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Chilling accumulation in temperate fruit trees in Spain under climate change

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Abstract. Temperate fruit trees account for almost half of the worldwide fruit production, with Spain one of the largest world producers. Growing trees are quite vulnerable to cold temperatures. To minimise the effect of these cold temperatures, they stop their growth over the coldest months of the year, a state called dormancy. In particular, endodormancy, i.e. a dormancy related to the plant's inner physiological factors, requires accumulating cool temperatures to finish dormancy ("be broken"). The accumulation of cool temperatures according to specific rules is called chilling accumulation, and the chilling accumulation required to break dormancy is different for each tree crop and variety. There are several methods to calculate the chilling accumulation, all of them based on temperature only. Under global warming, it is expected that the fulfilment of the chilling requirements to break dormancy in temperate fruit trees could be compromised. In this study, the impact of climate change on the chilling accumulation over Peninsular Spain and the Balearic Islands was assessed. For this, bias-adjusted results of 10 Regional Climate Models (RCMs) under Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5 were used as inputs of four different methods for calculating chilling accumulation, and the results were compared for the near and far future under both RCPs. These results project a generalised reduction in chilling accumulation regardless of the RCP, future period or chilling calculation method used, with higher reductions for the far future and the RCP8.5 scenario. The projected winter chill decrease may threaten the viability of some tree crops and varieties in some areas, but also shows scope for varieties with lower chilling requirements. The results are relevant for planning future tree plantations under climate change, supporting adaptation of spatial distribution of tree crops and varieties in Spain.

1 Introduction

Fruit tree species are included in a complex group of plants often classified according to their temperature requirements and their response to different climatic conditions. According to this criterion, these species can be divided into three main groups, 1) temperate (e.g., apple, pear, peach), 2) subtropical (e.g., citrus, fig), and 3) tropical (e.g., banana, mango) fruit trees (Gil-Albert, 1998).

Temperate fruit trees are in turn subdivided into two subgroups: 1) a group of fruit trees that usually have high resistance to hard cold winters but are sensitive to hot summers and 2) another group also resistant to hard cold winters, but to a lesser extent than the former, and more resistant to hot summers. The most representative species within the first subgroup are apple and pear trees, European plum trees and cherry trees. The second subgroup includes all cultivars of peach trees and Japanese plum trees. Vineyard, apricot trees, olive trees and almond trees could be also included in this last subgroup, although some of their climatic requirements are nearer the subtropical fruit trees, which are very sensitive to light frosts in winter and demand high temperatures during the vegetative period. This group includes all citrus species, fig, pecan, pistachio, avocado, cherimoya trees, loquat, persimmon trees and date palm trees. Tropical fruit trees are not resistant to frosts. For example, banana, mango, guava and coconut trees are included in this group.

Growing fruit trees is an important source of wealth for farmers. Spain is one of the largest producers of fruits and vegetables in Europe, with 7437 million euros from $7.4 \cdot 10^6$ t of exported fruits in 2017 (FEPEX, 2018) from a total fruit production of $11.24 \cdot 10^6$ t (MAPA, 2018). With a broad range of climates, Spain produces temperate fruits, subtropical (mainly citrus but also other crops) and even some tropical fruits. In absolute terms, among fruit crops olive trees occupy the largest land area ($2.52 \cdot 10^6$ ha), followed by vineyard ($0.94 \cdot 10^6$ ha), almond ($0.58 \cdot 10^6$ ha), citrus ($0.26 \cdot 10^6$ ha) and peach trees ($0.09 \cdot 10^6$ ha). According to its agricultural production, Spain ranks first in the world for production of olives, fourth for peaches and fifth for grapes and pears (FAOSTAT, 2018). In terms of productivity, one of the most important groups of fruit trees are the temperate trees, accounting for approximately 48% of the total world fruit production (FAOSTAT, 2018). In Spain, temperate trees are concentrated mainly on the east coast, along the river valleys of the coast, especially in the Ebro and Jucar valleys. Olive trees are concentrated in the south of Spain, especially in the Guadalquivir River valley. Vineyards have a more diffused distribution but are abundant in central Spain (Fig. 1).

Growing trees are quite vulnerable to cold temperatures. To minimise the effect of these cold temperatures, they change to a hardy state during the coldest months of the year, stopping their growth and modifying their cells. This state is called dormancy and it was defined by Lang et al. (1985) as “any temporary suspension of growth of any structure containing a meristem”. These authors also defined different dormancy types depending on the factors that regulate them. In this sense ecodormancy is related to environmental factors, paradormancy to physiological factors outside the affected structure (e.g. apical dominance) and endodormancy is linked to physiological factors inside the affected structure. Since the early 19th century, it has been known that endodormancy requires accumulating cool temperatures to be broken (Knight, 1801). Endodormancy is the way fruit trees endure the lowest temperatures of the year and synchronise with environmental factors (i.e. seasonal temperature pattern).

Therefore, the accumulation of cold periods as experienced by the plant is relevant to estimating the dormancy break date. For this purpose, several models have been proposed to calculate winter chill, all based on the accumulated time with temperatures between certain thresholds. The Chilling Hours model is the oldest and the simplest one, quantifying winter chill as the number of hours during the winter season, when temperatures are between 0 and 7.2°C (Bennett, 1949; Weinberger, 1950). The Utah Model (Richardson et al., 1974) uses chilling units and considers that temperatures have a different response depending on the temperature range they belong to, with temperatures above the threshold having a negative effect on chilling accumulation. Chilling portions are the units of the Dynamic model (Fishman et al., 1987a; Fishman et al., 1987b), which accounts for the temporal sequence of cool and warm temperature periods observed in chilling accumulation.

Each tree species and variety has specific chilling requirements for correct plant development, usually related to the environmental conditions where it is grown (e.g. climate). The fulfilment of these requirements can be estimated using different methods, such as those mentioned above. As a result, for a given crop tree a range of estimates of chill accumulation has to be considered. For instance, for the apricot varieties considered in Campoy et al. (2012), the estimated accumulated chilling varies: 413 chill hours (chilling hours method), 631 chill units (Utah method) and 37 chill portions (Dynamic method) for the 'Palsteyn' variety, and the 777 chill hours, 1172 chill units and 64 chill portions for the 'Orange red' variety.

Given that the driving variable of dormancy start and break is temperature, global warming has to be taken into account in any assessment of future fulfilment of tree chilling requirements. In fact, in absence of significant mitigation measures, global warming is likely to reach 1.5ºC between 2030 and 2052 compared to pre-industrial annual mean global temperature levels (IPCC, 2018). In this respect, several researchers (Campoy et al., 2011; Luedeling, 2012; Gabaldón-Leal et al., 2017) have pointed out that under this warming scenario, the fulfilment of chilling requirements for some crops and varieties is likely to be compromised. To develop suitable adaptation strategies for both the short and long term, reliable projections of chilling units under different emission scenarios or Representative Concentration Pathways (RCPs, van Vuuren et al., 2011) are needed.

