Guest editor report: nhess-2018-392; original title “Chilling accumulation in temperate fruit trees in Spain under climate change”

Answers are in green font.

The authors have undertaken an ambitious research in assessing winter chill across Spain, as derived from meteorological observations and climatic projections. Each of the two reviewers have provided an excellent and detailed revision of the manuscript, to which the authors have responded in a detailed manner.

The two reviewers reach consensus on a number of critical points. The interactive comments from both reviewers have been well documented and the authors have formulated solutions to take the manuscript further in two separate documents (RC1 and RC2). I agree with the solutions presented by the authors. Below I highlight some points of attention for the authors.

Thank you for your comments.

Overall the research can be documented better in the manuscript such that justice is done to the rigorous work undertaken. The processing of meteorological observations and climate scenarios, and their relation to the impact on the Spanish fruit trees uses state-of-the-art methodology. Therefore I would suggest that the authors revise the manuscript according to their documentation and replies to the reviewers.

A new version of the manuscript has been produced incorporating the answers we proposed in the previous revision phase (see revised paper attached). The documentation of the undertaken research has been improved following referee's instructions.

The following major points require the authors’ attention:

1. Avoid vague descriptions and formulate more precisely what has been done, certainly in the abstract. [an example: “near and far future” is vague; define the periods “2021-2050” and “2071-2100”] Overall a focus on precise findings will improve the readability of both manuscript and abstract.

"Near and far future" terms have been removed from the paper, using “2021-2050 period” and “2071-2100 period” instead. Also, we made an effort to focus on main findings across all the manuscript and especially in the abstract and introduction, which have also been reduced following referee's advice (see revised paper attached).

2. A comprehensive review of chilling requirements for different species will be of enormous relevance and interest to an international audience. To this extent, the authors’ suggestion of adding a table is excellent. References to the literature, as already documented in the authors’ replies to the reviewers, could be extended to include research that is relevant to Spain or similar climatic environments (e.g. California).

New Table 1 reports the information of the chilling requirements for main varieties of different tree crops. The new references found following the referee's suggestions and included in our reply have been incorporated in the manuscript, mainly in the discussion section, stressing those studies especially relevant for Spain or dealing with Mediterranean environments.

3. An important outcome of the research relates to winter chill reduction. It would be useful to discuss the number of times chilling requirements are compromised for the different periods studied.

Table 1 has been extended beyond we proposed in our reply to the referees to follow this suggestion from the editor (see Table 1 in the revised paper attached). We have selected some locations (from the areas mentioned in the discussion section) to compute the mean number of compromised seasons for the different periods studied, for the same varieties of the Table 1. A paragraph commenting this example has been included at the end of the results section (lines 10 to 15 in page 10 of the clean revised version) and is also mentioned in the discussion (paragraph from lines 9 to 32 in page 13 of the clean revised version).

4. The choice of keeping the different chill model results separately is underpinned by the reviewers' preference for the dynamic model, and therefore I recommend to keep the results separately as currently done. Nevertheless, a better documentation of the different chill models and temperature thresholds will clarify the comments made.

We agree with the editor's comment. Following her suggestion and those made by both referees, we have improved the documentation of the chill models used, their origin and the relationships and differences between them. This has been done mainly in section "2.2. Chilling modelling", but also in the introduction (lines 15 to 25 in page 4 of the clean revised version), discussion (from line 22 in page 11 until line 21 in page 12 of the clean revised version) and supplementary material (Codes 1S to 9S).

5. I leave it to the authors to decide whether to share their code in the supplementary material or document the formulas used.

We have included the codes in the supplementary material as it was strongly advised by the referees.

Since most of the above points have been documented in the replies to the reviewers, the revised manuscript can be reviewed by the handling editor.

In our comments we offered to send the manuscript to a professional Editing English service. The deadline set did not allow to do so (we had only 10 days to review the paper including Easter period), but we are willing to do so if the editor thinks this is needed.

Responses to referee comment [RC1]

Interactive comment on "Chilling accumulation in temperate fruit trees in Spain under climate change" by Alfredo Rodríguez et al.

We thank the reviewer for his thoughtful comments. Our answers are highlighted in green italics.

Rodriguez et al. present an assessment of past and future winter chill in Spain, using an ensemble of climate scenarios and four chill models. It seems to me that the climate data processing was very well done; the way scenarios were prepared seems very reasonable. The authors' expertise in this field is evident.

Thank you for this comment

Unfortunately, the study has some shortcomings regarding the estimation of winter chill, which will have to be addressed.

