ORIGINAL ARTICLE

Climate change impacts on winter chill in Mediterranean temperate fruit orchards

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Abstract

Temperate trees require low temperatures during winter and subsequent warm conditions in early spring to flower and eventually bear fruit. Many parts of the Mediterranean region feature winters with low and sometimes marginal chill accumulation. To assess historic and future agroclimatic conditions for cultivating temperate trees (including almonds, pistachios, apricots, sweet cherries and apples), we mapped winter chill throughout this important growing region. We used on-site weather records (1974–2020) to calibrate a weather generator and produced data for historic and future scenarios. To broaden our analysis, we spatially interpolated chill for the whole Mediterranean basin. We supplemented our simulation outcomes by collecting expert knowledge (from farmers and researchers) regarding observed climate change impacts on temperate orchards as well as future risks and concerns generated by climate change. Results showed that northern African growing regions have experienced major chill losses, a likely cause of the irregular and delayed bloom highlighted by experts. The same regions, together with southern Europe, may lose up to 30 Chill Portions by 2050 under a moderate warming scenario. For the future, experts foresee increasing risk of spring frost in early-blooming cultivars, exacerbated bloom-related problems and increasing occurrence of heat waves. Our results provide evidence of likely climate change impacts on temperate orchards. Expert knowledge proved instrumental in interpreting the simulation results as well as in orienting climate change adaptation strategies. The results we present are useful for farmers and orchard managers planning new plantings, as well as for researchers and policy makers developing strategies to adapt fruit orchards to the impacts of climate change.

Keywords Chill requirements · Climate change · Tree dormancy · Warm winters · Chill maps · Future scenarios · Temperate fruit trees

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Communicated by George Zittis

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Introduction

Temperate fruits are produced worldwide in temperate as well as Mediterranean climate regions. Temperate fruit species represent a key component of economic development and food security for many developed and developing countries. The area surrounding the Mediterranean Sea is among the largest production zones of temperate fruits in the Northern hemisphere (FAOSTAT 2022). Sweet cherry, almond, pistachio, apricot and apple are some examples of relevant temperate trees cultivated in the Mediterranean area. In addition to the Mediterranean basin, temperate fruit trees are cultivated in other Mediterranean climate regions, such as the Central Valley of California, some regions of Australia, the Central Valley of Chile and South Africa (Darbyshire et al. 2011; Luedeling et al. 2011a; ODEPA 2017). Temperate fruit production in the Mediterranean area is, however, threatened by rising temperatures due to global warming (Benmoussa et al. 2018; Campoy et al. 2011; El Yaacoubi et al. 2014). According to Cherif et al. (2020), annual mean temperatures in the Mediterranean basin are already 1.5 °C above pre-industrial levels, and increasingly dry environmental conditions have been observed in recent decades. Drought periods and rising temperatures can greatly affect physiological processes within trees, including bud initiation and differentiation, winter dormancy, flowering, fruit set and fruit development (Campoy et al. 2011; El Yaacoubi et al. 2014; Lopez et al. 2006). Such processes are critical for achieving economically sustainable yields in temperate orchards, making the assessment of climate change impacts on temperate fruit production a crucial task for future orchard planning.

Temperate fruit species (e.g., almonds, pistachios, apricots, sweet cherries and apples), which originate from temperate climates, exhibit a dormancy period during winter. Throughout dormancy, trees remain visually inactive until environmental conditions are adequate for growth (Fadón et al. 2020; Luedeling 2012). To overcome dormancy and be able to flower, trees require low temperatures during a first stage of dormancy and subsequent warm conditions during a second phase (Campoy et al. 2011; Faust et al. 1997; Luedeling 2012). These two phases of dormancy are known as endo- and eco-dormancy (Benmoussa et al. 2017a; Guo et al. 2015; Lang et al. 1987; Luedeling et al. 2013). Although the precise nature of the link between these phases remains unclear, some research suggests that the endo- and eco-dormancy phases may partially overlap (Harrington et al. 2010; Pope et al. 2014). Whereas trees need to accumulate a cultivar-specific amount of chill during endo-dormancy, during eco-dormancy they require exposure to cultivar-specific levels of heat (Luedeling 2012). Once both the chill and heat requirements of trees are fulfilled, bud burst and subsequent bloom can take place. These agroclimatic requirements to overcome dormancy can be estimated either experimentally through chilling-forcing experiments (Campoy et al. 2019; Fernandez et al. 2019; Ruiz et al. 2007, 2018) or statistically by analyzing long-term phenology data sets (Benmoussa et al. 2017a; Delgado et al. 2021b; Fadon et al. 2021; Fernandez et al. 2021b). Knowledge on the specific agroclimatic requirements of cultivars can help farmers and practitioners in the decision-making process when managing orchards or planning new investments.

Whereas the need for heat units during dormancy appears to be secured in a context of global warming, the requirement of cool conditions presents a challenge for many temperate orchards. Insufficient chill in temperate species may produce irregular and heterogenous bud burst, leading to problematic pollination and fruit set, and lowering yield potentials (Erez 2000). Chill requirements of trees may become a limiting factor under future scenarios in many regions, including the Mediterranean (Benmoussa et al. 2020; Delgado et al. 2021a; Egea et al. 2022; Fraga and Santos 2021; Rodriguez et al. 2021). In fact, some impacts of these challenging conditions on temperate fruit production have already been observed. For instance, a number of studies have shown that, compared to the past, the onset of flowering has advanced in response to rising temperatures in central and southern Europe, Asia and Oceania (Bartolini et al. 2019; Darbyshire et al. 2017; El Yaacoubi et al. 2014; Menzel et al. 2006). Regarding chill accumulation, Luedeling et al. (2011a) highlighted that whereas cool regions (such as Germany) are expected to experience largely stable chill accumulation, mild-winter climates may be severely affected by global warming. Future climate projections suggest that the greatest winter chill losses can occur in regions such as the Mediterranean basin, the Central Valley of California, southwestern Europe, central Chile, and the Cape region of South Africa (Delgado et al. 2021a; Fernandez et al. 2020a; Luedeling et al. 2009b; Midgley and Lötze 2011; Rodríguez et al. 2019). Compared to the levels observed in 2018, Benmoussa et al. (2020) projected a decline in chill accumulation between 18 and 26% for various regions across Tunisia by 2055 under the Representative Concentration Pathway (RCP) 4.5 scenario (which represents a likely temperature increase between 1.1 and 2.6 °C compared to pre-industrial conditions; IPCC (2014)). In southern Spain, Rodríguez et al. (2019) forecasted a likely decline in chill accumulation by between 15 and 30 Chill Portions (CP; according to the Dynamic model; Erez et al. (1990); Fishman et al. (1987a); Fishman et al. (1987b)) when comparing the near future (period 2021–2050) under the RCP4.5

scenario to the period 1976–2005. Although the recent studies by Benmoussa et al. (2020) and Rodríguez et al. (2019) have provided useful insights for specific regions of the Mediterranean basin, a more general analysis of the whole region may provide additional guidance to farmers trying to adapt their orchards to the impacts of climate change, as well as to other actors aiming to support such adaptation.

Implementing climate change adaptation strategies presents a considerable challenge for farmers and practitioners. Such strategies (e.g., changing cultivars or even species in the case of temperate orchards) may often imply radical decisions that farmers hesitate to make due to cultural or market-related reasons, or simply due to personal preferences (Nguyen and Drakou 2021). Considering expert knowledge, i.e., experiences by local farmers and practitioners, may help in providing suitable adaptation strategies to the impacts of climate change in agricultural systems. Local experts can provide useful information on the perception of climate change impacts as well as on prior, current and future challenges and risks. According to Nguyen and Drakou (2021), climate change perception and awareness were among the most relevant factors for explaining farmers' willingness to adopt sustainable agricultural practices in Vietnamese coffee orchards. Expert knowledge from relevant stakeholders has been used in the past through Decision Analysis approaches in studies from a number of fields (Do et al. 2020; Rojas et al. 2021; Ruett et al. 2020). Expert knowledge representing the perception of farmers from different regions around the Mediterranean Sea about climate change impacts is likely to help in framing the results of empirical analyses on historic as well as future weather scenarios.