Coupled Ocean-Atmosphere General Circulation Models (GCMs) are a useful tool to provide data for climate change impact models (Coupled Model Inter-comparison Project phase 5; Taylor et al., 2012). However, their coarse horizontal resolution (typically 100–200 km) is a significant limiting factor. Due to the increasing demand of policymakers and end users for regionalised projections, the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative has recently been created (Giorgi and Gutowski, 2015). CORDEX EUR-11 is based on Regional Climate Model (RCM) outputs and provides regionalised projections of key atmospheric variables at 0.11º resolution (~12 km) over Europe.

Even if RCMs have been proved to be a useful tool to describe climatic features in the tropics (Nikulin et al., 2012; Gómara et al., 2018) and extratropics (Jacob et al., 2014; Casanueva et al., 2015), they still present biases in temperature and precipitation over Europe (Casanueva et al., 2016; Dosio, 2016), overestimating future temperature projections for instance (Boberg and Christensen, 2012). Several techniques have been developed so far to minimise and handle model biases, as future projections of threshold-based indices may not be reliable when models' outputs are used without prior bias adjustment. Through the use of transfer functions (e.g. Piani et al., 2010a; Piani et al., 2010b), temperature biases from RCMs are often adjusted, showing good performance not only for the central tendency measurements, but also for probabilistic distribution properties over time (e.g. Dosio et al., 2012; Dosio, 2016; Ruiz-Ramos et al., 2016).

The objective of this paper is to assess the impact of climate change on temperate fruit tree chilling accumulation in peninsular Spain and the Balearic Islands, which in turn will strongly affect the viability of different crops/varieties in the near (2021–2050) and far (2071–2100) future. For that purpose, the last generation of high-resolution, bias-adjusted climate projections were applied to a suite of chilling accumulation models to represent the response of the main tree crops in Spain, the main novelty of this study.

2 Material and methods

2.1 Observed and simulated climate data sets

The climate variables required by the chilling models used in this study are hourly minimum (Tmin) and maximum (Tmax) temperatures. To this aim, available daily observations of Tmax and Tmin for the 1976–2015 period were selected from the Spanish Meteorological Agency (AEMET) weather station records. Missing records up to 10 days were allowed and linearly interpolated to fill the gaps.

Additionally, daily Tmax and Tmin for the same period were taken from the freely distributed, high-resolution observational gridded data set Spain02 (v5, Herrera et al., 2012; Herrera et al., 2016) with horizontal spatial resolution of 0.1° (*ca.* 10 km). This gridded data set was selected for its high data density and resolution, higher than other observational data sets (e.g. E-OBS, Haylock et al., 2008).

Daily outputs of simulated daily Tmax and Tmin for peninsular Spain and the Balearic Islands were extracted from 10 different CORDEX EUR-11 RCM historical simulations (12 km horizontal resolution; see Supplementary Table 1). The 10-model ensemble (hereafter EUR-11) used in this study is based on the availability of model runs (at the chosen resolution) at the time of data processing. This ensemble size is considered to be large enough by the agricultural impact community to retrieve robust results (Martre et al., 2015; Rodríguez et al., 2019). The outputs of the EUR-11 ensemble for two RCPs were considered: 1) +4.5 W/m^2 radiative forcing increase at the end of the 21st century relative to pre-industrial levels (RCP4.5) and 2) the same but for +8.5 W/m^2 (RCP8.5).

Subsequently, the Tmax and Tmin data of each member of the EUR-11 ensemble were bias-adjusted, relative to the 1976–2005 Spain02 observation data set, for the historical or baseline period (1976–2005), the near future (NF, 2021–2050 RCP4.5/RCP8.5) and the far future (FF, 2071-2100 RCP4.5/RCP8.5) climate conditions (hereafter EUR-11 refers to the temperature bias-adjusted ensemble). A previous bi-linear interpolation was applied to Spain02 0.1° areal-representative grid to match the 0.11° rotated CORDEX grid. The bias-adjustment technique applied has been extensively described and applied in previous studies (Piani et al., 2010a; Piani et al., 2010b; Dosio and Paruolo, 2011; Dosio, 2016; Ruiz-Ramos et al., 2016; Dosio and Fischer, 2018). It consists of a histogram equalisation method that makes use of a two-parameter linear transfer function, which is applied to simulated model outputs. The resulting bias-adjusted data has a cumulative distribution function (CDF) comparable to that of the observational data set. Detailed information on the technique and scripts used here can be found as supplementary material in Ruiz-Ramos et al. (2016).

The chilling models used in this study require hourly temperature data. The approach initially presented by de Wit et al. (1978) was used to estimate hourly data from daily fields for both observed and simulated data sets. The method estimates the hourly temperature taking into account the sunrise time (previously estimated using the latitude and the day of the year) as well as daily Tmax and Tmin (Reicosky et al., 1989).

2.2 Chilling modelling

Once hourly data had been prepared, four different methods were used to estimate chilling over Peninsular Spain and the Balearic Islands. Several methods were considered: the Utah method (Richardson et al., 1974) originally developed for peach trees, two of its adaptations; the North Carolina method (Shaltout and Unrath, 1983) developed for apple trees, the method specifically developed by De Melo-Abreu et al. (2004) for olive trees, and the Dynamic method (Fishman et al., 1987b), also developed for peach trees. Methods based on the Utah method use chilling units, while the Dynamic model uses chilling portions (in this paper the chilling unit terminology will be utilised in general unless stated otherwise).

The Utah method is a mathematical model that calculates the number of chilling units accumulated within several temperature ranges, where optimum efficiency for chilling unit accumulation is within 2.5 and 9.1°C. Temperatures outside that range have lower efficiencies and temperatures above 15.9°C penalise chilling accumulation by subtracting chill units. The North Carolina method is an adaptation of the Utah method where temperature ranges have been adjusted for apple trees.

The chilling accumulation method proposed by De Melo-Abreu et al. (2004) has been adapted from the Utah method and applied to different olive tree cultivars, using a piecewise function that reaches the maximum chilling unit accumulation when the temperature is optimal. Chilling units linearly decrease as temperature diverges from the optimum, accumulating negative chilling units for high temperatures (penalisation).

The Dynamic model computes the chilling in a two-step scheme. First, cold temperatures promote the formation of a precursor in a reversible process. Second, once the precursor has reached a certain threshold, warmer temperatures promote the irreversible transformation of the precursor into a chilling portion.