Major issues:

1) Similar work has been done before, for various countries and also at global scale. It remains somewhat unclear what the particular advantage of this new approach is. A (smaller) ensemble approach was already used 10 years ago (Luedeling et al., 2009a) for California and shortly afterwards at the global scale (Luedeling et al., 2011). In these studies, we used a weather generator rather than just climate model outputs, which (in my view) makes the methodology used then more robust than what is presented here. Admittedly, some other elements of these assessments were not as well done as what is described in the current manuscript, and it's good to see a study using RCPs rather than SRES scenarios (though we did this here: Benmoussa et al., 2018, but not as a spatial analysis), but the novelty of the current methodology isn't sufficiently described.

We have softened the language about the novelty of our study throughout the paper and we have acknowledged as previous works the studies pointed by the reviewer (Luedeling et al. 2009, 2011). Besides, we have further described the methodology followed to design the climate ensemble, enhancing the description of the improvements and contributions of our study in the text: 1) Studies done in other countries would be of little help for Spanish farmers that previously could only find scarce information from studies performed in other regions, or worldwide with not enough resolution; 2) In recent studies working with multi-model ensembles formed by crop models, ensemble results tend to improve as the number of members of the ensemble increases, for instance, in Martre et al. (2015) the committed errors decreased as the ensemble members grow with little decrease beyond 10 members. This debate was analysed from the statistical point of view in Wallach et al. (2018). We consider that this is an improvement from the former studies using 3 climate models.

From this point only, in our view this work represents an improvement in terms of robustness, due to the ensemble design and composition.

We have clarified the text to stress that in this study we did not use the climate model outputs directly. Instead, a bias adjustment process was applied to the outputs prior to be applied to the models. The bias adjustment techniques are considered a valid alternative to apply on climate model outputs to crop models, especially suitable for handling the complex orography of the Iberian Peninsula (Maraun and Widmann, 2018). Of course, weather generators can also be a reasonable approach.

Luedeling, E., Zhang, M., and Girvetz, E. H.: Climatic Changes Lead to Declining Winter Chill for Fruit and Nut Trees in California during 1950–2099, PLOS ONE, 4, e6166, 10.1371/journal.pone.0006166, 2009.

Luedeling, E., Girvetz, E. H., Semenov, M. A., and Brown, P. H.: Climate Change Affects Winter Chill for Temperate Fruit and Nut Trees, PLOS ONE, 6, e20155, 10.1371/journal.pone.0020155, 2011.

Maraun, D., and Widmann, M.: Statistical Downscaling and Bias Correction for Climate Research, Cambridge University Press, Cambridge, 2018.

Martre, P., Wallach, D., Asseng, S., Ewert, F., Jones, J. W., Rotter, R. P., Boote, K. J., Ruane, A. C., Thorburn, P. J., Cammarano, D., Hatfield, J. L., Rosenzweig, C., Aggarwal, P. K., Angulo, C., Basso, B., Bertuzzi, P., Biernath, C., Brisson, N., Challinor, A. J., Doltra, J., Gayler, S., Goldberg, R., Grant, R. F., Heng, L., Hooker, J., Hunt, L. A., Ingwersen, J., Izaurralde, R. C., Kersebaum, K. C., Muller, C., Kumar, S. N., Nendel, C., O'Leary, G., Olesen, J. E., Osborne, T. M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M. A., Shcherbak, I., Steduto, P., Stockle, C. O., Stratonovitch, P., Streck, T., Supit, I., Tao, F. L., Travasso, M., Waha, K., White, J. W., and Wolf, J.: Multimodel ensembles of wheat growth: many models are better than one, Glob. Change Biol., 21, 911-925, 10.1111/gcb.12768, 2015.

Wallach, D., Martre, P., Liu, B., Asseng, S., Ewert, F., Thorburn, P. J., Ittersum, M., Aggarwal, P. K., Ahmed, M., Basso, B., Biernath, C., Cammarano, D., Challinor, A. J., De Sanctis, G., Dumont, B., Eyshi Rezaei, E., Fereres, E., Fitzgerald, G. J., Gao, Y., Garcia-Vila, M., Gayler, S., Girousse, C., Hoogenboom, G., Horan, H., Izaurralde, R. C., Jones, C. D., Kassie, B. T., Kersebaum, K. C., Klein, C., Koehler, A.-K., Maiorano, A., Minoli, S., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G. J., Palosuo, T., Priesack, E., Ripoche, D., Rötter, R. P., Semenov, M. A., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Wolf, J., and Zhang, Z.: Multimodel ensembles improve predictions of crop–environment–management interactions, Glob. Change Biol. (in press), doi:10.1111/gcb.14411, 2018.

