose objective is to be fertilized and then become fruits. Usually olive blooming is seen in mid-May with a total duration of around three weeks (from the first flower opens to the last one);
3) Pit hardening (or fruit set). Through this phase the fruit bone begins to harden, until olive reaches a given size and an intense green color, accumulating reserves until maturity (Fiorino, 2003).

At the first step (Chapter 1), we aim to model and validate projected dates for three aforementioned phenological phases, of early and mid-late budbreak olive cultivar representatives, over the Mediterranean environment. We integrate observations from several experimental sites with different environmental characteristics in Italy, and frame an innovative method (Chill Anti-Chill (Cesaraccio et al., 2004) + Growing Degree Days Model (McMaster and Wilhelm, 1997)) which, combines chilling and sequentially forcing per phenological phases. Meanwhile, the PhenoFlex model is also applied to compare and validate the modelling performance for single locations of both approaches.

Then (Chapter 2), we implement the Chill Anti-Chill_Growing Degree Days Model (CAC_GDD model) for the Euro-Mediterranean using future RCPs (Representative Concentration Pathways) and different GCM_RCM combinations (Global Climate Model_Regional Climate Model combinations) to project the future changes/shifts of three successive phenological phases for early and mid-late budbreak olive cultivars in a spatial scale. Application of the Analysis of Variance also can illustrate spatial agreement/disagreement between climate models in terms of future phenological timing projections.

Finally (Chapter 3), we develop a large-scale spatial analysis using a series of seven agro-climatic indicators (i.e., length of the phenological stages, frequency of dry days, hot days, frost days, heavy rainfall days, extreme windy days and unfavorable windy days) based upon the projected phenological phases of two olive cultivars representatives under a changing future climate in various environmental stratifications of the Euro-Mediterranean region. We use future RCPs and different GCM_RCM combinations to figure out the climate change signals of the agro-climatic stressors under the dynamic temporal shifts of phenological stages.

Figure1 presents the research workflows and the relationship between the main research steps which, correspond to three singl manuscripts for publication.

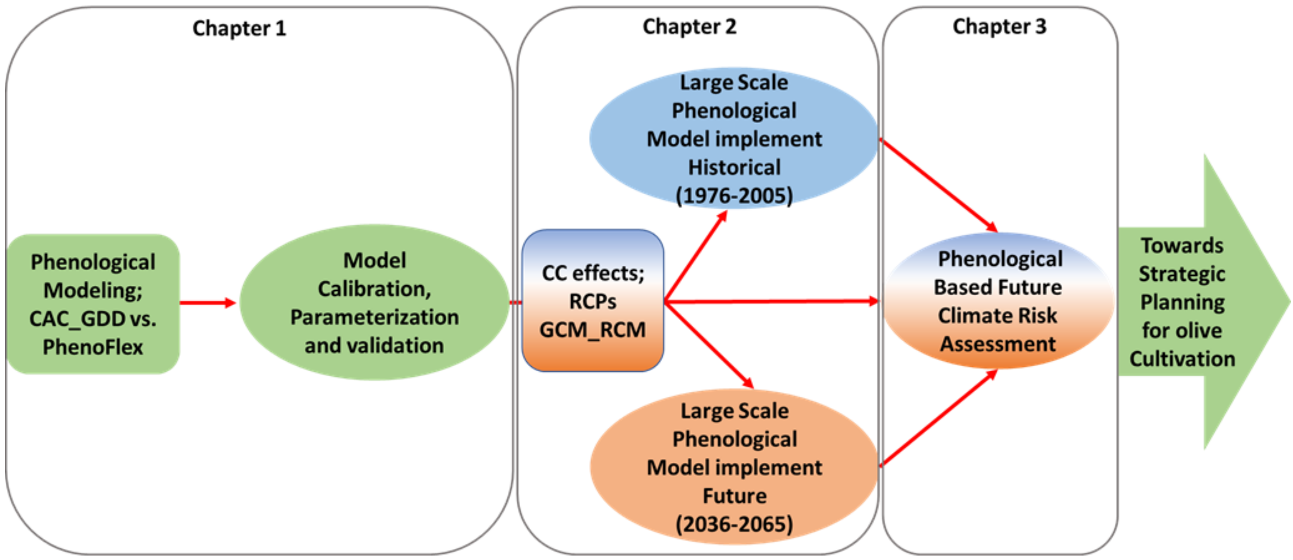

Figure 1. The general research workflows and the analysis-process of the phenological modeling, climate change impacts on the phenological stages and relevant agro-climatic risks. Using historic (1976-2005) and future (2036-2065) timeseries, from RCPs and the climate model projections.

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CHAPTER 1

Title:

“Modelling phenological phases across olive cultivars in the Mediterranean”

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Abstract

Modelling phenological phases in Mediterranean environment often implies tangible challenges to reconstruct regional trends over heterogenous areas using limited and scattered observations. The present investigation aims to project phenological phases (i.e., sprouting, blooming and pit hardening) for early and mid-late olive cultivars in the Mediterranean, comparing two phenological modelling approaches. The Phenoflex is a rather integrated but data demanding model, while a combined model of Chill and Anti-Chill days and Growing Degree Days (CAC_GDD) offers a more parsimonious and general approach in terms of data requirement for parameterization. We gathered phenological observations from nine experimental sites in Italy and temperature timeseries from European Centre for Medium-Range Weather Forecasts, Reanalysis v5. Best performances of the CAC_GDD (RMSE: 4 days) and PhenoFlex model (RMSE: 5-9.5 days) were identified for the blooming and sprouting phases of mid-late cultivars respectively. The CAC_GDD model suited better to our experimental conditions at projecting pit hardening and blooming dates (correlation: 0.80 and 0.70, normalized RMSE: 0.6 and 0.8, normalized standard deviation: 0.9 and 1.0). Optimization of the principal parameters confirmed that mid-late cultivars are more adaptable to thermal variability. Spatial distribution illustrated almost synchronies of blooming dates between early and mid-late cultivars com-pared to other phases.

Keywords: Phenological modelling; Olive cultivars; Phenological stages; the Mediterranean en-vironment; CAC_GDD model

1. Introduction

Countries around the Mediterranean basin have a principal and traditional role in olive production and its by-products. In fact Spain, Italy, Greece, Turkey, Tunisia, and Portugal all together account for more than 95% of olive oil production worldwide [1].

Olive (Olea europaea L.) is one of the long-lived tree crops, cultivated for thousands of years in the Mediterranean region. Its initial origin is identified from the eastern Mediterranean side and then expanded over the other parts of the Mediterranean basin in southern and southwestern Europe, and northern Africa [2].

The olive tree`s growing area is mainly restricted to the region from 30° to 45° N [3]. This restriction suggests that climatic and particularly temperature conditions are the key factors driving and limiting olive growth processes. However, there are other ecological parameters affecting suitability of olive growth in different environments, e.g., soil characteristics. An olive tree typically cannot withstand temperatures below -8°C for more than one week, and high summer temperatures may also damage its yield performance [4].

Temperature acts as the main driver of olive tree phenology by regulating the release from the endo-dormancy period, after the accumulation of adequate cold units during wintertime (chill units), and then the release from the eco-dormancy period, whose duration is dependent on forcing/heating units accumulated from the ending point of endo-dormancy to bud breaking stage [5]. Hence, the breaking of winter rest and onset of the pursuant vegetative stages are highly dependent on temperature [6]. Chilling and heating methods presented different temperature ranges to account for chill and heat accumulation. Indeed, these consider both lower and upper thresholds, beyond which temperature does no longer affect a crop physiologically in terms of growing and rest period. However, divergences and uncertainty lay about the required chill and heat accumulations and the period of time needed to complete phenological phases for different cultivars [7]. Flowering dates for olive were modelled [8] considering olive development from the beginning of the season (i.e. 1st of February) and temperature sum reaching a defined amount of growing degree-days (GDD) for the onset of flowering. On the other hand, GDD accumulation depends highly on the specific olive cultivar and the initial date for heat accumulation.

In addition to temperature, there are still genotype and several physical-environmental variables (e.g., distance from the sea, photoperiod, latitude, topography, rainfall, etc.), which are also influencing olive blooming and other phenological stages [9,8,10,11,12]. Several authors observed a delay in blooming with increasing latitude and elevation and attributed this trend to the lower heat accumulation in the cooler zones [13,10,14,15]. According to Aguilera et al. [13], the earlier blooming dates of olive cultivars grown in southern Mediterranean regions (e.g., Tunisia) result from tree adaptation, a defense mechanism against temperatures above 30-35°C occurring during late spring months. Indeed, it was suggested that high temperatures are detrimental to the development and fertility of flowers [16].

Despite the varietal-specific phenological behavior (both in terms of timing and annual variability) of several tree species [17,18,19], still only few papers have proposed and compared phenological models for specific cultivars [8,20]. Several crop phenological models have already been developed and implemented by investigators in environmental and agricultural sciences to project phenological stages [18,21,22,23,24,25]. Previously available studies on olive phenology focused on modelling and estimating mainly early phase in spring time (e.g., bloom). For instance, Rojo et. al. [7] developed a research to define thermal accumulation to fulfill the chilling and heating requirements for the budbreak stage of olive trees in Toledo, central Spain; Lecce, southeastern Italy; and Chaal, central Tunisia. Considering both chilling and forcing requirements they developed a phenological model which confirmed the highest performance in Toledo (with an error of about 2 days). Zouari et al. [20] applied the growing degree day (GDD) model to estimate heating requirements of four olive cultivars for flowering stages in southern Tunisia. They obtained a large inter-annual variation of GDD amounts while comparing differences between cultivars (from 100 to 267 GDD). Orlandi et al., [26], developed a project study to find linkages between olive flowering and heat accumulation using the GDD model in Mediterranean regions of Italy and Tunisia. The results confirmed that the olive species showed various heat requirements for flowering, according to the latitudes of the experimental sites. Also, a phenological model was implemented for olive cultivars in Italy with a reverse modelling approach using the developmental rate function, which is built on linear and nonlinear functions, to predict phenological stages from budbreak to complete flowering [27] for single locations.

The PhenoFlex model [24] was developed recently to predict phenological stage of deciduous fruit trees in spring (e.g., budburst). It links both the dynamic model (for chill accumulation) and the growing degree hours model (for heat accumulation) with a very large number of parameters that offer high flexibility in simulating dormancy breaking. However, such an extensive parameterization usually requires a high number and years of observations, which are barely available for many sites.

Mainly, the above-mentioned studies were carried out separately at single locations that are characterized by specific environmental conditions and well adapted local cultivars, so using their results, spatial projection of the phenological phases and validation over a wide region could have more limitations since they could not meet a comprehensive range of environmental conditions.

Modelling phenological stages of olive trees at regional or global scales (e.g., Mediterranean basin) is highly challenging due to limited and scattered observations across heterogenous environments. Some complex phenology models, qualified for a single phenological stage, e.g. Phenoflex that was built upon many parameters, dependent on long-term phenological observations and hourly temperature time series, would miss to project comprehensively reliable phenological dates in our above-mentioned challenging experimental conditions. So, a general approach with less parameter demanding structure and flexible projection capability may perform better in modeling successive phenological phases of olive crop over a complex Mediterranean environment, and consequently assist producers, particularly in a changing climate context, with crop cultivation management, planning crop practices in orchards, and mitigating climate-induced risks. [28].

This study aims to model and validate simulated dates for three main phenological phases, including sprouting, blooming, and pit hardening of early and mid-late budbreak olive cultivars, over the Mediterranean environment. To this end, we integrated observations from several experimental sites with different environmental characteristics in Italy, and framed an innovative method to combine chilling and sequentially forcing per phenological phases. Hence, to estimate the sprouting phenological phase, we first implemented the Chill Anti-Chill Days model [18] and then, to estimate the blooming and pit hardening stages we applied the growing degree days model [23] as a complementary method to accumulate only heat units initiating from the sprouting dates. Simultaneously, we applied also the PhenoFlex model, which is a complex process-based approach. The modeling performance of both approaches were compared by applying some statistics including root mean square error (RMSE), correlation, and standard deviation by phenological phases and cultivars. Spatial implementation and projections of modelling outputs was developed over Italy by phenological phases and cultivar types.

2. Materials and Methods

2.1. Data collection

Phenological observations were obtained from different sources including the PHENAGRI project (1996–2003) [29], the national network of CREA and the Agricultural Department at the University of Sassari. We collected phenological data of four olive cultivars as the representatives of early and mid-late sprouting cultivars from nine experimental sites in Italy. The distinction of the two cultivar types was based on the observed mean phenological dates. The phenology-date difference between our selected early and mid-late budbreak cultivars reached the peak with about 32 days for the sprouting phase, and then the pit hardening and the blooming phases showed differences of about 28 and 10 days, respectively (Table 1). Figure 1 shows the geographical distribution of each experimental site in Italy. Most of these sites are good representatives of a wide range of Mediterranean climate type, spanning from the southern ones (Belice Mare, Sicily) with higher annual mean temperatures (18.9°C), to temperate climatic zone [30] i.e., northern sites (Montepaldi and Sant Apollinare) characterized by lower mean annual temperatures around of 15°C. The observation data sets in Julian day (JDay) format included three main phenological phases: sprouting, blooming, and pit hardening. The number of phenological observations/records to establish a timeseries list vary for each phenological phase and cultivar, e.g., from 11 to 32 records (Table 2).

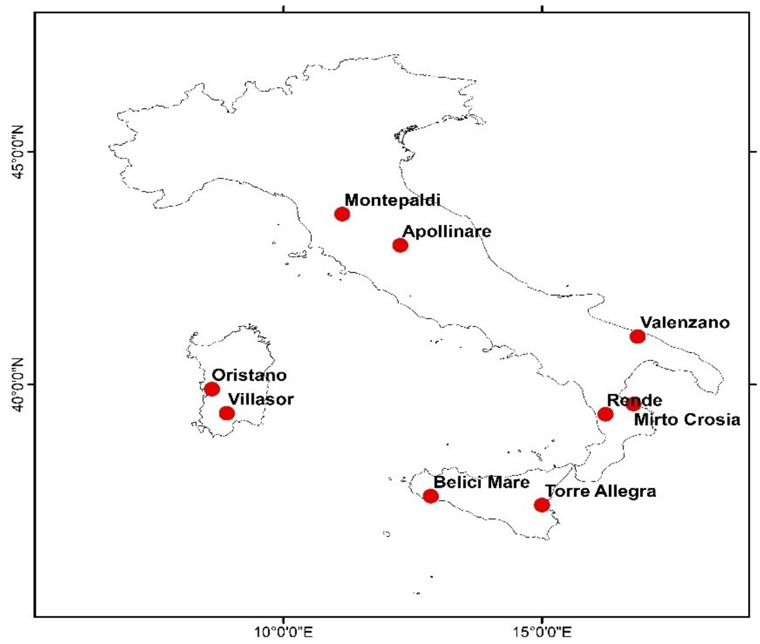


Figure 1. Experimental sites in Italy with olive phenological observations and associated dates.

Table 1. Mean observed dates (in JDay) of investigated phenological phases for selected early and mid-late budbreak olive cultivars.

Phenological phase Cultivars	Sprouting	Blooming	Pit Hardening
Carolea/early	96 (April 6)	138 (May 18)	186 (July 5)
Picholine/early	97 (April 7)	140 (May 20)	187 (July 6)
Frantoio/ mid-late	124 (May 4)	148 (May 28)	214 (Agust 2)
Moraiolo/mid-late	134 (May 14)	151 (May 31)	215 (Agust 3)

Table 2. Experimental sites in Italy, with available phenological monitoring and number of years of phenological observations for early (i.e. Carolea, Picholine) and mid-late (Frantoio, Moraoiolo) Olive cultivars.

Location/sites	Latitude (decimal degree)	Longitude (decimal degree)	Tm	cultivar	Years of data availability	Length-year
Montepaldi (Tuscany, FI)	43.66°	11.14°	15.8°C	CAROLEA	1997-1999	3
				PICHOLINE	1997-1999	3
				FRANTOIO	1997-1999	3
				MORAIOLO	1997-1999	3
Villasor (Sardinia, CA)	39.38°	8.91°	16.9°C	CAROLEA	1997-1999	3
				PICHOLINE	1997-1998	2
Oristano (Sardinia, OR)	39.9°	8.62°	17°C	CAROLEA	2014-2019	6
				FRANTOIO	2014-2020	7
Valenzano (Apulia, BA)	41.03°	16.85°	16.5°C	CAROLEA	1997-2000	4
				PICHOLINE	1997-2000	4
Torre Allegra (Sicily, CT)	37.41°	15.00°	16.6°C	CAROLEA	1997 and 1999	2
				PICHOLINE	1997 and 1999	2

Belice Mare (Sicily, TP)	37.60°	12.85°	18.84°C	CAROLEA	1997-1998	2
				PICHOLINE	1997-1998	2
Rende (Calabria, CS)	39.36°	16.23°	16.3°C	CAROLEA	1999	1
				PICHOLINE	1997 and 1999	2
Saint Apollinare (Perugia,PG)	43.04°	12.25°	14°C	CAROLEA	1997-1999	3
				PICHOLINE	1997-1999	3
				FRANTOIO	1997-1999	3
				MORAIOLO	1997-1999	3
Mirto Crosia (Cosenza, CS)	39.72°	16.75°	18.14°C	CAROLEA	2001-2003 ,2015,2018,2019 and 2021	8
				MORAIOLO	2001,2002,2003, 2019 and 2021	5
				FRANTOIO	2001,2002,2003, and 2019	4

For each year where dates of phenological observations are available, the daily maximum, minimum, and mean temperatures were retrieved. The temperature timeseries were gathered from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) [31], since weather stations were not available near all the experimental sites. Also, some of them provided fragmentary time series. Indeed, the use of reanalysis product facilitate parameterization and validation of model assessments more closely linked to climate model products used for regional projections. Meanwhile, a previous study [32] found that using ERA5 reanalysis temperature data series, olive phenological modeling provided fairly accurate phenological projections. This dataset is based on the hourly ECMWF ERA5 reanalysis data at 2 m above the surface level with a horizontal resolution of 0.1° and aggregated at a daily temporal scale.

Figure 2 shows the dispersion of daily mean temperature between all experimental sites and the selected years for which phenology was monitored. Temperature distribution confirmed the lowest and highest median ranks in February (6.7°C) and August (27.5°C), respectively. During winter and summer, the temperature percentiles (25th-75th and 5th -95th) are more stretched, which indicates higher temperature variability between the experimental sites in cold and warm seasons. Figure 2 also shows box plots of the distributions of phenological dates from the experimental sites for sprouting (A), blooming (B) and pit hardening (C).

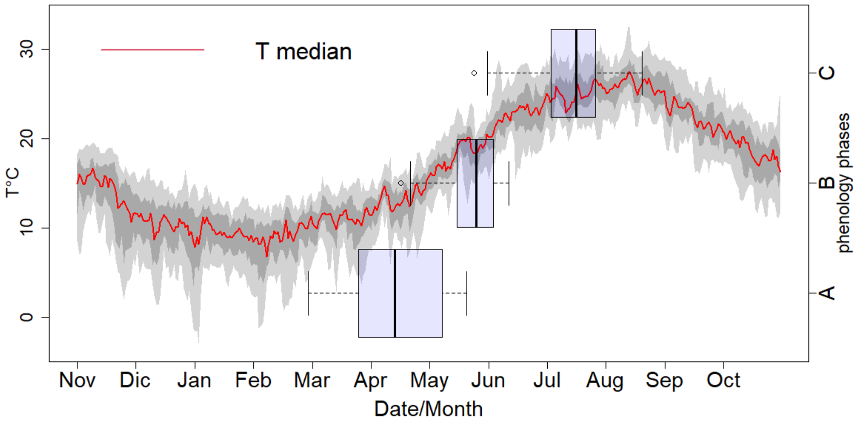


Figure 2. Mean and range of daily temperatures for those years with available observations from the experimental sites. Red line as median, dark grey shade is the 25th to 75th percentile, and light grey shade is the 5th to 95th percentile. Boxplots show the dispersion of the observed phenological dates (JDay) per phase, including Sprouting (A), Blooming (B), and Pit hardening (C) between all experimental sites, cultivars, and available years. The median line is in the center, the boxes and the whiskers extended from 25th to 75th percentile, and from 10th to 90th percentile, respectively.

2.2. Phenological models

Chill anti-chill days model (CAC model) or chilling and forcing model [18], is a sequential model, that accumulates chill days until the chill requirement is fulfilled and endo-dormancy over. Then the accumulation of anti-chill days starts during the eco-dormancy stage to overcome the quiescence. Indeed, dormancy stage divides into two phases, (1) the endo-dormancy in which plant reaches the peak of chilling accumulation, once meeting the chill need, (2) the eco-dormancy phase begins in which crown buds are in suspension and their growth are influenced by environmental factors, i.e. temperature/heating [33].

To calculate chill days (Cd) and anti-chill days (Ca), we implement a set of equations using the single triangle degree day computation method for different temperature conditions (Table 3). In the original reference (citation), there are 5 cases, to which we added one last more based on temperature data peculiarity (i.e. max daily temperature below 0°C). Indeed, to calculate chill and anti-chill days, this model includes two basic parameters: a temperature threshold (Tc) and chilling requirement (Cr). To find best values or optimize these parameters, we developed an error function in R computer language to employ the fitness function of the genetic algorithms (GA) package [34]. GA is implemented for stochastic optimization and to optimize the provided error function in fitness, binary, real-valued, and premutation representations, which are available in the package. This package needs some inputs: temperature timeseries (min, max, mean), phenological observation data, and pre-selected lower and upper bounds of the parameters (Tc:7 to 14, Cr: -80 to -200). We changed these bounds in optimization process to find the lowest possible errors. After making all inputs arranged in the code, we set the number of iterations to 1000.

Table 3. Chill days (Cd) and anti-chill days (Ca) equations, accounting for mean (Tm), maximum (Tx) and minimum (Tn) daily temperatures, and threshold temperatures (Tc).

Case	Temperature conditions	Chill days	Anti-chill days
1	$0 \leq Tc \leq Tn \leq Tx$	$Cd=0$	$Ca=Tm-Tc$
2	$0 \leq Tn \leq Tc < Tx$	$Cd=-[(Tm-Tn)-((Tx-Tc)^2/2(Tx-Tn))]$	$Ca=((Tx-Tc)^2/2(Tx-Tn))$
3	$0 \leq Tn \leq Tx \leq Tc$	$Cd=-(Tm-Tn)$	$Ca=0$
4	$Tn<0 \leq Tx \leq Tc$	$Cd=-[Tx^2/2(Tx-Tn)]$	$Ca=0$
5	$Tn<0<Tc<Tx$	$Cd=-(Tx^2/2(Tx-Tn))-((Tx-Tc)^2/2(Tx-Tn))$	$Ca=((Tx-Tc)^2/2(Tx-Tn))$
6	$Tn<Tx<0<Tc$	$Cd=0$	$Ca=0$

Since the CAC model was developed to estimate only the first phenological stage, end of dormancy, a combined method of chill anti-chill days model + growing degree days model (CAC_GDD model) was developed to include and estimate blooming and pit hardening stages. If the CAC model was used to assess two or three consecutive phases of a particular cultivar, different amounts of chill requirements per phase would be accounted for, which is per se against the crop physiology principals. Indeed, the starting dates to accumulate heating would be different spatially (point by point) and temporally (year by year) and this way we present a dynamic method for GDD accumulation. The main parameters that GDD model requires to calculate heat accumulation for subsequent phenological stages include temperature base (Tb), maximum temperature base (Tx.base), and heating requirement (Hr).

GDD equation is as following:

$$GDD = (Tx + Tn) / 2 - Tb$$

Where, Tx: daily maximum temperature, Tn: daily minimum temperature, and Tb: base temperature. Daily minimum and maximum temperatures should be set to Tb if less than Tb and set to an upper-temperature threshold (Tx.base) when greater than that threshold, because most plants cannot grow efficiently beyond these thresholds [23]. To run the calibration using this method, an error function was again developed based on the GDD model to set into GA function to optimize the parameters. The inputs including temperature timeseries (min, max), phenological observation data, sprouting observation data as the pervious phenological date, and pre-selected lower and upper bounds of the mentioned 3 parameters (e.g., Tb: 4 to 10, max Tb: 25 to 35, Hr:300 to 1400).

The PhenoFlex model is based on the structure of the dynamic model and the growing degree hours model (GDH) for chilling and heating accumulations [24]. This model fits the main parameters of both dynamic and GDH models to the phenological observation dates. A generalized simulated annealing algorithm (GSA) was applied to calibrate the model. The principal parameters to fit the PhenoFlex model are as follows:

yc - chilling requirement; critical value of y, which defines the end of chill accumulation

zc - heat requirement; critical value of z, which defines the end of heat accumulation

s1 - slope parameter that determines the transition from the chill accumulation to the heat accumulation period in PhenoFlex

Tu - optimal temperature of the Growing Degree Hours (GDH) model

E0 - time-independent activation energy of forming the Precursor to the Dormancy-Breaking Factor (PDBF)

E1 - time-independent activation energy of destroying the Precursor to the Dormancy-Breaking Factor (PDBF)

A0 - amplitude of the (hypothetical) process involved in forming the precursor to the dormancy-breaking factor in the Dynamic Model

A1 - amplitude of the (hypothetical) process involved in destroying the precursor to the dormancy-breaking factor (PDBF) in the Dynamic Model

Tf - transition temperature parameter of the sigmoidal function in the Dynamic Model, also involved in converting PDBF to Chill Portions

Tc - upper threshold in the GDH model

Tb - base temperature of the GDH model

slope - slope parameter of the sigmoidal function in the Dynamic Model, which determines what fraction of the PDBF is converted to a Chill Portions.

Thus, PhenoFlex package [35], needs several inputs to fit model parameters with observations including: observed dates of the desired phenological phase; a function called PhenoFlex_GDHwrapper, which uses heating model considering GDH concept; a season based timeseries of maximum and minimum temperatures in hourly scale corresponding to the observed phenology years; and finally, the default-based initial estimates, upper, and lower changeable bounds of the aforementioned 12 parameters.

2.3. Data preparation

Daily temperature data series from ERA5 repository were extracted as NetCDF over a spatial window (5-20°E and 35-47°N) at spatial resolution of 0.1 degree for the period 1985-2015, with an additional list of yearly vectors (November of previous year to October) for the coordinates of each experimental site. For the basic processing of temperature data series, the Climate Data Operator (CDO) was used. Observed phenological data series per cultivars and phenological stages were imported in R as vector lists. We made data frames for all weather and phenological observation data series to use in the model fitting functions.

2.4. Calibration and validation of phenological models

We developed error functions for CAC model and GDD model separately. CAC`s error function works based on the computation method of chill and anti-chill units. Still, the growing degree days error function was built on the GDD function in the pollen library [36] using the sprouting dates as the starting point. Both the developed error functions have been nested in the GA function to optimize the parameters. Providing all above-mentioned parameters and inputs with each of the models using the maximum number of iterations of the algorithm (i.e.1000), GA function found the best-fitted parameters with the lowest RMSE.

The PhenoFlex model fits data based on the generalized simulated annealing algorithm (GSA). To run the phenology fitter, we used weather timeseries seasonally arranged (November-October), and phenological observation data series. Daily maximum and minimum temperature timeseries were converted to the hourly timeseries, based on the idealized daily temperature curve presented by Linvill [37]. The number of iterations was set to 1000, with five search steps in the algorithm (as recommended in the default).

To validate the results, we performed a Leave-one-out cross-validation (LOOCV) which, is considered suitable when the number of observations is limited [38]. We coded and applied a LOOCV in R to calculate RMSE values from both approaches (CAC_GDD and PhenoFlex) per cultivars and phenological phases. LOOCV iteratively uses one observation to test the performance of the model (i.e., the RMSE) calibrated with all the remaining observations. Thus, the mean and standard deviation of these values are used to assess the strength and variability of the performance of each model.

After obtaining the calibration and cross-validation results for each phenological model, the observations versus estimated values were statistically tested using the root mean square errors (RMSE) and coefficient of correlation. Furthermore, Taylor diagram was plotted to show additional measures of model performances by phenological stage comparing the modeled to the observed values. Spatially the phenological dates were projected using CAC_GDD model, focusing on Italy. For the spatial implementation, a mapping code was developed in R, and then the optimized parameters were used along with the long-term mean daily temperature timeseries over 30 years (1985-2015) from ERA5 repository with a spatial resolution of 0.1 degrees over a window of 5-20°E and 35-47°N including Italy.

3. Results

RMSE values obtained from calibration of CAC_GDD model by phenological phases showed lowest errors for blooming (4 to 12 days) and then pit hardening (5 to 13 days) stages, while errors were about double (6 to 24 days) for the estimates of the sprouting stage. The PhenoFlex model found similarity with chill anti-chill days model in sprouting phase with errors ranging from 5 to 24 days. However, PhenoFlex produced larger errors in blooming stage (14 to 18 days) and pit hardening (13 to 42 days). Comparing models` functionality based on the cultivars, higher errors were generally observed for early budbreak representatives (i.e., Carolea and Picholine) regardless of the phenological models for all three phenological phases, ranging from 9 days for the CAC_GDD model in blooming phase to 42 days for the PhenoFlex model in pit hardening phase. In contrast estimated errors were lower for the mid-late budbreak cultivars, Frantoio and Moraiolo and range from 4 days for the CAC_GDD model in blooming phase to 23 days for the PhenoFlex model in pit hardening phase

Table 4. The Root Mean Square Error (RMSE, in Days) from calibration of the phenological models (CAC, CAC_GDD, and PhenoFlex) by phenological phases and cultivars.

Phase	Sprouting		Blooming		Pit hardening	
Olive cultivar	phenoFlex	CAC	phenoFlex	CAC_GDD	phenoFlex	CAC_GDD
Carolea	22	20	14	9	40	10
Picholine	24	24	14	12	42	13
Frantoio	9.5	9	18	4	13	5
Moraiolo	5	6	16	4	23	6

Note. CAC, chill anti-chill days model; CAC_GDD, chill anti-chill days and growing degree days model.