The chilling period was calculated separately for each chilling model, year, member of the EUR-11 ensemble and grid cell. The chilling units' accumulation, built on an hourly basis, was calculated from the moment in autumn at which chilling units (or portions) started to increase until the moment that it reached its maximum (Fig. 2a). Therefore, the beginning and end of the period vary in each case. Once the annual chilling sum of a cell was calculated, the 30-year mean value of each member of the EUR-11 ensemble was computed (Fig. 2b). Then the median of the ensemble members was calculated (Fig. 2c). Repeating the process for each cell of the CORDEX grid over peninsular Spain and the Balearic Islands, chilling maps were obtained for each of the chilling models (Fig. 2d).

Chilling model programming, calculations and data processing were done by means of MATLAB software (MATLAB, 2017). Scripts are available by contacting the authors and under quotation.

2.3 Data set validation and projection calculation

To evaluate how the interpolation of daily Tmax and Tmin from Spain02 affects the results, chilling units calculated with 42 AEMET station data and with the closest Spain02 cell, according to the nearest neighbour method, were compared. This evaluation was conducted mainly to check whether the hourly time series derived from the Spain02 data is comparable to the time series of the AEMET stations over coastal and mountainous areas, although the entire grid over Spain was compared. The mean percentage absolute error (MAPE) between AEMET-based and Spain02-based chilling units calculated with the four chilling methods was computed for the baseline period.

In the same way, to evaluate the results obtained with the bias-adjusted EUR-11 ensemble for this specific application, the MAPE between Spain02-based chilling units and the median of chilling units from the EUR-11 ensemble was calculated for the baseline period and for the four methods.

Then chilling projections were computed with the four methods and for the NF and FF periods for the EUR-11 ensemble. Changes between baseline and future simulated chilling were calculated. Projections were derived from individual RCMs by first averaging each time series (30-year mean of chilling accumulation) and then calculating the ensemble median among the resulting 10 means (one per ensemble member).

Inter-annual variability was measured by the ensemble mean coefficient of variation (CV) of the yearly chilling units of each period (30 years) of Spain02 and the 10 EUR-11 ensemble members. Uncertainty coming from RCMs was measured by ensemble inter-model spread, in turn estimated by the ensemble interquartile range (IQR) of the 10 ensemble members' 30-year means.

3 Results

3.1 Performance under current climate

Chilling units calculated with Spain02 are in good agreement with those obtained from the corresponding AEMET stations (Fig. 3c, filled dots), with most of the locations with MAPE values lower than 5% whatever chilling method was used. Only a few coastal or mountainous locations presented MAPE values higher than 20%. Therefore, the Spain02 data set was considered acceptable for use as the observational gridded data set to perform the EUR-11 ensemble bias adjustment.

Chilling units calculated with the four chilling methods for every CORDEX cell with Spain02 (Fig. 3a) and with the EUR-11 ensemble (Fig. 3b) were in good agreement (Fig. 3c), with MAPE chilling values of EUR-11-based compared to Spain02-based generally lower than 5%. MAPE values were higher than 20% only for some coastal or mountainous regions. Therefore, the remaining temperature biases after bias adjustment were small enough to enable the bias-adjusted EUR-11 ensemble to adequately reproduce the chilling units' behaviour derived from the observational data set in most locations. The ensemble median for the 1976–2005 period (Figs. 3b, 4a) was taken as the chilling accumulation simulated by the EUR-11 ensemble. Inter-annual variability of chilling accumulation was similarly simulated when using Spain02 and the EUR-11 ensemble, with small differences for the De Melo-Abreu and Dynamic methods in the southern half of Spain (Fig. 1S in suppl. mat.).

As simulated by EUR-11, the North Carolina model estimated higher chilling accumulation in the North of Spain, followed by the Utah and De Melo-Abreu models, while the opposite trend was found for the South and East coast. However, the differences were less than 500 chill units in most locations, especially between the North Carolina and Utah methods (Fig. 4a). The Dynamic model showed a spatial pattern of chilling accumulation close to the De Melo-Abreu model, although direct comparison is not possible because they used different units.

The mean inter-annual variability measured with the CV (Fig. 4b) was, in general, lower than 20% for most of the grid cells whatever chilling method was considered. The Dynamic method presented the lowest results with maximum CV values for some points of the South coast of the Iberian Peninsula. The De Melo-Abreu method showed CV values similar to the Dynamic method with the exception of the mountainous regions where the CV was higher. Finally, the Utah and North

Carolina methods performed similarly with the CV around 10% in northern Spain and around 20% in southern Spain, with higher values on the South and East coasts.

The uncertainty associated with the EUR-11 ensemble was very low, as the ensemble spread measured by the IQR (Fig. 4c) was lower than 100 chilling units (or 5 chilling portions for the Dynamic method) for all four chilling models and all the simulated areas except for small mountainous areas. There, only the Dynamic method presented low IQR values while the method presenting the highest uncertainty was the De Melo-Abreu method.

3.1 Chilling projections under climate change scenarios

The EUR-11 ensemble median results show a general decrease of chilling units and portions over all simulated areas for both the NF and FF under both RCPs, as expected (Figs. 5a, 6a, 7a and 8a). Under RCP4.5, a decrease of up to 600 chill units (and up to 30 chill portions in the Dynamic method) is projected for the NF (Fig. 5b). A slightly higher but similar decrease is projected under the RCP8.5 scenario in the NF (Fig. 6b). CV and IQR values (Figs. 5c, 5d, 6c, 6d) are similar for the NF between RCP4.5 and RCP8.5 and for all methods, with the Utah and North Carolina methods presenting higher CV values than the De Melo-Abreu and Dynamic methods. The IQR obtained when using the Utah and North Carolina methods is slightly higher than when the De Melo-Abreu and Dynamic methods are applied (considering categories to compare the IQR portions).

The decrease in chilling units and portions is more pronounced by the end of the century, as shown by the results for the FF under both RCPs, with the Utah and North Carolina chilling methods showing the largest decreases (Figs. 7, 8). For RCP4.5, a generalised decrease of up to 900 chill units (and 45 chill portions) is projected (Fig. 7b). This decrease reaches 1200 chilling units (and 60 chill portions) under RCP8.5 (Fig. 8b). Both inter-annual variability and climate model uncertainty (CV and IQR, respectively) increase with respect to the NF for every chilling method; both are higher in the RCP8.5 scenario. As found in the NF, the Utah and North Carolina chilling methods presented higher CV and IQR values than the De Melo-Abreu and Dynamic methods.

4 Discussion

The chilling portion results are in agreement with the projections from Luedeling et al. (2011) in the Mediterranean region for different periods, where emission scenarios and global climate models were averaged (see Fig. 6 in Luedeling et al., 2011). Our work shows the spatial distribution of a generalised decrease in chilling sums projected for the rest of the 21st century. Gabaldón-Leal et al. (2017) used an adapted version of the De Melo-Abreu method to calculate the projected chilling units for olive trees in the Andalusia region, also showing a generalised decrease in chilling accumulation projected for the rest of the century. To our knowledge this is the first study providing chilling unit projections under climate change with the rest of the methods considered; therefore, comparison with previous results was not possible for these methods.