The main aim of this study is to provide an overview of chill accumulation in the Mediterranean region for historic and future climate scenarios. We analyzed historic conditions (observed and simulated scenarios) using on-site records from 357 weather stations and projected future climate settings based on two RCP scenarios (RCP4.5 and RCP8.5) by 2050 and 2085 using 15 General Circulation Models (GCMs). We applied an interpolation procedure (Fernandez et al. 2021a) to map winter chill accumulation (in terms of Chill Portions) across the Mediterranean region. We collected expert knowledge to contextualize the results of the spatial analysis and represent the perception of farmers and practitioners about the impacts of climate change as well as foresee future challenges and risks regarding temperate fruit production in the Mediterranean region. This collection of expert knowledge was conducted within an international project spanning Germany, Spain, Morocco and Tunisia, and complemented with information from national research programs (see "Funding" section).

Materials and methods

Weather data collection

We identified 5000 weather stations within the Global Summary Of the Day database (GSOD 2021) that were located in the Mediterranean basin. We filtered this list of weather stations to retain those with records starting before 1974 and ending after 2020. Additionally, we excluded from the analysis all weather stations located north of 48°N and south of 25°N to narrow the analysis to the Mediterranean basin only. After applying these filters, we retained 792 weather stations, for which we downloaded temperature records from the GSOD database. After downloading, we retained all weather stations containing complete data for at least 90% of days within the study interval (1974–2020) for minimum and maximum temperature. This process reduced the dataset to 374 weather stations, with a mean data coverage of 97% for minimum and maximum records (430 and 427 missing days out of 17,167 intended records, respectively). Due to a lack of weather stations complying with the data coverage requirement in some areas of northern Africa, we included 13 weather stations from Libya and Egypt that only had complete records for between 70 and 87% of days for minimum and maximum records. The final set of 387 weather stations (Fig. 1) was used as primary source of data for further analyses (see Table S1 in the supplementary materials for additional information on all weather stations).

Gap-filling procedure

We filled the gaps in the primary weather stations following the procedures described in previous studies (Buerkert et al. 2020; del Barrio et al. 2021; Fernandez et al. 2020b) with some modifications. In brief, we used data from auxiliary weather stations to fill the gaps in the records from our main weather stations after correction for between-station biases. These auxiliary sources of data were 712 weather stations (from the same database) showing at least 20% of data coverage for minimum and maximum temperature between 1974 and 2020. To correct for between-station biases, we compared the records from the primary weather stations to each of the 712 auxiliary data sources for all days for which data were available for both stations. For minimum and maximum records, we computed the mean difference and standard deviation of the difference relative to the primary weather stations. We excluded auxiliary weather stations showing a mean difference greater than 3 °C for both metrics to retain only representative sources of data. After sorting the list of auxiliary weather stations according to mean difference, we filled the gaps in
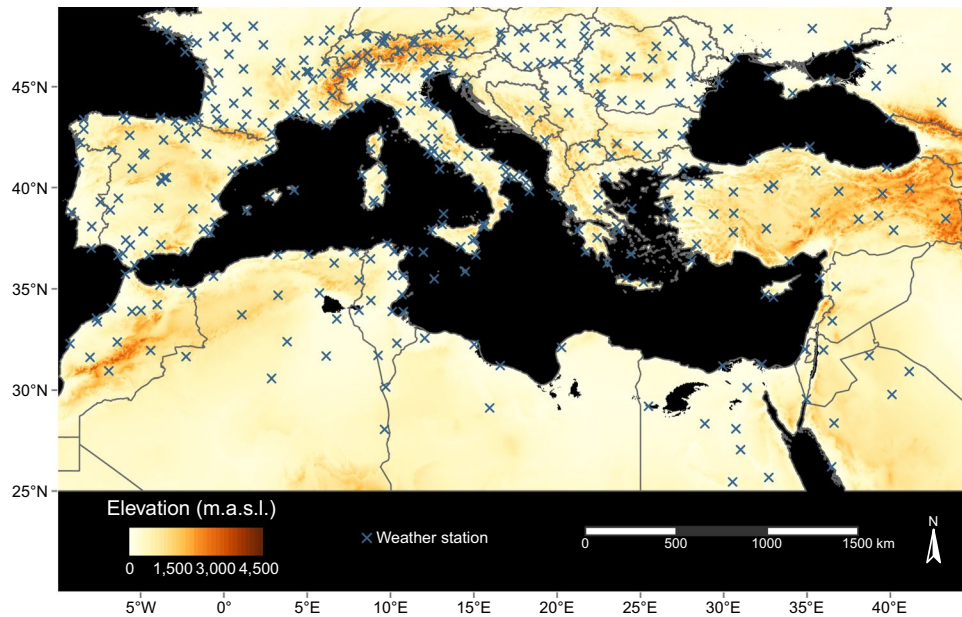
Fig. 1 Map of the Mediterranean basin displaying the elevation profile of the region and the 387 weather stations found at the beginning of the analysis. Note that further steps of our analysis (including the comparison of data from different sources) reduced the number of weather stations used for interpolation to 346. In the figure, the yellow-to-red legend represents the elevation above sea level (in meters) according to the Amazon Web Services Terrain Tiles database, whereas the blue crosses show the specific location of the weather stations according to information from the Global Summary Of the Day database

the primary data set with data from the auxiliary weather station after subtracting the mean difference computed for each metric (minimum and maximum temperature). This process was implemented for each primary station using one auxiliary source of data at a time until no more alternative weather stations were available.

Since the auxiliary weather stations still provided insufficient data to fill the gaps in some of the main stations, we implemented a second approach to fill the remaining gaps using data from the Prediction Of Worldwide Energy Resources (POWER 2021) project led by NASA. We first downloaded records of daily temperature extremes from the NASA POWER database for the locations of the 387 primary weather stations. This database contains gridded historic data for the time between 1981 and 2020. We then filled the remaining gaps in the primary data set with data downloaded from the NASA POWER database after applying our bias correction procedure. In this version of the patching procedure, we computed the bias correction as the mean difference between databases for the same location (mean difference for minimum and maximum records between GSOD and NASA POWER). Since we were using data from the same locations but from different sources, we did not set a bias threshold to exclude weather stations for this stage of the gap-filling procedure. Our two gap-filling approaches resulted in 24 weather stations showing about 100 missing days. After removing these stations, we retained 363

sources of temperature data showing a maximum of 25 and 45 missing days for minimum and maximum records, respectively, between 1974 and 2020. We filled these remaining gaps through linear interpolation (Luedeling 2018) as implemented in previous studies (Benmoussa et al. 2020).

Temperature generation for assessing historic and future scenarios

We evaluated historic scenarios by computing winter chill accumulation in each winter season (between November 1 and March 1) of the gap-filled data set. Additionally, we analyzed winter chill accumulation based on historic simulated scenarios to enhance the capacity of the analysis to reliably identify medium- and long-term trends. To this end, we generated 10 historic scenarios representing conditions for each 5th year during the 1975 to 2019 interval. For each of these scenarios, we computed monthly averages of minimum and maximum temperatures based on a 15-year running mean of the respective variables. Monthly averages were therefore computed using data for the 15-year period spanning the reference year ± 7 years for any given scenario year (except for the first and last scenarios for which we only used the 7 following and previous years, respectively). We then inserted these scenarios into a weather generator (Cordano and Eccel 2016) to produce 101 years of synthetic data representing

the likely conditions during each of the scenario years. Weather generators are statistical models that simulate realistic random sequences of atmospheric variables such as temperature, precipitation and wind (Wilks and Wilby 1999) based on a calibration dataset. In RMAWGEN (Multi-Site Auto-Regressive Weather Generator with R; Cordano and Eccel (2016)), the weather generator used in our study, observed time series of daily maximum and minimum temperature are used to calibrate the parameters of a vectorial autoregressive model (VAR model). Coupled with monthly mean weather variables, the VAR model enables the user to generate several stochastic daily scenarios (Cordano and Eccel 2016). The historic scenarios produced with the weather generator allowed us to analyze historic chill accumulation in the Mediterranean area based on a distribution of 100 plausible chill values for each simulated scenario.