2) Another innovation the authors point out isn't really a feature but rather a bug in my view. As highlighted on page 9, ll. 1-2, this may well be the first study that projected climate change impacts for these four chill models. However, there are good reasons for there not being more studies, in particular no recent studies. The reason is simply that most of these models can't be trusted to accurately describe chill accumulation. There have been a number of model comparisons over the years that have consistently found the Dynamic Model to be superior to the others (e.g. Benmoussa et al., 2017; Luedeling et al., 2009b; Ruiz et al., 2007; Zhang and Taylor, 2011; there are quite a few more). Adding old, obsolete models to such a study would be like adding a flat-earth model to a GCM ensemble – it makes little sense to consider models that have been shown to be inadequate. The situation with chill models is not the same as with GCMs – we do have a clear idea of which models are better, and there is really no rationale in my view to go for an ensemble approach.

We admit that the methodology has probably not been adequately transmitted, as this is a key point of this work. The ensemble approach was only considered for climate models but results from the different chill models were considered, calculated and interpreted individually. The difference is that while chilling projections calculated with different climate projections and the same chilling model have been averaged, chilling projections from different chilling models were not. We have tried to clarify this point to avoid any impression of comparison between chilling model results in the results and discussion sections.

We are willing to discuss the validity of the models used. We agree with the first reviewer that there are several studies concluding that the Dynamic Model (DM) exhibits a higher accuracy than the Richardson based models (RbM, as Utah, North Carolina and De Melo-Abreu models). However, the reported improvement in the papers quoted by the referee is very small (e.g. Ruiz et al., 2007). Those studies also report varieties and locations where RbM models perform better. Also, some of these papers and others claim there is not a significant difference between models, for instance:

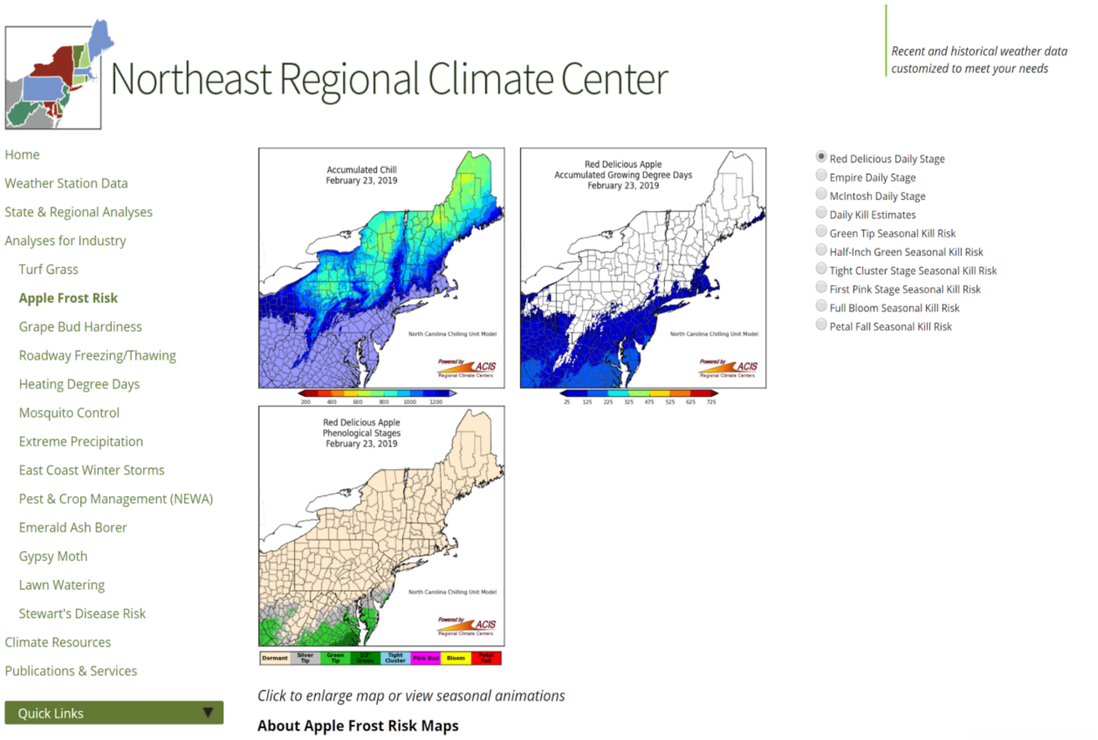
"In this study, ***differences [between DM and Utah model] were not found*** *between these two models when estimating the chilling requirements for seven sweet cherry cultivars in north-western Murcia", Alburquerque et al. (2008), for cherry trees in Spain*