The principal model parameters to estimate phenological dates, were optimized by phenological phases, cultivars, and phenological models (Table 5). The use of the CAC model to estimate sprouting dates suggested that the best temperature thresholds (Tc) for early budbreak cultivars range from 8.2 to 9.5°C, whereas for mid-late budbreak cultivars, from 9.7 to 11.2°C. The optimized chill requirements (Cr) for early budbreak cultivars would range from -115 to -122 chill units, while for the mid-late representatives -133 to -137 chill units. The CAC_GDD model optimized three parameters, including base temperature (Tb), maximum base temperature (Tx), and heat requirement

(Hr), to estimate both blooming and pit hardening dates. The derived best Tb and Tx parameters, range from 4.5 to 7°C and 26.3 to 31.5°C, respectively, and vary according to phases and cultivars. Optimized Hr parameter present higher values for early than mid-late budbreak cultivars in the blooming phase (437 - 568 GDD° versus 370 - 388 GDD). Using the same calibrated Tb and Tx of the blooming stage, we tried to optimize Hr for the pit hardening phase, but then mid-late cultivars obtained higher heat requirements (1275-1315 GDD versus 1003-1073 GDD).

Table 5. Optimized parameters for the chill anti-chill and growing degree-days phenological models, by phenological phase and cultivar, using the genetic algorithm method.

Phenological phase	Cultivar	CAC		CAC_GDD		
		Tc	Cr	Tb	Tx	Hr
Sprouting	Carolea	9.5	-115	-	-	-
	Picholine	8.2	-122	-	-	-
	Moraiolo	11.2	-133	-	-	-
	Frantoio	9.7	-137	-	-	-
Blooming	Carolea	-	-	5.9	31.5	437
	Picholine	-	-	7	28.3	568
	Moraiolo	-	-	4.5	29.5	370
	Frantoio	-	-	5.3	26.3	388
Pit hardening	Carolea	-	-	5.9	31.5	1074
	Picholine	-	-	7	28.3	1003
	Moraiolo	-	-	4.5	29.5	1315
	Frantoio	-	-	5.3	26.3	1275

Note. CAC, chill anti-chill days model; CAC_GDD, chill anti-chill days and growing degree days model; Tb, estimated base temperature; Tx, estimated max temperature; Hr, estimated heating requirement; Tc, estimated temperature threshold; Cr, estimated chilling requirement.

The results of the leave-one-out-cross-validation (Table 6) verifies the model calibration. As expected, this validation shows similar results for CAC and PhenoFlex models in the sprouting phase particularly for the late cultivars by indicating mean RMSEs ranging from 5.74-11 and 5.65-12.48 days respectively. However, the differences between two phenological approaches become higher for blooming (CAD_GDD: 3.47-12.23 days and phenoFlex: 29.9-36.4 days) and extremely ramped up in pit hardening phase (CAD_GDD: 4.5-14 days and phenoFlex: >40 days). In regards to the standard deviation values of obtained RMSEs through cross-validation, the phenoFlex model indicates the highest variability from 0.5 to 5.87 versus CAC_GDD with a range of 0.4-1.4.

Table 6. The results obtained from the cross-validation analysis (LOOCV) of two phenological models per phenological phases and olive cultivars. Including mean and standard deviation values (in days) and the number of sample/observations.

Phase		Sprouting		Blooming		Pit hardening	
Olive cultivar		phenoFlex	CAC	phenoFlex	CAC_GDD	phenoFlex	CAC_GDD
Carolea	Mean	22.4	20.43	29.9	8.82	>40	9.8
	Stdv.	1.5	0.87	0.5	0.61	3	1

	Sample number	22		21		13	
Picholine	Mean	26.8	24.94	36.4	12.23	>40	14
	Stdv.	1.1	1.3	4.2	0.83	1.9	0.97
	Sample number	16		16		14	
Frantoio	Mean	12.48	11	31	6	>40	4.5
	Stdv.	1.4	1.5	2.2	0.4	3.35	0.5
	Sample number	12		12		6	
Moraiolo	Mean	5.65	5.74	34	3.47	>40	5.6
	Stdv.	1.3	1.16	4.5	1	3.27	0.72
	Sample number	6		6		6	

Using the optimized parameters and temperature time series, modelled dates and phenological phases were determined for different cultivars. Appendix 1 shows the accumulation of chill and anti-chill units for the sprouting stage, and GDD accumulation for both the blooming and pit hardening stages as an example for Carolea cultivar along years with available phenological data a for different sites. After fulfillment of the chill requirement (e.g., -115 chill unit), anti-chill units accumulate until zero (i.e., balance out chill unit), for which point in time sprouting occurs. For the blooming and pit hardening dates GDD units accumulate until heat requirements are fulfilled (e.g., 437 GDD for blooming and 1074 GDD for pit hardening).

The estimated dates for all phenological phases and cultivars were compared to observations. The CAC_GDD model values showed correlation coefficients with significant level (P-value<0.05) for the three phenological phases (0.55, 0.71, 0.80, respectively), and higher than for the bloom and pit hardening phases estimated from the PhenoFlex model (0.53, 0.28, 0.49, respectively by phenological phase) (Appendix 2).

The estimated phenological dates considering both models exhibited the lowest variability in the blooming phase during spring season, coping with a narrower distribution of temperature and observed phenological dates, as shown in figure 2. For both models, estimated sprouting dates have distributions more similar to the observations, or higher predictability, than for blooming or pit hardening (Figure 2 and 3): median values of sprouting stage (observation= 12 Apr., CAC= 15 Apr. and Flex=20 Apr.) versus median values of blooming stage (observation=25 May., CAC_GDD=29 May, Flex=15 May), and median values of pit hardening stage (observation=15 Jul., CAC_GDD=17 Jul., Flex=10 Jun). Using a normalized Taylor diagram, the applied phenological models` performances were compared through standard deviation, RMSE, and correlation coefficient together (Figure 4). For the experimental set and data available in our study, CAC_GDD models showed higher consistency with observed phenological dates than the PhenoFlex model for blooming and, in particular, for pit hardening phases. In particular, CAC_GDD shows higher correlation coefficients compared to PhenoFlex model (i.e., blooming: 0.7 vs. 0.28, pit hardening: 0.8 vs. 0.49), lower RMSE (i.e. blooming: 0.8 vs 1, pit hardening: 0.6 vs. 1.3) and standard deviations closer to the observations (i.e., blooming: 1 vs. 0.5, pit hardening: 0.9 vs. 1.5). For the sprouting phase, both models indicated similar behavior and predictability skills (r=0.54, Sd=0.4, and RMSE=0.9).

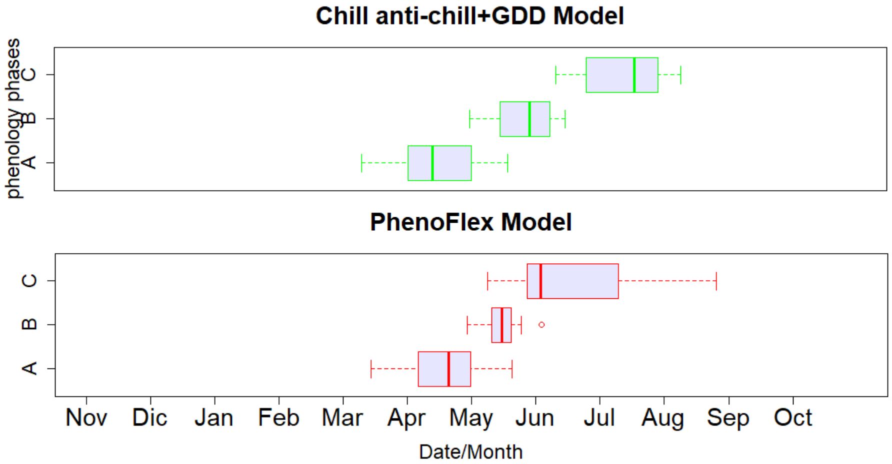


Figure 3. Boxplots show distributions of phenological dates estimated by CAC_ GDD model (top plot) and PhenoFlex model (bottom plot) for all olive cultivars and phenological stages, including A) Sprouting, B) Blooming, and C) Pit hardening.

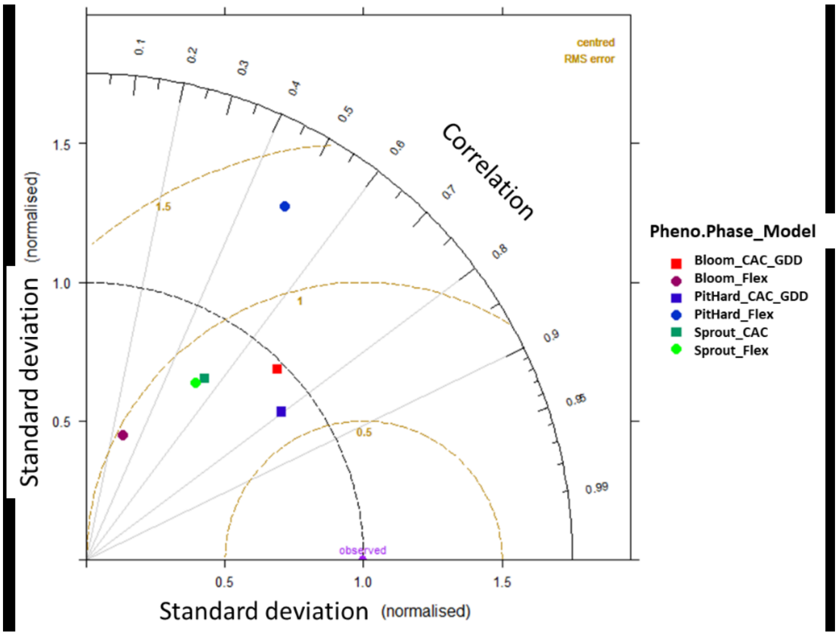


Figure 4. Normalized Taylor diagram shows CAC_GDD and PhenoFlex phenological models` performances to estimate the selected olive cultivars phenological dates.

To verify the model`s functionality with spatial distribution, we implemented the CAC_GDD model over Italy using ERA5 reanalyzes data for the 1985-2015 period, which was evaluated as provviding better performance under the available training conditions. Spatial patterns identify clearly later estimated phenological development dates over colder climate, i.e., higher latitudes and mountainous regions and earlier estimated dates over southern regions and low lands for any phenological phase or cultivar type. For sprouting, blooming, and pit hardening phases the estimated dates over highlands (i.e., mountainous areas) and northern regions showed JDay values >130, >160, and >210, respectively. Whereas, the aforementioned phenological dates were the latest estimates in southern regions and low lands, e.g., around coastal areas. Comparing the estimated dates of late and early budbreak cultivars (diff=late - early) over the study area, we mostly found differences greater than 15 days for sprouting and pit hardening stages. Still, a smaller difference was observed for the blooming stage, as the late cultivars reported general delays smaller than 15 days comapred to early cultivars.

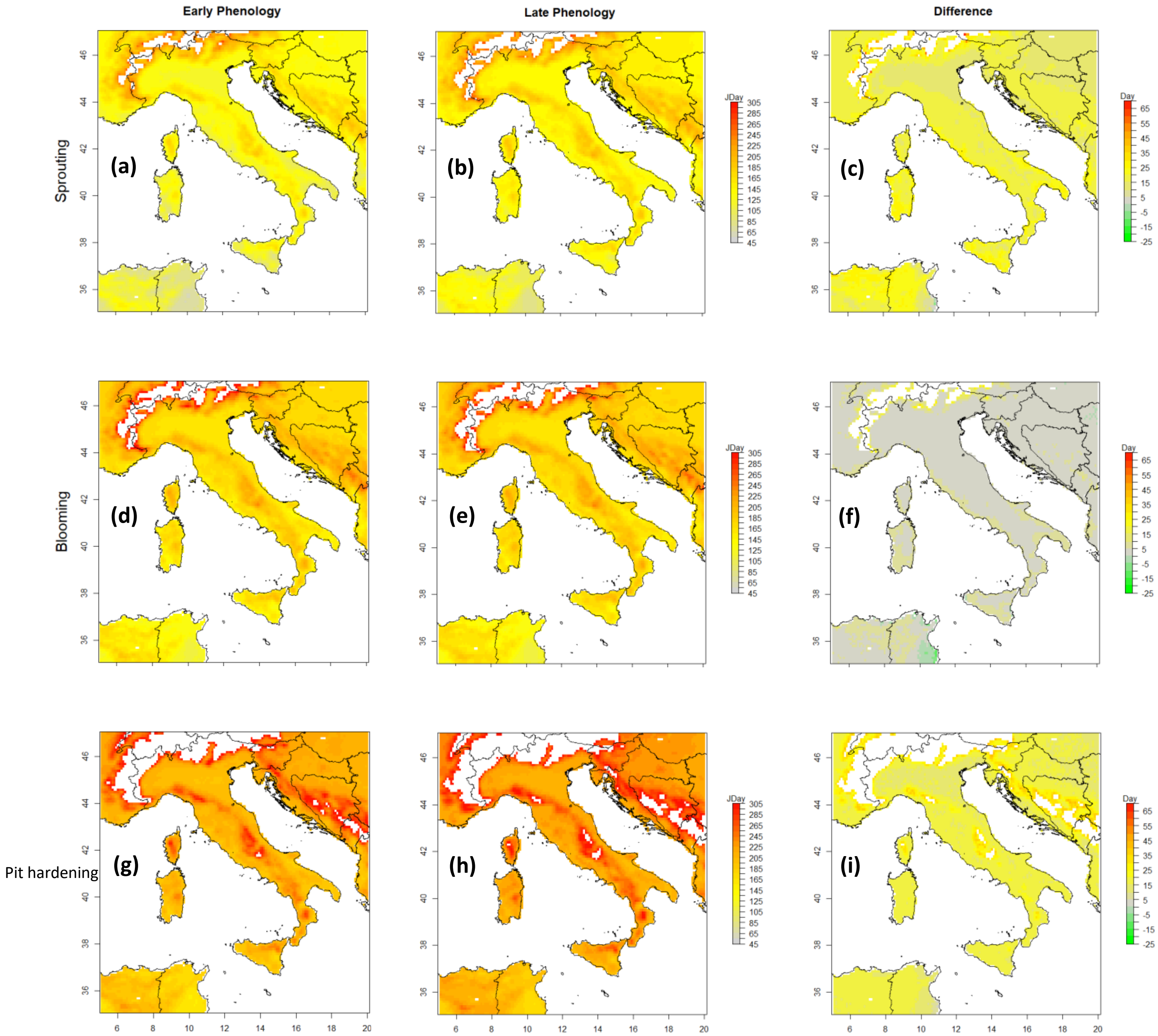


Figure 5. Spatial implementing CAC_GDD model to estimate olive phenological phases/dates (in JDays) including Sprouting (a, b, c), Blooming (d,e,f), and Pit hardening (g,h,i) for early (a,d,g) and late (b,e,h) budbreak cultivars over Italy. The right column (c,f,i) shows the spatial difference between late and early cultivars (diff=late - early) for estimating phenological dates. Calculations were done with long-term daily mean temperature timeseries from ERA5 over a 30-year of historic period (1985-2015).

4. Discussion

The present study compared two approaches to derive and evaluate estimates of olive phenological phases by applying chilling and forcing-based models, which could be inferred from scattered monitoring over a large Mediterranean environment. Our results suggested that generalized projections of olive phenology might be possible under the available modeling setup, especially with the CAC_GDD model, which can support strategic management of olive cultivation and anticipation of long-term changes (e.g., under climate change projections) for more structural adaptation at regional scale.

Overall, the CAC_GDD approach, which is based on both the single triangle method [18] and heat accumulation [23], provided more feasible results under our scattered experimental setup than PhenoFlex model [24], which is based on the dynamic model [39] and on Growing-Degree-Hours Model [40,41]. CAC_GDD approach requires fewer parameters for calibration while avoiding over-fitting, especially with inadequate data. The present approach uses climate daily data preventing the implementation of artifacts to transform into climate hourly data. In addition, CAC_GDD reported fewer model projection failures under the wide climatic range in a large-scale spatial implementation, and the approach required less computational effort and processing time, which might facilitate its implementation on a large scale for management tools. PhenoFlex provides a more complex process-based representation considering many parameters, but also requires more processing time and suffering to a certain extent model assessment failure in a comprehensive spatial implementation. PhenoFlex is an open-source model with a flexible adaptation to various species and cultivars based on a strong biological and experimental structure for dormancy dynamics. This integrated model may easily outperform other models to reconstruct complex phenological related dynamics at local scale and especially in relation to dormancy [24]. However, such a detailed work-flow, with large number of parameters and degrees of freedom may have undermined the more articulated and accurate representation of phenological phases by PhenoFlex given the more limited and scattered number of observations available, which is unfortunately often common status to many tree crops in the Mediterranean areas and thereafter penalize feasible projections at regional scale.

The RMSE values indicate a better performance of the CAC_GDD model for the blooming stage of the mid-late budbreak cultivars, while PhenoFlex performed its best with sprouting stage of the mid-late cultivars. Both models performed better for the mid-late budbreak cultivars than the early ones, regardless of the phenological stages. These findings suggest us that the cultivars differ for their sensitivity to weather conditions, with mid-late cultivar being more sensitive. In the framework of climate changes and increasing uncertainties of weather events, the possibility to select between cultivars characterized by different sensitivity degree to seasonal weather might be a useful decision-making tool for producers. The best performance of the phenological model was found for blooming stage of the mid-late budbreak representative cultivars through our approach with an error of around 4 days. The reason behind this finding likely is that mid-late cultivars show similar behavior or parameters, in threshold temperatures (Tc, Tb, and Tx) and Hr. In contrast, Carolea and Picholine, selected as early budbreak cultivars show different discrepancies between each other. These findings highlight the importance to consider the varietal factor to perform reliable and reproducible phenological models. Moreover, it is worth noting that Moraiolo and Frantoio, as mid-late cultivars, are native to the same area (Central Italy), while this is different in the case of Carolea (South Italy) and Picholine (France) [42, 43]. These findings encourage us to formulate the following hypotheses: (1) Cultivars from similar historical growing areas with similar environmental conditions have developed common adaptive capacities and features; (2) Environments characterized by several limiting factors for olive tree species' growth related to both extreme temperature and short-term periods proper to achieve some critical phenological phases (e.g., blooming), might have selected cultivars with high sensitivity to temperature changes, thus cultivars that allow better predictions. However, such hypotheses are based on limited data from just four cultivars; the enlargement of the study to other cultivars is needed to verify them and investigate possible common varietal patterns.

The CAC_GDD model calibrated for each distinct cultivar resulted in optimal temperature thresholds that align with their early and mid-late phenological behavior. The optimized base temperature (Tc) , and the corresponding chilling requirements (Cr) were comparatively lower for early cultivars as opposed to their counterparts. The Tc and Cr values derived from the models underscore substantial distinctions among the cultivars: a difference about 3 °C (e.g., Tc = 8.2 °C for Picholine compared to Tc = 11.2 °C for Moraiolo) and approximately 20 chill days difference (e.g., Cr = -115 for Carolea compared to Cr = -137 for Frantoio). Given the projections of escalating temperatures in the future climate scenarios, particularly impacting the winter seasons, coupled with the fact that distinct cultivars exhibit specific threshold temperatures and chill prerequisites, challenges pertaining to the productivity of traditional cultivars and their corresponding geographical domains will be plausible. Notably, a significant number of these well-established cultivars have evolved over centuries through selective breeding and adaptation to specific microclimates [43]. Furthermore, the determination of such critical values will assume even greater significance in aiding producers` decisions regarding the most appropriate cultivars in response to anticipated shifts in climatic conditions. Analogous observations could potentially extend to threshold temperature parameters (Tb and Tx) for heat accumulation, which in this context could rise concerns of risks such as late frost events or heatwaves coinciding with critical flowering phases.

Our obtained RMSE values are in accordance with some previous publications, e.g., [27,44,13,8], which showed errors of modeling for blooming/flowering stage for olives in a range from 3 to 8 days in different areas.

The results obtained by Cesaraccio et al., [18], to estimate budbreak/sprouting stage using chill anti-chill days model for olive crop in Oristano (in Sardinia) showed an error about 8 days, which can approximately confirm (of course depending on the cultivars) our obtained RMSEs for sprouting stage, that ranged from 6 to 24 days, as we found out lower errors (6-9 days) for mid-late, and higher errors (20-24 days) for early budbreak cultivars.

Overall, the cross-validation confirmed validity of calibration results with very less differences for CAC_GDD model, than phenoFlex which showed extremely higher RMSEs particularly over the pit hardening phase. Large difference might be due to the manner, phenoFlex accumulates heating and chilling starting from November first to predict pit hardening dates in summer. This is a longer prediction, using longer time spans where the model could be particularly prone to errors. Notably, the phenoFlex is a model qualified basically to project only a single phenological phase, e.g., flowering [24], so that has not yet framed to work over some successive phases. Unlike, CAC_GDD accumulates heating to predict the pit hardening stage initiating from the already estimated sprouting dates and using the new parametrizations based on the growing degree days model, and accordingly avoids such higher errors with consecutive phenological phases.

Comparing the functionality of the abovementioned approaches in terms of prediction of the three phenological phases, we found better modeling performance of the CAC_GDD particularly for two phases, including pit hardening and blooming, while for sprouting both PhenoFlex and CAC_GDD models showed pretty similar situation with relatively poor modeling performance. We could then refer mainly to the blooming phase to assess more accurately results performances. Most of the previous phenology studies projected and focused on olive's flowering/blooming stage as reported in the following examples. Findings of de Melo-Abreu et al. [8], using a thermal time method to estimate flowering dates showed a range of RMSE from about 2-5 days and a margin error of 0.57-0.74, indicating acceptable model performance. Rojo et al. [7], predicted olive pollination date (which would be considered the representative of the flowering stage) in Toledo (Spain), Lecce (Italy), and Chaal (Tunisia) using chilling and heating accumulations; the results displayed a mean absolute error about 4.5 days in average, which confirmed the accurate prediction of the flowering stage. Moriondo et al. [22], using the Unichill model demonstrated a good simulation of flowering with RMSEs around 3 and 3.8 days in calibration and validation, respectively. Although the previous studies indicated lower errors, they were instead developed and established over separate single sites. So those model assessments are not qualified to project phenological phases over a large area for a spatial analysis, while our approach tried to consider an extensive range of environmental and bio-physiological conditions combining observations from eight experimental sites in Italy.

Optimization of the principal parameters to estimate sprouting dates suggested higher Tc (average ~10°C) and Cr (average ~-135 chill units) values for the mid-late budbreak cultivars than for the early representatives (Tc: average ~8.8°C, and Cr: average ~-118 chill units). On average, we found differences of 1.2°C of Tc and -17 chill units of Cr. Indeed, temperature thresholds and chill requirements optimized by the chill anti-chill days model vary by cultivar type. Similar results, particularly considering our findings for mid-late olive cultivars, have been reported by Orlandi et al., [45] for threshold temperature estimation (6-12°C) and by Cesaraccio et al., [18] for threshold temperature (10.6 °C) and chill requirement (-138 chill units). The higher Tc and Cr values of mid-late cultivars suggest an adaptation feature to avoid early spring frosts, consistent with the typical environmental conditions of Frantoio and Moraiolo' areas of origin [30].

Using the CAC_GDD model, we optimized the principal parameters for the blooming and pit hardening stages. The observed Tb (average 6.5°C) and Tx (average 29.9°C) values for early budbreak cultivars were higher than those estimated for mid-late representatives (Tb: average 4.9°C, and Tx: average 27.9°C) with a difference around 1.6°C of Tb and 2°C of Tx. Heat requirements optimized to represent the blooming stage for early cultivars were about 128 GDD higher than for mid-late ones (means 502 versus 379 GDD). As GDD accumulation starts from sprouting, mid-late budbreak cultivars with delayed sprouting dates accumulate heating later than early ones and need less GDD till blooming. On the other hand, for the pit hardening stage, early budbreak representatives showed lower heat requirements than the mid-late sprouting cultivars (i.e., means 1038 versus 1295 GDD). Therefore, the pit hardening event occurs also earlier for them. Previous studies about heat requirements, e.g., [10,8] confirmed our results, indicating a range of 180-560 GDD of heat requirement for flowering of olive cultivars and Tb values from 5 to 12.5°C. Using a machine learning model, Oses et al. [46], found base temperatures below 10°C, similar to our optimized Tb values, to predict olive phenology that results in better model performance. Notably, the mentioned threshold values vary with the experimental sites' climatic characteristics and the cultivar`s type. Warmer regions and early budbreak cultivars can have a higher base temperature. In contrast, cooler regions and late budbreak cultivars, e.g., high lands and higher latitudes or late budbreak cultivars can have lower base temperature. Consequently, differences in the estimated principal parameters can depend on bio-geographical characteristics [10]. Considering the optimized Tb values, mid-late olive cultivars seem more resistant under cold climates. Bio-physiologically, temperature changes could disturb olive`s phenological process, quality, and yield, as low temperatures could cause bark cracking and death of thick branches. On the other hand, high temperatures shrink the fruit body and its pulp [47].

Because of lower temperature variability during the blooming season between the experimental sites in Italy, the observed and modeled dates were similar, with a mean range of about 21 days between the 25th and 75th percentiles. Therefore, increasing temperature variability during sprouting and pit hardening phases (cold and warm seasons respectively), the corresponding range of phenological dates was stretched with a mean range of about 35 days for both sprouting, and pit hardening between the 25th and 75th percentiles. di Paola et al. [27] found similar consistency between temperature and olive phenological date distributions in Italy. Despite higher temperature variability in the warm season, the CAC_GDD model demonstrated the best performance for the pit hardening phase regardless of the cultivar type. Due to limited previous studies on phenological phases other than blooming, these findings may be particularly relevant to improve estimate of pit hardening phase, which is applicable for different olive cultivars or other species. Pit hardening is considered a critical phase of olive fruit development that usually corresponds to the end of the first phase of fruit growth, which is characterized by intense cell division and sink of assimilates in endocarp tissues [48]. It indicates the beginning of oil accumulation in the fruit [49]. Forecasting pit hardening date is a useful tool for irrigation management [50], application of phytosanitary products [51], further estimation of the peak of oil accumulation, and determination of the optimal harvest period [49].

The CAC_GDD`s implementation and projections were also verified spatially over Italy. All three phenological phases showed the earliest estimated dates over warm climates including southern regions and low lands (e.g., around coastal areas). However, the late phenological dates were estimated over mountainous areas (e.g., the Alps and Apennine mountains). This result demonstrates the relationship between spatial changes in temperature and the fulfillment of different cultivars' heat requirements and, consequently, olive phenological dates' timing [7]. In summary, in a warmer climate, forcing units or growing degree days accumulate faster to reach the required threshold than in cold areas. However chilling requirement can be met also earlier in warm climate if daily temperatures do not exceed Tc during endo-dormancy. In some hyper-cold regions (i.e., in the Alps), the model failed to accurate estimate of phenological dates. This result is likely due to the lower temperatures, i.e., below the temperature thresholds, that prevented the model from accumulating adequate chilling or heating to fulfil the defined requirements. Consequently, no phenological dates were obtained.

Spatial results confirmed that the model had smaller differences between blooming dates of early and late cultivars than for both sprouting and pit hardening phases over most of the study area, i.e. less than 15 versus more than 15 days. This projection is likely due to the optimized parameters of CAC_GDD varietal model. Indeed, in warmer climates, sprouting advances and differences in phenological dates between the two varietal types are smaller. Moreover, earlier sprouting dates occurring during the year with lower probability of days with temperatures exceeding Tx.base thresholds and lower Hr requirements could advance blooming dates for the mid-late cultivars. Relative to projected climate change, a marked advance in blooming date caused by warming is beneficial since it might avoid production losses due to flower damage caused by heat waves [52] particularly in a warm climate. However, the preliminary nature of these spatial projections would suggest a new investigation with more data from more cultivars in olive-growing regions (e.g., North Africa) to improve parametrization and validation.

5. Conclusions

Two approaches applying chilling and forcing-based models were compared to determine the performance for predicting olive phenology. This investigation presented a combined method (CAC_GDD) to estimate olive phenological phases and compared results using a more complex and data demanding model (PhenoFlex). Under our experimental conditions, over a large Mediterranean environment with scarce and scattered observations, the CAC_GDD model, with lower parameter demand and simple approach demonstrated more reliable performance than the PhenoFlex model to generalize projections at regional scale in at least two phenological phases, i.e., the blooming and pit hardening stages. However, in terms of cultivar type both models performed relatively better for the mid-late than the early budbreak cultivar.

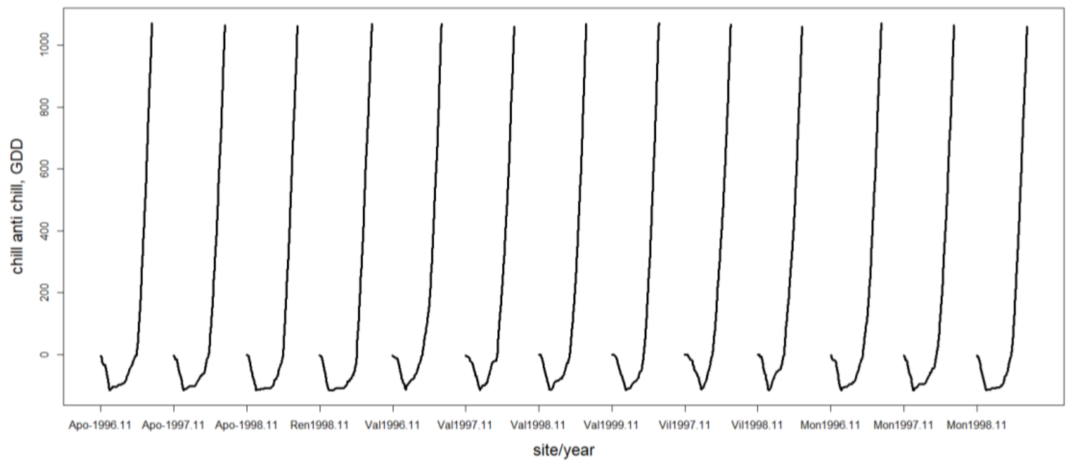
The CAC_GDD showed some advantages for modeling the phenological phases. For example, the CAC_CDD (1) requires less parameterization, (2) the use of daily temperature timeseries with no artifacts, i.e., no transformation into hourly data, (3) less computation effort, (4) faster processing, and (5) reduced model projection failures in a spatial implementation.

Considering bio-geographical characteristics that determine temperature thresholds, i.e., heat and chill needs for each species, the optimized principal parameters through the present approach showed clear differences by olive cultivar types. The mid-late budbreak representatives were more adaptable than early cultivars to the cold climate when considered sprouting. Still, they could also adapt to warmer climates by anticipating earlier blooming dates.