For future conditions, we used a similar approach to the methods described above with a slight modification. In this case, we used monthly averages of daily temperature extremes obtained from the ClimateWizard database (maintained by the International Center for Tropical Agriculture – CIAT; Girvetz et al. (2009)) as input for the weather generator. Because the spatial resolution (2.5 to 3.5 degrees) of General Circulation Models (GCMs) available in ClimateWizard is often too coarse for temperature projections to be used directly in climate-related studies (Girvetz et al. 2009), this database offers statistically downscaled temperature projections at a finer resolution (~ 25 km). Temperature projections are generated by 15 GCMs (Table S2) for two Representative Concentration Pathway (RCP) scenarios and various time horizons. In this study, we assessed chill conditions under the RCP4.5 and RCP8.5 scenarios by the period 2035–2065 (represented by the year 2050) and 2070–2100 (represented by the year 2085). Since ClimateWizard contains temperature projections relative to the period 1950–2005 (by default), we implemented a baseline adjustment procedure to be able to compare the projections with our historic data. The baseline adjustment consisted of generating two absolute temperature scenarios (monthly averages of daily minimum and maximum temperatures) based on the data recorded on site. Whereas the first scenario represented the period of interest in our study (1974–2019), the second scenario represented the period available in the ClimateWizard database (1974–2005). We then obtained a relative temperature scenario based on the data recorded on site by computing the difference between these two absolute scenarios. We used the resulting relative temperature scenario to adjust the future scenarios downloaded from the ClimateWizard database. The final adjusted temperature scenario was used as input to the weather generator to produce 101 years of weather records according to 15 GCMs. As we explained for the generation of historic scenarios, the weather generator combines monthly averages of daily temperature extremes expected under future conditions with a VAR model (based on data recorded on site) to generate daily weather scenarios. We removed 6 weather stations at this stage of the analysis, since the ClimateWizard database had no future projection data for weather stations located on small islands in the Mediterranean Sea.

Computation of chill metrics

We computed winter chill accumulation in terms of Chill Portions (CP) according to the Dynamic model (Erez et al. 1990; Fishman et al. 1987a, b). Compared to alternative chill models, the Dynamic model has emerged from various model comparison studies as the most adequate option to represent the process of chill accumulation in mild-winter climates (Fernandez et al. 2020b; Luedeling et al. 2009c; Zhang and Taylor 2011). Since the Dynamic model requires hourly temperatures as input, we derived hourly records from daily temperature extremes based on an idealized daily temperature curve. This curve depends on the latitude of a place and uses a sine function for daytime warming and a logarithmic decay function for nighttime cooling (Almorox et al. 2005; Linvill 1990). We defined the winter season for chill accumulation as between November 1 and March 1 for all scenarios and years as suggested in earlier studies (Fernandez et al. 2020b; Luedeling et al. 2009b).

Chill was computed for the remaining 357 weather stations for (i) all years on record (observed chill), (ii) all synthetic years for each past scenario (historic simulated chill) and (iii) all synthetic years for each combination of GCM, RCP and time horizon. To summarize the results and provide farmers with an estimate that accounts for production risks, we used the concept of Safe Winter Chill (SWC; Luedeling et al. (2009a)). SWC is defined as the 10th quantile of a chill distribution and represents the chill level that is likely to be exceeded in 90% of years. This metric helps farmers identify scenarios under which the cultivation of temperate fruit species may no longer be viable and may be useful in designing future adaptation strategies. We computed SWC for the observed period (46 actual winters), for each simulated historic scenario (100 simulated winter seasons for each scenario) and for each combination of GCM, RCP and time horizon (100 simulated winter seasons for each scenario). We summarized the scenarios generated by the climate models by producing "optimistic," "intermediate," and "pessimistic" climate model classes that were defined as the 15th, 50th and 85th quantile of the SWC distribution, respectively, across 15 climate models.

Spatial interpolation of Safe Winter Chill

We implemented the methods developed by Fernandez et al. (2021a) and Benmoussa et al. (2020) to interpolate SWC in the Mediterranean area. In a preliminary step, we used data for all locations to interpolate a surface using Kriging to generate a chill surface covering the area of interest. We corrected this preliminary interpolation using two co-variables (which are known to be significantly correlated with chill accumulation; Fernandez et al. (2021a)) with a known spatial distribution: the monthly averages of daily minimum and maximum temperatures in January. We downloaded historical gridded data for the period 1970–2000 for the two co-variables with a resolution of 30 arcseconds (~ 1 km^2) from the WorldClim database (Fick and Hijmans 2017). In addition to these gridded data from WorldClim, we computed the values for the co-variables (monthly averages of daily minimum and maximum temperatures in January) using the records from the weather stations and implemented an ordinary Kriging procedure. To retain weather stations showing comparable values between databases for the two co-variables, we removed from the analysis the weather stations for which the difference between WorldClim and on-site data was greater than 2 °C. This process reduced the dataset to 346 weather stations that could be used for the spatial interpolation of SWC.

Using data recorded on site from the remaining weather stations, we then created a 3D correction model. This 3D correction model considered the monthly averages for daily minimum and maximum temperature in January (*x*- and *y*-axis, respectively in Fig. S1) and the observed SWC (contour surface in Fig. S1) for a given combination of the two co-variables (Fernandez et al. 2021a). We introduced the data of the monthly averages of daily extremes from both databases (WorldClim and on-site records) to the correction model and obtained a surface of estimated SWC. By subtracting the surface generated with the on-site data from the one generated with the WorldClim data, we produced an SWC correction map that was later added to the preliminary SWC interpolation produced through ordinary Kriging. This allowed generating an SWC map for the Mediterranean region based on the locations as well as two correction co-variables. We implemented this interpolation procedure for the historic observed scenario, for all historic simulated scenarios, and for all future scenarios.

Cross-validating the spatial interpolation

We implemented a cross-validation procedure to assess the performance of the spatial interpolation method. In general, this procedure aimed to compare the estimation of SWC in a location using all 346 weather stations with the estimation for the same place using a sample of stations when producing the interpolation. We first split the main data set of weather stations into 8 data subsets to be used as part of the evaluation and training procedure at different times. Each of the 8 data subsets serves once as evaluation data set, whereas the remaining 7 times, it is merged with 6 other subsets into a large training data set (used for generating the SWC estimates). We implemented this procedure until all data subsets were part of the evaluation process at least once. We later obtained the residuals for the weather stations by subtracting the value obtained with the validation procedure from the original SWC value estimated using all weather stations. Since the interpolation method used a different 3D correction model for each evaluated scenario, we implemented the cross-validation procedure for all scenarios described in the "Computation of chilling metrics" section. Additionally, we used five repetitions in the cross-validation to reduce the risk of artifacts that may arise while splitting the main dataset. We summarized the results by computing the median and standard deviation for the residuals across scenarios and repetitions.

Collecting warm-winter experiences from Mediterranean orchards

To position our results in a real-world context, we collected expert knowledge from farmers, farm advisors and researchers working with temperate fruit trees in the Mediterranean region. We gathered inputs from experts working in Tunisia, Morocco and south- and northeastern Spain. To collect these inputs, we used open questions addressing four main topics regarding climate change impacts on temperate fruit production. The main topics we aimed to cover with this analysis were (i) the current situation regarding chill accumulation in the main growing regions, (ii) challenges and concerns of farmers regarding future production conditions, (iii) noticeable changes in the array of species and/or cultivars grown in the region and (iv) noticeable modifications in the production cycle of temperate fruits. Although we prespecified the main topics of interest, we did not develop predefined questionnaires and workshops to collect experiences from experts. With this approach, we aimed to generate a narrative perspective of the situation in the Mediterranean region rather than implementing a structured and systematic procedure to collect information. We therefore used these inputs only to contextualize and discuss the overall results of our study.

Data processing tools, figure generation and reproducibility

All data processing, analyses and figure preparation were implemented in the R programming environment (R Core

Team 2021). For agroclimatic analyses such as weather data collection and computation of agroclimatic metrics, we used the chillR package (version 0.72; Luedeling (2021)). We used the nasapower package (Sparks 2018) for obtaining the data from the NASA POWER database. For generation of synthetic temperatures, we used the RMAWGEN package (Cordano and Eccel 2019) through functions of the chillR package. For figure preparation, we mainly used the tmap package (Tennekes 2018). All procedures developed to collect data, conduct analyses and generate figures are available in a public GitHub repository (https://github.com/EduardoFernandezC/chill_mediterranean).

Results

To facilitate the visualization of results in the main manuscript, we only include figures representing the "intermediate" climate model class for future scenarios. Additional figures showing the results for the "pessimistic" and "optimistic" climate model classes can be found in the supplementary materials accompanying this study (Fig. S2 to S5).

Performance of the interpolation method

In general, the interpolation method showed good performance (Fig. 2). The median of residuals, computed for each weather station across scenarios and replications, ranged from −3.30 CP (Q25%) to 4.49 CP (Q75%) and showed a central value of 0.56 CP. The standard deviation of residuals ranged between 2.18 CP (Q25%) and 4.32 CP (Q75%) and showed a median of 3.09 CP.