"We have obtained ***very homogeneous results with the Utah and Dynamic models****[...] The chilling requirements of the evaluated cultivars in the 3 years studied were quite homogeneous, according to the Utah and Dynamic models. Besides, the relationship between the two models was very close (R= 0.99).", Ruiz et al. (2007), for apricots in Spain. This team is also using Utah model for prune tree in Spain (Ruiz et al., 2015).*

These results take part of the Luedeling et al. (2012) review; see Table 2, where for two studies in Spain DM appears with better performance, and for other two cases Utah model and DM appear with equivalent performance.

Therefore, in our view, although under for some cases DM has shown a better performance, we cannot conclude that DM is a better model for Spain in general terms.

This is also supported by other researchers using other models besides the DM in recent papers, as for instance (Darbyshare et al, 2013, made a study to evaluate the global warming on winter chilling in Australia using 0-7.2ºC, Modified Utah, and Dynamic Model; Miranda et al., 2013 compares Weinberger, Utah, North Carolina, Low Chilling and Dynamic for peach; Aybar et al., 2015, using a de Melo-Abreu model for analysing the suitability olives varieties in Argentina; Marra et al., 2017, using Richardson model and Chilling hours model, but no DM, for cherry in Italy; Sawamura et al., 2017, investigated the chilling requirements of peach in Japan using the Weinberger and Utah model). Also, the North Carolina model is currently being used by the Northeast Regional Climate Center from USA administration, implemented by the University of Cornell for apple tree (see below).



Source: http://www.nrcc.cornell.edu/industry/apple/apple.html

Therefore, we respectfully disagree with the referee's assessment of North Carolina model being obsolete as it is being currently used. Even the Chilling Hours Model, which is the oldest method to estimate winter chill accumulation (not considered in our paper), and considers all hours with temperatures ranging from 0 to 7.2 ºC equally effective, continues to be useful, as is still widely used in climate change impact and adaptation studies (see for example grapevine studies as Londo et al., 2014; Houston et al., 2018).

Additionally, if it was the case that DM is superior for our particular case, it would be important to notice that even with climate models, one could argue that some are non *adequate to reproduce specific (and also very important) climate aspects (e.g., the monsoon), but they are used anyway. We agree with the reviewer where he says (Luedeling et al, 2012): "All the models still leave a lot to be desired in terms of accuracy and some dormancy breaking behaviour at warm sites could not be explain at all".*

Finally, we think that the main point is here is that all these models were developed, more than for specific locations, for specific tree species (peach for RbM). And the current practice is two or three models of chilling accumulation being used against phenological data of a specific species, generally with several varieties, and obviating that the model was fitted for a different crop (peach), assuming that there are not differences among species. In the few works where chilling accumulation models have been fitted for a different species than peach, differences respect to the fit for peach appeared. In our work, we have prioritized the adjustment parameters made to the RbM for different species (apple, which became North Carolina model; and olive, which became De Melo-Abreu model), under the hypothesis that the model would perform better if fitted to the behaviour of that species than if the model was is used with the parameters established for peach. In the case of the peach tree, the initial parameters of MbR and DM have been used.

Alburquerque, N., García-Montiel, F., Carrillo, A., and Burgos, L.: Chilling and heat requirements of sweet cherry cultivars and the relationship between altitude and the probability of satisfying the chill requirements, Environ. Exp. Bot., 64, 162-170, https://doi.org/10.1016/j.envexpbot.2008.01.003, 2008.

Aybar, V. E., Melo-Abreu, J. P., Searles, P. S., Matias, A. C., Del Rio, C., Caballero, J. M., and Rousseaux, M. C.: Evaluation of olive flowering at low latitude sites in Argentina using a chilling requirement model, Span. J. Agric. Res., 13, 10, 10.5424/sjar/2015131-6375, 2015.

Darbyshire, R., Webb, L., Goodwin, I., and Barlow, E. W. R.: Impact of future warming on winter chilling in Australia, International Journal of Biometeorology, 57, 355-366, 10.1007/s00484-012-0558-2, 2013.