The projections of the chilling accumulations provided in this study have a lower uncertainty coming from simulated climate scenarios (as indicated by IQR values) than the common uncertainty levels of impact assessments (e.g. Lorite et al., 2018; Tao et al., 2018). This is probably because these chilling methods are based only on temperature, and there is higher agreement in the climate change signal related to mean temperature increases than for other climate variables. When other climate variables are required for impact assessment, the uncertainty is usually higher (e.g. Olesen et al., 2007). For olive trees, previous studies indicate that the lack of knowledge on crop chilling requirements may introduce much more uncertainty than climate projections (Gabaldón-Leal et al., 2017). In any case, according to the validation process, the high-resolution bias-adjusted CORDEX data provide temperature values with adequate quality for this particular application. However, it is important to stress that in spite of the relatively low IQR values shown here (except for mountainous and coastal areas), in certain places these temperature values were approximately 50% of the value of the change.

Special attention should be paid to the south-western zones of Andalusia, with a substantial oceanic influence, and coastal locations of the Mediterranean where the evaluation of the selected data sets did not perform as well as for the rest of the country and where tree crops are significant. Our results support the hypothesis of a poor representation of stations in these areas by the interpolated Spain02 data set. In addition, some authors have noted part of these zones as potential areas of crop extension for climate change adaptation (Gabaldón-Leal et al., 2017 for olive trees). In these areas precisely, inter-annual variability (as indicated by CV values) appears to be quite large, which may pose an additional challenge, especially in the FF and for the warmer scenarios. Inter-annual variability also depends on the methods used; this could be related to the discrete nature of the Utah and North Carolina methods compared to the others.

Uncertainty was also higher in some mountainous regions, where chill increases are found for warmer climate projections for both the Utah and De Melo-Abreu methods. At first glance contradictory, this is explained by the temperature thresholds used in the methods and is in agreement with the findings reported by Luedeling (2012), who found that warming from a cold baseline (with temperatures so low that they do not contribute to the chilling sum) can lead to winter chill increases, while warming from a warmer baseline should lead to chilling decreases. Nonetheless, few tree crops are grown in these areas.

However, uncertainty from the chilling models themselves remains. A previous study (AEMET, 2018) analysed the risk of frost in Spain using the chilling hours method instead of chilling units, for the 2002–2012 period in peninsular Spain. However, according to Luedeling (2012), a number of studies show that other approaches, like those used here, exhibit better performance. Nevertheless, the accuracy of these models under some conditions is still low (e.g. Benmoussa et al., 2017, for almond trees in warm Mediterranean locations). To overcome this limitation and improve the existing models, until models based on the functional understanding of dormancy processes are developed (Campoy et al., 2011), the experimental data sets existing on chilling requirements of tree crops and varieties must be extended. Targeted field experiments should be designed for this purpose.

The method used in this study to compute the chilling sum period every year is a methodological novelty that was crucial to increase the quality of our projections, since the expected warmer temperatures for the Iberian Peninsula will definitely affect the onset and duration of such a period. Thus, the computation period has evolved dynamically over the 21st century for every climate and chilling model, RCP, moment in the century and location considered.

According to our results, it is expected that some areas where temperate trees are currently grown will not be suitable in the FF for some crop varieties depending on the RCP. For example, the broadly cultivated Golden Delicious apple variety requires 1050 chilling units (calculated with the North Carolina method; Hauagge and Cummins, 1991), but our results show that those chilling requirements will not be obtained under a RCP8.5 scenario in the Ebro valley, where these apples are currently grown. For olive trees, although MAPE validation values at the southeastern-most part of the Andalusia region presented the highest values, reasonable doubts can be raised on the viability of important olive tree varieties such as Picual, with requirements of 469 chilling units (applying the De Melo-Abreu method; De Melo-Abreu et al., 2004) in that region, in the FF under the RCP8.5 scenario. This result is in agreement with the reduction in the suitable cultivation areas in Andalusia for this variety, as found by Gabaldón-Leal et al. (2017).

Further work to advance towards more accurate projections of chilling sums, while new experimental data are generated, would be to analyse the probabilities that the chill requirements of most important crops and varieties in Spain are fulfilled, as well as for the low-limit chill requirements of each species. This would enable us to analyse the chances of local adaptation, given that matching chill sums and varieties must be done at the local scale. The analysis should be done not only in terms of mean or median results from the different climate models, but also providing additional measures of robustness, as 1-year events can have long-lasting consequences on tree crops. This becomes a relevant issue when analysing ensemble scenarios with high associated uncertainty (e.g. FF or RCP8.5). It could be possible to use a hypothesis-based index such as the ensemble outcome agreement index (e.g. EOA, Rodríguez et al., 2019) to test the robustness of a hypothesis that imposes a conservative threshold, i.e. that a variety meets its chill requirements at a specific location and time at 90% likelihood.

Finally, this study is yet another call for action, to carry out not only adaptation but also mitigation measures, to limit the warming rate within the 1.5°C as claimed by the last IPCC special report (IPCC, 2018). The present results strongly support that local adaptation would be much more feasible for moderate warming scenarios (RCP4.5 and below) than for RCP8.5.

5 Conclusions

A generalised chilling unit reduction is projected across peninsular Spain and the Balearic Islands regardless of the climate scenario, future period and chilling calculation method used. The reduction is expected to be higher for the far future period (2071–2100) and for the RCP8.5 scenario.

A winter chill reduction may threaten the viability of some crops and varieties, especially in some areas that already have a low number of chilling units, where their reduction may jeopardise the cultivation of some tree crops within the near future.

An attempt to improve chilling projections was made here by combining for the first time high-resolution RCM outputs, bias-adjusted against a gridded observational data set and contrasted with station data, four chilling models and an evolving chilling period onset. As a result, the uncertainty related to these projections coming from climate data is lower than in other impact assessments, while further studies are needed to improve our knowledge on chilling requirements and modelling for a wide range of tree crops and varieties.

Finally, this climate change impact should be considered for future tree crop plantation and choice of variety, and also for designing adaptation strategies; these results enable local adaptation by helping to match chill sums and varieties over the 21st century. Such an adaptation would benefit from mitigation, which is much more feasible for moderate warming scenarios.

Author contribution

The conceptualisation and methodology design were done by MRR and AR. The tree physiological aspects were supervised and written by DPL and AC. ES supervised the methodology and analysis process related to climate data processing. The bias-adjustment technique was developed by AD. IG produced the bias-adjusted data. AR developed and applied all the code scripts used to generate the results, including the figures. AR and MRR prepared the manuscript and all co-authors reviewed it and contributed to the final version.

Competing interests

The authors declare that they have no conflict of interest.