Despite the good overall performance of the interpolation method, we identified a few weather stations showing substantially different values for the median residuals compared to most other locations. The respective weather stations were all located at high elevation, such as the Jungfraujoch in Switzerland (46.6°N and 7.9°E, 1571 m above sea level), Mussala in Bulgaria (42.2°N and 23.6°E, 2575 m above sea level) and Vârful Omu in Romania (45.4°N and 25.4°E, 1631 m above sea level). For these stations, we computed median residuals of −66.6 CP, −43.8 CP and −39.7 CP, respectively. Similarly, we identified 22 weather stations for which the cross-validation procedure did not provide a value for estimating the median residual. This resulted from these weather stations showing a combination of minimum and maximum temperature that fell outside the 3D correction model generated with the respective sub data sets used for cross-validation.

Historic chill accumulation in the Mediterranean region

Overall, historically observed levels of SWC in the Mediterranean region ranged from 30 to 100 CP (Fig. 3). In general, the lower bound of this range was estimated for eastern countries of northern Africa and the Middle East,

Fig. 2 Cross-validation procedure implemented to assess the performance of the interpolation method. In each location, the size of the bubble represents the standard deviation of the residuals (among scenarios and replications), whereas the color represents the median residual (in Chill Portions). The red crosses represent weather stations for which the cross-validation procedure assigned missing values due to exclusion of these stations from the 3D correction model. The histogram in the bottom right corner shows the distribution of the residuals
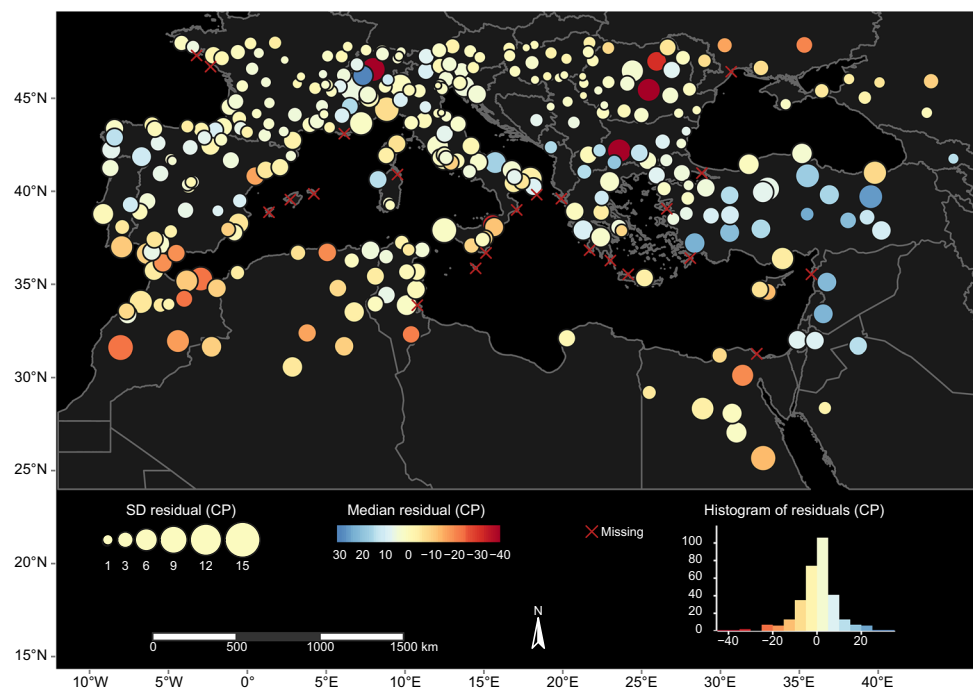
Fig. 3 Safe Winter Chill (SWC) in the Mediterranean region for a historic scenario. The color legend shows the median of observed SWC between 1975 and 2020 computed in Chill Portions (CP) according to the Dynamic model. The areas with gray hatching in the map represent regions excluded from the 3D correction model. The red crosses show the locations of the weather stations used in this analysis

Historic observed
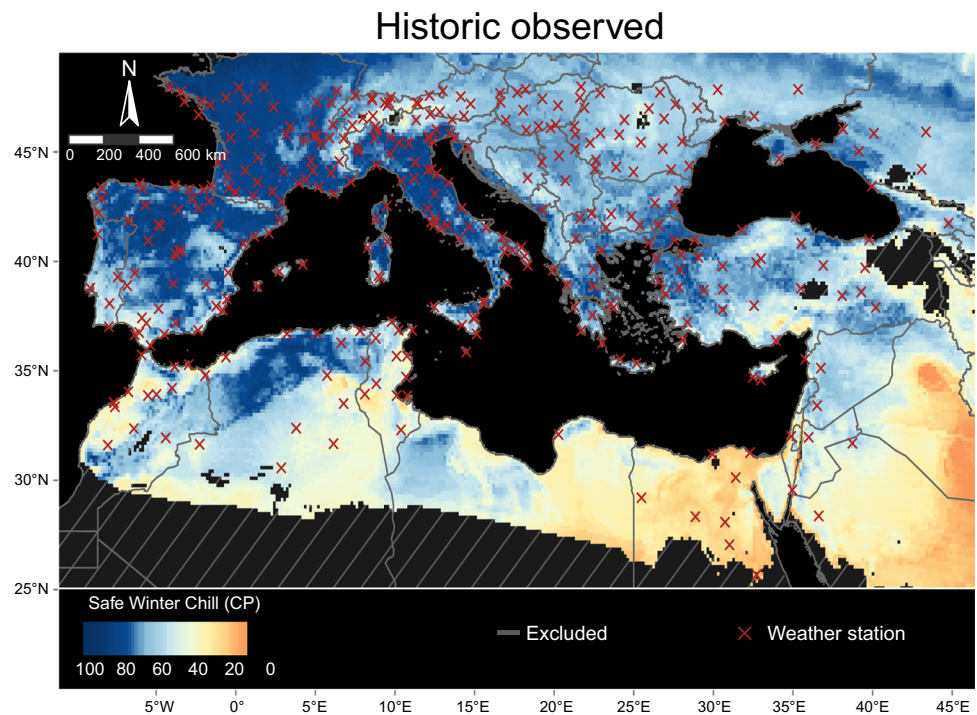
including Libya, Egypt, Saudi Arabia and Iraq. Similarly, we estimated low-chill accumulation in small areas of northern Africa such as Tunisia (northeast, central east and south), western Morocco and inland regions of Algeria. However, SWC levels of about 60 CP were also observed in some parts of these countries. The areas with the greatest observed chill were inland regions of Spain, Greece and Turkey, as well as northern Algeria (mainly uncultivated mountainous regions), northern Portugal, northern Italy and most of France. In these regions, SWC reached a median of about 90 CP annually between 1975 and 2020. Many countries east and northeast of the Mediterranean Sea showed SWC values between 40 and 60 CP.

Absolute chill levels and change based on historic simulated scenarios

We observed similar results when comparing the median SWC for historic observed and historic simulated scenarios (Fig. 3 versus upper panel in Fig. 4). When analyzing SWC changes between 1975 and 2019 (2019 minus 1975 based on historic simulated scenarios), we observed that many countries of the Mediterranean region have experienced considerable SWC losses (bottom panel in Fig. 4). Inland areas of Spain, Portugal, Greece and Turkey showed a reduction by about 20 CP. Similar values were observed in western Tunisia, southern France and most parts of Italy. Smaller SWC reductions by about 10 CP were observed in northern France, southern Spain and some regions of northern Africa. These regions, however,

showed different SWC base levels, with about 90 CP in northern France, between 40 and 60 CP in southern Spain and below 40 CP in some regions of northern Africa. Conversely, major increases in SWC were observed between 1975 and 2019 in southern Germany, Austria and other continental areas of northern Europe.

Chill changes under future scenarios

Future SWC levels in the Mediterranean region mainly depend on the global warming scenario and time horizon evaluated. Under RCP4.5 by 2050, chill is likely to decline by about 20 CP in many areas of northern Africa such as the coastal regions of Morocco, Algeria and Tunisia (Fig. 5). Similar results were projected for the southern coasts of Spain and Italy. In continental areas of southern Europe, the likely decline may range between 5 and 10 CP (Fig. 5). Minor increases in SWC were projected in high-elevation regions of southern and eastern France, northern Italy and eastern Europe.

Under RCP8.5, changes in SWC across the Mediterranean region are more alarming (Fig. 6). By 2050, chill levels in most areas of northern Africa are likely to decline by about 30 CP compared to the historic median between 1975 and 2019. Some regions of western Tunisia, northern Algeria and central Morocco might experience a decline by between 15 and 20 CP by the same year. Similar results were projected for most regions of Portugal and southwestern and southern Spain. Minor chill increases by about 10 CP were projected for some small areas of northern and eastern Spain.