Houston, L., Capalbo, S., Seavert, C., Dalton, M., Bryla, D., and Sagili, R.: Specialty fruit production in the Pacific Northwest: adaptation strategies for a changing climate, Clim. Change, 146, 159-171, 10.1007/s10584-017-1951-y, 2018.

Londo, J. P., and Johnson, L. M.: Variation in the chilling requirement and budburst rate of wild Vitis species, Environ. Exp. Bot., 106, 138-147, https://doi.org/10.1016/j.envexpbot.2013.12.012, 2014.

Luedeling, E.: Climate change impacts on winter chill for temperate fruit and nut production: A review, Scientia Horticulturae, 144, 218-229, https://doi.org/10.1016/j.scienta.2012.07.011, 2012.

Marra, F., Bassi, G., Gaeta, L., Giovannini, D., Palasciano, M., Sirri, S., and Caruso, T.: Use of phenoclimatic models to estimate the chill and heat requirements of four sweet cherry cultivars in Italy, Acta Hortic., 1162, 57-64, 10.17660/ActaHortic.2017.1162.10, 2017.

Miranda, C., Santesteban, L. G., and Royo, J. B.: Evaluation and fitting of models for determining peach phenological stages at a regional scale, Agric. For. Meteorol., 178-179, 129-139, https://doi.org/10.1016/j.agrformet.2013.04.016, 2013.

Ruiz, D., Campoy, J. A., and Egea, J.: Chilling and heat requirements of apricot cultivars for flowering, Environ. Exp. Bot., 61, 254-263, https://doi.org/10.1016/j.envexpbot.2007.06.008, 2007.

Ruiz, D., Egea, J., Salazar, J. A., and Campoy, J. A.: Necesidades de frío para la salida del letargo y necesidades de calor para florecer en variedades de ciruelo japonés (Prunus salicinia L.), XIV Congreso Nacional de Ciencias Hortícolas. SECH 2015. Retos de la Nueva Agricultura Mediterránea, Orihuela, Spain, 2015.

Sawamura, Y., Suesada, Y., Sugiura, T., and Yaegaki, H.: Chilling Requirements and Blooming Dates of Leading Peach Cultivars and a Promising Early Maturing Peach Selection, Momo Tsukuba 127, The Horticulture Journal, 86, 426-436, 10.2503/hortj.OKD-052, 2017.

3) Related to the previous points, we've done several studies to compare the response of various chill metrics to climate change. First, they differ greatly in their sensitivity to warming (Luedeling et al., 2009c). Second, they are not comparable, with the ratio between different chill metrics varying tremendously across the globe, especially along climate gradients (Luedeling and Brown, 2011). Especially at the warmest end of the climatic range for temperate fruit trees, most models fail (Balandier et al., 1993; Benmoussa et al., 2017a, 2017b; Linsley-Noakes and Allan, 1994). The Dynamic Model is the only model I know that has a chance of somewhat describing changes correctly across different climates. This is the reason why in our 2011 paper (Luedeling et al., 2011) we only report Chill Portions (we actually calculated other metrics too, if I remember correctly, but I consider the results meaningless). This reasoning is actually described in several places in this paper and elsewhere (e.g. Luedeling, 2012). Just as an illustration, in the literature we found the chilling requirement of 'Ohadi' pistachios quantified at 1000+ CH in Turkey, but they grow well at 100 CH in Tunisia. This difference is not trivial at all and illustrates how badly off we can be if we use the wrong model.

- *With regard the comparison of various chill metrics:*

We have introduced the reference Luedeling et al. (2009) as previous work on the comparison of response of various chill metrics to climate change. At the same time, we have stressed that this is not the objective of this paper and review the manuscript removing explicit and implicit comparisons between models. In fact, we have not *averaged results from different chilling models, keeping results separately, as explained in Answer#2. We have stressed it more in the paper, specifically in the Material and Methods section.*

- *With regard the performance of different models:*

For a general answer, please see Answer#2. With regard models' performance in warm regions particularly, a worst performance is found not only for RbMs, but also for DM (Benmoussa et al., 2017 for pistachio in warm Sfax region in Tunisia):
https://www.sciencedirect.com/science/article/pii/S0098847217301119
"highlight: The Dynamic Model does not work well under Tunisian climate conditions." *This supports our argument that the performance of these models is not so different. Due to the lack of knowledge and data (especially for chilling portions) for accurate model calibration, including warm regions, we believe that uncertainty is better handled if not just one model is considered, even if they are not directly comparable.*

Benmoussa, H., Luedeling, E., Ghrab, M., Ben Yahmed, J., and Ben Mimoun, M.: Performance of pistachio (Pistacia vera L.) in warming Mediterranean orchards, Environ. Exp. Bot., 140, 76-85, https://doi.org/10.1016/j.envexpbot.2017.05.007, 2017.