For the model calibration and validation, the present investigation considered a more comprehensive range of environmental and bio-physiological conditions combining phenological observations from nine experimental sites. The CAC_GDD model could project phenological phases over a large area demonstrating the olive phenology spatial pattern. The model only failed to accurately project phenological dates over very high lands (i.e., in the Alps mountain region). Indeed, the model failures occurred only when daily maximum and minimum temperatures were beyond the thresholds. These conditions prevent the model from accumulating sufficient chilling and heating units to meet the requirements. From a spatial point of view, we found smaller difference in phenological dates between early and mid-late cultivars for the blooming phase over most parts of the study area revealing higher phenological plasticity of the mid-late cultivars.

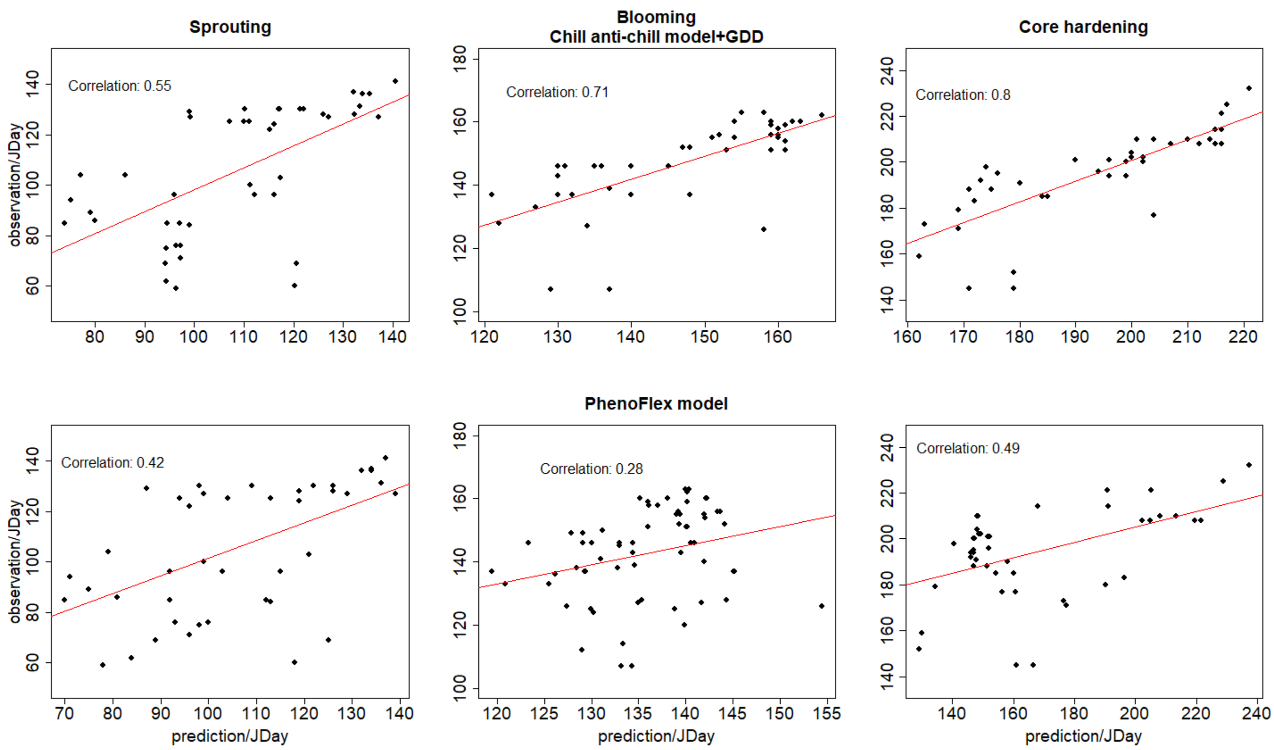
Our approach will support olive producer's response to future climate change through resilient strategic management of olive cultivation, varietal choice, cultural practices, and mitigating climate-induced risks based on the reliable projections of different phenological dates. As the future research vision, the CAC_GDD model can support scaling up spatially to a large region, e.g. Euro-Mediterranean, to display the environmental differences in phenological projections under future climate change scenarios. Nevertheless, collecting more phenological observations of additional olive cultivars and from other olive-growing regions would support our approach to producing more integrated and comprehensive validation results and promote our model`s performance.

Appendix A



Appendix A1. Accumulation of chill anti-chill and GDD units (T°C) to estimate the dates of Sprouting, Blooming and Pit hardening phenological phases of an olive cultivar (e.g., Carolea) for some experimental sites and years with available phenological observation dates. Accumulation initiates from first November of the previous year.

Appendix B



Appendix B1. Correlation between observed and estimated dates of the phenological phases including Sprouting (left column), Blooming (center column), and Pit hardening (right column) per phenology models including chill anti chill model + GDD (CAC_GDD model) (top row) and PhenoFlex model (bottom row). Each phenological phase has different number of cases regarding for the experimental sites and years with phenological observation data availability. Significance of correlation for all combinations showed P-value<0.05.

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CHAPTER 2

Title:

"The Phenological Phases of Early and Mid-late Budbreak Olive Cultivars in a Changing Future Climate over the Euro-Mediterranean Region"

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Abstract

Future climate changes will likely alter the length and timing of phenological phases of olive crop. The timing and management of agronomic practices (planting, irrigation, fertilization, crop protection, harvesting, etc.) are based on phenological phases and plant development. Consequently, accurate phenological assessments are essential to define climate risks and guide optimal management apt to mitigate climate change effects on olive development. This research highlights future changes in olive phenological phases (i.e., sprouting, blooming, and pit hardening) over the Euro-Mediterranean region for both early and mid-late budbreak cultivars. We apply a Chill, Anti-Chill, and Growing Degree Days combined model to project the timing of phenological phases based on an ensemble of high-resolution climate projections at 0.11° from EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment) for historical (1976-2005) and future (2036-2065) periods under three emission scenarios (RCP2.6, RCP4.5, and RCP8.5). The results showed that more than 75% of the study area would experience significant earlier phenological development for olive by 2050, with 5 to 10 days earlier relative advancement for RCP8.5 compared to other RCPs. We observed greater olive phenological advances (i.e.,>20 days) within the colder/northern areas, indicating potential climate suitability, while the southern Mediterranean is still facing high potential phenological disturbance (advances of 10-25 days). Future differences in phenological earliness between the cultivars (5-15 days) demonstrate the vulnerability of the early cultivar in the Mediterranean despite consistent thermal suitability for the mid-late cultivar in northern Europe and colder zones. Good agreement between different climate model projections with analysis of variance confirmed our findings' accuracy levels over the study area.

Keywords

Olive phenology, Phenological modelling, Climate changes, Olive cultivars, the Euro-Mediterranean region, EURO-CORDEX repository.

1. Introduction

Olive cultivation boasts a rich history within the Mediterranean basin, where the climate aligns well with olive tree`s growth (Orlandi et al., 2013; Moriondo et al., 2015), embracing approximately 80% of the olive growing area in the globe (Fig. 1). A few countries within the Mediterranean basin (i.e., Spain, Italy, Greece, Turkey, Tunisia, and Portugal) produce more than 95% worldwide olive oil (Deiana et al., 2019). Climate change projections, however suggest extreme impacts on olive production in the Mediterranean region due to accelerated warming and drying conditions (MedECC, 2020).

There is a high risk that the climate change impacts on olive trees would threaten yield quality and quantity (Fraga et al., 2021; Medda et al., 2022). In particular, changing climate conditions might influence olive`s physiological processes (Brito et al., 2019; Petridis et al., 2012) and thus phenological timing (Villalobos et al., 2006; Fraga et al., 2019; Galán et al., 2005). For instance, previous studies showed rising temperatures would affect the timing of olive`s phenological phases, i.e., lengthening the growing season (Pérez-López et al., 2008), and particularly altering the flowering stage (Orlandi et al., 2010; Avolio et al., 2012; Aguilera et al., 2014; Osborne et al., 2000). Olive farming holds significant economic value in numerous Mediterranean countries. Ponti et al. (2014), estimated that smaller private olive farms, and the associated businesses, are likely to face economic losses due to climate change mainly in Italy and Greece, during the upcoming decades.

Earlier studies illustrate climate change impacts on olive from different aspects. For instance, Fraga et al., (2019), used an ensemble of climate models, future scenarios, and dynamic crop models, to calculate agro-climatic indicators over southern Europe, linking their variations to olive productivity changes. Poleward shift in olive growing areas as projected in the future because of increasing temperature and improved climate suitability in northern regions (Moriondo et al., 2013; Tanasijevic et al., 2014). A study developed by Rodríguez Sousa, et al., (2020) estimated a range of temperature increase from 0.8 to 2.3°C along with an annual rainfall decrease of around 200 mm over the Mediterranean region for 2050, which displace olive growing areas towards the more humid and cooler regions (e.g., northern regions and highlands).

Actually, olive is a resistant tree crop to grow in rough environments (Fernández, 2014; Sanzani et al., 2012) which, indicate the fact of its higher environmental adaptability. Some studies projected northerly shifts for olive orchards under future warming conditions (De Melo-Abreu et al., 2004; Ramos et al.,2018; Therios, 2009) that could be interpreted to a remarkable thermal adaptability in line with its phenological plasticity (De Lisle et al, 2021). Indeed, higher/lower heating requirements across genotypes to meet growth stages in cooler/warmer areas, respectively, suggest the thermal adaptation capacity of olive trees. Varying biological responses across olive genotypes can be potentially considered for adaptation goals under future changing climate (Aguilera et al., 2014).

In relation to phenological implications, only a few large-scale studies were conducted (Aguilera et al., 2014; Garcia-Mozo et al. 2008; Mariani et al., 2013), and they focused solely on the olive flowering stage. Some studies (e.g., Di Paola et al., 2021) developed a phenological model to predict many phenological phases of olive using observations from different experimental sites to calibrate a statistical inference model. While some resulted in good model performance, the results were not implemented spatially to study future climate model projections over a large area.

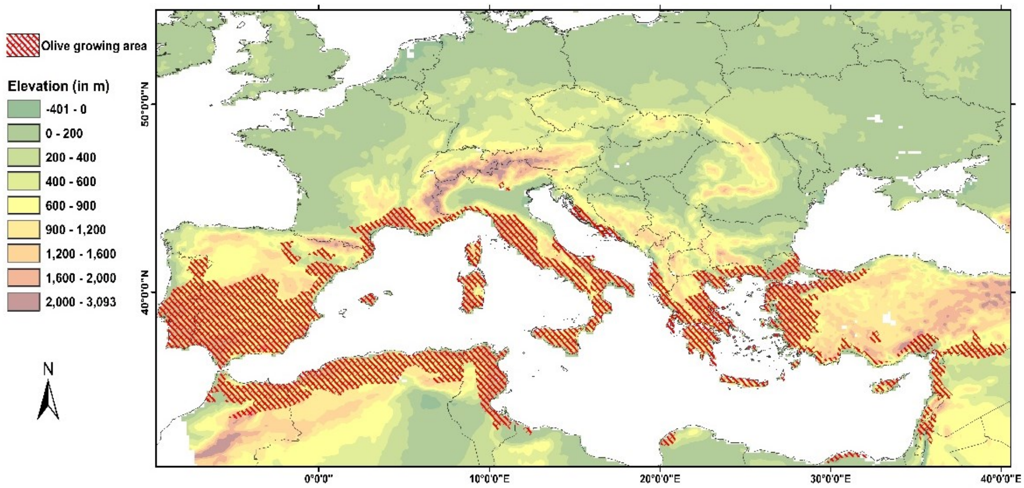


FIGURE 1. The topographic map of the study area including Euro-Mediterranean region and olive growing zones over the Mediterranean basin (crossed red lines) (land monitoring services, Copernicus (CLC 2018), and Rodríguez Sousa *et al.* 2020).

Earlier work from Moriondo and Bindi (2007) investigated the impact of increasing temperature on the phenology of Mediterranean crops, including olive trees, by using general and regional circulation models on a broad spatial scale. The results pointed out both changes in growing season length and anticipated crop development, which may increase the risk of extreme climate events during some phenological phases, i.e., budbreak and anthesis. de Melo-Abreu et al., (2004) used a combination of temperature-based phenological models and climate projections to predict that olive trees near Cordoba, Spain, would experience earlier flowering phases, from 5.2 to 10 days, in response to applied warming scenarios and models. While some studies showed more remarkable phenological advancement, for instance, another study in southern Spain used a thermal model (Galan et al., 2005) and demonstrated that global warming projected by regional climate models would result in an advancement of about 1-3 weeks of olive flowering within the mid-elevation inland regions of the study area. A similar study predicted around 10-20 days of potential advance in the flowering phase of olive crops in Southern Italy using projected growing degree days accumulation (Orlandi et al., 2013). Based on a study from Chmielewski and Rotzer (2001) that considers atmospheric circulations, which result from the positive phase of the North Atlantic Oscillation Index (NAO-index) over Europe in late winter and early spring, a plant phenological advancement of about 5-7 days per 1°C temperature rise was projected. The change was attributed to dominant westerly winds and higher temperatures caused by the NAO index.

As shown in the aforementioned examples, warming can alter the timing of olive phenology, which leads to consequential effects on plant development and production. In addition to causing earliness of olive flowering, an investigation by Benloche-González et al. (2018) confirmed that a 4°C temperature increase makes the flowering stage longer and leads to abortion of ovary and reduced final yield. Insufficient chilling units during dormancy prevent olive trees from setting fruit properly

(Torres et al., 2017), so decreased chilling under global warming can lead to fruit loss (Fraga et al., 2019; 2022).

Temperature variations during different growth stages of olive trees can cause various biophysiological effects. For instance, Tura et al. (2009) reported that warm conditions during the olive crop maturation phase and sufficient water availability in the autumn and spring seasons improved the volatile compounds and oil quality. A study by Ben-Ari et al. (2021) showed that olive oil quantity and quality depend on temperature solely after the pit hardening stage in the warm months of year. However, high temperatures commonly impact olive fruit growth throughout its entire development period. Since these effects would differ spatially-temporally, it would be worthwhile to project the successive phenological stages of olive crops over large areas at a yearly scale using different historic and future climate projections. The projections might provide large-scale patterns of olive phenological changes. In addition, they may support olive growers by providing management tools and strategic planning within olive growing areas for a changing climate.

Some crop models' approaches may build upon statistical relationships between relevant variables such as climate, crop development, and final yield, while other process-based phenological models, by integrating chilling and forcing, physiologically predict crop phenological phases using weather data and parameters calibrated with observations (Fraga et al, 2019; Moriondo et al., 2015; Luedeling et al., 2021). Since temperatures impact differently quality and quantity of final yield during any crop phenological stage, the adaptation of the crops to climate change and climate-induced risks through modeling crop phenological stages is fundamental for the evaluation of climate change effects on crop growth and production (Moriondo and Bindi, 2007). Consequently, establishing tools to project the phenological stages of tree crops is crucial for determining management in a changing climate (Luedeling et al., 2021). Considerable research is still needed to predict successive phenological stages scaled up from the local to the regional level. Since there is a high correlation between crop growth, yield, and temperature (Magugu et al., 2016; Porter and Gawit, 1999), phenological models mainly rely on temperature as an input variable (e.g., McMaster and Wilhelm, 1997; Cesaraccio et al. 2004; Luedeling et al. 2021). Temperature variations in different stages of plant development can influence phenological timing and impact on growth and yield. For example, Rojo and Perez-Badia, (2015) studied the relationship between temperature and timing of flowering stage for Cornicabra olive cultivar in central Spain (Toledo province). Their findings showed a positive correlation between temperature rise and phenological postponing, e.g., between temperature and the onset of the dormancy stage. However, a negative correlation between temperature rise and phenological earliness was observed for the early spring flowering stage.

Previous studies mainly focused on modeling the olive flowering stage (Orlandi et al., 2010; Avolio et al., 2012; Aguilera et al., 2014; Osborne et al., 2000; De Melo-Abreu et al., 2004; Galan et al., 2005; Orlandi et al., 2013). Several of these papers developed multiple phenological phase models but never scaled up to a larger area, as Di Paola et al. (2021) did. In this investigation, considering biophysiological importance of different growth stages of olive crops, we addressed the climate change-induced uncertainty that may affect olive phenological timing and consequently the current olive cultivation, variety choices and the climate suitability. Since all the agronomical practices are based on farmers` knowledge of specific varieties and environments, this phenological modeling could lead to management tool to support decision makers and olive farmers in the present and future periods.

Our research objective is to assess the possible effects of the climate change on several consecutive phenological phases (i.e., sprouting, blooming, and pit hardening) of olive tree in a large area encompassing the whole Euro-Mediterranean region (Fig. 1), by considering different cultivar types, in order to provide scientific base to guide agronomic practices and climate risk management.

2. Materials and Methods

We applied a recently tested and validated phenological modelling implementation (CAC_GDD, combination of the Chill, Anti-Chill days and the Growing Degree Days models) in Mediterranean environments, which offers: 1) a parsimonious and general approach in terms of data requirement for parameterization, 2) comparable predictability skills to other more complex and data demanding models, especially under limited training data, and 3) fast processing for regional applications over heterogenous environments in combination with large ensembles of climate data projections (Didevarasl et al., 2023). In addition, representatives of both early and mid-late/late budbreak olive cultivars are considered to compare the cultivar-based phenological projections for the management objectives. We applied the phenological model using future RCPs (Representative Concentration Pathways) and different GCM_RCM combinations (Global Climate Model_Regional Climate Model combinations) to project the future phenological changes. Then, we calculated climate change signals for each combination of phenological stages, RCPs, and RCMs. Meanwhile uncertainty analysis for the climate model projections using the ANOVA test (Analysis of Variance) was performed through yearly estimated dates of the phenological phases (time series of 30 years) to illustrate spatial agreement/disagreement between climate model projections. The flowchart (Fig. 2) presents the structure of our investigation and the relationship between the main parameters.

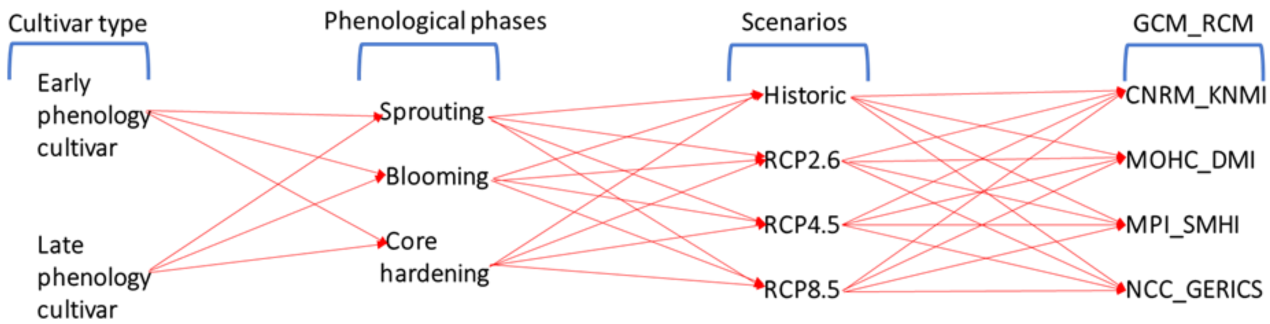


FIGURE 2. The structure of the model implementation based on the cultivar types, phenological phases, historic and future timeseries, and the climate model projections. We present 96 combinations to project the phenological dates over 30 years (historical: 1976-2005; future: 2036-2065).

2.1. Data collection

The climate data time series include maximum, minimum, and mean near-surface temperatures (at 2m above ground) and were gathered from the EURO-CORDEX climate data repository (Jacob et al., 2014; Jacob et al., 2020). These datasets are provided at daily temporal resolution, and with a spatial resolution of 0.11° for the European domain through dynamic downscaling with RCMs (Regional Climate Models) driven by GCMs (Global Climate Models), which provide lateral boundary conditions to the regional models. The EURO-CORDEX experiment also covers a historical period, for which recent climate observations exist. These experiments, which follow the observed changes in climate forcing, show how the RCMs perform for the past climate when forced by GCMs and can be used as a reference period for comparison with scenario runs for the future. The EURO-CORDEX ensemble of climate change projection experiments use different RCP (Representative Concentration Pathways) forcing scenarios. These scenarios include the RCPs 2.6, 4.5, and 8.5, providing different pathways for the future evolution of atmospheric greenhouse gas and aerosol concentrations. In impact and risk analysis, understanding the uncertainty sources in climate change projections is necessary. Basically, the main sources of uncertainty are categorized in anthropogenic and natural factors as follows: 1) Socio-economic assumptions, 2) Greenhouse gas emission scenarios, 3) Models to calculate concentrations, 4) Global and regional simulations (Giorgi, 2010).

As an experimental framework, we applied four model simulations of different GCM_RCM combinations (i.e., CNRM_KNMI, MOHC_DMI, MPI_SMHI, and NCC_GERICS) (appendix 1) for historical (1976-2005) and future (2036-2065) 30-year time-frame periods under three RCPs (i.e., 2.6, 4.5, and 8.5). Temperature data series were arranged as yearly timeseries starting from 1st of November of the previous year to the end of October over a window of -10-40°E and 30-54°N (Fig.1) and stored as NetCDF files. The temperatures were converted from Kelvin to degrees Celsius, and values over water bodies were eliminated. The CDOs (Climate Data Operators) were used to generate the time series. We calculated long-term daily mean temperature values over the study area for both historical and future 30-year periods. Spatial median values were calculated per GCM_RCM combinations of historical and future RCPs (Fig.3). Furthermore, daily anomalies of maximum and minimum temperatures were calculated (ANO= Future values – Historical values) to infer climate change signals for future during the growing season (Fig.4). Both Tmax and Tmin almost in all seasons show future increase up to about +3°C by RCP8.5. Typically, the utmost increases in temperatures are projected for the most cold and warm months of the year.

In the Mediterranean environment limited availability of widespread phenological observations raise usually serious challenges to modelling phenology. Hence, the phenological data restrictions in the study area limited our selection to only aforementioned three specific phenological phases:

1) Sprouting (or emergence of the spring bud). For the olive tree, sprouting stage begins usually at late winter. During this phase the buds change to buds of two types (i.e., vegetative buds and flower buds), which form floral clusters;

2) Blooming (or flowering): This phenological phase is a key stage, through which the olive tree traverses into its annual cycle. In this stage the olive tree, shows a great number of flowers whose objective is to be fertilized and then become fruits. Usually olive blooming is seen in mid-May with a total duration of around three weeks (from the first flower opens to the last one).

3) Pit hardening (or fruit set): Through this phase the fruit bone begins to harden, until olive reaches a given size and an intense green color, accumulating reserves until maturity. This phenological stage of olive starts in July-August. This stage is very critical for the olive trees, since they may face risk lack of water and high temperatures (Fiorino, 2003).

The olive cultivars, for which we apply the phenological modeling, include early (i.e., Carolea and Picholinare) and mid-late budbreak (i.e., Frantoio and Moraiolo) representatives, based on phenological observation dates and differentiation of the two cultivar types gathered from experimental sites in Italy (Didevarasl et al., 2023).

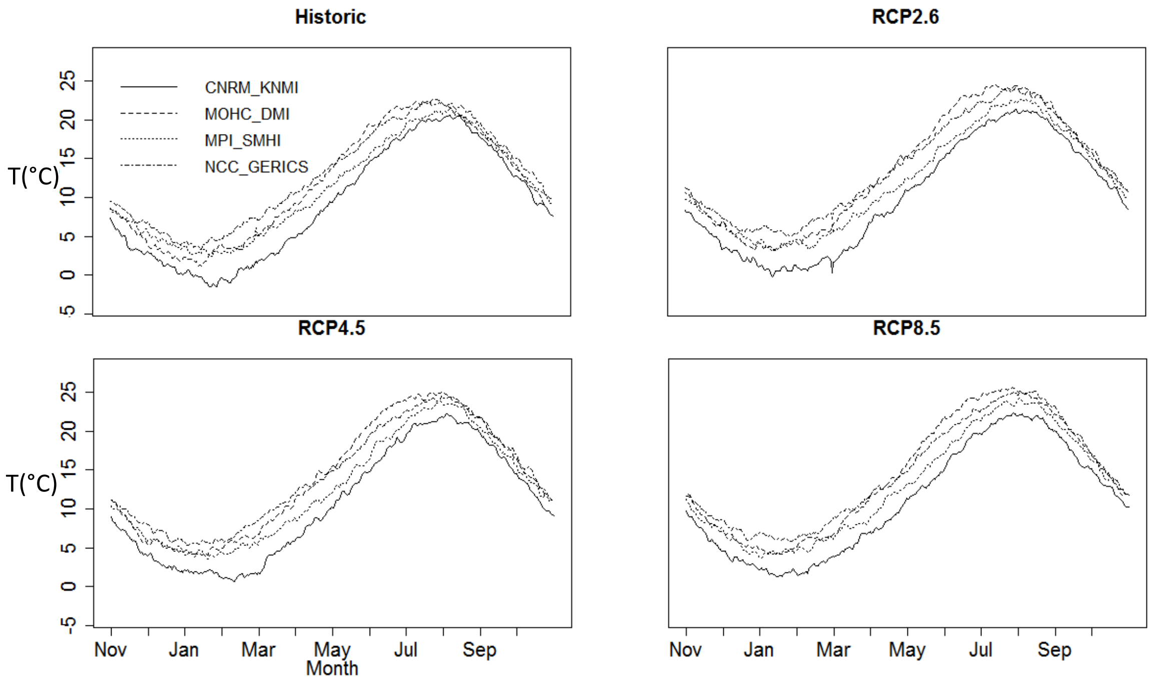


FIGURE 3. Daily spatial median temperature values over Euro-Mediterranean region (from 1 Nov. of pervious year to 31 Oct) calculated using long-term daily mean temperature of 30-year periods of historical (1976-2005) and future (2036-2065) RCPs (2.6, 4.5, and 8.5) per climate model projections (e.g., CNRM_KNMI, MOHC_DMI, MPI_SMHI, and NCC_GERICS). The timeseries are derived from the Euro_CORDEX repository.

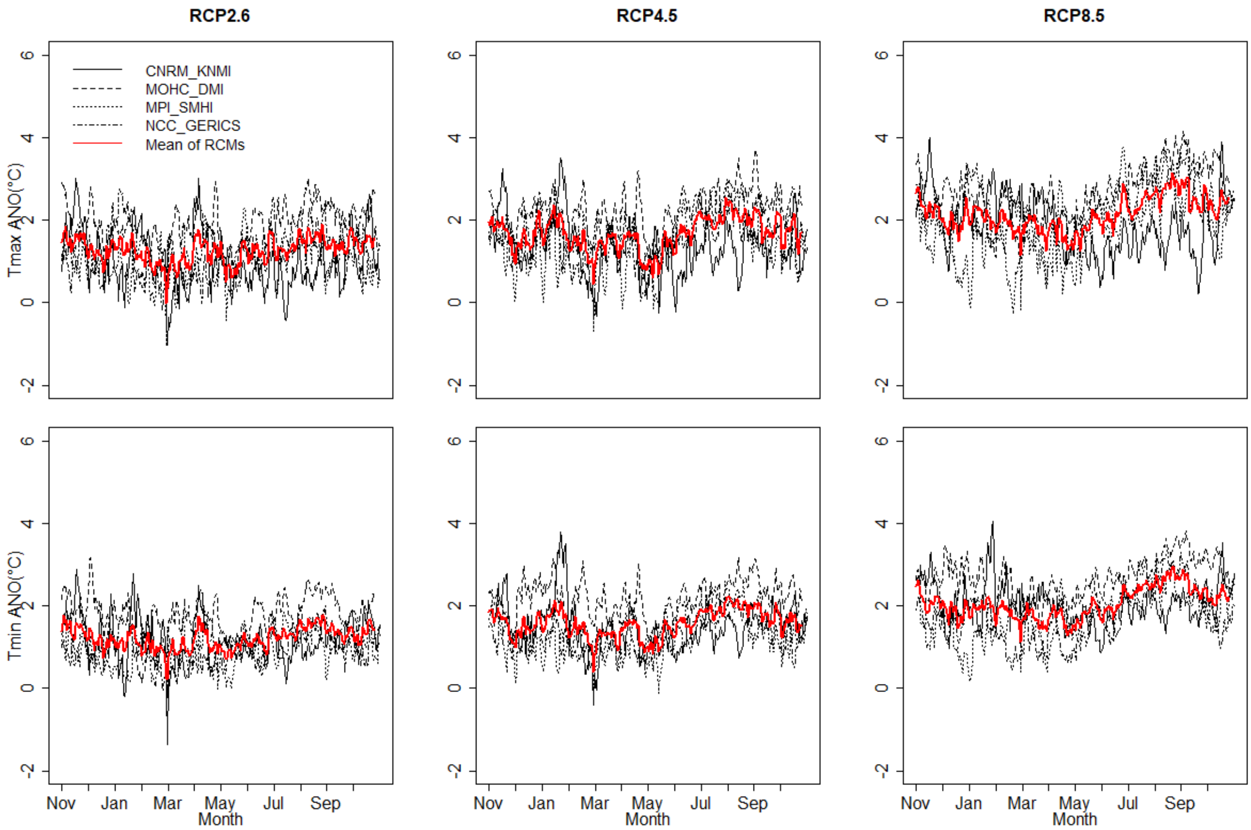


FIGURE 4. Daily anomaly of maximum and minimum temperatures (top and bottom rows respectively) over Euro-Mediterranean region (from 1 Nov. of pervious year to 31 Oct) calculated using long-term daily temperature for 30-year historical (1976-2005) and future (2036-2065) periods under different RCPs (i.e. 2.6, 4.5, and 8.5) and climate model projections. (Note: ANO= Future temperatures – Historical temperatures).

2.2. Spatial implementation of the phenological model

The Chill, Anti-Chill (CAC) model or chilling and forcing model developed by Cesaraccio et al., (2004) is a sequential model that accumulates chill days up to fulfilling the chill requirement, and then anti-chill days during eco-dormancy stage to overcome the quiescence condition. The model was defined based on the single triangle degree day method (Zalom et al. 1983; Snyder et al. 1999), including five temperature conditions (Table 1). One additional condition based on our temperature data set availability over the study area was added to make a total of six temperature cases. The two parameters required by this model, i.e., temperature threshold (Tc) and chilling requirement (Cr), were obtained for each early and mid-late budbreak olive cultivar from previous study (Didevarasl et al, 2023; and Table 3), where they have been optimized and validated, indicating better model performance for mid-late cultivar. Specific codes in R programming language (version: 2022.02.3+492) were developed to calibrate and spatially implement the model. We first implemented the CAC model in R as a basic function for subsequent steps. Secondly, we adapted the model for the spatial analysis. In this way, the model calculates the phenological dates for each grid point and year over the study area. The CAC model was applied to project sprouting dates.