## Historic simulated (median 1975 − 2019)
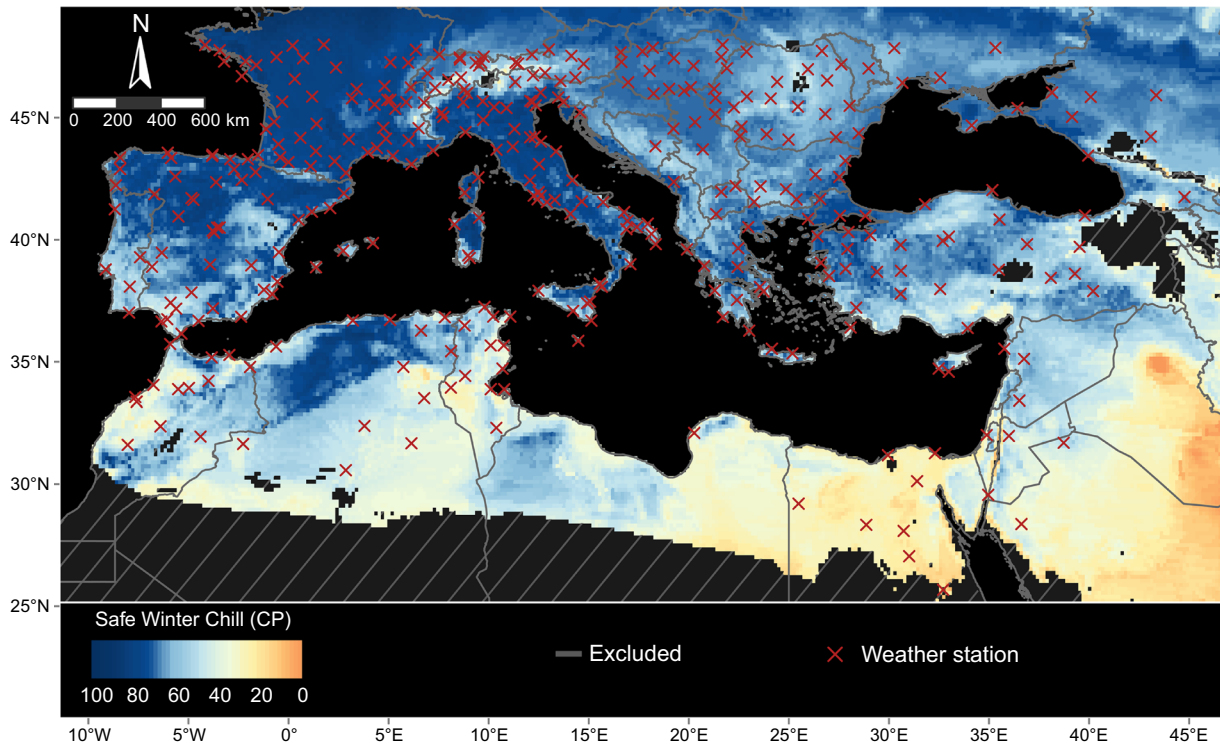
Chill change 2019 − 1975
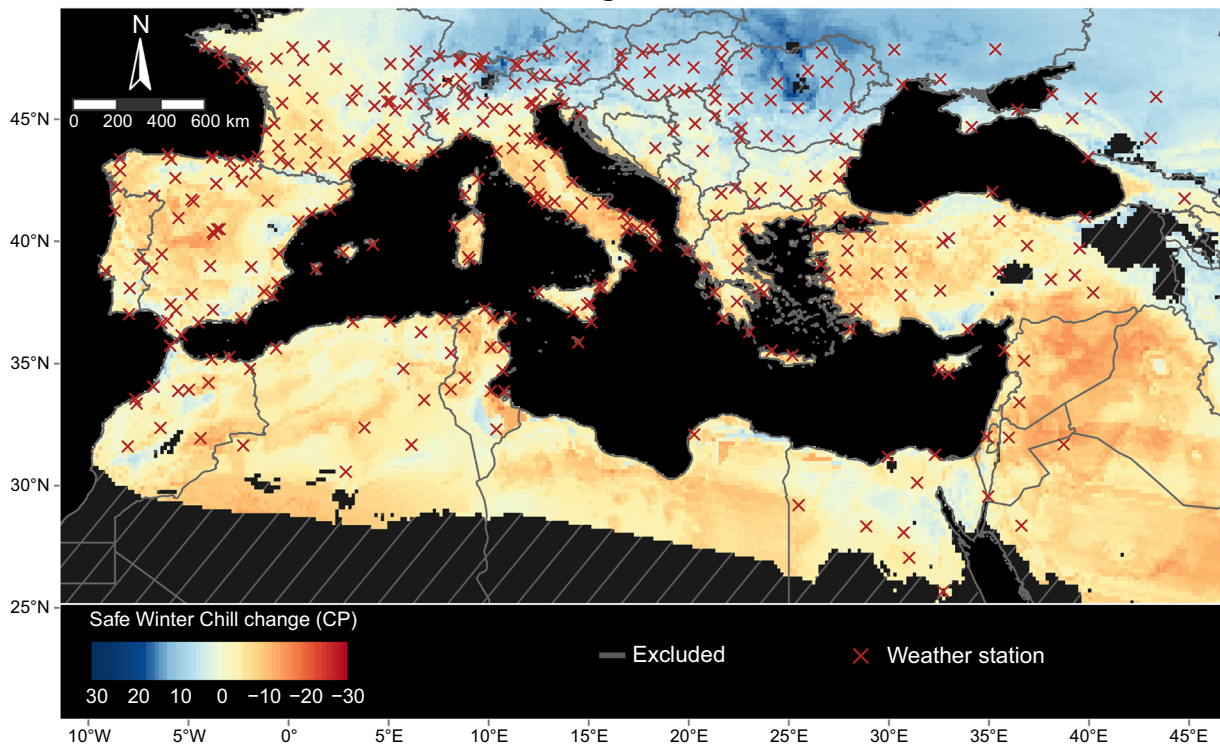
Fig. 4 Safe Winter Chill estimation for the Mediterranean region based on historic simulated scenarios. In the upper panel, we show the median SWC (in Chill Portions according to the Dynamic model) computed across 10 historic simulated scenarios between 1975 and 2019. In the bottom panel, we show the difference in SWC between the historic simulated scenarios 2019 and 1975. In both panels, the areas with gray hatching represent regions excluded from the 3D correction model. The red crosses represent the location of the weather stations used in the analysis
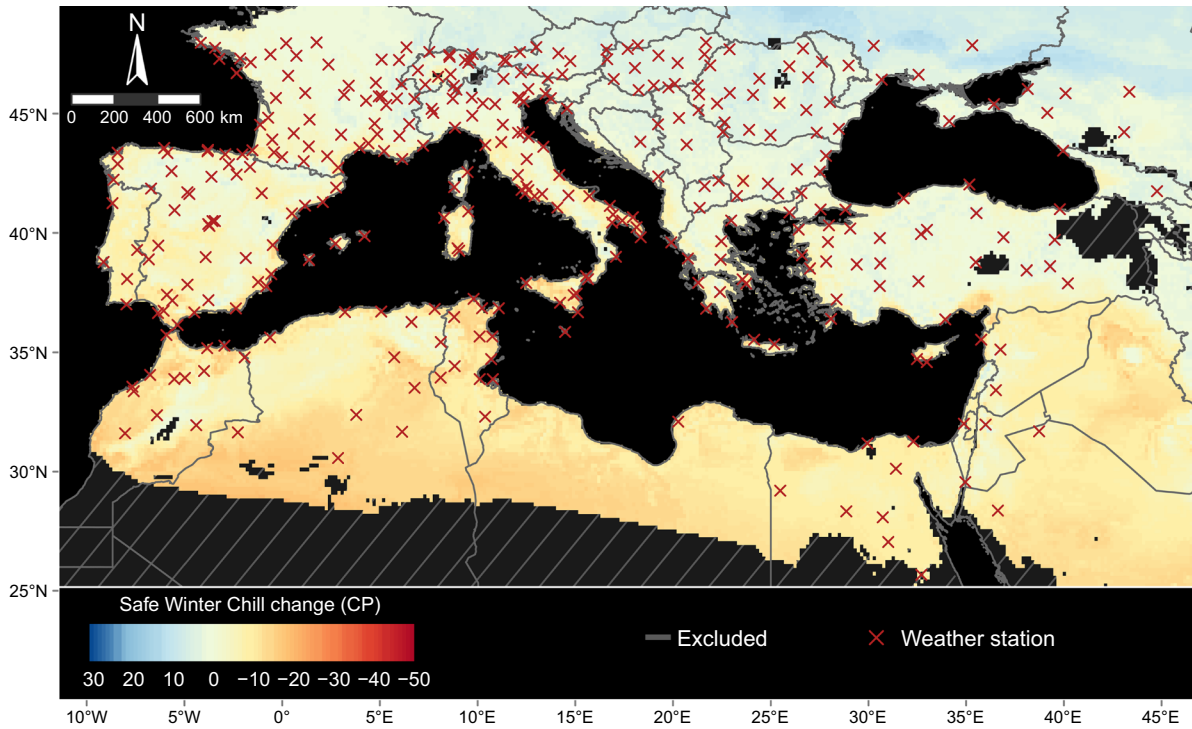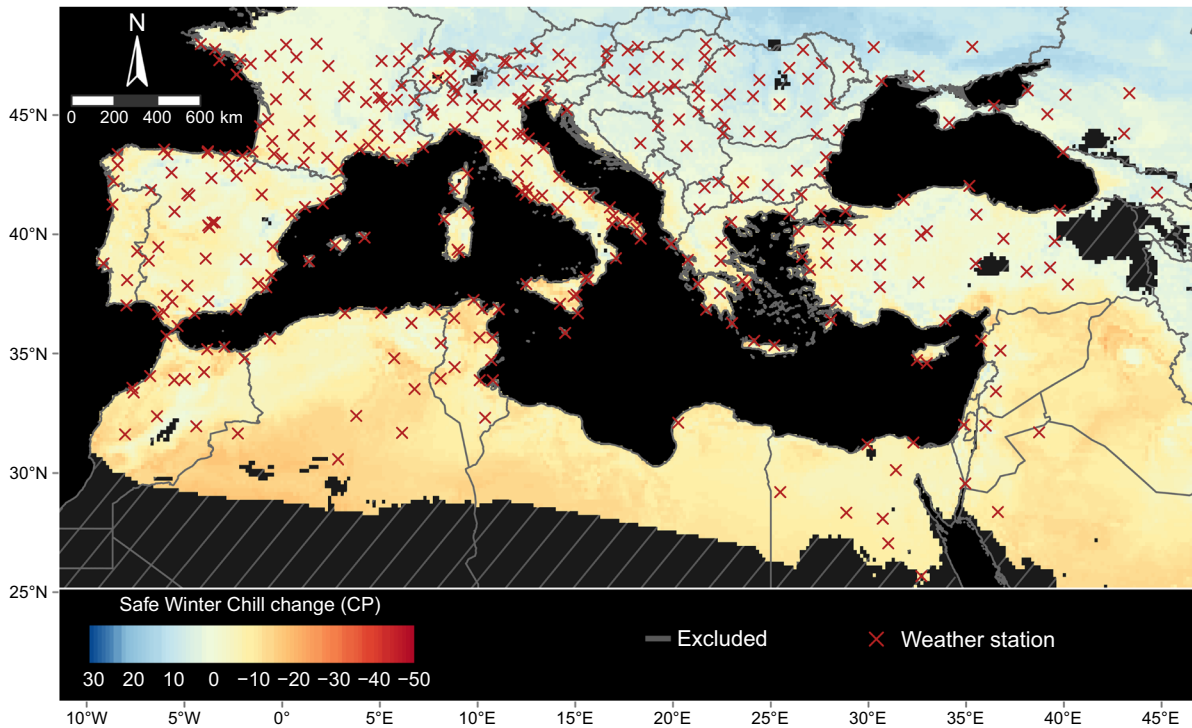
Fig. 5 Estimation of Safe Winter Chill change for the Mediterranean region under the RCP4.5 scenario by two time horizons (2050 and 2085) relative to historic simulated scenarios. In both panels, we show the difference in SWC between the respective combination of future scenario and year and the median across historic simulated scenarios between 1975 and 2019. For future scenarios, we used the results of the "intermediate" climate model class (median SWC value among 15 General Circulation Models). The areas with gray hatching in the maps represent regions excluded from the 3D correction model. The red crosses represent the locations of the weather stations used in the analysis