Luedeling, E., Zhang, M., Luedeling, V., and Girvetz, E. H.: Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central Valley, Agric. Ecosyst. Environ., 133, 23-31, 10.1016/j.agee.2009.04.016, 2009.

4) One particular criticism of chill models has been that they are calibrated for a particular site and not necessarily generally valid. There is a reason why the North Carolina Model and the Utah Model are named after geographic areas, not after crops, and why researchers in various places saw the need to make adjustments. For example, in South Africa the Utah Model regularly produced negative chill totals at the end of the season. This was 'addressed' by removing the chill negation (resulting in the Positive Utah Model: Linsley-Noakes and Allan, 1994). The necessity of these 'empirical hacks' clearly indicates that these models can't be trusted across climatic gradients – which is critically important for a credible climate change assessment.

We agree with the referees 1 and 2 that, ideally, a site specific calibration would be desirable for any simulation exercise, as is the general practice in agronomic studies. As the second reviewer points out, indeed, the conditions of a calibrated model at one site do not completely coincide with those found in other locations. However, the state of the art of chill modelling is not yet there, and current practice is to apply these models elsewhere (see for instance many previous studies using these models in locations other than Utah, all of them without site-specific calibration, e.g. Alburquerque et al., (2008) for cherries in Spain; Razavi et al., (2011) for peach and Apricot in Iran; Sawamura et al., (2017) for peach in Japan). We think that in our case this is justified because in the model all the parameters that the researchers believe have relevance in the process are included. In our case, the main driver is temperature regime; and *actually, in the case of North Carolina model for apples, the main production area is Northern Spain, with climatological characteristics (temperature) more similar to North Carolina than the Spanish average. Accordingly, we have delimited more the concrete area of the apple tree production in the introduction section.*

However, as we have discussed previously in Answer#2, we think that the main point here is that all these models were developed, more than for specific locations, for specific tree species (peach for RbM). And the current practice is two or three models of chilling accumulation being used against phenological data of a specific species, generally with several varieties, and obviating that the model was fitted for a different crop (peach), assuming that there are not differences among species. In the few works where chilling accumulation models have been fitted for a different species than peach, differences respect to the fit for peach appeared. In our work, we have prioritized the adjustment parameters made to the RbM for different species (apple, which became North Carolina model; and olive, which became De Melo-Abreu model), under the hypothesis that the model would perform better if fitted to the behaviour of that species than if the model was used with the parameters established for peach. In the case of the peach tree, the initial parameters of MbR and DM have been used.

This is a research gap indeed. As stated in Luedeling et al. (2011), estimates in Chill Portions (for the Dynamic model) are less widely available than estimates in other metrics, and although if the knowledge gap in that sense have been reduced nowadays, estimates for many crops and varieties are still not available. We agree that, ideally, more experimental data should be generated to improve the chilling simulation, not only because of the differences between locations, but mainly due to the huge uncertainty related to the species and variety requirements, that in our view, is much more important than that related to the models. We agree that is a scientifically relevant issue, so we have included a comment on this on the discussion to raise awareness on the referee's point.

Alburquerque, N., García-Montiel, F., Carrillo, A., and Burgos, L.: Chilling and heat requirements of sweet cherry cultivars and the relationship between altitude and the probability of satisfying the chill requirements, Environ. Exp. Bot., 64, 162-170, https://doi.org/10.1016/j.envexpbot.2008.01.003, 2008.

Luedeling, E., Girvetz, E. H., Semenov, M. A., and Brown, P. H.: Climate Change Affects Winter Chill for Temperate Fruit and Nut Trees, PLOS ONE, 6, e20155, 10.1371/journal.pone.0020155, 2011.

Razavi, F., Hajilou, J., Tabatabaei, S., and Dadpour, M.: Comparison of Chilling and Heat Requirement in Some Peach and Apricot Cultivars, Research in Plant Biology, 1, 40-47, -, 2011.

Sawamura, Y., Suesada, Y., Sugiura, T., and Yaegaki, H.: Chilling Requirements and Blooming Dates of Leading Peach Cultivars and a Promising Early

Maturing Peach Selection, Momo Tsukuba 127, The Horticulture Journal, 86, 426-436, 10.2503/hortj.OKD-052, 2017.