TABLE 1. Chill days (Cd) and anti-chill days (Ca) equations for the six temperature conditions that relate the maximum (Tx) and minimum (Tn) temperature to the threshold temperatures Tc and 0°C, where Tm is the mean daily temperature.

Case	Temperature conditions	Chill days	Anti-chill days
1	0≤Tc≤ Tn≤ Tx	Cd=0	Ca=Tm-Tc
2	0≤Tn≤ Tc< Tx	$Cd=-[(Tm-Tn)- ((Tx-Tc)^2/2(Tx-Tn))]$	$Ca=((Tx-Tc)^2/2(Tx-Tn))$
3	0≤Tn≤ Tx≤ Tc	Cd=-(Tm-Tn)	Ca=0
4	Tn<0≤ Tx≤ Tc	$Cd=-[Tx^2/2(Tx-Tn)]$	Ca=0
5	Tn<0< Tc< Tx	$Cd=-(Tx^2/2(Tx-Tn))- ((Tx-Tc)^2/2(Tx-Tn))$	$Ca= ((Tx-Tc)^2/2(Tx-Tn))$
6	Tn<Tx<0<Tc	Cd=0	Ca=0

To estimate subsequent blooming and pit hardening phases, the CAC_GDD model (The Chill, Anti-Chill days_Growing Degree Days model) was built as a combined model that uses the sprouting dates from the CAC model to initialize the heat accumulation process. For heat accumulation, we used the GDD function (McMaster and Whilhelm, 1997) in the pollen library in R (Nowosad, 2021), which is based on the heat accumulation model that requires temperature base (Tb), maximum temperature base (max Tb) and heating requirement (Hr) (Table 3).

GDD equation is as following:

1) $GDD = (Tx + Tn) / 2 - Tb$

Where, Tx is the daily maximum temperature, Tn is the daily minimum temperature, and Tb is the base temperature. The minimum and maximum temperatures are set equal to Tb if less than Tb, and to an upper-temperature threshold (max Tb) whenever the minimum and maximum temperatures are higher than max Tb because most plants cannot grow efficiently beyond these thresholds (McMaster and Wilhelm, 1997).

We implemented the phenological models by phenological phases, i.e., sprouting (CAC model) and blooming and pit hardening (CAC_GDD model), for 3 RCPs and climate model simulations (4 RCM combinations) within the Euro-Mediterranean region and over 30 years using the optimized parameters per early and mid-late budbreak cultivars (Table 2). To optimize the main parameters of CAC and CAC_GDD models using genetic algorithms (GA) package in R, the temperature timeseries (minimum, maximum and mean temperatures), phenological observation data, and pre-selected lower and upper bounds of the model parameters (Tc:7 to 14, Cr: -80 to -200, Tb: 4 to 10, Tx: 25 to 35, Hr:300 to 1400) were arranged and set into a specific developed function.

TABLE 2. The optimized main parameters of chill anti-chill and growing degree-days phenological models by phenological stage and cultivar type (Didevarasl et al., 2023).

Phenological stages	Cultivar Type	Tc	Cr	Tb	Tx	Hr
Sprouting	Early	9.5	-115	-	-	-
	Late	11.2	-133	-	-	-
Blooming	Early	-	-	5.9	31.5	437
	Late	-	-	4.5	29.5	370
Pit hardening	Early	-	-	5.9	31.5	1074
	Late	-	-	4.5	29.5	1315

Note. Tc, estimated temperature threshold; Cr, estimated chilling requirement;Tb, estimated base temperature; Tx, estimated max temperature; Hr, estimated heating requirement.

2.3. Climate change signal and uncertainty analysis

After the spatial implementation of the phenological models at yearly scales (30 years period for both present and future scenarios), we calculated climate change signals/anomalies by subtracting the projected phenological dates of future (PDF) period from the historic (PDH) dates (equation 2) corresponding to each climate model simulation. Since we consider 4 RCM combinations × 3 RCPs × 3 phases, we have 36 combinations for each cultivar type. In addition, to show the results as concisely as possible, we calculated the mean of four RCM combinations, resulting in nine combinations/maps for each cultivar.

2) Anomaly= PDF – PDH

Meanwhile, to consider the uncertainty across climate model simulations in estimating phenological dates at the pixel level/spatially, we developed a specific code in R to run the ANOVA test (Analysis of Variation). We used the anomaly timeseries of 30 years for each climate model projection (30×4=120) in each pixel/grid point to apply the ANOVA test. The F statistic from the ANOVA provides a comparison of the statistical distribution of climate models, assessing the variability between and within the models. Thus, the F statistic evaluates if there is a difference/similarity of phenological dates between climate models. Indeed, different P-values (e.g., 0.1, 0.05, 0.01, 0.001) corresponding to F values provide thresholds of significance to evaluate agreement or disagreement between the climate models in terms of increasing or decreasing the phenological projected dates over the future period.

At the end to find the magnitude of future phenological changes comparing the late and early cultivars, the anomaly values of the late cultivar were subtracted from the early one (difference= ANO late – ANO early) at the pixel level over the study area.

3. Results

Overall, the spatial distribution of anomalies as the representative of climate change signals illustrates the earlier onset of the phenological dates in all three phases of both early and mid-late olive cultivars under the future RCPs and climate model simulations. In all combinations, median values are lower than zero, and even third quartiles mostly showed negative values (Fig. 5). This condition was observed at least for around 75% of the study area, indicating advanced timing in the phenological phases ranging from 0 to around 50 days (ignoring outliers) over the future period (2036-2065). Under

RCP8.5 the phenological advances seemed more extreme, particularly in the pit hardening stage in both early and late cultivars. Each climate simulation showed unique distributions per phenological phase. Comparing the phenological phases, pit hardening indicated extremely negative skew distribution with higher variability illustrating relatively greater future phenological earliness. Meanwhile, the late budbreak cultivar showed such more negative distribution in all three phenological phases when comparing the median values (Fig. 6) of all combinations. Indeed, the late budbreak cultivar showed the phenological timing earliness greater than the early ones (ranging over the climate models and RCPs, sprouting: -8 to -15 vs. -7 to -14, blooming: -9 to -17 vs. -8 to -16, and pit hardening: -12 to -22 vs. -6 to -20), as that highlighted in pit hardening phase with a 4-day difference in average.

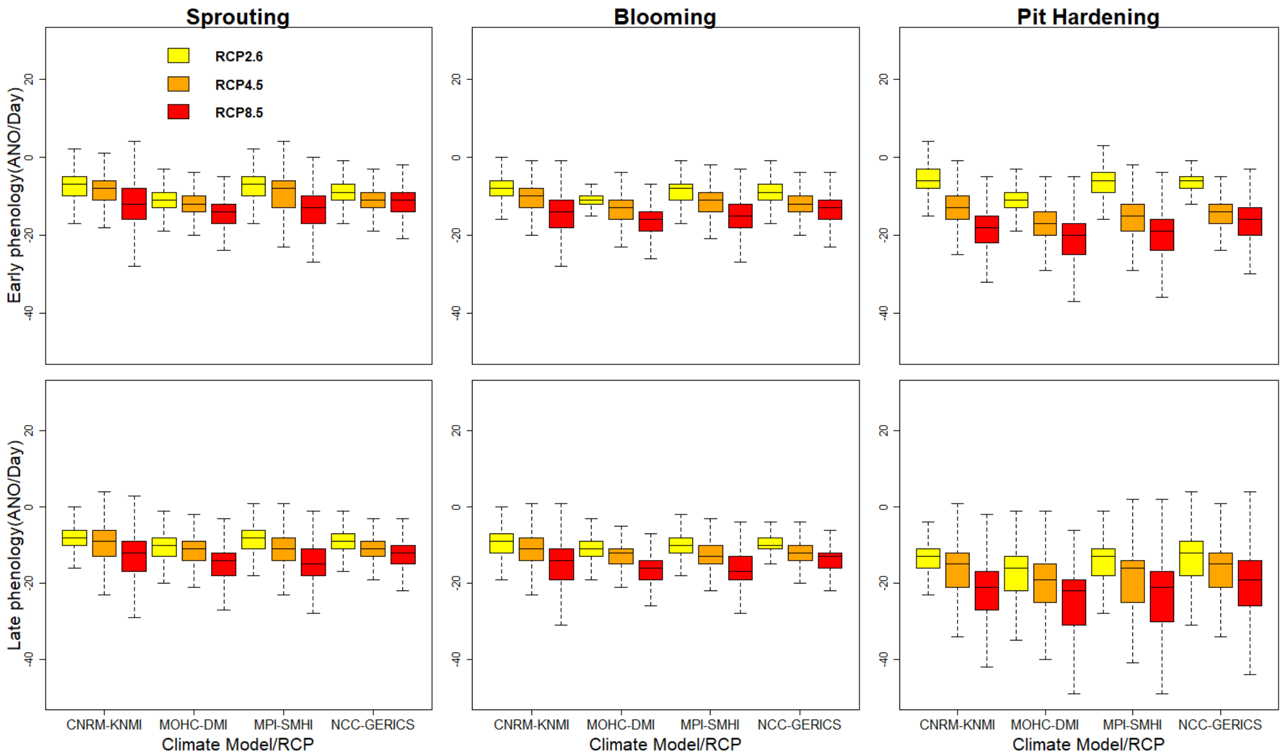


FIGURE 5. Boxplots to show spatial distribution of anomaly values (in day) of the projected phenological dates of early and late budbreak olive cultivar (top and bottom rows respectively) by phenological phases (Sprouting, Blooming and Pit Hardening), RCPs and climate model simulations/RCM combinations. The anomaly values are obtained subtracting the future phenological dates from the historic ones to find the climate change signals during future period (2036-2065) in terms of advancing/postponing in timing of the phenological phases over the Euro-Mediterranean region.

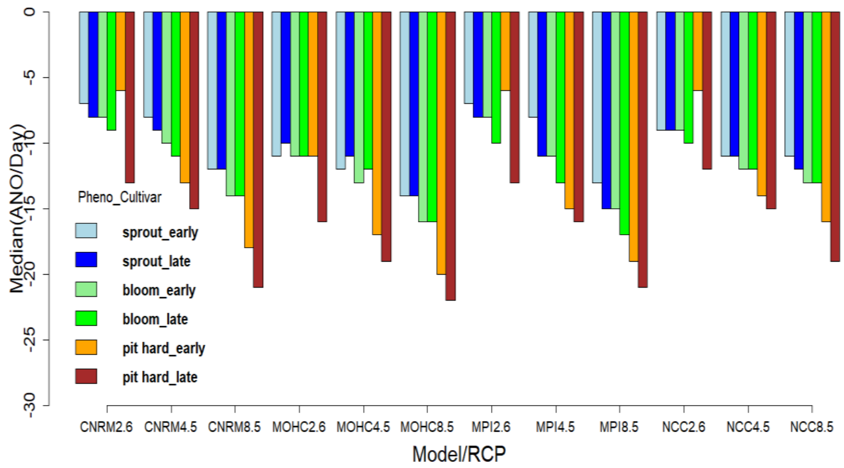


FIGURE 6. Spatial medians of anomaly values (in day) per GCM_RCMs and RCPs (X axis), based on three phenological phases (sprouting, blooming and pit hardening) and two types of olive cultivar (early and late Budbreak cultivars) over Euro-Mediterranean region.

In the spatial distribution, anomaly values illustrated unique average patterns across RCM combinations, phenological phases, and RCPs scenarios for both early and late budbreak cultivars (Figs. 7 - 8). Advances in the phenological timing mainly prevailed over the study area for the future period. Relatively, in all combinations under RCP8.5 the results projected phenological timing earliness dominating most parts of the study area, and this situation even becomes more expanded spatially for late budbreak cultivars in pit hardening stage over northern Europe despite the Mediterranean. Olive growing regions around the Mediterranean Sea and northwestern Africa illustrated greater phenological earliness (around -10 to -25 days) in both cultivar types and all three phenological phases, whiles through pit hardening phase similar range and even greater advances (in late cultivar cases) expanded toward northern regions. Extreme earliness usually encompasses regions with different climatic conditions than the current olive-growing areas. It appears that areas with extreme increasing/decreasing temperatures could depict such harsh phenological changes over the future period. Over some olive growing regions (e.g., Italy and Spain), we found that RCPs 4.5 and 8.5 show a range of greater phenological advances (around 5 to 10 days) than RCP2.6.

But delays of the phenological timing were projected only in some limited zones over the lowlands of northeastern Africa (in the sprouting phase, around 0-25 days), some spots over the Alps highlands (in blooming phase, >25 days), and over northern Europe only under RCP2.6 of CNRM_KNMI model in pit hardening phase (around 0-25 days) mainly for early budbreak cultivars (refer to Appendices 2-4). However, this situation is more unusual for the late cultivars. The blank (unavailable value) zones over the study area imply the phenological model failures. They mainly are shown over highlands (e.g., Alps), some northern regions, lowlands in North Africa, and along sea shores. Meanwhile, areas highlighted by dashed lines indicate disagreements between RCMs, using the ANOVA test and considering the signification threshold of $P<0.05$.

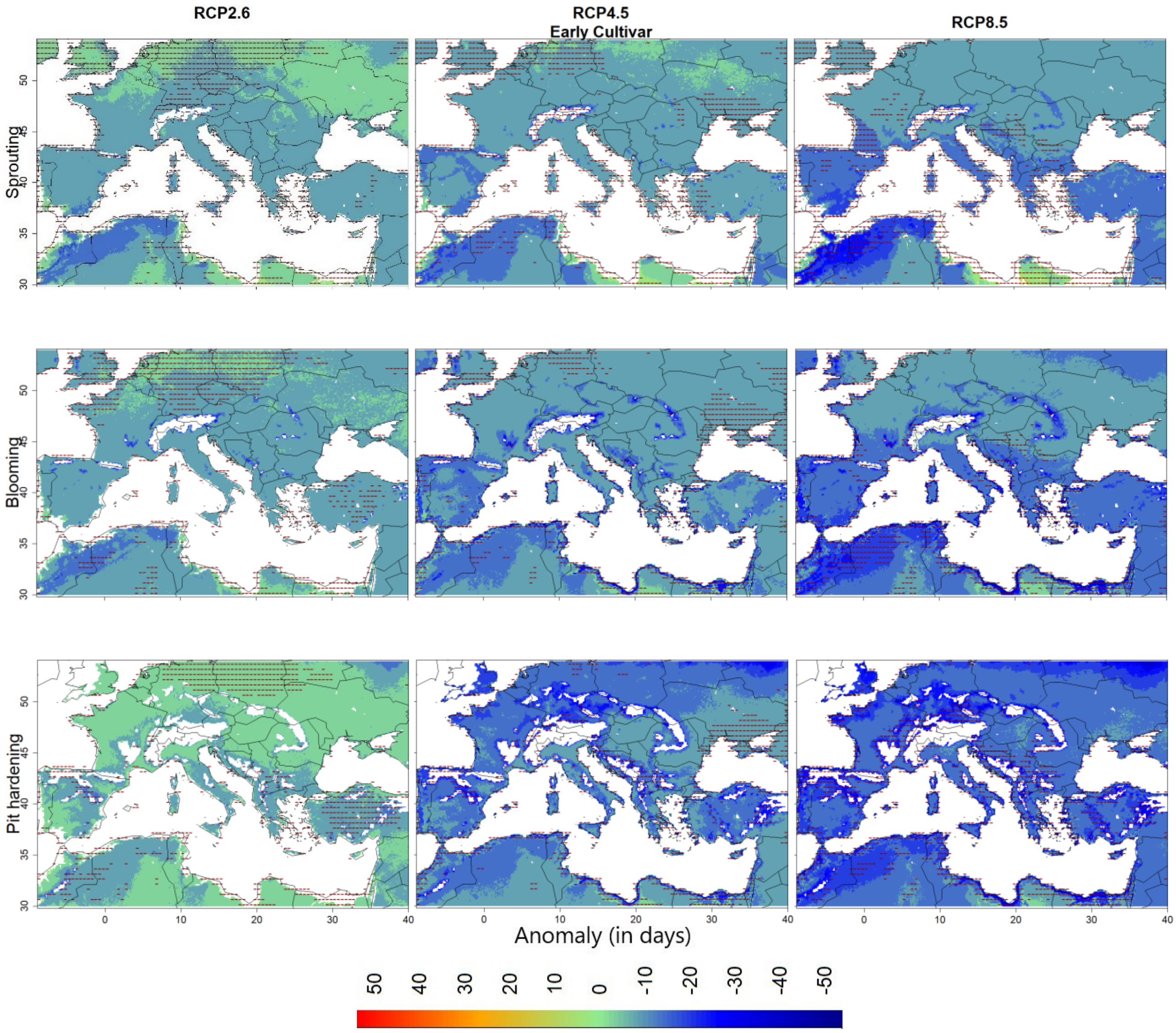


FIGURE 7. Difference (in days) in the timing of phenological phases (sprouting (top row), blooming (middle row), and pit hardening (bottom row)) of the early budbreak olive cultivar between future (2036-2065) and historical (1976-2005) period per RCPs (RCP2.6 (left column), RCP4.5 (middle column), RCP8.5 (right column)). The dashed lines indicate areas with disagreement between the climate model projections in terms of phenological earliness/delay considering the signification level of $P<0.05$ (Note: 1. Plots derived from mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

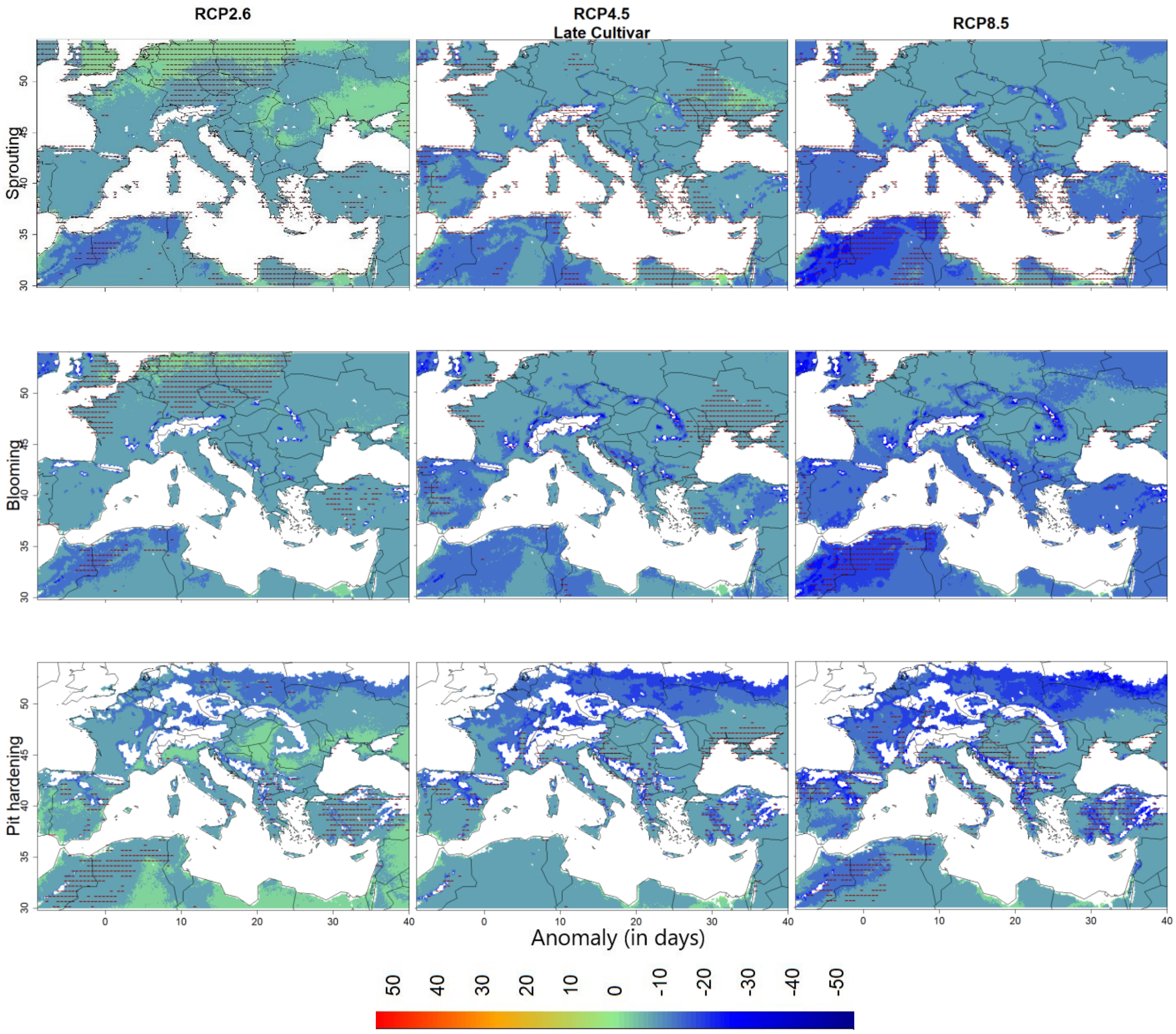


FIGURE 8. Difference (in days) in the timing of phenological phases (sprouting (top row), blooming (middle row), and pit hardening (bottom row)) of the late budbreak olive cultivar between future (2036-2065) and historical (1976-2005) period per RCPs (RCP2.6 (left column), RCP4.5 (middle column), RCP8.5 (right column)). The dashed lines indicate areas with disagreement between the climate model projections in terms of phenological earliness/delay considering the signification level of P<0.05 (Note: 1. Plots derived from mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

When assessing the agreement across climate model projections, we found unique patterns by the phenological phases and the RCPs through both early and late budbreak cultivars (Fig. 9-10). Nevertheless, according to the RCPs, we observed spatial similarity in all three phenological phases. Considering P<0.05 (threshold F-value of 2.7), under RCP2.6 in all three phases, mainly northern Europe and some limited regions over the lowlands of northern Africa (highlighted in northeastern Africa) illustrated statistical difference/disagreement between four RCMs with a 0.05 or less probability that the differences are due to random errors, in terms of phenological timing changes for the future period. The same disagreement was observed over Turkey for pit hardening in the late sprouting cultivar. RCP4.5, illustrated disagreement between RCMs over an area north of the black sea, northern African lowlands, and some limited zones over northern Europe in both cultivar types, whereas for RCP8.5 the areas with climate models` disagreement are dispersed over central Europe and northern Africa through all phenological phases. Areas with model differences were mostly found over coastal zones and northern parts, which may suffer diverse modelling representations of sea-land atmospheric interactions. Meanwhile, through the sprouting stage, the disagreement between the climate models seemed to be more expanded spatially, as temperature`s median values (Fig. 3) showed higher divergence between RCMs relatively during winter to spring.

On the other hand, considering P>0.05 (threshold F-value of 2.7) implies agreement/similarity between climate models in earliness/delay of phenological timing over future periods with only a 0.05 probability that the differences were random. That covers most of the study area through all three phenological phases and RCPs of both cultivar types. The blank regions are originated from model failures, through projections for 30 years per RCMs, which mainly cover the highlands, the northern parts, and some areas over North Africa, mainly through the blooming and pit hardening phases. The areas with model failures were intensively expanded for the late budbreak cultivar projections and in the pit hardening stage.

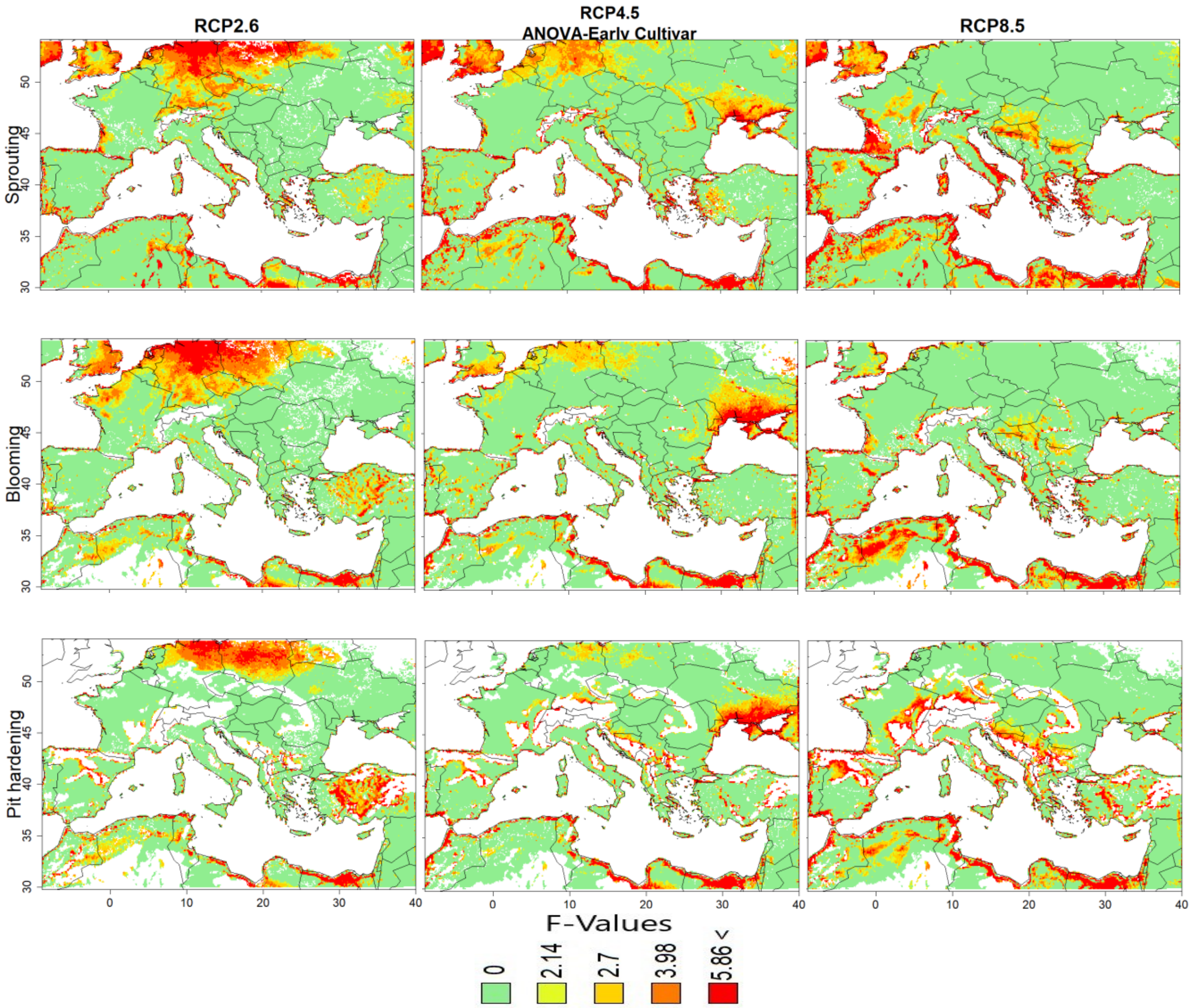


FIGURE 9. Spatial patterns of F-values derived through ANOVA test per phenological stages (sprouting (top row), blooming (middle row), and pit hardening (bottom row)) of the early budbreak olive cultivar and RCPs (RCP2.6 (left column), RCP4.5 (middle column), and RCP8.5 (right column)) over the study area. F-values (0-2.14, 2.14-2.7, 2.7-3.98, 3.98-5.86, 5.86<) corresponding to each signification level (P>0.1, P>0.05, P>0.01, P>0.001, Sign.) demonstrate different probabilities of agreement/disagreement (green color/red color) between four RCMs. (Note: Blank areas show unavailable values/phenological model failures).

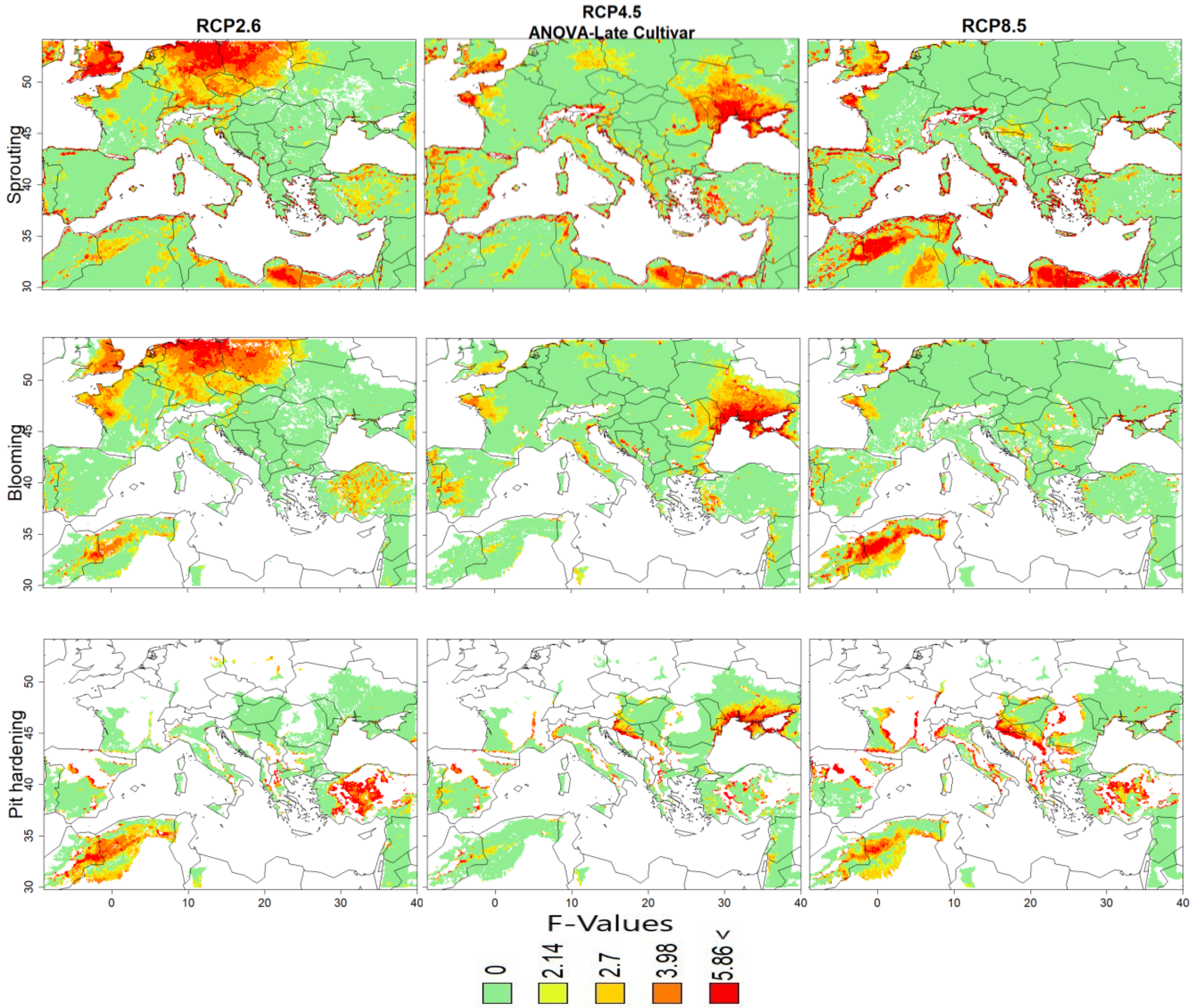


FIGURE 10. Spatial patterns of F-values derived through ANOVA test per phenological stages (sprouting (top row), blooming (middle row), and pit hardening (bottom row)) of the late budbreak olive cultivar and RCPs (RCP2.6 (left column), RCP4.5 (middle column), and RCP8.5 (right column)) over the study area. F-values (0-2.14, 2.14-2.7, 2.7-3.98, 3.98-5.86, 5.86<) corresponding to each signification level (P>0.1, P>0.05, P>0.01, P>0.001, Sign.) demonstrate different probabilities of agreement/disagreement (green color/red color) between four RCMs. (Note: Blank areas show unavailable values/phenological model failures).