By 2085 under RCP8.5, chill decline may range between 20 and 40 CP in Morocco, Algeria, Tunisia and the Mediterranean coastal areas of Spain, Italy, Greece and France. Smaller declines by about 10 CP are projected for inland areas of Spain, France, Italy and Turkey. Our results suggest chill increases in many countries of eastern Europe.

Climate change impact experiences from Mediterranean regions

Overall, our collection of experiences from experts around the Mediterranean area suggests an agreement about current challenges among regions, yet it also exposed some variation (Table 1). In the "Ebro Valley" (northeast Spain), for example, experts highlight that mild-winter conditions (often cold enough to break dormancy) have increased the risk of challenging bud differentiation, flowering and fruit set in high-chill cultivars. Experts in this location ("Ebro Valley") as well as from "Meknès" (in Morocco) experienced advancing bloom dates mainly in low-chill cultivars (with some exceptions in high-chill species such as apple), probably because of rising temperatures during the eco-dormancy phase. According to the experts, this situation may increase the risk of spring frost events in the "Ebro Valley," a colder place compared to "Meknès" (Table 1). For Tunisia and "Murcia" (southern Spain), experts pointed out a number of situations including delayed and extended bloom periods, heterogeneity of phenological stages, sparse foliage, physiological disorders (e.g., double fruits) and low-quality fruits because of warm temperatures during winter as well as during the growing season. In extreme cases, they experienced bud and flower abortion, potentially explaining 30–40% of yield losses. Rising temperatures during the flowering period may also cause flower abnormalities or lead to problematic fruit set, as suggested by experts from northeastern Spain and Tunisia. In "Meknès," experts identified a delay in the onset of the chilling accumulation process from early to late November as well as long, heterogeneous and irregular bud burst and flowering in some apple cultivars. The occurrence of branches with few leaves during the growing season was also observed by experts in the Moroccan setting. Other challenges such as fruit damage due to extreme temperatures in summer were mentioned by experts from the "Ebro Valley."

Similar to the experiences collected for current challenges, main concerns regarding future developments tended to converge across the evaluated regions. Among these concerns, experts from northeast and southern Spain, Morocco and Tunisia mentioned asynchrony between pollen donors and receptors, which may result from difficulties in overcoming dormancy and initiating bloom in self-incompatible cultivars (Table 1). Additionally, experts from both the "Ebro Valley" and "Murcia" in Spain highlighted the likely occurrence of physiological disorders resulting from high temperatures. Among these, extraordinarily warm conditions during winter can produce inadequate dormancy release and even bud abortion and high summer temperatures can cause double pistils in stone fruit flowers (e.g., sweet cherry) in the next season. For future scenarios, experts from different countries agreed on some adaptation strategies, including the relocation of orchards, replacement of traditional orchards with low-chill crops and possibly cooling orchards through overhead irrigation and shade nets during winter (Table 1).

Discussion

We used spatial interpolation to assess the likely impacts of climate change on winter chill accumulation in the Mediterranean basin. Our approach is based on the methods described by Fernandez et al. (2021a), who proposed the use of averages of daily minimum and maximum temperatures for a particular month in winter (January in our case) as correction variables to account for large intra-regional differences in climatic conditions on a continental scale. Similar to the results of the earlier study by Fernandez et al. (2021a), our cross-validation analysis revealed small overall residuals across the 357 weather stations used for the interpolation (−0.85 CP versus 0.56 CP, respectively), suggesting a good performance of the method. It should be noted, however, that we observed large residuals for weather stations located in high-elevation areas including Jungfraujoch in the Swiss Alps, Mussala in the Balkans (Bulgaria) and Vârful Omu in the Bucegi mountains of Romania. Since these weather stations are located in very particular environments (all above 1,500 m.a.s.l.), we consider it plausible that correction models created without data from these stations fail to accurately represent the climatic conditions of such environments, producing large residuals. Additional data from nearby stations and, to some extent, from similar climatic settings may be required to minimize the residuals for these and other high-elevation weather stations in the cross-validation assessment.