5) The presumably innovative outlook of possibly using estimates of the amount of chill that is exceeded 90% of the time (p. 10, l. 29) isn't so innovative after all. In fact, we already used this 'Safe Winter Chill' approach in several publications, dating back to 2009 (Luedeling et al., 2009a, 2011). It has also been picked up by others (though I don't currently remember who that was).

The novelty was referred to the EOA index application (see Rodríguez et al., 2019) to analyse the robustness of projections of having a safe winter chill. In other words, it refers to the robustness metric (the EOA index) application, not to the safe winter chill definition, which is used only as the hypothesis for the EOA index. We have reformulated the sentence in the further work paragraph to make it clearer. Also, we have added a quotation (Luedeling et al., 2009) wherever in the manuscript that reference to safe winter is done.

Luedeling, E., Zhang, M., and Girvetz, E. H.: Climatic Changes Lead to Declining Winter Chill for Fruit and Nut Trees in California during 1950–2099, PLOS ONE, 4, e6166, 10.1371/journal.pone.0006166, 2009.

Rodríguez, A., Ruiz-Ramos, M., Palosuo, T., Carter, T. R., Fronzek, S., Lorite, I. J., Ferrise, R., Pirttioja, N., Bindi, M., Baranowski, P., Buis, S., Cammarano, D., Chen, Y., Dumont, B., Ewert, F., Gaiser, T., Hlavinka, P., Hoffmann, H., Höhn, J. G., Jurecka, F., Kersebaum, K. C., Krzyszczak, J., Lana, M., Mechiche-Alami, A., Minet, J., Montesino, M., Nendel, C., Porter, J. R., Ruget, F., Semenov, M. A., Steinmetz, Z., Stratonovitch, P., Supit, I., Tao, F., Trnka, M., de Wit, A., and Rötter, R. P.: Implications of crop model ensemble size and composition for estimates of adaptation effects and agreement of recommendations, Agric. For. Meteorol., 264, 351-362, https://doi.org/10.1016/j.agrformet.2018.09.018, 2019.

6) Another alleged innovation is the variable duration of the chilling period, which is determined by the minimum and maximum chill accumulation. Sure, this is new, but is it correct? The authors don't present any evidence for this. I realize that some authors have claimed that something like this makes sense (e.g. Cesaraccio et al., 2004 for their own model, but others have also said this for the Utah Model I think), but is there really any evidence? Actually, I strongly doubt that trees can make use of chill accumulation over the entire cold period. We've done a number of studies where we tried to statistically determine the chill-responsive period (Guo et al., 2015; Luedeling and Gassner, 2012; Luedeling et al., 2013a, 2013b), and we've always found periods that are much shorter than the full winter season. Now this may mean various things, including that trees are pretty safe from chill shortfalls in many places, but I suspect that it would make sense to end the chilling period earlier than an automatic algorithm would suggest (actually, if I could change one thing about our earlier studies, I would shorten the period we considered, which seems much too long now in hindsight).

The referee's discussion and the studies quoted (Guo et al., 2015; Luedeling and Gassner, 2012; Luedeling et al., 2013a, 2013b), in our view, reflect that there is a lot to learn about how trees work in relation to chilling accumulation. We agree that it is reasonable to question if trees can make use of the whole chilling accumulation period, and we have commented this fact about the possibility of an overestimation of the chilling accumulation in the discussion.

At the same time, we have decided not to choose a fixed period approach. On the one hand, a fixed starting date and duration for the chilling period for sure will introduce errors, as every year is different for every location and for every climate model. Some studies use self-regulating dates (we have quoted them)for chill models because of the lack of reliable physiological markers and the inefficacy of fixed dates to account for the mentioned seasonal climate variability (Measham et al. 2017). For instance, Marra et al. (2017), where an approach to calculate the starting date, using a self-regulating algorithm similar than in the present study, found that the applied method allowed a significant improvement compared to other studies that fix the date at October 1st. Also, results in the Measham et al. (2017) study show a larger variability in the chilling portions accumulation using a fix dates approach than a self-regulating one, as some chilling portions were excluded due to a late initial date. On the other hand, we have decided not to select a fix final date, even when it could be very well defined, because it will become eventually meaningless in a climate change context. A fixed period would cause a lot of problems and inconsistencies when the cold period is clearly shifted along the year at the end of the century.