4. Discussion

This investigation depicts an integrated method to spatially characterize climate change effects on olive phenological development, accounting for different climate model projections and cultivar types. Our study provides a comprehensive view of the entire phenological cycle compared to previous studies focused on a single phenological phase, e.g., mainly flowering (Aguilera et al., 2014; Garcia-Mozo et al. 2008; Mariani et al., 2013). Furthermore, we scaled up the model spatially over a large territory, the Euro-Mediterranean region, which allows us to overcome the limitations of the previous studies focusing primarily on single locations (e.g., Abou-Saaid et al. 2022; Di Paola et al. 2021; Medina-Alonso et al. 2020; Orlandi et al. 2010).

Regarding climate change effects on olive phenology, all combinations (cultivar types × phenological phases × RCPs × RCMs) suggest potentially increasing associated risks with a pattern of phenology earliness for at least over 75% of the study area. Regarding the cultivars, all three phenological phases of the late budbreak cultivar would experience more enhanced phenological earliness over the study area than the early one. Indeed, greater advances were projected for the pit hardening phase of the late budbreak cultivar, particularly in RCP8.5, namely the scenario with higher GHG (Greenhouse gases) concentration and consequently larger warming. The projections suggest that the phenological advances for all three phases might range between 5 and 10 days greater than the other RCPs under RCP8.5. Some previous studies (e.g., Rojo and Pereza-Badia, 2015, Moriondo and Bindi, 2007; Benlloch-González et al., 2018) obtained similar results. Regarding temperature, as one of the most influencing meteorological variables for phenological development (Bonofiglio et al. 2008; Orlandi et al. 2010; Osborne et al. 2000), increasing temperatures lead to relevant phenological timing advances for tree crops, and in the specific olive trees. Although warming during autumn could lengthen dormancy and consequently cause a delayed pre-flowering/awakening stage, warming during late winter and/or early spring might increase heat accumulation, leading to advances in flowering and post-flowering stages. This situation could explain the observed positive/negative correlations between temperature changes and phenological timing of olive tree in pre/post-flowering stages. In other words, temperature increase corresponds to delay in pre-flowering stage, and to earliness in post-flowering stage. Indeed, lower chilling and higher heating projections for the future period could lead to earliness in the timing of olive phenological stages, influencing the quantity and quality of the final yield (Bonofiglio et al. 2009; Garcia-Mozo et al. 2008; Osborne et al. 2000). This effect might be more enhanced over southern and western areas (Fraga et al. 2019), as outlooks of future temperature with more significant increases in the cold months of year. Instead, due to future warming and subsequent suitable temperature ranges, chilling requirements might be fulfilled over the colder climate of northeastern Europe (Luedeling et al. 2011), leading to earlier phenological stages. Over southern areas, different mechanisms may play with larger heating over late winter and early spring that would accelerate phenological advances of olive trees despite lower chilling accumulations. Hence, generated spatial patterns illustrate dominant phenological advances in both northern and southern parts of the study area. Given that our implemented phenological models (i.e., CAC and CAC_GDD) used together chilling and heating units to estimate phenological timing, our projections show phenological earliness expanded almost throughout the Euro-Mediterranean region. Furthermore, in the pit hardening phase for both cultivars, the spatial patterns show greater phenological advancement ranges over colder areas, across different RCM projections and RCPs, due to both chilling increase in the cold season and suitable heating for GDD summations during the spring-summer period. However, in the southern regions, the phenology might advance less than in the cold areas due to lower chilling accumulations leading to a lengthening endodormancy stage. Thus, we infer a transit of suitable climate conditions for olive from the Mediterranean basin towards the northern areas through future period, as reported already by some previous researchers (e.g., Rodríguez Sousa, et al. 2020; Tanasijevic et al. 2014; Moriondo et al. 2013). Some coastal regions of North Africa and southern Europe mainly through the blooming and the pit hardening phases of the early budbreak cultivar (under RCPs 4.5 and 8.5), illustrate severe advances (>15 days). This situation could emerge regarding lower chill and heat requirements of this cultivar type, plus warmer winter rather than the areas nearby because of less 24-hour temperature variations, leading to accelerated GDD accumulations. A previous investigation by Orlandi et al. (2013) supports indeed such an outlook, indicating more than 15 days of future advances in GDD summations over southern Italy along coastal areas. Also, recently published research by Grillakis et al. (2022) in Crete Island, Greece, which demonstrates climate characteristics close to above-mentioned zones, found similar results, indicating an extreme advance of olive flowering stage ranging from 6 to 26 days under RCP4.5 and 8.5. Shifts of phenological timing would cause severe impacts, particularly in olive growing regions over the Mediterranean basin regarding climate risks, e.g., frost events during late winter- early spring (Orlandi et al. 2010; Baldocchi and Wong 2008).

On the other hand, some limited zones over North Africa show delays ranging from 5 to 25 days for the sprouting phase of the early budbreak cultivar under specific single climate projections, as shown in Appendix 2. This finding implicates the effect of higher minimum temperature on prolonging the accumulation of sufficient chill units over the warm and humid climate of northern African lowlands and coasts during the winter season. However, over the nearby areas, the earliness is again dominant, which confirms a more continental climate with a higher difference between minimum and maximum temperatures, which allows the model to reach the chill requirement earlier and provides more time for accumulating heat units to fulfill eco-dormancy. Nevertheless, most of the previous studies did not report phenological delay for future periods since most of them were developed on a local scale using the observations from local olive genotypes and, accordingly, not scaled up spatially to larger regional areas (e.g., Grillakis et al. 2022; Aguilera et al. 2014). Also, in some cases, they calculated individual chill and heat units (e.g., Gabaldón-Leal et al. 2017; Fraga et al. 2019), unlike a sequential phenological model such as our CAC or CAC_GDD models.

Model failures mainly indicate insufficient chilling and/or heating sums to fulfil both requirements. In the blooming and especially in the pit hardening phases, the model failures are more widespread over the study area and more exacerbated for the late budbreak cultivars. Since chill and heat units are accumulated daily over a year, the model fails if they do not reach the specific requirements by the end of a 365-day period. For instance, a phenological phase (e.g., the pit hardening) in summer would likely show more model failures than a winter-spring phase (e.g., the sprouting) since this phase has a sufficient number of days ahead to fulfill the requirements. Spatially, the cold (e.g., mountainous highlands and some northern Europe areas) and warm-humid areas (e.g., the coastal lowlands of North Africa and the Mediterranean basin) where there are model failures occurred due to missing the predefined chilling or heating requirements. This finding is confirmed by de Melo-Abreu et al. (2004), who mentioned the possibility of insufficient chilling in warm climates, and

Gabaldon-lea et al., (2017), who found a lack of chilling conditions over the coastal regions of southern Spain where the model also failed in our spatial patterns.

Comparing late and early cultivars in terms of the magnitude of future changes of the phenological timing (Fig.11), we found that the current olive growing regions in the Mediterranean are often subjected to higher changes/advances by the early cultivar patterns (5-15 days more than the late cultivar) dominantly through the pit hardening (under RCPs 4.5 and 8.5) and then the sprouting phase. For the blooming stage, however, both cultivars show almost similar amplitude of changes except for the coastal regions of North Africa and southwestern Europe, where extreme changes for early cultivars are shown again. This finding confirms the possible greater vulnerability of early budbreak cultivars compared to late cultivars under future climate change. A recently published study by Abou-Saaid et al. (2022) also indicated that higher variability of chill and heat requirements for early cultivars can lead to greater shifts in phenological projections. Whereas the late cultivar in northern Europe and northern Africa illustrate intensive changes/earliness (5-15 days more than the early cultivar) in the pit hardening and the sprouting phases respectively, implying possible adaptability of the late cultivar to the future warming at least in the colder climate zones.

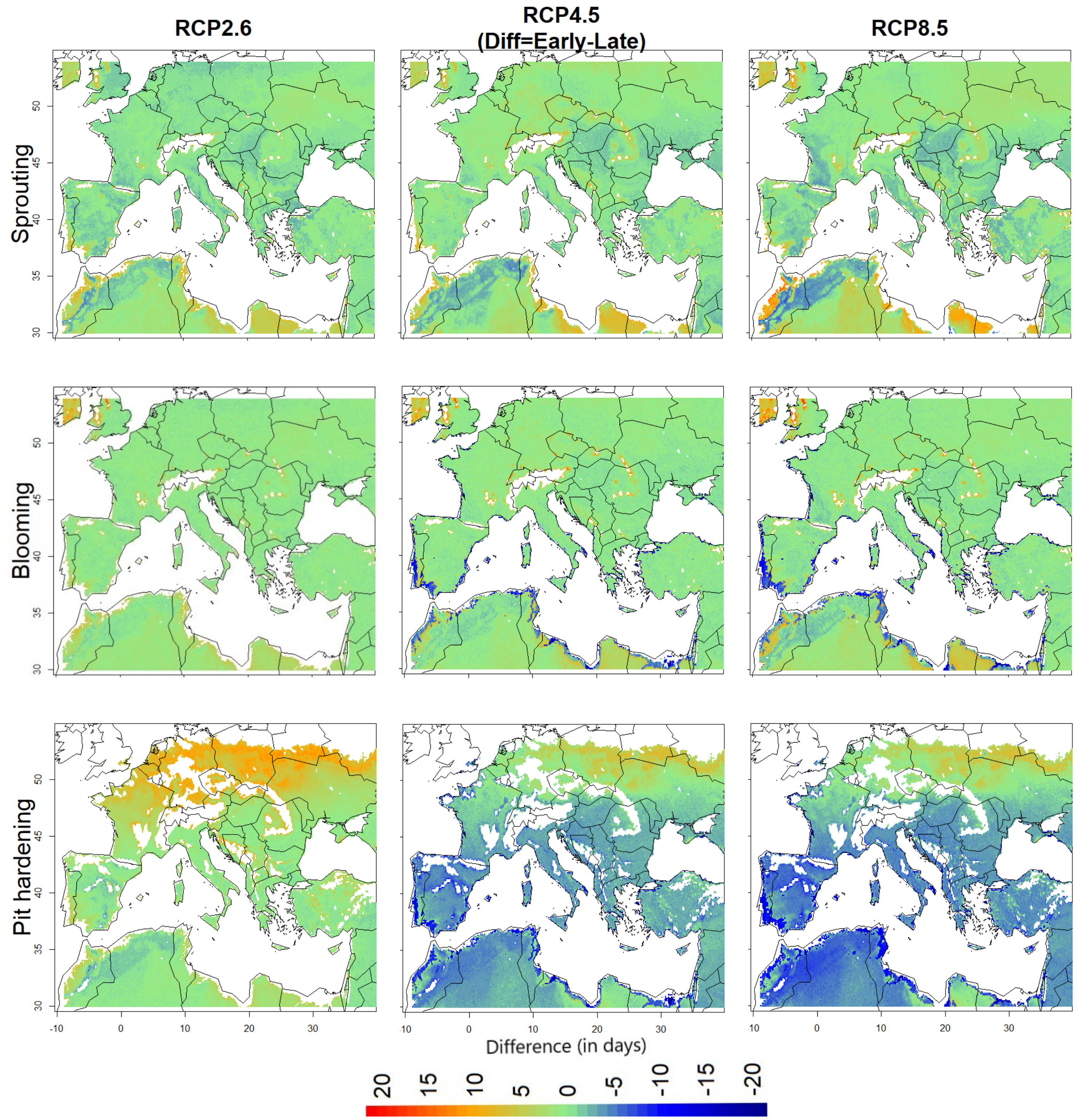


FIGURE 11. Difference in anomaly values (in days) between late and early cultivar types (diff= – early - late) to find out the magnitude of changes over future periods per phenological phases (sprouting, blooming and pit hardening) and RCPs (2.6, 4.5, and 8.5).

The spatial distribution of ANOVA analysis results manifests notable similarity between phenological phases per RCPs in terms of possible phenological changes in the future. Agreement between the RCMs prevailed over the study area, which aligns with widely expanded phenological earliness. This situation is evident for both cultivar types. Our finding is basically in accordance with forcing for future climate scenarios, and the model projections mainly indicate that the Euro-Mediterranean region will experience increased warming during plant development with a high agreement between the RCMs (Fraga et al. 2019). Climate model projections highlight disagreements over northern Europe in RCP2.6, over northern regions of the black sea in RCP4.5, and dispersed over central and western Europe and North Africa in RCP8.5. The results are supported by previous studies (e.g., Fornaciari et al. 1998 and Orlandi et al. 2005), which reported considerable uncertainties in the projection of olive chilling requirements. The coastal areas of the Mediterranean basin (e.g., North Africa and southern Europe) show mostly disagreements between the climate model projections. Different analytical representations of sea-land atmospheric interactions also likely influence this characteristic. Areas with disagreements represent the uncertainty inherent to different climate projections. On the other hand, the regions with the most certainty are also highly prone to climate change impact in terms of future changes for olive phenology.

Briefly, three consecutive olive phenological phases (i.e., Sprouting, Blooming, and Pit hardening) spatially show different levels of future advances over the study area. The highest expected advances will emerge in the Mediterranean mainly during sprouting and blooming stages, whiles northern/colder regions also illustrate remarkable advances in pit hardening phase. This situation could be potentially resulted from higher temperature increase in warm/cold months of year in northern/Mediterranean regions respectively. Thus, we may expect possible climate vulnerability on olive production in terms of quantity and quality losses in the Mediterranean, versus potential climate suitability to olive growth over the northern Europe or mountainous areas in the future period.

5. Conclusion

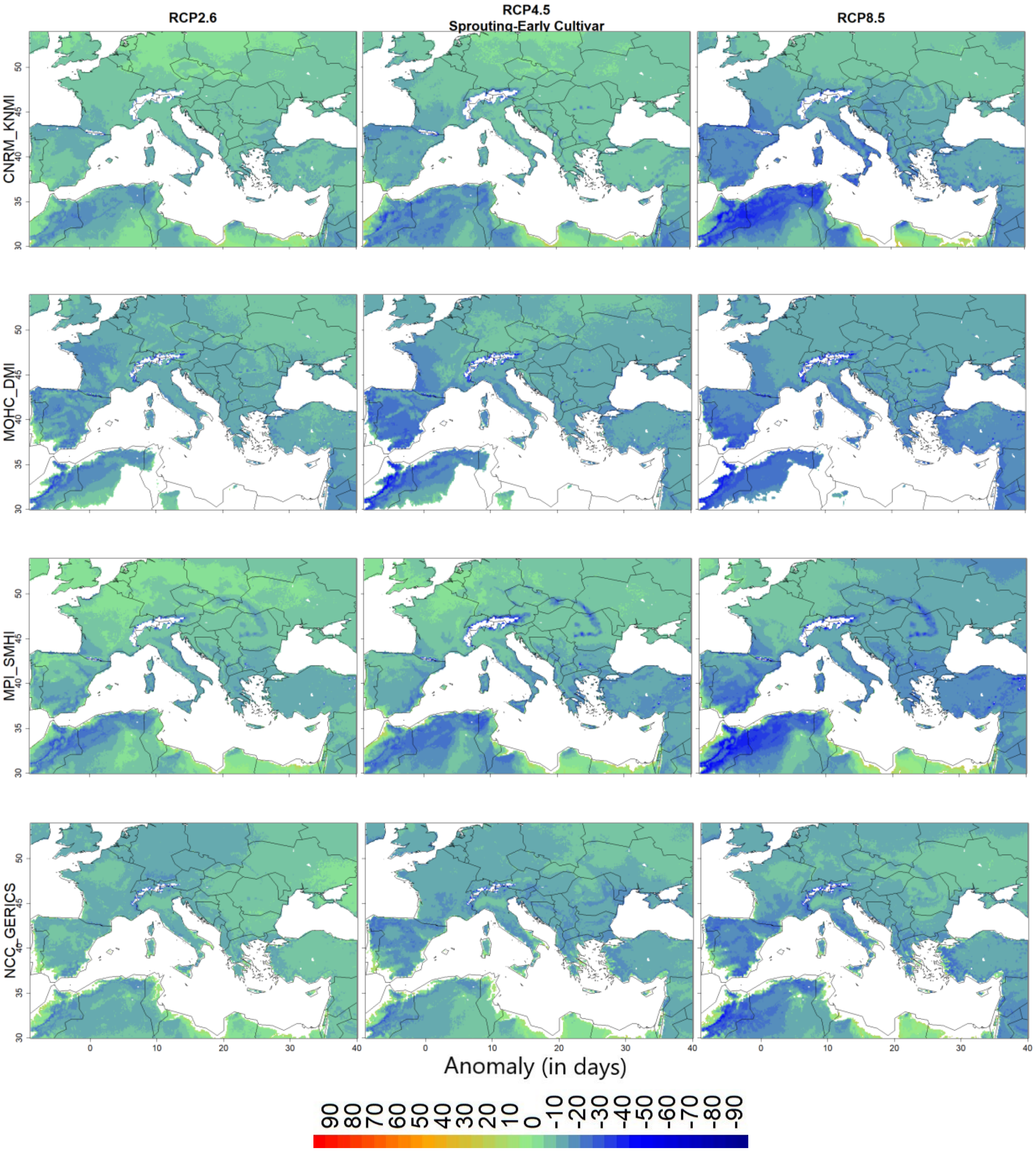
We integrated three successive phenological phases of two early and late olive representative cultivars to project through four climate model projections using historical and future RCPs. A comparable framework was presented regarding different global emission scenarios and their effects on olive biophysiological processes by cultivar types. This approach provides a comprehensive management tool on a large spatial scale for the decision-makers and olive producers throughout the study area. Spatial modeling extended over a wide area encompassing western Europe to the Middle East and northern Africa to northern Europe (i.e., the so-called Euro-Mediterranean region) projecting the future phenological changes under different climate change conditions. The results showed widespread earliness in olive phenological timing throughout the study area in the future, exacerbated by higher warming, confirming the influence of increasing temperature on phenological advances. Nevertheless, the cold climate zones over highlands (e.g., the Atlas Mountains) and northern/northeastern Europe showed greater future phenological earliness, implying a manifestation of a more suitable climate for olive growth and consequently, a possible spatial shift from the current olive growing regions, unless limited by other environmental constraints to physiological processes.

Agreement between climate model projections prevailed over most of the study area would anticipate almost certain risks linked to phenological advances in the Mediterranean olive orchards and, conversely the emergence of climate favorability to olive growth over the colder zones. However, comparing the late and early budbreak cultivars, we conclude that the late cultivar, will be more resistant to future warming in the olive-growing regions of the Mediterranean basin (showing less phenological advances) and thermally more adaptable in the northern cold areas (showing more phenological advances) during the future period. This finding is only obtained from a single temperature-based phenological modeling, however, other than the temperature, which is the primary driver of plant phenology, there are other ecological parameters (e.g., soil characteristics, precipitation, radiation etc.) that may affect the suitability of olive growth in different environments. For further research, calculating some agro-climatic indicators, e.g., frost/hot days, wet/dry days, etc., for different olive phenological stages under climate change scenarios would be worthwhile regarding future climate stress assessment on olive cultivation.

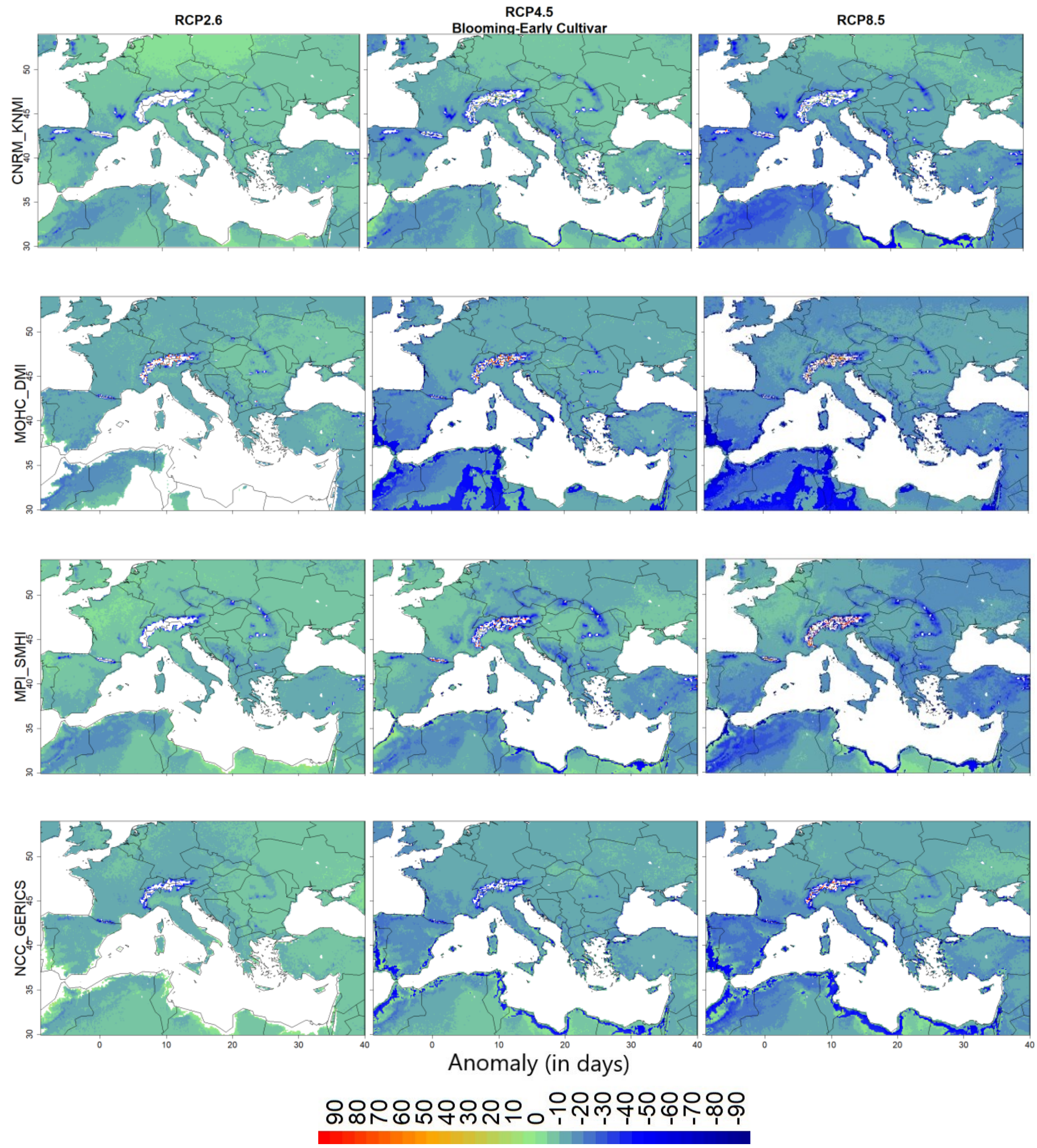
Appendixes

Appendix 1. Global and regional climate models (GCM and RCM respectively) considered in the investigation (Navarro-Racines *et al.* 2020).

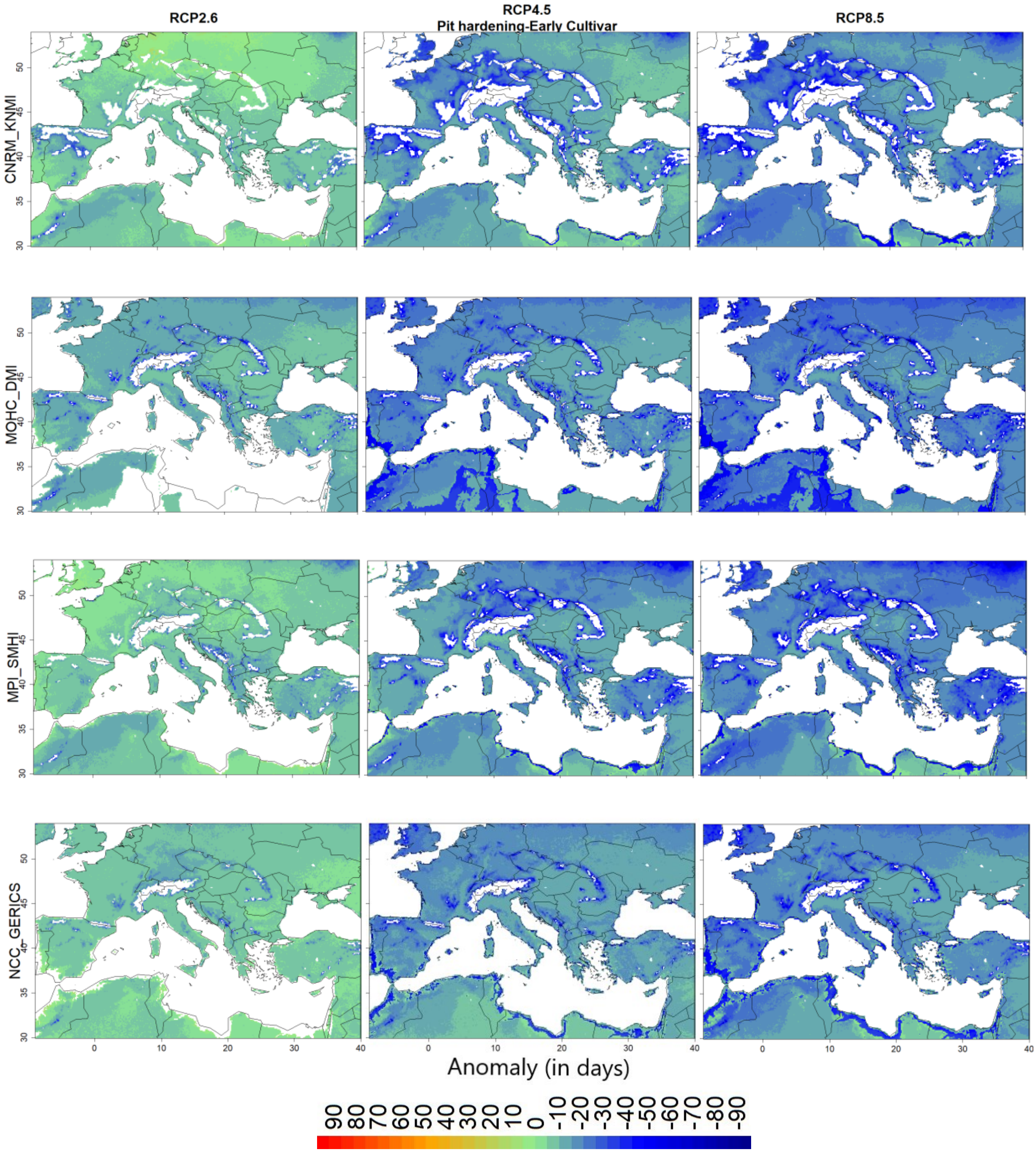
GCMs		RCMs	
Model	**Institute**	**Model**	**Institute**
CNRM-CERFACS-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	KNMI-RACMO22E	Royal Netherlands Meteorological Institute
MOHC-HadGEM2-ES	UK Met Office Hadley Centre	DMI-HIRHAM5	Danish Climate Centre at the Danish Meteorological Institute
MPI-M-MPI-ESM-LR	Max Planck Institute for Meteorology	SMHI-RCA4	Swedish Meteorological and Hydrological Institute
NCC-NorESM1-M	Norwegian Climate Centre	GERICS-REMO2015	Max Planck Institute for Meteorology



Appendix 2. Difference (in days) in timing of sprouting stage of early phenology olive cultivar between future (2036-2065) and historic (1976-2005) period per GCM_RCMs (CNRM_KNMI (top row), MOHC_DMI (second row), MPI_SMHI (third row), and NCC_GERICS (bottom row)) and RCPs (RCP2.6 (left column), RCP4.5 (middle column), RCP8.5 (right column)) to find out climate change signal over the study area (Note: Blank areas show unavailable values/phenology model failures).



Appendix 3 Difference (in days) in timing of blooming stage of early phenology olive cultivar between future (2036-2065) and historic (1976-2005) period per GCM_RCMs (CNRM_KNMI (top row), MOHC_DMI (second row), MPI_SMHI (third row), and NCC_GERICS (bottom row)) and RCPs (RCP2.6 (left column), RCP4.5 (middle column), RCP8.5 (right column)) to find out climate change signal over the study area (Note: Blank areas show unavailable values/phenology model failures).



Appendix 4 Difference (in days) in timing of pit hardening stage of early phenology olive cultivar between future (2036-2065) and historic (1976-2005) period per GCM_RCMs (CNRM_KNMI (top row), MOHC_DMI (second row), MPI_SMHI (third row), and NCC_GERICS (bottom row)) and RCPs (RCP2.6 (left column), RCP4.5 (middle column), RCP8.5 (right column)) to find out climate change signal over the study area (Note: Blank areas show unavailable values/phenology model failures).