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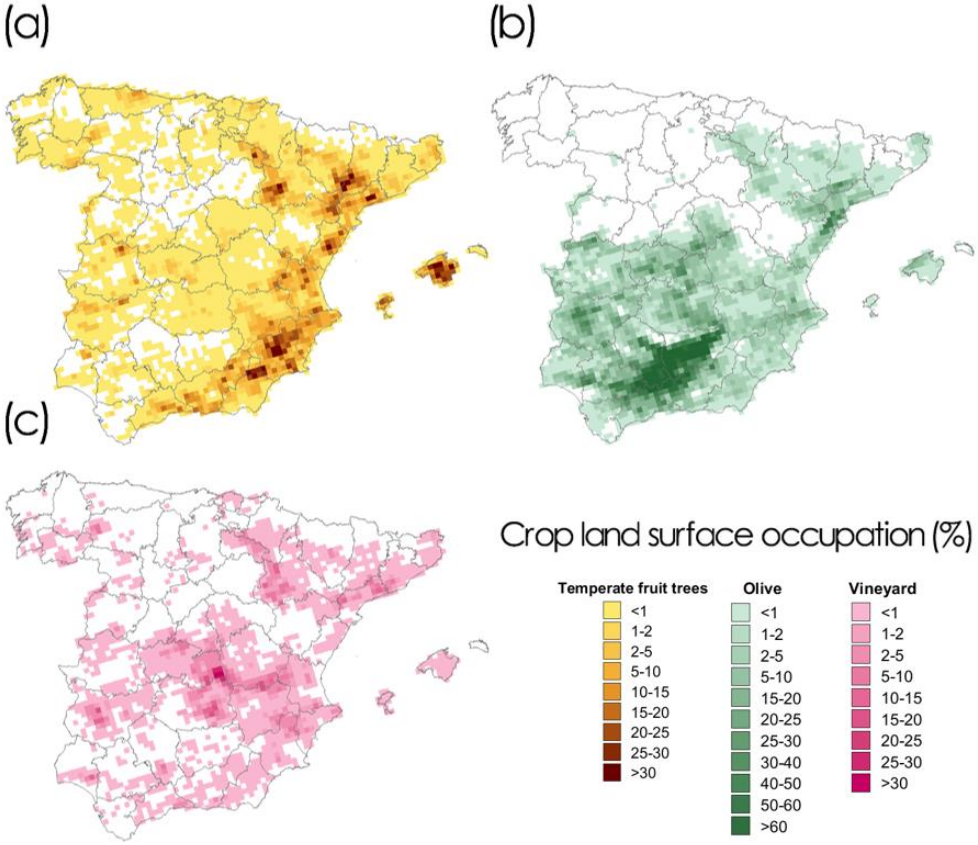

Figure 1. Percentage of land surface occupation for temperate fruit trees (orange colour tones, plot a), olive (green colour tones, plot b) and vineyard (pink colour tones, plot c) in 2011. Maps were created with the information available from the Spanish Soil Occupation Information System (SIOSE, 2015)

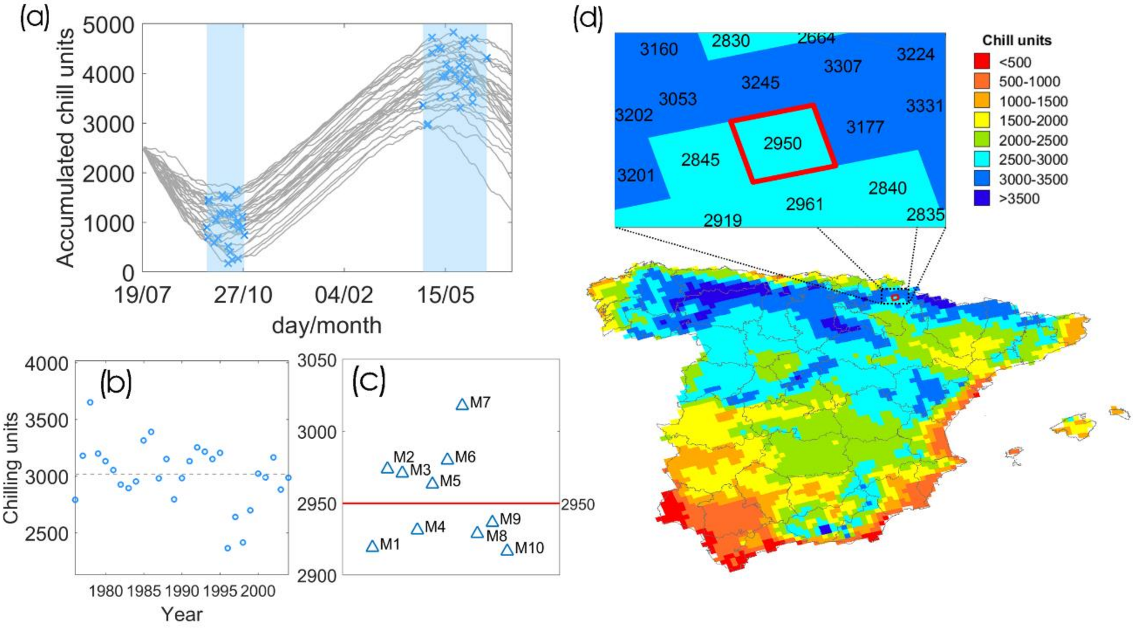

Figure 2. Methodological example: Chilling accumulation calculation process using the North Carolina chilling model in a particular location (42.86ºN, 1.57ºW) for the 1976–2005 period. Plot a) shows the initial and final chilling accumulation dates for each year (blue crosses) of the EUR-11 ensemble member IPSL-CM5A-MR/RCA4 and the date spread (vertical blue band). Plot b) shows the annual accumulated chilling units (blue dots) and the model mean (dashed horizontal line). Plot c) shows every ensemble member's mean (M, blue triangles) and the ensemble's median (red horizontal line). The results for each grid cell are then used, for each RCM, to create the map shown in plot d).