Absolute historic levels of SWC (the median between 1975 and 2020) in the Mediterranean region ranged from 30 to 100 CP. Regarding changes between 1975 and 2019, our results suggest major SWC decline in some inland regions of Spain, southern France, Italy, Greece and Turkey. Similarly, countries in northern Africa (Morocco, Algeria, Tunisia and Libya) and in the Middle East showed considerable SWC decline by about 20 CP. These results
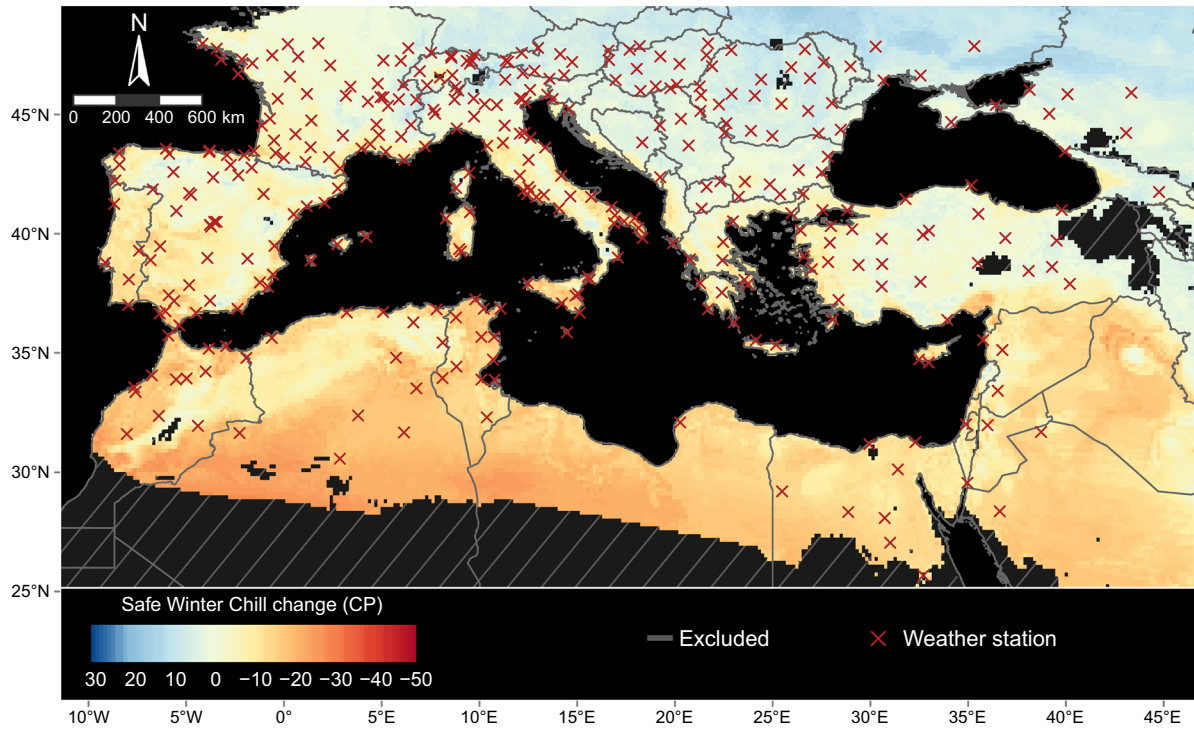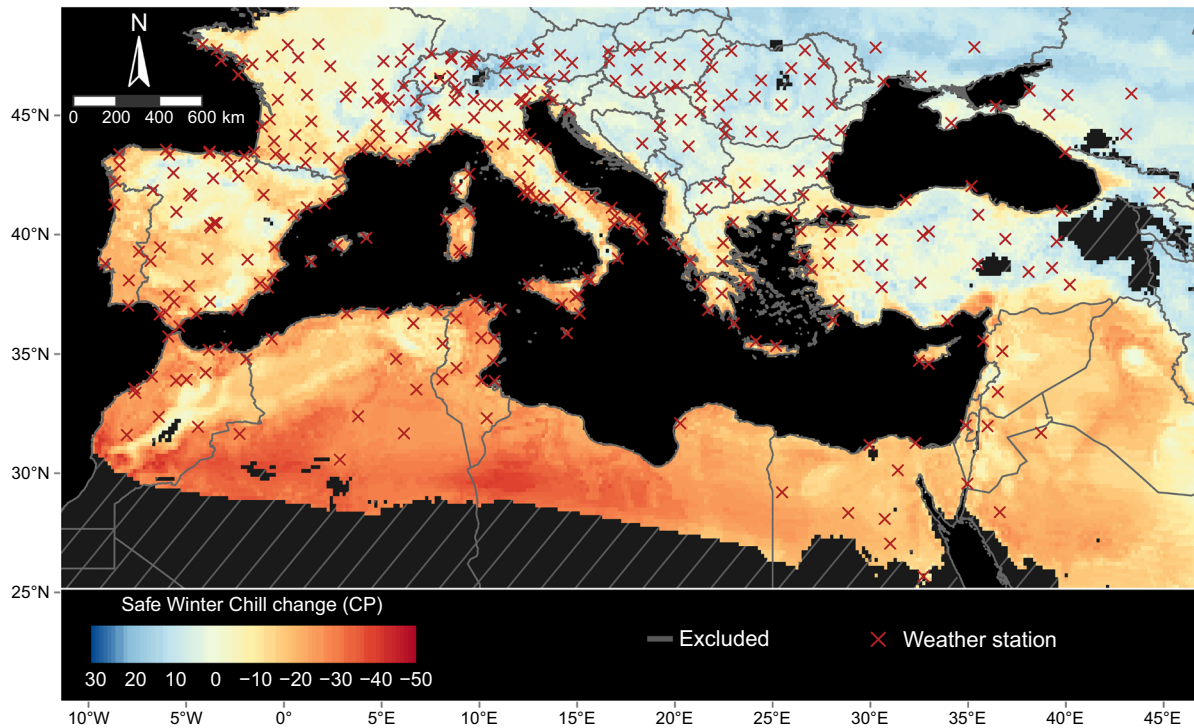
Fig. 6 Estimation of Safe Winter Chill change for the Mediterranean region under the RCP8.5 scenario by two time horizons relative to historic simulated scenarios. In both panels, we show the difference in SWC between the respective combination of future scenario and year and the median across historic simulated scenarios between 1975 and 2019. For future scenarios, we used the results of the "intermediate" climate model class (median SWC value among 15 General Circulation Models). The gray hatched areas in the maps represent regions excluded from the 3D correction model. The red crosses represent the locations of the weather stations used in the analysis

confirm earlier findings reported by Rodríguez et al. (2019) and Egea et al. (2022) in Spain, and Benmoussa et al. (2020) in Tunisia, as well as results from a global-scale study by Luedeling et al. (2011a), who estimated the greatest winter chill losses in the Mediterranean basin. According to Lavee and May (1997), insufficient winter chill in temperate fruit and nut species may lead to irregular and uneven bud burst as well as bud abortion in extreme cases, which may result in significant yield reductions. Historic winter chill losses appear to already have affected the cultivation of temperate fruit species in Mediterranean orchards, raising awareness among farmers and experts about the impacts of climate change on these systems. As mentioned by temperate fruit experts from northern and southern Spain, Morocco and Tunisia, temperate tree species have shown some of the symptoms of insufficient chill described by Campoy et al. (2011) and Lavee and May (1997). Analyzing data from pistachio trees cultivated in Tunisia, Benmoussa et al. (2017b) suggested a considerable decline in yield, which was probably caused by insufficient winter chill. In addition, experts highlighted the occurrence of physiology-related phenomena, including advanced spring phenology (Bartolini et al. 2019; El Yaacoubi et al. 2014), as well as problematic bud differentiation, fruit set and fruit development. High temperatures during spring may result in pollen and pistil deformation (Kozai et al. 2004; Rodrigo and Herrero 2002), a concern mentioned by experts from both the Ebro Valley and Murcia in Spain. Whereas the temperate fruit industry has, to some extent, overcome many of the early challenges presented by climate change in some mild-winter regions, projections for future scenarios raise concerns regarding the sustainability of many orchards.