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CHAPTER 3

Title:

"Phenological-based climate change hazard assessment for olive cultivation in the Euro-Mediterranean region"

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Ready for submission

Abstract

The Mediterranean is considered a region extremely prone to risks of global warming and extreme events due to climate change. Future conditions may disturb several traditional farming activities such as olive cultivation, which is one of the most widespread and strategic agro-economic activities for several Mediterranean countries. So, evaluation of future climate stressors relevant to olive crop development could be highly worthwhile to direct feasible agronomic and adaption practices mitigating climate change effects. This work aims to propound a comprehensive framework based on dynamics of olive phenological stages to evaluate intensification of future climate hazards over the whole the Euro-Mediterranean region. Phenological stages are projected by Chill, Anti-Chill, and Growing Degree Days combined model (i.e., CAC_GDD method) for early and mid-late olive cultivars using an ensemble of high-resolution climate projections at 0.11° from EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment) repository, through historical (1976-2005) and future (2036-2065) time frames under three representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5). A series of seven climate indicators are defined, based on three main variables (e.g., temperature, precipitation, and wind speed), to assess future signals of climate stressors during olive growth stages. The results showed significant future prolongation (up to 40 days) in pit hardening to the harvesting phenological stage together with increased frequencies of dry days, unfavorable windy days (up to 50 days) and extreme windy days (up to 5 days), and especially for early cultivars and under more pessimistic scenarios (i.e. RCP8.5). Frequencies of frost days (up to 4 days) and hot days (up to 10 days) ramp up in pre and post blooming stages for early and mid-late cultivars respectively, threatening current olive orchards during future period. Briefly, olive cultivations in the Mediterranean could be susceptible to intensified climate stressors under future changing climate mainly in blooming and pit hardening stages. Nevertheless, northern/cooler areas illustrated less climate-induced vulnerabilities in critical olive growing stages (e.g., blooming to pit hardening).

Keywords

Climate changes, Climate stress assessment, Olive phenology, CAC_GDD phenological model, The Euro-Mediterranean region.

1.Introduction

Olive (Olea europaea L.) is one of the oldest and more traditional evergreen trees characterizing vegetative landscape of the Mediterranean climate type and widely spread in semi-arid areas (Caracuta, 2020; Connor, 2005; Petruccelli et. al. 2022). Currently, olive is cultivated also in Australia, China, North and South America, South Africa, New Zealand, Japan, and India under climates with cold to mild winters and warm to hot summers, receiving most of precipitation portion in the cold months of year (Sanzani et al, 2012).

Olive also shows great capacity to grow in harsh environmental conditions, e.g., with water scarcity, variant daily-seasonally temperatures, high humidity (Fernández, 2014; Sanzani et al., 2012). However, climatic factors are restricting olive distribution worldwide, for instance not spanning in cold regions roughly above 45° latitude in northern and southern hemispheres (Fiorino and Mancuso, 2000). During the dormancy period, temperatures around -7 to -8°C may damage olive growth (Sanzani et al., 2012), while in summer time when temperature exceed 35 to 40°C, heat stress limits photosynthetic capacity along with reductions in stomatal conductance of olive trees (Haworth et al., 2018). Indeed, climate extremes, e.g., frequency of frost or hot days, wet or dry days, windy days, heavy precipitation days, etc. can impose some wrecking effects on olive growth in different phenological phases as well as the final yield. Meanwhile, yearly climate variability can impact olive cultivation system, drive disease outbreaks, pests and alternating bearing years (Fraga et al., 2021; Ali et al., 2014; Daane and Johnson, 2010; Sofo et al., 2018). Since, the Mediterranean region is considered a climate change hotspot and one of the most prone areas to global warming (Giorgi, 2006; IPCC, 2021), this situation may go on harshly over the future (MedECC, 2020, Hertig et al., 2013, Tanasijevic et al., 2014) by increasing intensity and frequency of climate extremes and advancing phenological timing due to warmer conditions affecting olive production in the Mediterranean basin (Fraga et al., 2021; Gabaldón-Leal et al., 2017; Mairech et al., 2021).

A research developed by Kaniewski et al., (2023) in the Levant region (a large area in the Eastern Mediterranean region) identified optimal conditions for olive blooming through paleoclimate analyses and showed that the climate/environmental extremes during the future decades will challenge olive cultivation under changing climate context.

Mairech et al. (2021) showed that, under different future climate scenarios, olive orchards will be highly impacted especially in the dry areas because of rainfall reduction and then water deficit. Although they found variant results over the study area, yield losses around 28% are expected over the Iberian Peninsula, while a 26% increase is expected in the central Mediterranean region.

In terms of climatic/environmental variables (e.g., water and carbon balance) influential on olive farming, a research by Mairech et al. (2020) indicated high relationship between their variability and olive yield. Other studies projected for future periods that increasing heat and evapotranspiration demand, rainfall deficit, changes in seasonal precipitations along with minimum and maximum temperatures will reduce olive yield over the Mediterranean (Koubouris et al., 2009; Rodriguez Diaz et al., 2007; Moriana et al., 2003; Iniesta et al., 2009; Galan et al., 2008; Rossi et al. 2020). Indeed, the future scenarios foresee rising temperatures that could lead to olive phenological earliness and also shortening of the growth stages (De Melo-Abreu et al., 2004; Gabaldon-Leal et al., 2017, Osborne et al., 2000; Giannakopoulos et al., 2009; Moriondo et al., 2008, 2010; García-Mozo et al., 2010), taking possible climate vulnerability on olive growth stages and consequently losses on its final yield.

A research developed by Tanasijevic et al. (2014), also illustrated significant future reduction of precipitation and increase of evapotranspiration demand, which can threat rainfed olive cultivations in the Mediterranean orchards. Some previous researches indicated that under future climate change the most vulnerable variables relevant to agricultural/horticultural crops, e.g., olive, would be biomass growth, crop evapotranspiration, phenological stages duration, water need and the final yield (Osborne et al., 2000; Pereira and De Melo-Abreu, 2009; Quiroga and Iglesias, 2009).

To assess climate risk for olive crop growth, agro-climatic indicators are deemed relevant independently for different phenological phases. Agro-climatic suitability models are also based on agro-climatic/ecoclimatic indicators to evaluate how the climatic conditions are favorable/unfavorable for a particular plant development process, or how they possibly barricade cultural practices during certain phenological stages (Caubel et al. 2015). For instance, increased frequency of dry days in olive sprouting stage is likely to decrease shoot development (Chartzoulakis et al. 2000; Xilayannis et al. 1999; Pierantozzi et al. 2013; Rapoport et al. 2012), and from pit hardening stage onward because of water stress the fruit production rate might diminish significantly (Beede and Goldhamer, 1994; Varol and Ayaz, 2012). Different temperature thresholds affect bio-physiologically olive growth. e.g., temperatures higher than 30°C reduce photosynthesis rate, higher than 35°C induce stomata closure, followed by limited gases exchange for photosynthesis and olive crop growth, and higher than 40°C pull in completely photosynthesis processes (Rallo and Cuevas, 2008; Benlloch-González et al. 2016; Ayaz and Varol, 2015). On the other hand, low temperatures and frost risks can damage olive tree`s shoot tip, foliation and branches bark respectively, depending on freezing intensities (Gucci and Cantini, 2001). Olive tree can suffer frost events in late winter, when cold hardiness may suddenly return after a limited exposure to higher temperatures (Kozlowski and Pallardy, 1997). Freezing temperature in early spring may likely damage olive`s young vegetation and bloom (Proietti and Regni, 2018). Windiness also impacts olive growth, as extreme winds can drop olive fruits and blooms and break shoots and young vegetation (Proietti and Regni, 2018). However, during all phenological phases of olive wind speed higher than 2m/s (Barranco navero, et. al., 2017) can disturb foliar treatments, and harvesting process. Intense rainfall during summer would damage olive growth and increase olive fly population (Di Paola et al. 2023). A research developed in north west of Arabi Saudi indicated that heavy rainfall events (on December 22, 1993, January 1, 1994, and October 17, 1997) damaged olive trees by sudden leaves defoliation, young trees destroying, and shoot tip burn respectively (Naser et la. 2018).

Under future climate scenarios the aforementioned climate indicators/extremes would be more intensified damaging increasingly olive crop (Moriana et al., 2003; Iniesta et al., 2009; Koubouris et al., 2009; Gabaldón-Leal et al., 2017; Rossi et al., 2020; Mairech et al., 2020 and 2021) in Mediterranean orchards. The impacts of climate extremes on olive crop can originate from abiotic (e.g., temperature, water availability, and weather extremes) and biotic (e.g., pests and diseases) parameters reducing yield quantity and quality (Sanzani et al., 2012; Fraga et al., 2021; Ponti et al., 2014; Bosso et al., 2016).

Previous studies projecting underlying climate indicators and climate extremes` risks to olive crop growth, mostly focused on temperature or water stresses (Haworth et al. 2018; Benlloch-González et al. 2016; Kaniewski et al. 2023; Lodolini et al. 2016; Mairech et al. 2021) without considering concurrent dynamics of successive phenological stages due to climate change with variyng sensitivity to climate stressors, and neither in a large spatial scale such as the Euro-Mediterranean region (e.g., Fernández, 2014; Di Paola et al. 2023; Kaniewski et al. 2023).

Hence developing a phenological-based study in a large environment to compare the relevant climate stressors` future intensity per olive cultivars, the phenological stages with dynamic length and in a large spectrum of bio-geographic zones is of high importance for olive cultivation and management of the field practices in future.

This investigation aims to develop a spatial analysis of agro-climatic stressors relevant to olive phenological stages under a changing future climate in various environmental stratifications of the Euro-Mediterranean region. To this end we consider three successive phenological phases (i.e., sprouting, blooming, and pit hardening) of early and mid-late olive cultivars for which to calculate the agro-climatic stressors (indicators), i.e., length of the phenological stages, frequency of dry days, hot days, frost days, heavy rainfall days, extreme windy days and unfavorable windy days. To find the climate change signal and effects on frequency of the agro-climatic stressors we calculated anomalies comparing historical to future scenarios.

2.Materials and Methods

2.1. Study area

Our study area encompasses the Euro-Mediterranean region from -10 to 40°E and from 30 to 54°N. Such wide area includes a large range of topography and bio-climate zones from extremely cold and wet to extremely hot and arid zones (Fig.1). The elevated mountainous regions (i.e., the Alps, the Pyrenees, and the Carpathians) characterized mainly by extremely cold and wet-mesic climates. The eastern and northeastern Europe, some highlands in northern Spain, south of France, central Italy, central and eastern Turkey show climate ranges of cold and mesic, cool temperate and dry-xeric. Typically, cool temperate and moist climate zones include western Europe and the foothills in central Europe. The Mediterranean basin mainly characterized by warm temperate and mesic-xeric climate types, and low lands of North Africa include hot to extremely hot and arid climates. Different bio-climatic zones or environmental stratifications are associated with unique climatic factors influencing physiological processes of plants that determine meanwhile environmental productivity (Leathwick et al., 2003, Metzger et al., 2013).

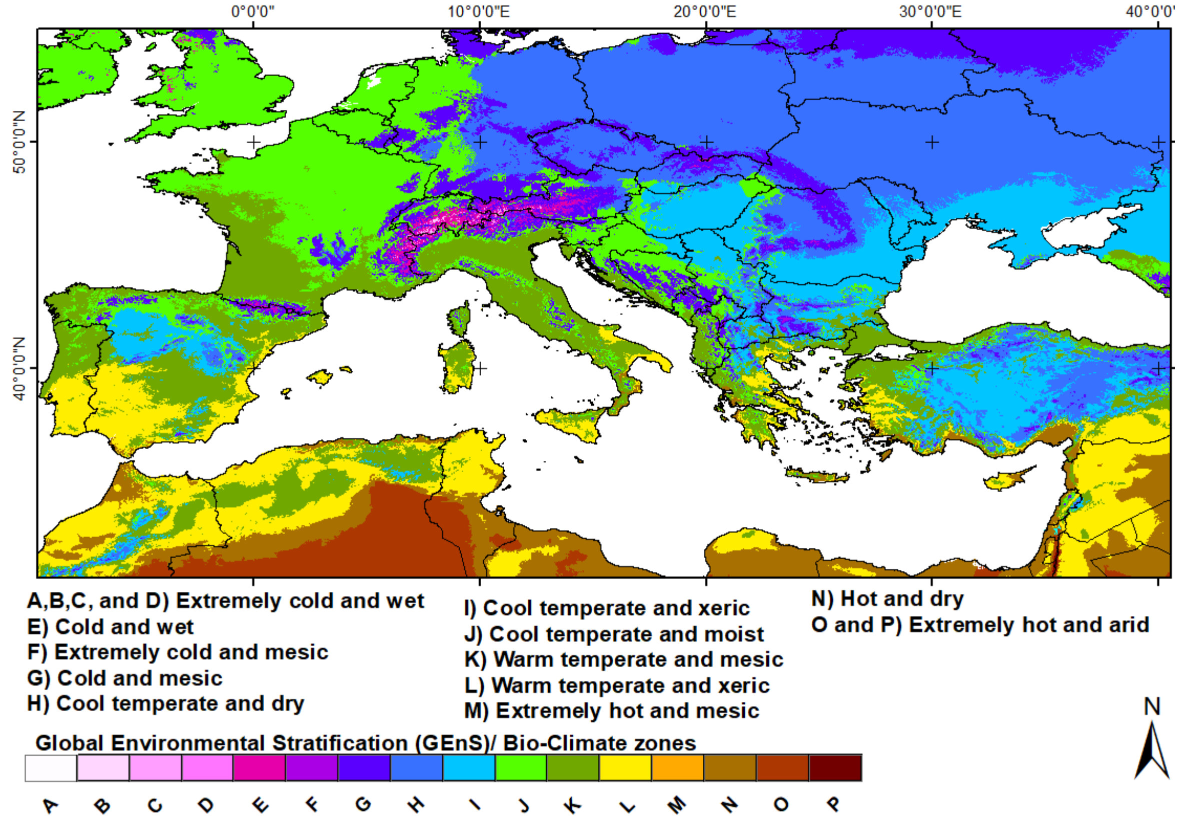

Figure 1. Study area including the Euro-Mediterranean region with the bio-climate zones derived from the global environmental stratification map (Metzger et al. 2013).

2.2. Data collection

The climate data time series include maximum and minimum near-surface temperatures (at 2m above the ground), mean precipitation flux (deposition of water to the Earth`s surface in the form of rain, snow, ice or hail) and wind speed (at 10m above the ground). The time series were collected from the EURO-CORDEX climate data repository (Jacob et al., 2014; Jacob et al., 2020) for the European domain at a spatial resolution of 0.11°, and with daily temporal resolution through dynamic downscaling with RCMs (Regional Climate Models) driven by GCMs (Global Climate Models). GCMs provide lateral boundary conditions to the regional models. The EURO-CORDEX experiment includes an historical period, for which recent climate observations exist. These experiments, that follow the observed changes in climate forcing, show how the RCMs perform for the past climate when forced by GCMs and can be used as a reference period for comparison with scenario runs for the future. The EURO-CORDEX ensemble of climate change projection experiments use different RCP (Representative Concentration Pathways) forcing scenarios. These scenarios include the RCPs 2.6, 4.5 and 8.5 providing different pathways of the future evolution of atmospheric greenhouse gas and aerosol concentrations.

We applied four model simulations as an experimental framework for different GCM_RCM combinations (i.e., CNRM_KNMI, MOHC_DMI, MPI_SMHI, and NCC_GERICS) (Table 1) for historic (1976-2005) and future (2036-2065) 30-year time frame periods under three RCPs (i.e., 2.6, 4.5, and 8.5). The data series (i.e., maximum and minimum temperatures, precipitation and wind speed) were arranged as yearly timeseries starting from November first of the previous year to the end of October over a window of -10-40°E and 30-54°N (Fig.3) and stored as NetCDF files. The spatio-temporal arrangement of the time series was aligned to the phenological model that starts from November first and ends to October 31st considered the usual beginning of the olive harvesting period (Barranco et al., 2017), over the Euro-Mediterranean region. The choice of a fixed date was necessary to perform onset from dormancy for the phenological model, indeed from that date the model starts to compute chill days. Furthermore, the same date was considered to separate different periods related to plant phenology and olive orchard management, which are affected to different climate stressors. The temperatures, and precipitation were converted respectively from Kelvin to degree Celsius, and from kg m^{-2} s^{-1} to mm3/d, but the wind speeds` unit was kept as it was in m/s. Values over the water bodies were removed. We used the CDOs (Climate Data Operators) to structure the basic time series, and calculated long-term daily average values of maximum and minimum temperatures, precipitation and wind speed over the study area for both historic and future 30-year periods. Spatial median values were calculated per GCM_RCM combinations of historic and future RCPs (Fig.2).

TABLE 1. Global and regional climate models (GCM and RCM respectively) considered in the investigation (Navarro-Racines *et al.* 2020).

GCMs		RCMs	
Model	**Institute**	**Model**	**Institute**
CNRM-CERFACS-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	KNMI-RACMO22E	Royal Netherlands Meteorological Institute
MOHC-HadGEM2-ES	UK Met Office Hadley Centre	DMI-HIRHAM5	Danish Climate Centre at the Danish Meteorological Institute
MPI-M-MPI-ESM-LR	Max Planck Institute for Meteorology	SMHI-RCA4	Swedish Meteorological and Hydrological Institute
NCC-NorESM1-M	Norwegian Climate Centre	GERICS-REMO2015	Max Planck Institute for Meteorology

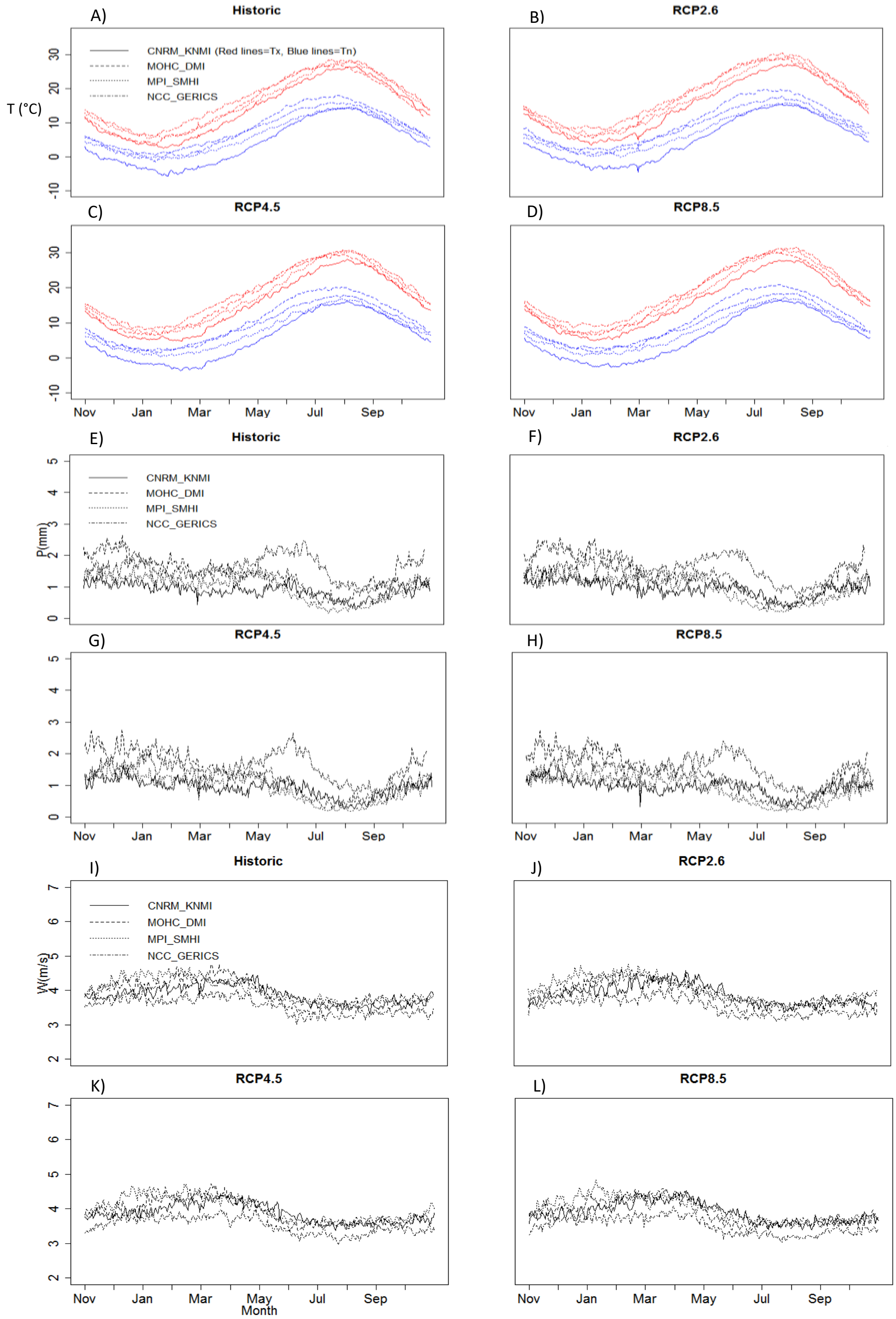

Figure 2. Daily spatial median values of temperatures (A,B,C,D) , precipitation (E,F,G,H), and wind speed (I,J,K,L) over Euro-Mediterranean region (from Nov.1st of pervious year to Oct. 31st) calculated using long-term daily mean values of 30-year periods of historical (1976-2005) and future (2036-2065) RCPs (2.6, 4.5, and 8.5) per climate model projections (e.g., CNRM_KNMI, MOHC_DMI, MPI_SMHI, and NCC_GERICS). The timeseries are derived from the Euro_CORDEX repository.

2.3. Olive phenological timing

Modeling olive phenology across a large range of bio-climate zones of the Euro-Mediterranean region will result in various olive phenological timing patterns. We applied the Chill, Anti-Chill (CAC) model (Cesaraccio et al., 2004) to project sprouting stage. CAC model is a sequential model, that accumulates chill units to meet the pre-defined chill requirement (Cr), and then anti-chill units during eco-dormancy stage to overcome the quiescence situation. The model is based on the single triangle degree day method (Zalom et al. 1983; Snyder et al. 1999) (Table 2). Temperature threshold (Tc) and chilling requirement (Cr), are two main parameters that the model needs, and they have been optimized and validated for each early and mid-late budbreak olive cultivars from previous study (Didevarasl et al, 2023; and Table 3). We implemented the CAC model in R programming language for a spatial analysis as a basis for subsequent steps. The model calculates the sprouting dates for each grid point and year over the study area.

TABLE 2 Chill days (Cd) and anti-chill days (Ca) equations for the six temperature conditions that relate the maximum (Tx) and minimum (Tn) temperature to the threshold temperatures Tc and 0°C, where Tm is the mean daily temperature.

Case	Temperature conditions	Chill days	Anti-chill days
1	0≤Tc≤ Tn≤ Tx	Cd=0	Ca=Tm-Tc
2	0≤Tn≤ Tc< Tx	$Cd=-[(Tm-Tn)- ((Tx-Tc)^2/2(Tx-Tn))]$	$Ca=((Tx-Tc)^2/2(Tx-Tn))$
3	0≤Tn≤ Tx≤ Tc	Cd=-(Tm-Tn)	Ca=0
4	Tn<0≤ Tx≤ Tc	$Cd=-[Tx^2/2(Tx-Tn)]$	Ca=0
5	Tn<0< Tc< Tx	$Cd=-(Tx^2/2(Tx-Tn))- ((Tx-Tc)^2/2(Tx-Tn))$	$Ca= ((Tx-Tc)^2/2(Tx-Tn))$
6	Tn<Tx<0<Tc	Cd=0	Ca=0

Newly presented CAC_GDD phenological model as a combined method (The Chill, Anti-Chill days_Growing Degree Days model) (Didevarasl et al, 2023) projects subsequent blooming and pit hardening stages using the sprouting dates estimated by CAC model as the initial date for heating accumulation. We used the GDD model (McMaster and Whilhelm, 1997) in the pollen library in R (Nowosad, 2021) for heating accumulation that requires temperature base (Tb), maximum temperature base (max Tb) and heating requirement (Hr) (Table 3).

GDD equation is as following:

1) $GDD = (Tx + Tn) / 2 – Tb$

Where, Tx is the daily maximum temperature, Tn is the daily minimum temperature, and Tb is the base temperature.

In our previous work (Didevarasl et al., 2023), the main parameters of CAC and CAC_GDD models were optimized using genetic algorithms (GA) package in R that requires the temperature timeseries (Tn, Tx, Tm), phenological observation data, and pre-selected lower and upper bounds of the model parameters (Tc:7 to 14, Cr: -80 to -200, Tb: 4 to 10, Tx: 25 to 35, Hr:300 to 1400) to be set into a specific developed function. Meanwhile, the performance of the models was calibrated and validated.

Again, in the previous chapter to project the phenological timing we implemented the phenological models by phenological phases, i.e. sprouting and blooming and pit hardening, for 3 RCPs and climate model simulations (four RCM combinations) within the Euro-Mediterranean region and over 30 years using the optimized parameters per early and mid-late budbreak cultivars (Table 3). Indeed, the phenological timing of every aforementioned combinations were projected in pixel levels. Through yearly projections we obtained dynamic lengths between the phenological stages per pixels, that might be unique for each olive cultivar.

TABLE 3. The optimized main parameters of chill anti-chill and growing degree-days phenological models by phenological stage and cultivar type (Didevarasl et al. 2023).

Phenological stages	Cultivar Type	Tc	Cr	Tb	Tx	Hr
Sprouting	Early	9.5	-115	-	-	-
	Late	11.2	-133	-	-	-
Blooming	Early	-	-	5.9	31.5	437
	Late	-	-	4.5	29.5	370
Pit hardening	Early	-	-	5.9	31.5	1074
	Late	-	-	4.5	29.5	1315

Note. Tc, estimated temperature threshold; Cr, estimated chilling requirement; Tb, estimated base temperature; Tx, estimated max temperature; Hr, estimated heating requirement.

2.4. Climate indicators

A series of seven climate indicators (stressors) more relevant to olive crops were considered including: Dry days; Extreme windy days; Unfavorable windy days; Frost days; Hot days; Heavy rainy days; and Length of the phenological phases. The indicators were selected according to their effects on specific growth stages (Fig.3). We considered the length between the consecutive phenological phases including sprouting to blooming (S-B), blooming to pit hardening (B-P), pit hardening to harvesting (P-H), harvesting to sprouting (H-S), and a short period of 15 days (7 days before and after specific phenological dates: sprouting (S7), blooming (B7), and pit hardening (P7)) over which the indicators were computed. We considered November first as an oproximate harvesting date from which chilling accumulations initiate in our phenological modelling. This way, we obtain a dynamic yearly phenological lengths as well as phenological dates with the corresponding indicators under historic (1976-2005) and future (2036-2065) climate scenarios (RCPs, 2.6, 4.5, and 8.5) using four GCM_RCMs (i.e., CNRM_KNMI, MOHC_DMI, MPI_SMHI, and NCC_GERICS), scaled up for the Euro-Mediterranean region.

The thresholds used for calculations, the rationale behind each indicator and the phenological phases used for were the following:

Dry days: the number of days when daily precipitation < 1mm (Cammarano, and Tian, 2018). Dry day frequency as a water stress indicator was computed for all consecutive phenological phases.

Extreme windy days: the number of days when daily averaged winds speed > 10.8 m/s (Reig-Gracia et al., 2019). In different growth stages of olive particularly when the trees are flowering and the drupes are ripening strong winds or storms may tear off blooms and leaves, damage branches and crops. So, we considered blooming to pit hardening and pit hardening to harvesting phases more vulnerable to this climate stressor.

Unfavorable windy days: the number of days when daily averaged winds speed > 2m/s (Barranco navero et al., 2017). Unstable windy situation relevant to disturbance of foliar treatments in olive orchards was computed for all consecutive phenological phases.

Frost days: the number of days when daily minimum temperature < 0°C (Schulzweida and Quast, 2015). Freezing temperature can damage tree`s shoot tips and blooms in late winter and early spring. This indicator was computed for two short phenological stages of ±7 days from sprouting and blooming dates, and from sprouting to blooming phases.

Hot days: the number of days when daily maximum temperature >31.5°C (for blooming to pit hardening phase and ±7 days from blooming date) (Didevarasl et al., 2023). The number of days when daily maximum temperature > 40°C (for ±7 days from pit hardening date) (Barranco navero et al., 2017). Higher temperatures in different growth stages particularly in spring and summer may restrict efficiency of olive growth. We computed hot day frequency for two short phenological stages of ±7 days from blooming and pit hardening dates, and from blooming to pit hardening phases.

Heavy rainy days: the number of days when daily precipitation ≥ 10mm (Cammarano, and Tian, 2018). Heavy rainfalls may damage olive tree`s flowers and crops if they are intensive during a short period of time. A short phase of ±7 days from blooming date and from pit hardening to harvesting were considered to this climate stressor.

Length of the phenological stages: the length/number of days between consecutive phases are computed, based on projection of the phenological dates. Shortening or lengthening of the periods between consecutive phenological phases may make olive crops vulnerable to climate stressors. All phenological phases (i.e. sprouting to harvesting) were considered for this index.