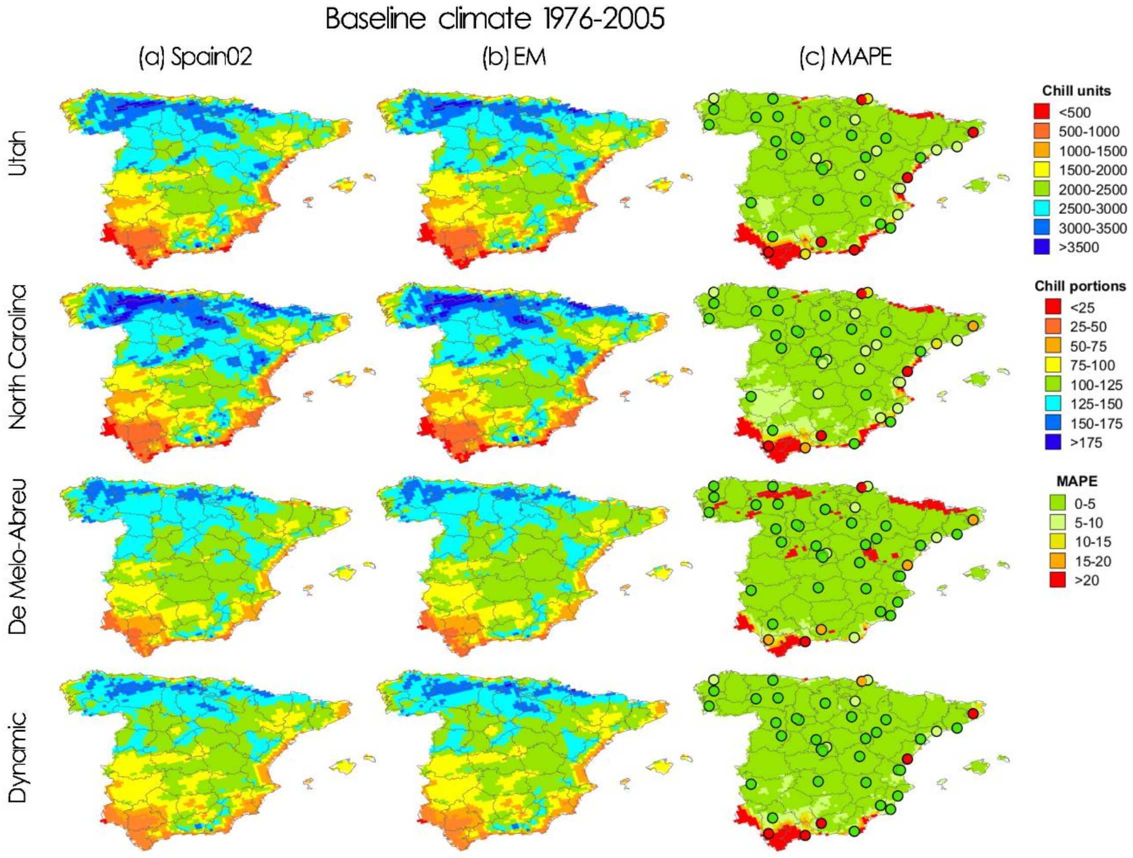

Figure 3. Evaluation of the chilling accumulation units for the baseline period (1976–2005). For each chilling method (rows), the map of the 30-year mean chilling sums calculated with the observational data set Spain02 (first column) and the map of medians of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (EM, second column). Mean absolute percentage error (MAPE) between chilling accumulation calculated with Spain02 and EM data sets (third column, map) and between those calculated with Spain02 and AEMET data sets (third column, dots).

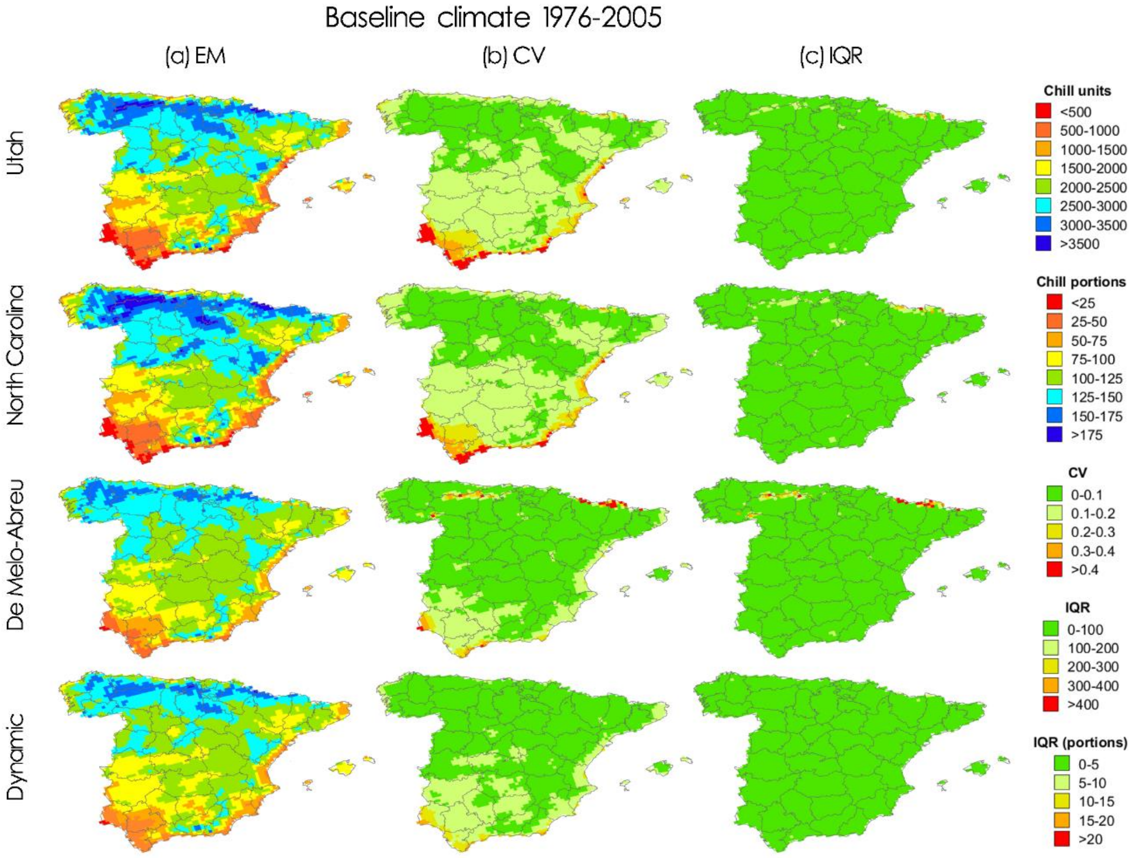

Figure 4. Maps of chilling accumulation, inter-annual variability and uncertainty results for the baseline period (1975–2005). For each chilling method (rows), the median of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (first column) and the 10 EUR-11 ensemble members' mean coefficient of variation (CV, expressed per unit) of the 30-year period (second column) and the ensemble's interquartile range (IQR) of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (third column).