Our projections for future scenarios suggest considerable SWC decline in the Mediterranean basin, regardless of the combination of RCP and time horizon evaluated, a situation that mirrors the results of many previous studies in the region (Benmoussa et al. 2020; Delgado et al. 2021a; Egea et al. 2022; Fraga and Santos 2021; Rodríguez et al. 2019). Some areas of northern Africa (including Morocco, Algeria, Tunisia and Libya) and southern Europe (including Spain, Italy and Greece) may experience a reduction by up to 30 CP relative to 1975–2019 by 2050 under the RCP4.5 scenario. Low-chilling conditions due to global warming imply several risks for farmers cultivating temperate species in the Mediterranean region. In the worst-case scenario, experts suggested a risk of having to abandon temperate fruit production due to insufficient accumulation of chill during winter in some marginal regions. As suggested by Benmoussa et al. (2020), the projections of SWC obtained in our analysis may indicate that high- and even medium-chill species or cultivars may only thrive in particular micro-climates in the

future. In accordance with previous studies (Chmielewski et al. 2018; Vitasse et al. 2018), experts acknowledged the probable increase in the risk of spring frost events in some early-blooming cultivars as well as asynchrony between pollen donors and pollen receptors in self-incompatible as well as dioecious species, which might jeopardize successful pollination, diminishing the prospect of sustainable fruit or nut yields, or require the replacement of current donor-receptor combinations to secure yields under future scenarios. Apart from dormancy-related risks, experts also hinted at additional climatic challenges, including the occurrence of heat waves and other unusual climatic events during the growing season, extended periods of drought and increasing pressure of pests and physiological disorders. Earlier studies have shown a negative correlation between high temperatures in spring and final fruit size in peach (Lopez et al. 2007), as well as a positive relationship between rising temperatures and the incidence and severity of pests in walnut orchards in a Mediterranean climate (Luedeling et al. 2011b). The concerns raised by temperate fruit experts stress the urgent need for developing and implementing measures to secure the future production of temperate fruits in the Mediterranean basin.

While abandoning temperate fruit production might become a reality in some marginal regions as a worst-case scenario (under RCP8.5), many of the remaining locations will probably be able to sustain the production of temperate fruits by implementing strategies to adapt to the impacts of climate change. The use of systems to enhance chill accumulation (e.g., the use of shade nets during winter or overhead irrigation on warm days) may be a feasible approach in regions affected by mild chill decline (Campoy et al. 2010; Gardner et al. 2013). For orchards located in areas showing low-chill accumulation, the application of dormancy-breaking products (including gibberellic acid, potassium nitrate and hydrogen cyanamide) can help trees overcome dormancy and homogenize bud burst and bloom (Guillamón et al. 2022; Perez and Lira 2005; Rahemi and Asghari 2004; Zhuang et al. 2013). The environmental implications as well as the legal restrictions of spraying some of these chemicals (particularly in the case of hydrogen cyanamide) in temperate orchards must, however, be considered when making such a decision. Mediterranean regions showing an increasing risk of being severely affected by climate change may need to develop long-term strategies, which may imply considerable technical and financial efforts. Developing new cultivars, particularly low-chill genotypes that are adapted to expected future climates, may be a crucial step in warm-winter areas. Such development may be challenging and expensive, since the breeding process must consider technical (e.g., productivity or pest and disease resistance) and market-related (e.g., consumer preferences and shelf life)

Table 1 Experts' perception regarding climate change impacts on temperate fruit production in the Mediterranean region. We show the main challenges and risks under current and projected future conditions for four main areas of temperate fruit production

Location	Climate condition	Current production challenges	Future concerns and potential risks
Ebro Valley (northeast Spain)	Continental Mediterranean climate	• Increasing frequency of milder winters compromises bud differentiation, flowering and fruit set in high-chill cultivars • Risk of frost damage in low-chill cultivars • Floral abnormalities due to high spring temperatures • Fruit damage due to high summer temperatures	• Need for replacing traditional orchards • Advanced or delayed phenology depending on the species and cultivar • Summers may be too hot to grow temperate fruit trees • Shifting cultivation sites to the highlands • Asynchrony between pollen donors and receptors in self-incompatible cultivars
Murcia (southern Spain)	Warm Mediterranean climate	• Insufficient chill for many traditionally grown apricot, peach, plum and cherry cultivars • Delay of phenology events (bud break and bloom) due to extension of the time needed to break endodormancy • Low and uneven bud break with bud abortion in extreme cases • Pollen and pistil abnormalities with challenging fruit set • Increasing occurrence of extreme climatic events	• Increasing occurrence of heat waves during dormancy and extreme climatic events during the growing season (e.g., floods, storms, hail) • Water scarcity • Increasing salinity due to rising evaporation rates caused by warming • Abandonment of temperate fruit production in marginal regions • Heat waves in summer (> 40 °C) • Asynchrony between pollen donors and receptors in self-incompatible cultivars • Need for low-chill cultivars
Meknès (Morocco)	Dry and hot continental climate	• Chill decrease due to increasing winter temperature • Flowering advance due to increasing spring temperature • Extended bloom and heterogeneity of phenological stages (particularly in apple) • Weak dormancy for high-chill apple cultivars • Fewer leaves in branches during the growing season	• Considerable chill losses • Deformation of vegetative and generative plant organs due to warmer conditions • Asynchronous bloom as well as bud abortion • Additional irrigation needs during hot seasons • Need for heat- and low-chill-tolerant species and cultivars to adapt to climatic constraints
Tunisia	Mediterranean climate	• Frequent severely warm winters (each 3–4 years) • Delayed and extended bloom and heterogeneity of phenological stages in *Prunus* spp. and pistachio • Pollen and pistil abnormalities and asynchrony between male and female organs in pistachio • Increased rates of double fruit and split pit in stone fruits • Delayed fruit maturity and production of low-quality fruits • Production losses up to 30–40% • Pest and disease proliferation due to warm temperatures • Intermediate seasons (autumn and spring) less pronounced • Increasing irrigation needs	• Water scarcity • Unpredictable climatic conditions (frequent severely warm winters, unusual weather and extreme events including late and torrential rainfall, storms and frequent hail events) • Need for replacing high-chill (e.g., peach) with low-chill species (e.g., olive) • Developing growing techniques (e.g., double grafting, use of dormancy-breaking agents) to sustain the cultivation of temperate trees • Farmers confused and unable to set a clear adaptation strategy • Challenges for various adaptation needs including biological and technical requirements, scientific, social, economic and financial needs, innovation and political decisions

attributes (Sherman and Beckman 2003). Offering a portfolio of potentially adapted cultivars (currently cultivated elsewhere) for a given location to orchard managers and decision-makers emerges as an alternative to long-term breeding programs. Studies assessing current and future agroclimatic conditions conducted at regional and local scale are likely to help researchers in developing such portfolios of adapted cultivars. For this alternative to be effective, knowledge on the agroclimatic needs of these target varieties during the dormant season is required. Accurate estimations of such requirements are challenging considering the limitations of current dormancy modelling approaches (Chuine et al. 2016; Luedeling 2012). Species- and even cultivar-specific model parameterization may be a promising approach to obtain better estimations of chill requirements (Egea et al. 2021) as well as accurate phenology predictions for temperate fruit species (Luedeling et al. 2021). By applying such frameworks in Mediterranean orchards, researchers may be able to identify potentially resilient genotypes to offer farmers alternatives to sustain temperate fruit production in a warming climate.

Conclusions

Our study provides evidence of the likely impacts of climate change on winter chill accumulation in the Mediterranean basin. The spatial interpolation approach we implemented in this assessment showed overall small residuals between the 357 weather stations, indicating good performance of the method. Similarly, the results of our collection of expert knowledge suggest the importance of including experiences from relevant stakeholders in climate change impact assessments as well as in the development of climate change adaptation strategies. Our results suggest that some regions of northern Africa and southern Europe are likely to experience major chill declines by 2050 even for a moderate global warming scenario (RCP4.5). Projections are most alarming for the worst-case scenario (RCP8.5) by 2085. Our collection of knowledge and experiences from experts working with temperate fruit trees in the Mediterranean region helped in framing the results obtained for past scenarios by highlighting some already visible impacts of climate change on temperate fruit orchards. For future scenarios, experts hinted at major risks and concerns (including abandoning fruit production in chill-limited regions) likely to be faced by farmers and acknowledged potential adaptation strategies. Among these, the development of new cultivars potentially adapted to expected future conditions may appear as the safest option, although breeding activities may require substantial technical and economic efforts. Producing a portfolio of cultivars for which the climatic requirements during dormancy have been estimated using improved methodologies (dormancy model re-parameterization) may offer a medium-term alternative for farmers producing temperate fruits. Matching chill and heat requirements of species and cultivars with the conditions expected for the future in a given location may help the temperate fruit industry in thriving under challenging climatic conditions.

Author contribution E Fernandez carried out the simulations and implemented the interpolation approach under the supervision of EL. E Fadón, HM and E Fernandez wrote the first draft of the manuscript with EL commenting on and editing the document. E Fadón, JR, DR, JAE, MBM, OK, AEY, MG, JE, HB, NB and OE collected the experiences from experts working in the Mediterranean region. E Fernandez, HM, E Fadón, JR, DR, JAE, MBM, OK, AEY, MG and EL contributed to analyzing and discussing the results.

Declarations

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