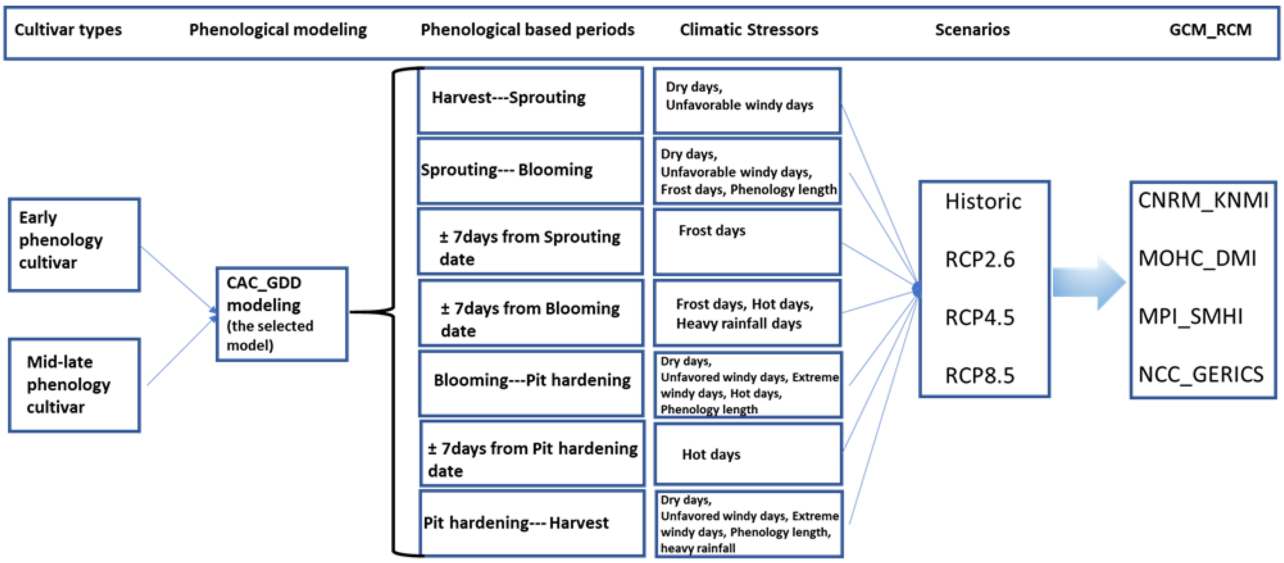

Figure 3. The research workflows and the analysis-process of the agro-climatic stressors based on the olive cultivar types, defined phenological time periods, historic and future timeseries, and the climate model projections. Over all there are 832 combinations (each agro-climatic stressor includes 32 combinations in every defined phenological period) to project agro-climatic stressors in the phenological periods over 30 years (historic: 1976-2005; future: 2036-2065).

After obtaining the yearly results from the calculation of climate indicators in a spatial scale over the Euro-Mediterranean region, long term mean values over 30 years for the historic (1976-2005) and future RCPs (2036-2065) by GCM_RCMs and cultivar types were calculated. In order to show the results concisely the averages from the four climate model projections (RCMs) were calculated. In the next step, to show the climate change signals through the indicators the anomaly values were computed subtracting the future RCPs from the historic (ANO= Future - Historic) per cultivars and RCPs over the study area.

3. Results

The spatial distributions of anomaly values show how climate indicators vary following projected climate change across phenological phases and RCPs. Some indicators, e.g., extreme windy days, frost days and heavy rainy days always show very narrow distribution although significant to enhance relevant climate risks (Fig. 4). Frequency of extreme windy days and heavy rainy days might show increasing values from pit hardening to harvest (up to 2 days). Regarding frost frequencies little increases in sprouting (±7 days from sprouting dates) and within sprouting to blooming phase were found. During blooming phase frost days anomalies decreased by one day on average. Also, early olive cultivars may indicate more frost days frequency (up to 1 day) comparing to the late cultivars.

Frequency of dry days, unfavorable windy days, hot days, and the phenological length show more stretched distributions with spatial median values mostly polarized (positive/negative) across the phenological phases and RCPs. Dry days anomalies from harvest period to sprouting decreased, on average, up to -7 days but with extremely deviated values. Whereas from sprouting to pit hardening decrease at maximum -1 to -2 days. However, during pit hardening to harvesting dry days anomalies increased to +12 days especially under RCP 8.5. Unfavorable windy days show also negative anomalies values over harvesting to sprouting (up to -9 days). During sprouting to blooming and blooming to pit hardening phases the median values are decreasing slightly up to -1 to -2 days. However, form pit hardening to harvesting phase the anomalies of unfavorable windy days increased around +11 days in RCP8.5.

Spatial median anomaly of phenological length illustrated a decreasing up to -2 days from sprouting to pit hardening. But during pit hardening to harvest period the median anomalies increased at maximum about +14 days under RCP8.5. The median anomaly values of hot days showed an increase by 1 to 3 days mainly in blooming to pit hardening stage, with very large positive deviance. But considering two short periods of ±7 days from blooming and pit hardening dates they illustrated median anomalies around zero however again with more positive deviations up to +3 days of increase.

Considering median anomalies (Fig. 5) usually early cultivars indicated higher increase in terms of climate stressors (around 2-3 days of median, or higher values with outliers) versus late cultivars, aligned to prolonging phenological phases particularly in pit hardening to harvest period. But the late cultivars might be more exposed to hot days mostly in blooming to pit hardening phase and in ±7 days around pit hardening dates. On the other hand, the frost days might hit more early cultivars in sprouting to blooming phase, and ±7 days around sprouting dates. The median anomalies of climate stressors illustrated higher values (e.g., ±1 to ±5 days) usually under RCP8.5 in comparison to other RCPs.

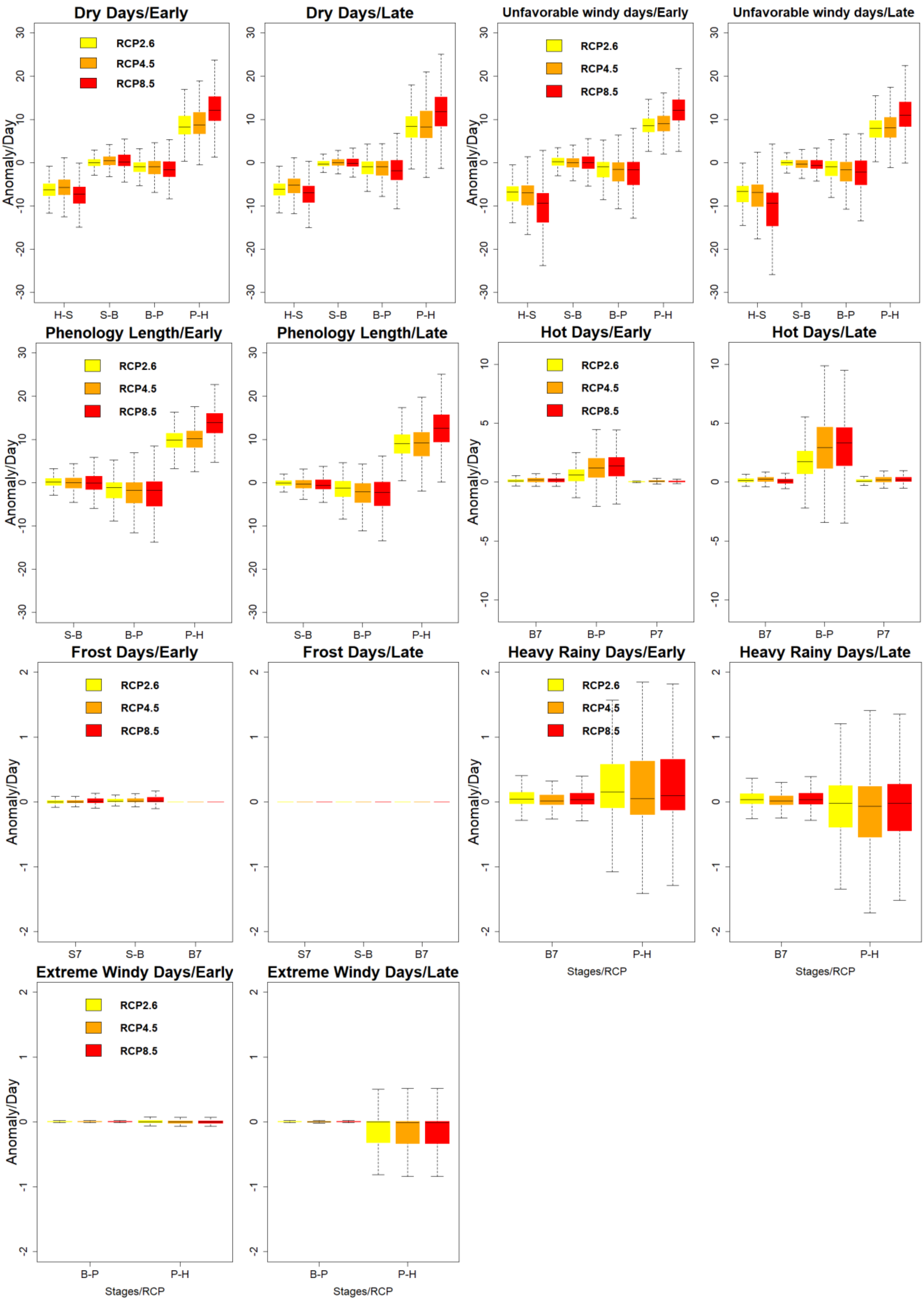
Dry Days/Early
Dry Days/Late
Unfavorable windy days/Early
Unfavorable windy days/Late
Phenology Length/Early
Phenology Length/Late
Hot Days/Early
Hot Days/Late
Frost Days/Early
Frost Days/Late
Heavy Rainy Days/Early
Heavy Rainy Days/Late
Extreme Windy Days/Early
Extreme Windy Days/Late
RCP2.6
RCP4.5
RCP8.5
Anomaly/Day
Stages/RCP
H-S
S-B
B-P
P-H
B7
P7
S7

Figure 4. Boxplots distribution of the anomaly values (in day) of estimated climate stressors (Respectively; Dry days, Extreme windy days, Unfavorable windy days, Frost days, Hot days, Heavy rainy days, and Length of the phenological phases) during different phenological stages (H-S; Harvesting to Sprouting, S-B; Sprouting to Blooming, B-P; Blooming to Pit hardening, P-H; Pit hardening to Harvesting, S7; ±7days from Sprouting, B7; ±7days from Blooming, and P7; ±7days from Pit hardening) of early and late budbreak olive cultivars by RCPs using average values from four RCMs. Anomaly values are derived as difference of climate stressors under future (2036-2065) and historic conditions (1976-2005) to highlight the climate change signals in terms of increasing/decreasing of climate stress over the Euro-Mediterranean region.

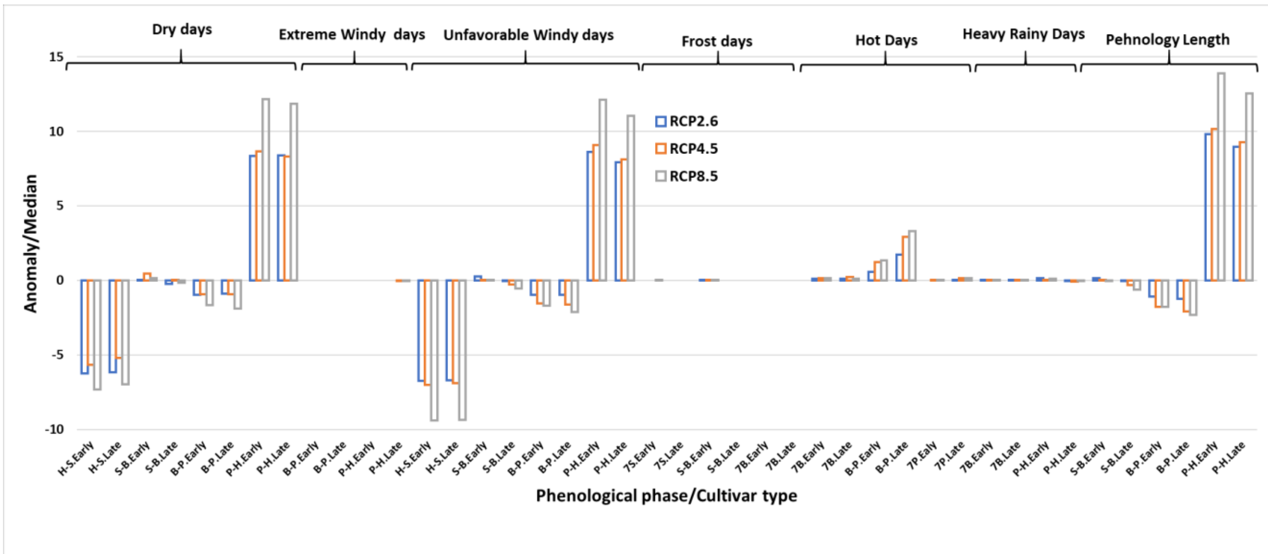

Figure 5. Spatial medians of long term mean anomaly values derived from the climate stressors per phenological stages (H-S; Harvesting to Sprouting, S-B; Sprouting to Blooming, B-P; Blooming to Pit hardening, P-H; Pit hardening to Harvesting, S7; ±7days from Sprouting, B7; ±7days from Blooming, and P7; ±7days from Pit hardening), the cultivar types (Early and Late) and RCPs (e.g., 2.6, 4.5 and 8.5) over the Euro-Mediterranean region.

While considering spatial anomalies of dry days frequency (Fig. 6) during autumn-winter season (harvesting to sprouting period), most parts of the study area illustrate for the future a decreasing number of dry day and particularly over northwestern Africa (-10 to -50 days), meanwhile over mountain regions, e.g. the Alps, the number of dry days increase remarkably (20 to 50 days). Through sprouting to blooming phase a limited anomaly of dry days is evident in the study area, with some decreasing, e.g. over Turkey`s eastern highlands and Carpathian Mountains (-10 to -20 days). Over blooming to pit hardening phase the northern regions and some eastern parts (e.g. Turkey) show slightly decreasing frequency of dry days (-10 to -20 days). But during pit hardening to harvesting period the number of dry days may increase mainly in southern and western Europe, North of Africa and Turkey (up to 30 days). Both early and late phenology olive cultivars present almost similar spatial patterns of dry days anomalies for the future period albeit slightly smaller anomalies in the late cultivar case over harvesting to sprouting and pit hardening to harvesting periods. Furtehrmore, highest anomalies of dry days is usually observed under RCP8.5.

Overall, future anomalies of extreme windy days (Fig. 7) show small changes in the study area (mainly from -1 to +1) through blooming to pit hardening as well as pit hardening to harvest period. However, in early sprouting cultivar during pit hardening to harvesting period in some limited zones mostly around sea shores of southern and southeastern Europe (e.g. the Strait of Gibraltar, Crete Island), northern Africa (e.g. in Tunisia) there are areas with substantial increase of extreme winds up to 5 days. For the late sprouting cultivar again during pit hardening to harvesting we found decreasing of extreme winds expanded mainly over northwestern Africa up to -5 days. RCPs don't indicate spatially very remarkable differences in the anomaly of extreme winds frequency.

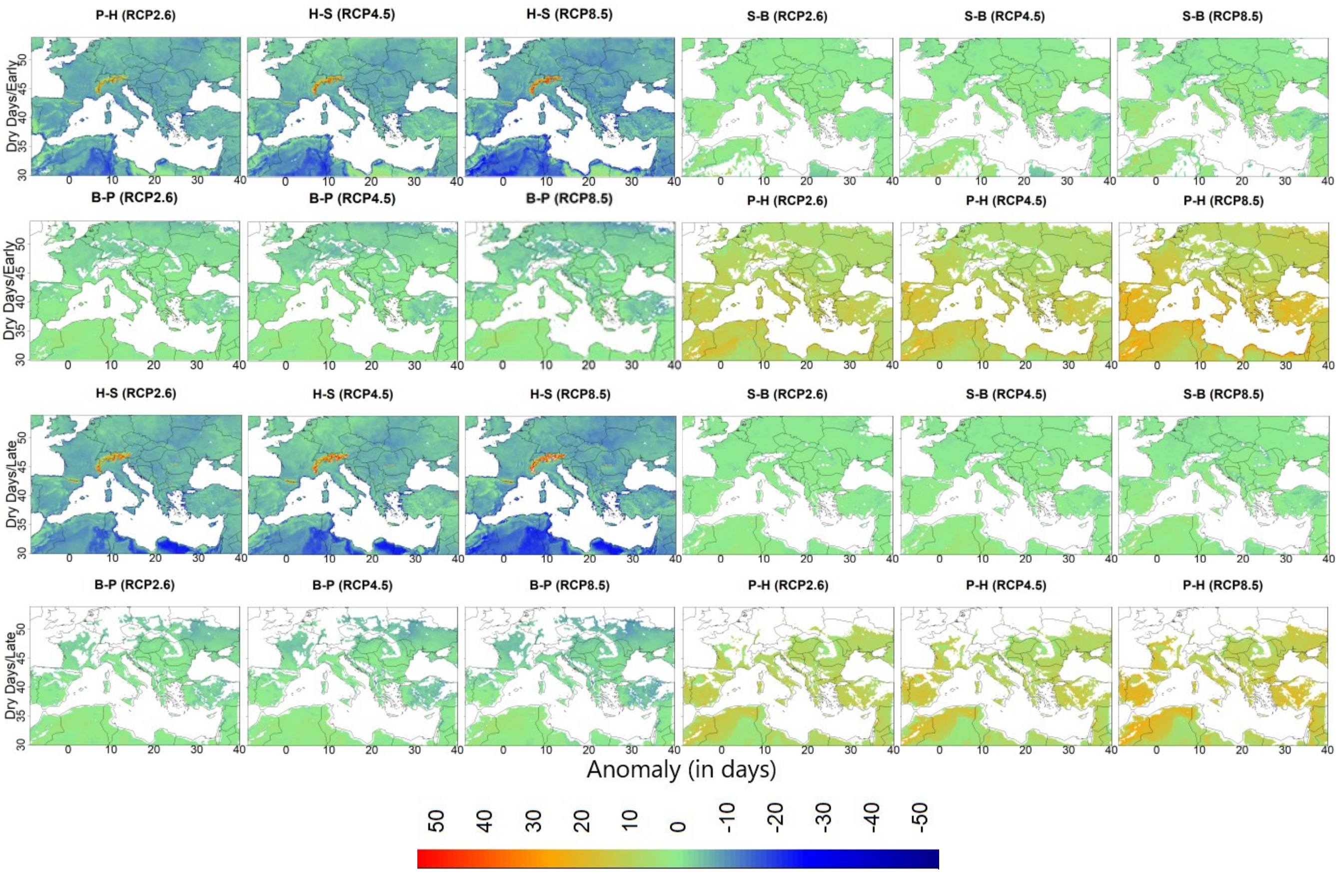

Figure 6. Difference in the number of dry days based on olive cultivar types (early phenology cultivar (first and second rows) and late phenology cultivar (third and fourth rows)), and the phenological phases including; H-S (Harvesting to Sprouting), S-B (Sprouting to Blooming), B-P (Blooming to Pit hardening), P-H (Pit hardening to Harvesting), between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

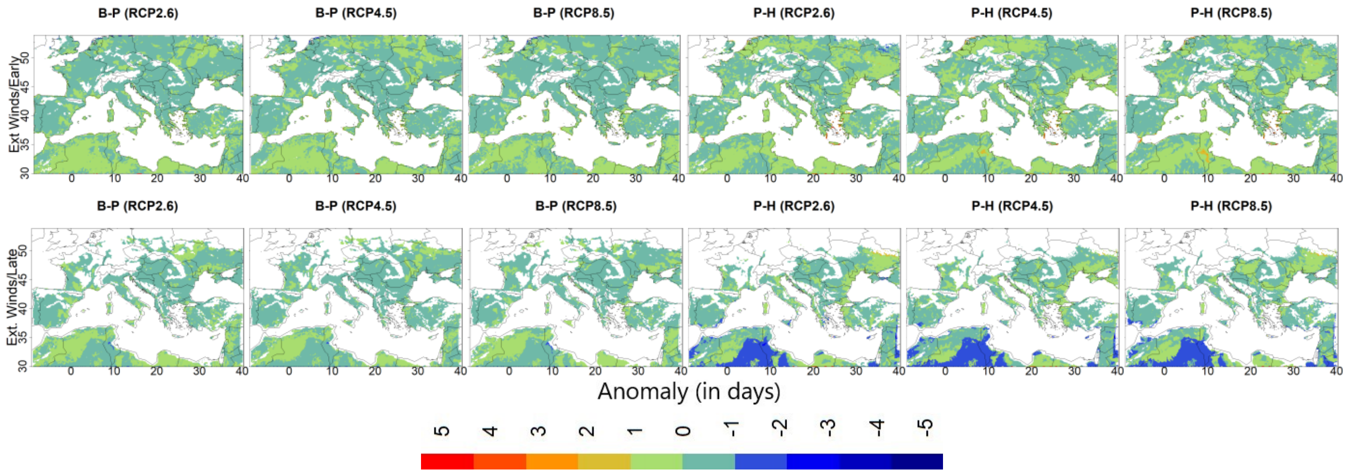

Figure 7. Difference in the number of extreme windy days based on olive cultivar types (early phenology cultivar (first row) and late phenology cultivar (second row)), and the phenological phases including; B-P (Blooming to Pit hardening), P-H (Pit hardening to Harvesting), between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

Anomalies of unfavorable windy days (Fig. 8) during harvesting to sprouting period illiustrate mainly relatively no change over most of the study area, however negative anomalies over southern and southwestern Europe, northwestern Africa and Turkey (-10 to -50 days) are evident in the future period. Instead, over mountainous areas (e.g. the Alps mountain chain) the number of unfavorable windy days would ramp up (20 to 50 days). Within sprouting to blooming phase unfavorable windy days show almost no difference. Meanwhile, negative anomalies are remarkable over western England, Turkey`s eastern highlands and Carpathian Mountains (-10 to -20 days). Through blooming to pit hardening phase, northern and some central and eastern parts of Europe show a decrease of unfavorable windy days (-10 to -20 days). On the other hand, in the pit hardening to harvesting period unfavorable windy days increase over several northern, southern and western regions of Europe, North of Africa and Turkey (around 30 days), while limited change showed in central regions. The spatial patterns of changes in unfavorable windy days illustrated considerable similarities for both early and late phenology olive cultivars with relatively smaller anomalies for the late cultivar in, e.g. blooming to pit hardening and pit hardening to harvesting periods. Higher anomalies are evident under RCP8.5 scenarios.

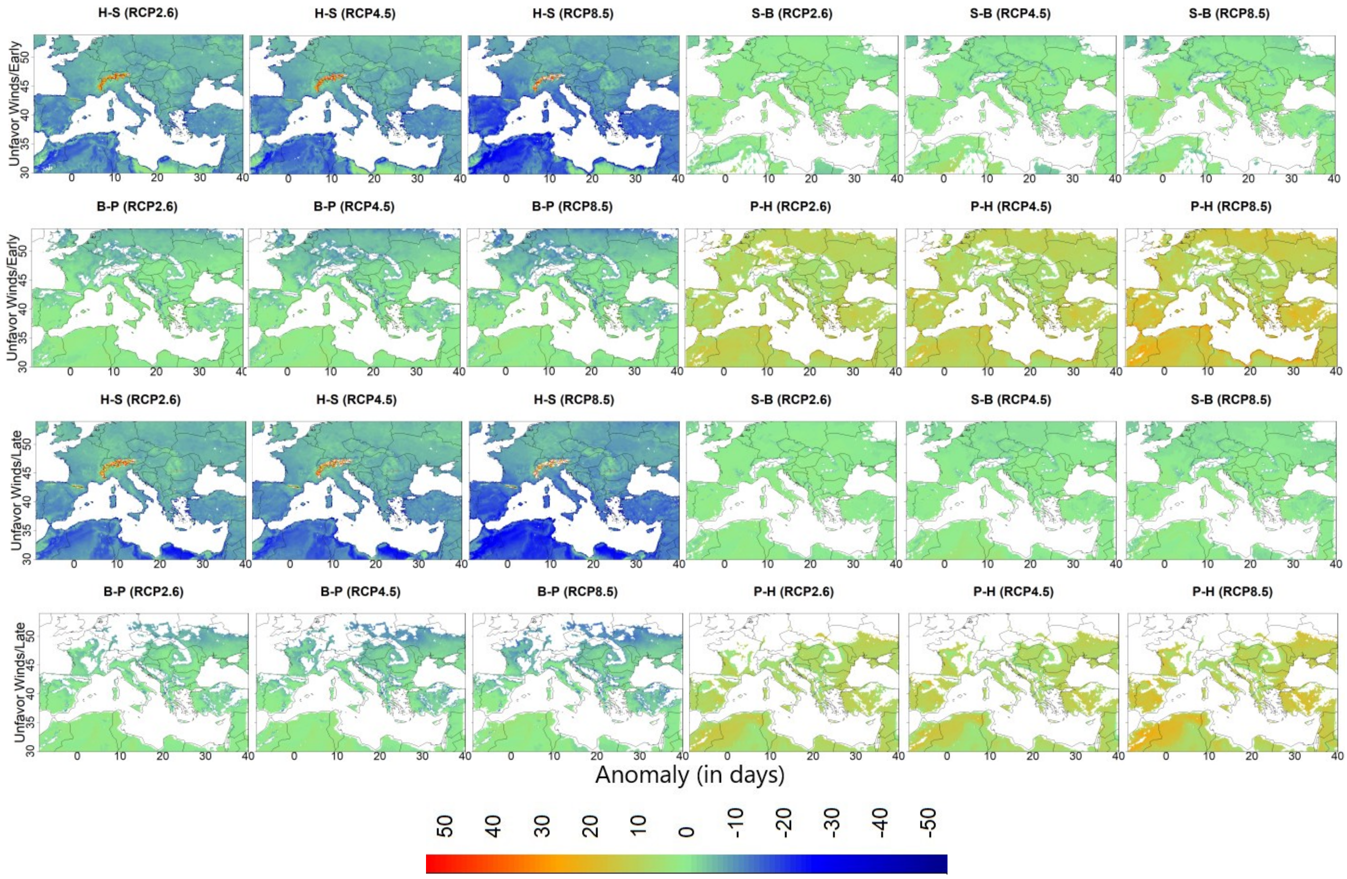

Figure 8. Difference in the number of unfavorable windy days based on olive cultivar types (early phenology cultivar (first and second rows) and late phenology cultivar (third and fourth rows)), and the phenological phases including; H-S (Harvesting to Sprouting), S-B (Sprouting to Blooming), B-P (Blooming to Pit hardening), P-H (Pit hardening to Harvesting), between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

The spatial distribution of anomaly of frost days for the study area is represented for early and late olive cultivars in Figure 9. Indeed, the early cultivars show more positively oriented anomalies spread-out spatially, albeit barely exceeding 1 day of increase during a short period of ±7 days from sprouting dates. However, in sprouting to blooming phase of early cultivar over some mountainous zones of northwest Africa a range of +1 to +4 days of frost days increase are projected under RCPs 4.5 and 8.5. In a short phase of ±7 days from blooming dates mainly the study area illustrates negative trend of frost days anomalies (around -1 day). On the other hand, regardless of the phenological phases, the late cultivar indicate greater decrease of frost days (around -1 day) for the future period in a spatial scale.

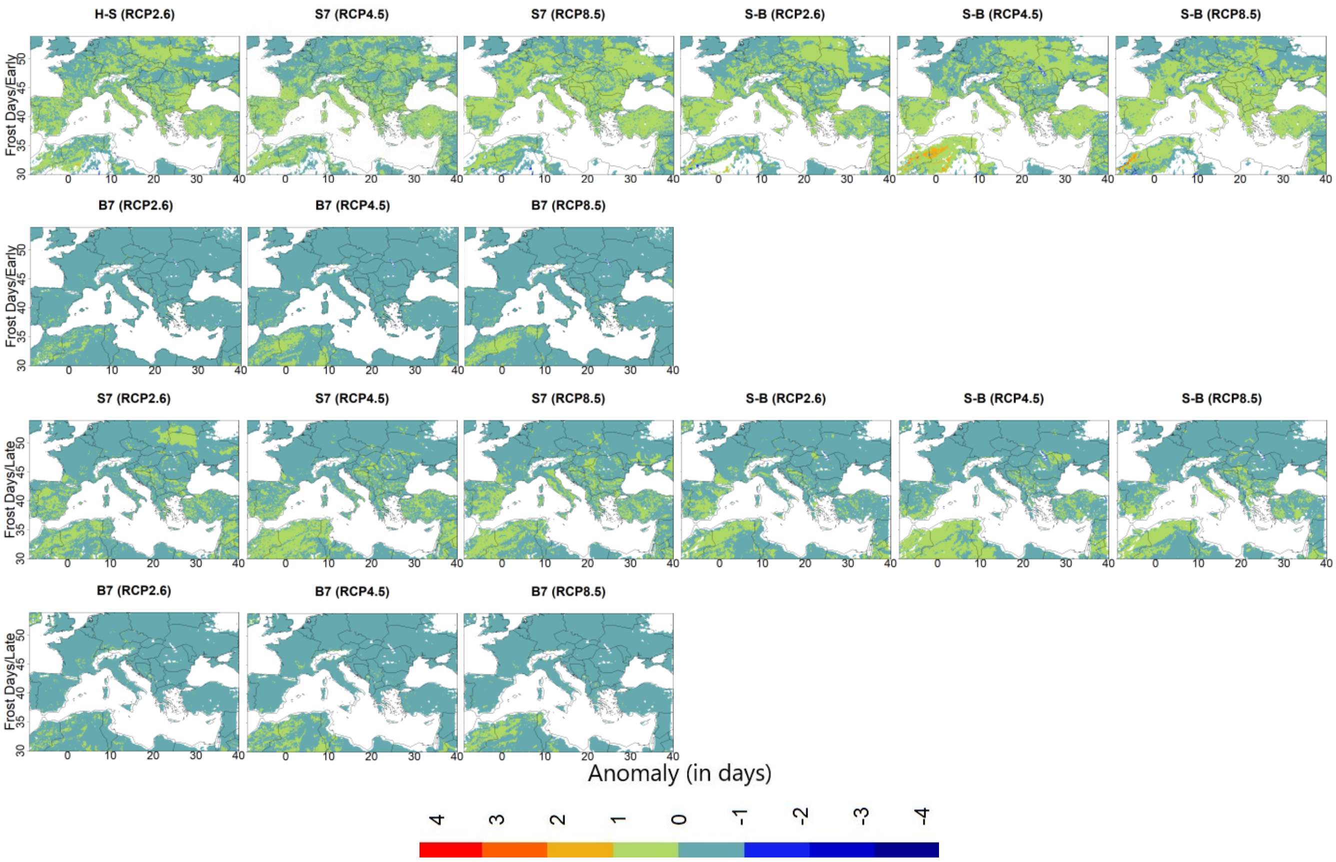

Figure 9. Difference in the number of frost days based on olive cultivar types (early phenology cultivar (first and second rows) and late phenology cultivar (third and fourth rows)), and the phenological phases including; S7 (±7 days from sprouting dates), S-B (Sprouting to Blooming), and B7 (±7 days from blooming dates), between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

Future spatial anomalies of hot days (Fig. 10) foresee an increase around 1-2 days during the short phase of ±7 days from blooming dates on averageover the study area. During the blooming to pit hardening phase the number of hot days ramp up to 10 days over southern, central and eastern parts including, e.g. Spain, Italy, eastern Europe, Turkey, and some zones in northern Africa. Meanwhile negative anomalies (up to -10 days) are found somewhere around northern Africa, and southern Spain. In a short period of ±7 days around pit hardening dates increasing number of hot days (mainly 1-2 days, and in late cultivar in some limited zones up to 5 days) are evident for most of the study area, with exception for northern regions and some mountainous zones. RCP8.5 scenarios provide higher anomalies in the future (e.g., around double of those from RCP2.6) particularly during blooming to pit hardening phase, which has a widespread increasing signal, and blooming phase of late cultivar over southern Spain and northwestern Africa with remarkable decreasing signals (up to -10 days). Late cultivars in general and remarkably in blooming to pit hardening phase showed greater increasing anomalies, equivalent to more than double compared to the early one.