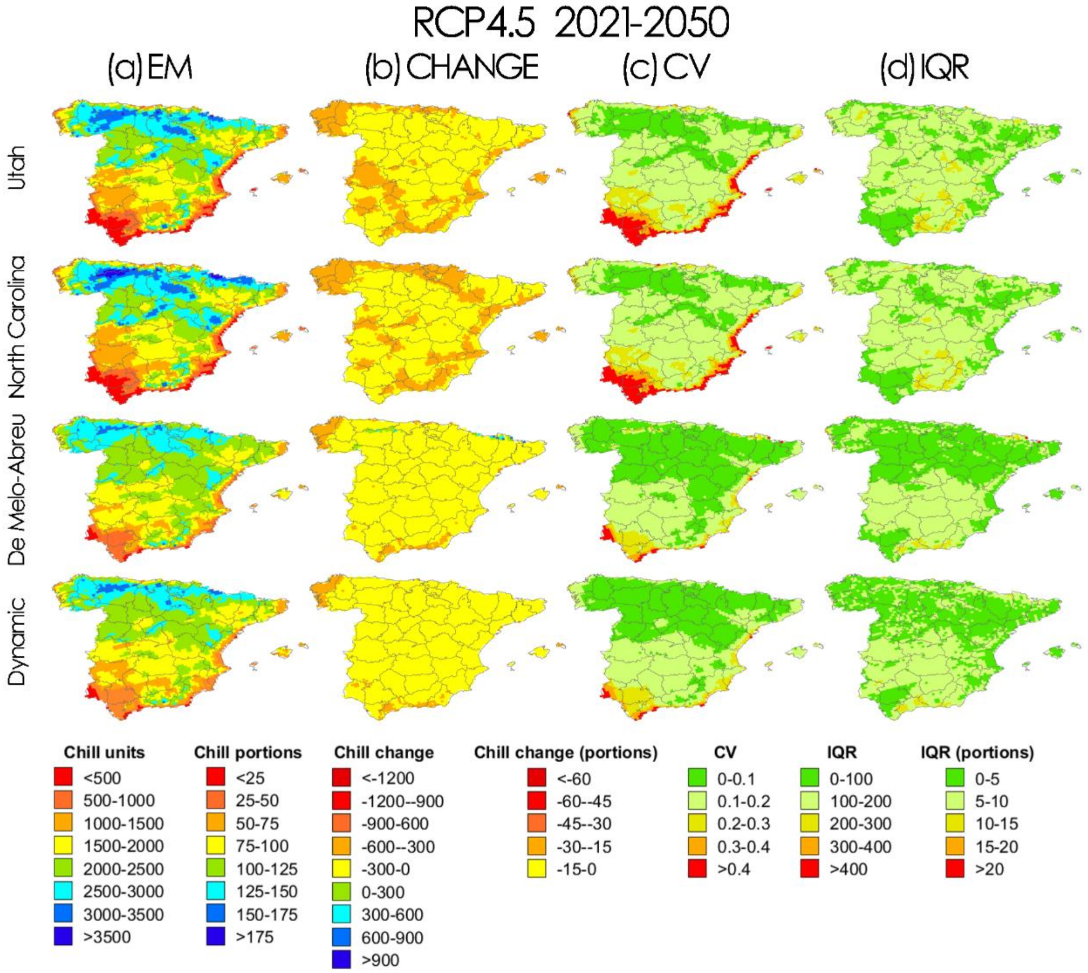

Figure 5. Maps of chilling accumulation, inter-annual variability and uncertainty results for RCP4.5 scenario in the NF (2021-2050). For each chilling method (rows), the median of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (first column), change in chilling accumulation with respect to the baseline period (second column), the 10 EUR-11 ensemble members' mean coefficient of variation (CV, expressed per unit) of the 30-year period (third column) and the ensemble's interquartile range (IQR) of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (fourth column).

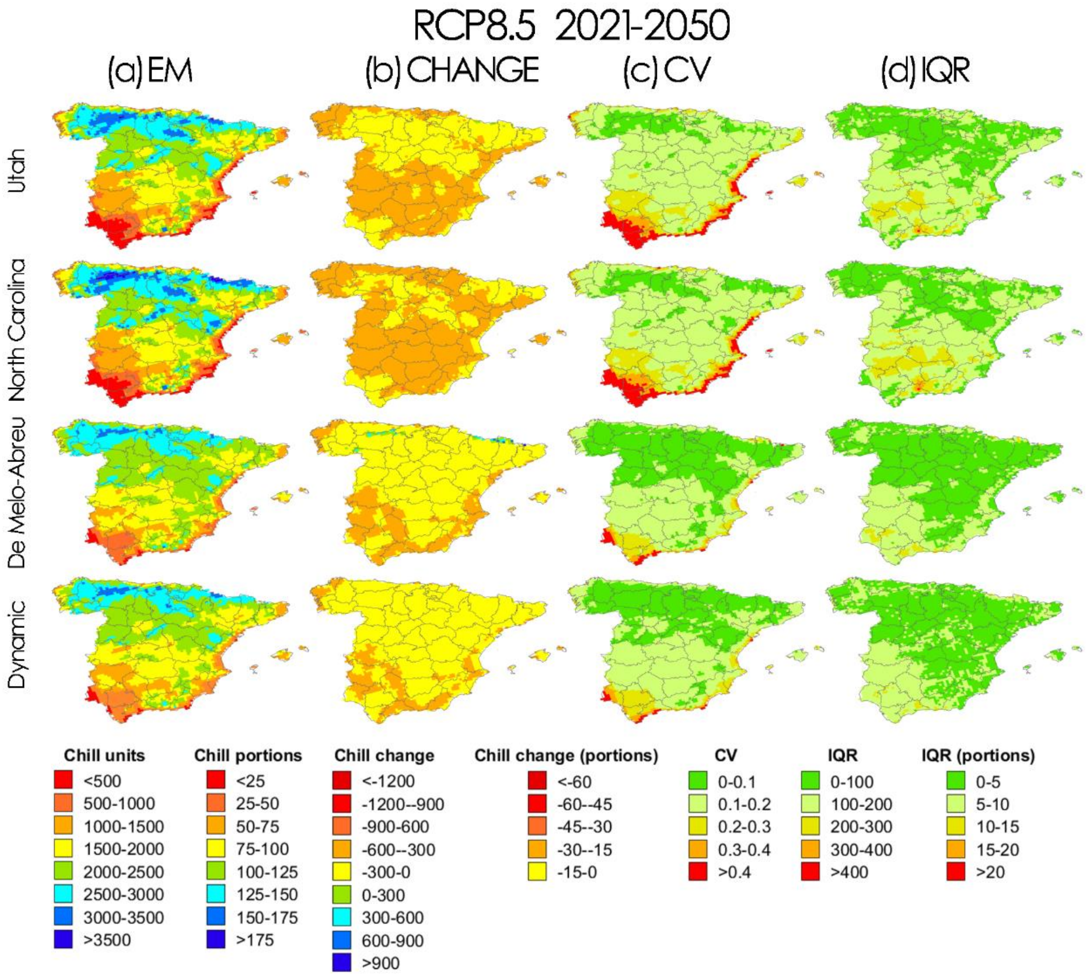

Figure 6. Same as Fig. 5 but for the RCP8.5.