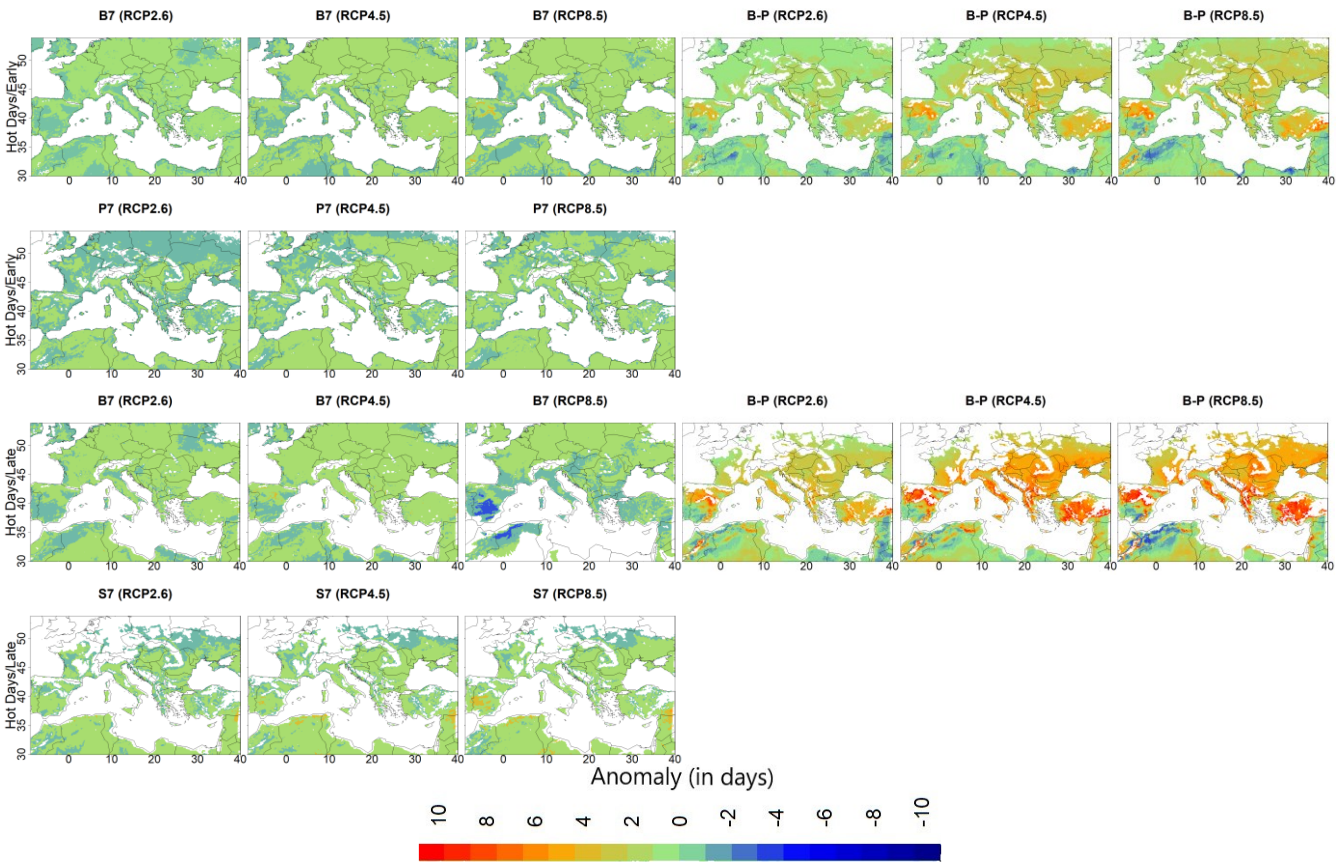

Figure 10. Difference in the number of hot days based on olive cultivar types (early phenology cultivar (first and second rows) and late phenology cultivar (third and fourth rows)), and the phenological phases including; B7 (±7 days from blooming dates), B-P (Blooming to Pit hardening), S7 (±7 days from sprouting dates) between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

Future anomalies of heavy rainy days (Fig. 11) during the short phase of ±7 days from blooming dates indicate widespread increasing signal around 1-2 days mainly in the study area. During the longer period between pit hardening and harvesting a future spatial pattern of heavy rains anomaly appears over the study area with decreasing signal in the western and southern parts (up to -10 days), more marked in western regions on Portugal (and some limited zones of northwestern Africa for the late cultivar), and increasing signal over the northern areas (around 5 days). Generally, regarding the heavy rains anomaly there are not remarkable differences between cultivars and RCPs in the spatial scale.

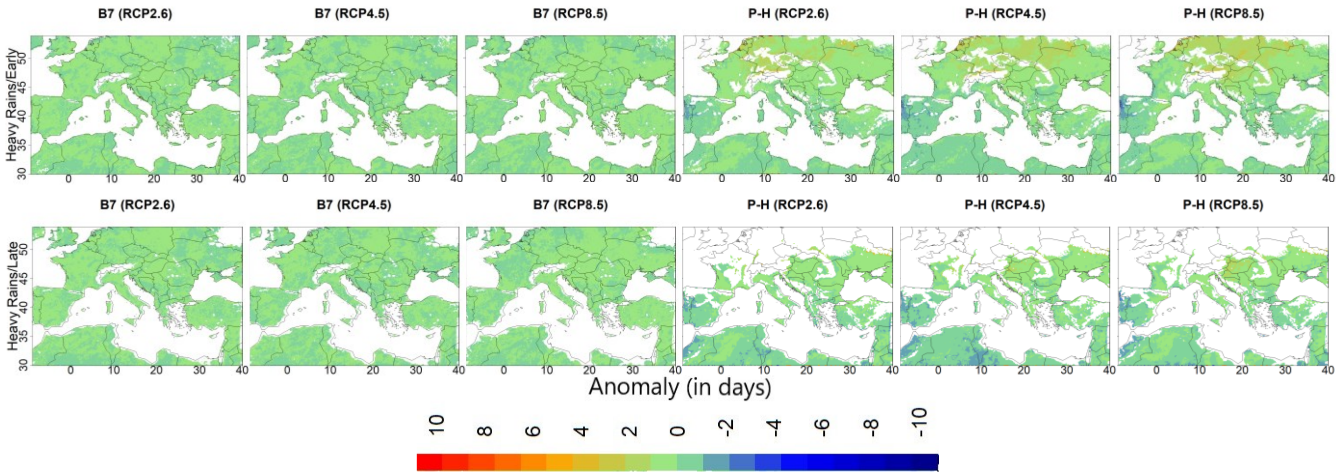

Figure 11. Difference in the number of heavy rainy days based on olive cultivar types (early phenology cultivar (first row) and late phenology cultivar (second row)), and the phenological phases including; B7 (±7 days from blooming dates), P-H (Pit hardening to Harvesting), between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

Spatial anomalies of phenological length (Fig. 12) for the future in sprouting to blooming phase illustrated mainly neutral situation (anomalies around zero) in the study area. However, some decreasing signals (up to -20 days) over northern areas and some mountainous regions (e.g., the Carpathian Mountains) and slight increasing (around 10 days) over southern areas (e.g., northern Africa, and Spain) are evident. In blooming to pit hardening phase northern and cooler areas mostly showed decreasing anomalies/shortening of the phenological phase (-10 to -30 days), but in southern regions/current olive growing areas the neutral situation or very slight increasing were found. On the other hand, positive signal /lengthening of pit hardening to harvesting period (around 10 to 30 days) was obviously dominant throughout the study area particularly under RCP8.5 over southern Europe and northern Africa around sea shores and low lands. Comparing early and late olive cultivars there is in general similarity between them in term of phenology length changes in the spatial scale. However, regarding pit hardening to harvesting phase the late cultivar showed less phenology lengthening than the early one.

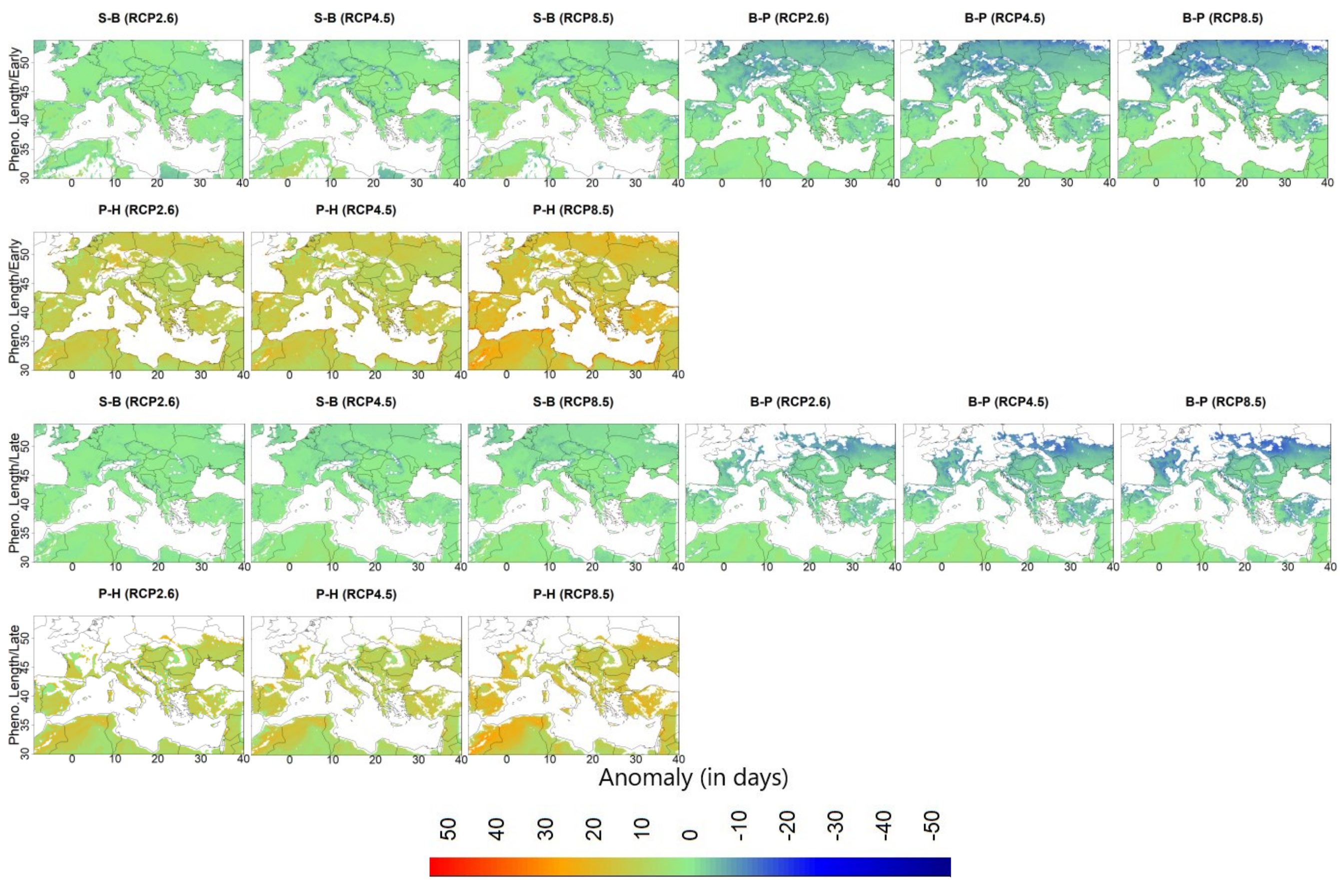

Figure 12. Difference in the phenological length based on olive cultivar types (early phenology cultivar (first and second rows) and late phenology cultivar (third and fourth rows)), and the phenological phases including; S-B (Sprouting to Blooming), B-P (Blooming to Pit hardening), P-H (Pit hardening to Harvesting), between future (2036-2065) and historic (1976-2005) periods per RCPs (2.6, 4.5 and 8.5). (Note: 1. Plots derived from long term mean values of four RCMs, 2. Blank areas show unavailable values/phenological model failures).

4. Discussion

This research integrates an evaluation of climate stressors using seven indicators framed within the olive phenological stages. While previous studies mostly focused on single sites/countries (Mafrica et al. 2021; Fernández, 2014; Di Paola et al. 2023; Kaniewski et al. 2023) and single indicators (Haworth et al. 2018; Benlloch-González et al. 2016; Kaniewski et al. 2023; Lodolini et al. 2016; Mairech et al. 2021), our work develops a comprehensive framework to project a climate risk assessment under different future climate scenarios and model projections over various phenological stages for early and late phenology olive cultivars in a large spatial domain including the Euro-Mediterranean.

Overall, considering future climate change risks through climate indicators, the period between pit hardening and the harvesting season (i.e. summer to early autumn period) might be more prone to climate stress aligned with the lengthening of this phase because of remarkable future earliness of the pit hardening dates/stage in the study area. Some indicators, e.g., dry days and unfavorable windy days, show increasing signal from olive pit hardening dates to November 1st particularly under RCP8.5 (>10 days of median value). Simultaneously extreme windy days and heavy rainy days show higher positive outliers as well. This period includes ripening stage of olive crop in which the climate projections, in accordance to our findings, anticipated remarkable decreasing in precipitation amount (dry days increase) for the Mediterranean (Brito et al. 2019; Stocker et al. 2013). Limited water availability for plants/olive trees because of reduced precipitation or lower penetration rate of water into soil especially in extreme rainfall events after a long period of drying condition, will make leaves senescent and fall off (Farooq et al. 2012). This situation may restrict olive canopy photosynthesis (Taiz and Zeiger, 2006) as well as nutrient uptake (Silva et al. 2011). Since water availability after pit hardening affects positively several quality parameters of table olives, like fruit firmness and flesh to pit ratio, as well critical drupe growth for oil accumulation rate (Sánchez-Rodríguez et al., 2019; Deiana et al., 2023), according to future scenarios, irrigation will assume even stronger importance in olive orchard management. Reports issued by IPCC (2021) and Kreienkamp et al. (2021) both confirmed our finding in increasing frequency of heavy rainfall days during summer that could lead to flooding with consequent damages on agriculture, plant growth and crops. A previous investigation by Outten and Sobolowski (2021) on future wind projections over European domain, indicated increase in wind speed particularly over the Mediterranean region. However, due to the highly turbulent nature of extreme winds which occur seldom and climate model`s limitations, the future projection of extreme wind speed is still associated with high uncertainties. Intense wind and rainfall events, albeit happening rarely may damage olive crops harshly, breaking thin and young branches, and causing drupe drop (Proietti and Regni, 2018; Di Paola et al. 2023 and Naser et la. 2018).

The phenological phase between blooming to pit hardening (i.e. spring to summer) period sounds to be more subjected to enhanced hot days' frequency in the future. Under RCP8.5 and late phenology olive cultivar, we found increasing hot days anomaly (>3 days of median value). In accordance to our result, previous studies (e.g., Molina et al. 2020; Perkins-Kirkpatrick and Gibson, 2017; Georgoulias et al. 2022; Sánchez et al. 2004) indicated an increase in hot days/heat waves frequency and intensity for future period over the Mediterranean environments. Another more olive-specific research by Gratsea et al. (2022) in a Mediterranean environment (i.e., Spain) showed an increase of >4 days in hot days frequency during near future period (2031-2061) for olive flowering stage in spring time.

High temperatures, above 30 °C during flowering may cause production losses caused by reduced fertility of pollen and pistil abortion (Benlloch-González et al., 2018). Intensifying hot days, in addition to higher evapotranspiration rate leading to plant`s water need increase, could cause early flowering which might be connected to higher risk of olive pests and diseases (Ribeiro et al. 2009). Higher summer temperatures also may boost olive ripening which, lead to shrinking fruit`s size and weight (Garcia-Inza et al. 2014). Heat stress may affect photosynthetic CO2 assimilation and also adversely affect plant water use by increasing Gs (stomatal conductance) H2O level (Bunce 2000; Urban et al. 2017).

In the short period around sprouting and during sprouting to blooming phenological phase (i.e. late winter and early spring) future frost days frequencies show slightly positive signal (about 1 day increase as median value). Indeed, rare nature of frost events shows a limited increase mainly for the early cultivars. However, other previous studies indicated reduced number of frost days on an annual scale under future RCPs over southeastern Mediterranean (Charalampopoulos and Droulia, 2022; Georgoulias et al. 2022). Another study in the European domain (Leolini et al. 2018) projected a future decrease of spring frost events mainly in western areas, while increasing in central Europe. On the other hand, advancing phenological phases due to global warming shifts the exposure of crops to spring frosts to earlier period (late winter), when possible freezing nights are still risky (Vroege, et al. 2021). According to Valverde et al. 2020, in late winter mostly over cooler and mountainous regions with Mediterranean climate regimes where the olive trees are growing, frosts may damage olive tissues which could cause knot disease. Frost occurrence around flowering stage may increase shotberry incidence leading to unusual low growth of fruit resulting from parthenocarpy (Koubouris et al. 2010). Indeed, frost damage leads to physical disturbance of cell structures, followed by fruit dehydration (Pearce, 2001).

Spatially over the Euro-Meditteranean domain, phenological length as temporal range between projected phenological dates illustrated quite variability acording to the different phenological stages. During sprouting to pit hardening phases mainly the study area shows limited anomalies, indicating very aligned changes in the consecutive phenological dates (sprouting and pit hardening) for the future period. However, considering different climate zones over the Euro-Mediterranean some northern and cooler regions show slightly decreasing length between sprouting and blooming, while warmer climate regions in southern and western parts witness almost no anomalies or little increases. Through blooming to pit hardening stage diverse future patterns emerged dividing northern and cooler climates with decreasing length from southern and warmer/temperate climates with neutral changes. This situation indicates unequal future shifts in the consecutive phenological dates (e.g. blooming and pit hardening) in the northern areas, namely pit hardening experiences greater earliness than blooming resulting in shorter length. However, in warmer climates the phenological shifts of two consecutive phases seem to be about equal. Changes in the spatial pattern of phenology length are quite different for pit hardening to harvesting stage, where a remarkable lengthening is projected throughout the study area intensified under RCP8.5 and in southern areas (e.g. including the Mediterranean and northern Africa coastal zones). This finding confirmed consistent earliness in olive pit hardening phase under future scenarios, because of warming conditions leading to faster GDD accumulations. Both early and late cultivars indicate very similar spatial patterns in terms of future changes in phenological length. Previous researches (e.g., Alcamo et al. 2007 and Pérez-López et al., 2008) projecting earliness in olive flowering phase and consequent lengthening of the growing season confirmed our findings. Also, other studies (Orlandi et al. 2013 and Grillakis et al. 2022) estimate future advances in GDD accumulation in southern/Mediterranean regions and confirm our findings in lengthening the growing season from pit hardening to harvesting by accelerated advances in pit hardening dates.

During harvesting to sprouting phase (including the cold months of year), reduced frequency of dry days and high precipitation for the future is widespread over the study area except for some mountainous regions, e.g., the Alps and the Pyrenees where future projections show an increase in dry days. For northern Africa and central Europe, a decrease in the future of dry days is more highlighted. Some reports relevant to climate change effects in European domain confirmed our findings by indicating increase of precipitation rate in winter time for the future (Bülow, K. 2019; Pörtner, H.O. 2022 and IPCC WGII, 2001). Sufficient precipitation in cold period can increase soil water content protecting olive trees from water stress. In the following phenological stage from sprouting to blooming (including late winter and spring time) a neutral signal of dry days frequency for the future over the entire study area was evident. However, from blooming to pit hardening phase most northern regions show decreasing frequency, while southern parts witness a neutral situation or slightly dry days increase. On the other hand, over pit hardening to harvesting period (mainly summer time to November) a dominant trend of increasing dry days is evident and in particular over southern areas and in the Mediterranean basin. Brito et al. 2019, Stocker et al. 2013 and Bülow, K. 2019, also confirmed our finding, indicating a general decrease in precipitation during summer time over southern Europe. This situation in ripening phase of olive crop could intensify water stress in olive growing regions affecting negatively the crop growth and quality (Taiz and Zeiger, 2006; Farooq et al. 2012; Silva et al. 2011).

The frequency of extreme windy days shows a slight future increase over some parts of the study area, rarely exceeding 1 day of increase. However, over pit hardening to harvest stage (summer to autumn period) in some southern costal zones in the Mediterranean basin, where olive orchards are common, an increase of extreme wind events up to 5 days are projected for the future. This situation could threaten olive growth by breaking branches and dropping the fruits before reaching enough maturity (Proietti and Regni, 2018; Di Paola et al. 2023 and Naser et la. 2018). Instead, unfavorable windy days, which may disturb agronomic treatment process in olive orchards, e.g., application of pesticides that could occurr within all phenological phases, shows a spatially widespread decreasing or neutral trend over the study area during harvesting to sprouting and sprouting to blooming phases. However, from pit hardening onward (during ripening period) the future increase of windy days is dominant over the study area and highlighted around most typical olive regions across the Mediterranean basin. Nevertheless, wind projection under different RCPs and climate models shows high uncertainty. A previous study (e.g., Outten and Sobolowski, 2021) confirmed our findings indicating a future increase of wind speed in southern Europe, while instead few others (Donat et al. 2011 and Outten and Esau, 2013) show future decreasing wind speed over the Mediterranean. Most of these studies confirm increasing wind speed over Northern Europe during summer to autumn period, in line to our finding. Meanwhile, the spatial patterns show overall similarity among early and late olive cultivars.

Future frost days in the Euro-Mediterranean are expected to increase by 1-day particularly over regions currently characterized by olive orchards around the Mediterranean basin. More risky situations are found for early cultivars over a short period around sprouting and between sprouting and blooming phases, while late cultivar may expect a more limited increase of frost days. Thus, under future climate change scenarios in Mediterranean environment the early phenology cultivars would experience greater phenological advances than late cultivars, and therefore may incur in enhanced frost day risk in early spring threatening olive blooms and its young leaf and branches. Other studies (Moonen et al. 2002; Bootsma, 1994) have previously shown an extension in growing season due to delay of autumn frosts and earliness in spring frosts under climate change, resulting in advances in plant`s phenological phases (e.g., sprouting and blooming), which may take frost risks in earlier period (Huang et al. 2021) as our finding illustrated for early olive cultivars.

On the other hand, projected future frequencies of hot day indicate widespread increase over the study area through spring and summer phenological phases for both olive cultivars. These findings are in line with some previous studies for Mediterranean environment (e.g., Gratsea et al. 2022; Molina et al. 2020; Perkins-Kirkpatrick and Gibson, 2017; Georgoulias et al. 2022; Sánchez et al. 2004). Blooming to pit hardening phase (i.e. spring to summer) will witness an intensification of hot days frequencies under future scenarios, markedly for most of the Mediterranean environment and olive growing areas. The late cultivars` spatial patterns indicated greater future occurrence of hot days than for early one, over several typical olive growing areas, mainly in Turkey, Greece, Italy and Spain. Despite frost days risk on early cultivars during pre-blooming stage, hot days stress would hit the late olive cultivars in post-blooming phase, namely during the fruit growth and ripening stage when fruit size would be negatively affected by dehydrating process (Garcia-Inza et al. 2014; Bunce 2000; Urban et al. 2017).

Heavy rainy days frequencies during future period indicated around an increase by 2 days throughout the study area, including most Mediterranean olive growing regions, in blooming phenological stage (spring season). In summer to autumn period (from pit hardening phase onward) most northern European regions show an increase of heavy rain events, while southern and southwestern areas (e.g. Portugal) foresee a decreasing trend. Previous studies (e.g., IPCC 2021 and Kreienkamp et al. 2021) also indicated an increase of heavy rainfall days during the warm months of year in accordance to our finding. Extreme rain events in such sensitive phases of olive growth could lead to breaking of olive flowers, fruits and leaf directly (Proietti and Regni, 2019; Di Paola et al. 2023). Both cultivars and future scenarios illustrated very similar spatial patterns, for each phenological phases possibly because rare nature of extreme rain events.

5. Conclusion

Present investigation introduced a comprehensive framework to assess the future signals of climate stressors during critical phenological phases of olive crops in a large environment, e.g., the Euro-Mediterranean, comparing two olive cultivars` spatial patterns under different future RCPs and climate model projections. The pit hardening stage indicated remarkable advances under future climate change projections in the study area leading to widespread lengthening of olive ripening period aligned to increased climate stressors, e.g., dry days, unfavorable windy days, extreme windy days and heavy rainy days. This situation confirmed olive ripening period would be highly subjected to future climate risks over the study area including typical olive orchards with very low differences among RCPs and olive cultivars.

Temperature based indicators, e.g., frost days and hot days were highlighted over the study area during sprouting to blooming and blooming to pit hardening phases respectively for the future period. Early phenology olive cultivars showed higher future vulnerability to frost events in late winter-early spring stage versus the late cultivars which would be frequently affected by hot days in mid spring-summer stage, intensified under RCP8.5. Both climate stressors could be threatening mainly for olive blooms, but considering next phenology stage solely hot events may damage early stage fruit growth.

Overall the Mediterranean environment, where most olive farming regions are present, would expect significant climate stress under future climate change scenarios along with the projected shift/earliness in different olive phenological stages. But northern and cooler regions mainly during blooming to pit hardening stage would show less climate vulnerability than the other parts. On contrary, considering cold months of year for pre-sprouting period, a remarkable decrease in the future for both dry days and unfavorable wind frequencies are expected over almost entire study area, protecting olive trees from water stress in spring season and facilitating treatment practices in the orchards respectively.

Our findings confirm that climate change effects on olive growth would be considered mostly negative, despite some possible positive aspects in the Mediterranean environment, where future olive cultivations are expected to face restrictions resulting from advances in olive phenological phases along with intensified climate stressors. In order to achieve a brighter future perspective of olive cultivation, comparing a wider range of phenological phases, cultivars, climate variables, and climate model projections using various phenological and crop models may bring up deeper insights through upcoming investigations.

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General Conclusion

This investigation introduced a comprehensive framework through an innovative modeling applicable to simulate and project consecutive phenological phases of two types of olive cultivars, evaluating future climatic vulnerability of olive cultivations, under future climate change scenarios in a large spatial scale including Euro-Mediterranean region. This approach provides a general management tool for the decision-makers and olive producers throughout the study area. We presented a combined method (CAC_GDD) to project olive phenological phases (i.e., Sprouting, Blooming, and Pit hardening) and compared results using a more complex and data demanding model (PhenoFlex). Under our experimental conditions, over a large Mediterranean environment with scarce and scattered observations, the CAC_GDD modeling, with lower parameter demand and simple approach demonstrated reliable performance compared to the PhenoFlex model to generalize the phenological projections at regional scale. Both models performed relatively better for mid-late than early budbreak cultivar. The mid-late budbreak representatives thermally were more adaptable than early cultivars to cold climate when considered sprouting. Still, they could also adapt to warmer climates by anticipating earlier blooming dates. The CAC_GDD model could project phenological phases over a large area illustrating the olive phenology spatial pattern. The model only failed to accurately project phenological dates over very high lands (i.e., in the Alps mountain region). Indeed, the model failures occurred only when daily maximum and minimum temperatures were beyond the thresholds.

The spatial modeling showed widespread earliness in olive phenological timing throughout the study area in the future, exacerbated by higher warming (e.g., RCP8.5), confirming the influence of increasing temperature on phenological advances. Nevertheless, the cold climate zones over mountains (e.g., the Atlas Mountains) and northern/northeastern Europe showed greater future phenological earliness, implying a manifestation of a more suitable thermal conditions for olive growth and consequently, a possible shift from the current olive growing regions, unless limited by other environmental constraints to physiological processes.

A general agreement between climate model projections over most of the study area would predict almost certain risks linked to phenological advances in the Mediterranean olive orchards and, conversely the emergence of thermal favorability to olive growth over the colder zones. However, comparing the late and early budbreak cultivars, we conclude that the late cultivar, will be more resistant to warming in the present olive-growing regions of the Mediterranean basin (showing less phenological advances) and more adaptable to the thermal conditions in the northern cold areas (showing more phenological advances) during the future period.

Assessment of future agro-climate stressors for the projected phenological phases indicated widespread lengthening of the pit hardening to harvesting phenological stage in the study area aligned to increased climate stressors, e.g., dry days, unfavorable windy days, extreme windy days and heavy rainy days. This situation would confirm that the olive ripening period will be highly subjected to future climate risks particularly in current olive orchards with remarkable association among RCPs and olive cultivars. However, early phenology olive cultivars showed higher future vulnerability to frost events in late winter-early spring/sprouting-blooming stage versus the late cultivars which would be frequently affected by hot days in mid spring-summer/blooming-pit hardening stage, intensified under RCP8.5. Overall the Mediterranean environment would be significantly subjected to agro-climate stress under future climate change scenarios a long with the projected earliness in different

olive phenological stages. But northern and cooler regions mainly during blooming to pit hardening stage would show less climate vulnerability than other regions.
Our phenological-based climate risk evaluation approach will support olive producer's response to future climate change through resilient strategic management of olive cultivation, varietal choice, cultural practices, and mitigating climate-induced stressors based on the reliable projections of different phenological stages in a large spectrum of environmental stratifications. CAC_GDD phenological modeling is capable to support scaling up spatially to a larger region, e.g. the Euro-Mediterranean, to display the environmental differences in phenological projections under future climate change scenarios. It is noteworthy, our findings are only obtained from a single temperature-based phenological modeling, and other than the temperature which, is however the primary driver of plant phenology, there are other ecological parameters affecting the suitability of olive growth in different environments, e.g., soil characteristics. Hence, in order to achieve a brighter future perspective of olive cultivation over the Euro-Mediterranean, comparing a wider range of phenological phases, cultivars, climate variables, and climate model projections using various phenological and crop models may provide deeper insights through upcoming investigations.

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