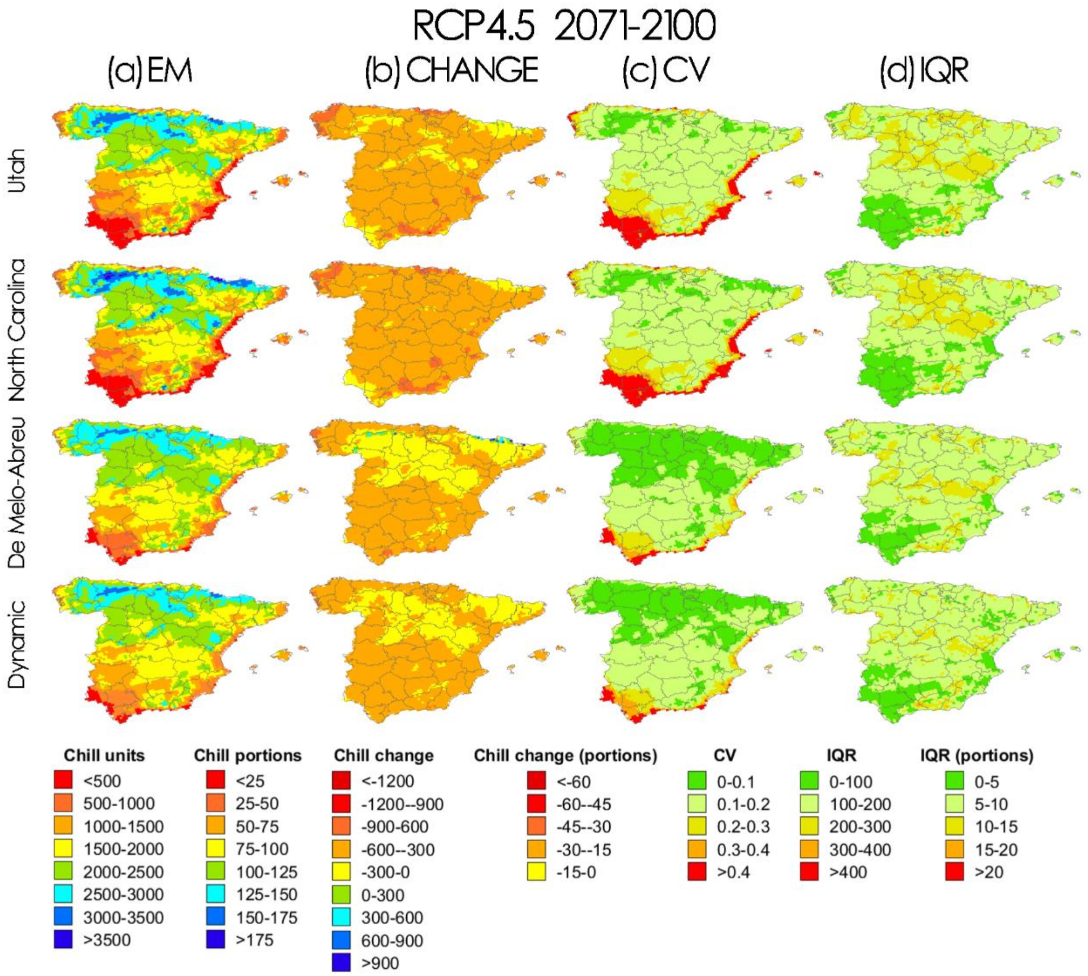

Figure 7. Same as Fig. 5 but for the FF (2071–2100).

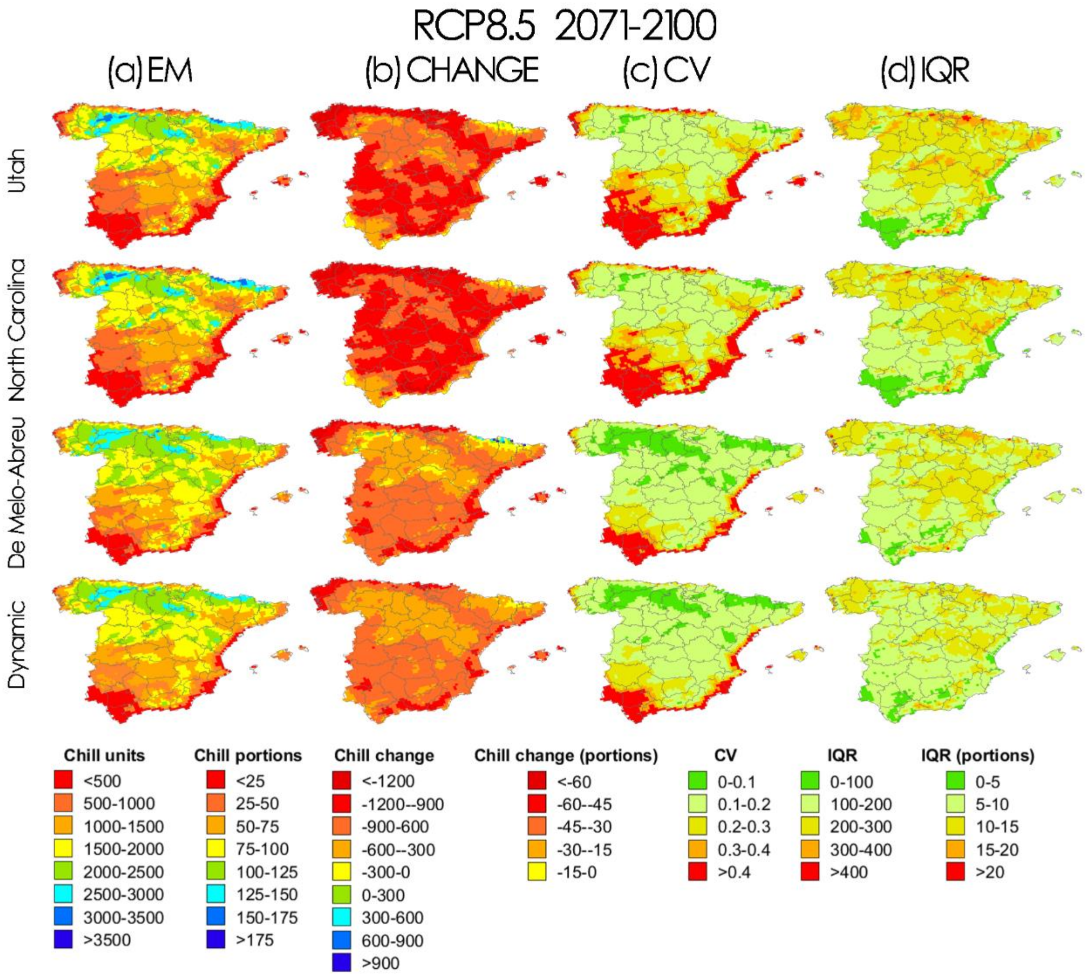

Figure 8. Same as Fig. 6 but for the FF (2071–2100).