Other argument that supports the use of a self-regulating method is that changes in chilling projections become very much comparable among different methods and with the present, even when having in mind the possible overestimation mentioned by the referee.

Marra, F., Bassi, G., Gaeta, L., Giovannini, D., Palasciano, M., Sirri, S., and Caruso, T.: Use of phenoclimatic models to estimate the chill and heat requirements of four sweet cherry cultivars in Italy, Acta Hortic., 1162, 57-64, 10.17660/ActaHortic.2017.1162.10, 2017.

Measham, P. F., Darbyshire, R., Turpin, S. R., and Murphy-White, S.: Complexity in chill calculations: A case study in cherries, Scientia Horticulturae, 216, 134-140, https://doi.org/10.1016/j.scienta.2017.01.006, 2017.

7) The paper starts with a strange introduction about the classification of fruit trees, which I'm not sure I agree with and which is also not relevant here. This paper is only about temperate species, so no need for such a general take. The first two paragraphs should be deleted.

Our attempt was to take into account that this journal serves to a wide and diverse community of readers (as stated in the NHESS journal aims and scope) with this general introduction. However, we have reduced and focused it following referee's suggestion. First two paragraphs have been removed.

8) I strongly urge the authors to make their code public, either in a repository or as supplementary materials to this paper. This will make it much easier to understand what was done. For instance, the statement that the authors used the method by Fishman et al. (1987a, 1987b) is not sufficiently detailed – anyone who's seen these papers knows that this is not at all trivial to implement (and I wonder if this is really the authors' source of the algorithm). Ideally, a paper should be reproducible, meaning that the methods should be sufficiently detailed for readers to repeat an experiment. This is often not really achievable, but it is not difficult for a modeling study such as the one described here. Please share the code. The main reason for this is that the actual results of this paper are not particularly helpful – pretty much the same has been shown before. The innovation (for the chill modeling community) lies in the climate data processing, but if this isn't actually shared with readers, nobody can easily make use of this methodology. In my view, the offer that readers can contact the authors isn't sufficient.

All the algorithms used in this paper have been programmed, implemented and executed by the authors. In our team we have experts from different fields, being a computer engineer one of them. The implementation of the model was done by using the model constants commonly used in standard applications, following other studies like Luedeling et al., (2011). We have included the reference in that sense as it has been followed the same procedure.

We chose to share the code by the formula "under request and quotation", that means a simple e-mail message of request without further registration, as our institution recommends to do so, to keep track of the research groups and publications derived using it. This is the case of many software developments (e.g. DSSAT source code available upon request).

However, as both referees raised this point, we have included the code as supplementary material. Specifically, we have included: chilling model codes, hourly temperature calculation and chilling computation period for the RbM models.

Luedeling, E., and Brown, P.: A global analysis of the comparability of winter chill models for fruit and nut trees, 411-421 pp., 2011.

9) Finally, I suggest that the authors compare their results (and maybe also their methods) with similar studies that have been done before. There have been quite a few, as the authors will realize if they do a systematic search, not necessarily on Spain, but on various other regions.

We have compared our results with the references included in the Answers#1, 2, 3, 4 and 6, and with Luedeling et al. (2009a and 2009b) for California and Darbyshire et al. (2013) for Australia, which are particularly interesting for us because they were conducted in regions with Mediterranean climate. This has been done in the discussion section.

Darbyshire, R., Webb, L., Goodwin, I., and Barlow, E. W. R.: Impact of future warming on winter chilling in Australia, International Journal of Biometeorology, 57, 355-366, 10.1007/s00484-012-0558-2, 2013.

Luedeling, E., Zhang, M., and Girvetz, E. H.: Climatic Changes Lead to Declining Winter Chill for Fruit and Nut Trees in California during 1950–2099, PLOS ONE, 4, e6166, 10.1371/journal.pone.0006166, 2009a.

Luedeling, E., Zhang, M., Luedeling, V., and Girvetz, E. H.: Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central Valley, Agric. Ecosyst. Environ., 133, 23-31, 10.1016/j.agee.2009.04.016, 2009b.

10) Even more finally, I suggest language editing. There is still some room for improvement in terms of language, and some statements are unclear.

The manuscript was edited by a professional language service previous to submission (the invoice will be privately sent to the editor due to data protection). The same service will be used on the revised manuscript if required.

Minor issues:

p. 1, l. 14: what are 'inner physiological factors'?

Lang et al., (1987) defined endodormancy as that which is regulated by physiological factors inside the affected structure. It is a definition widely used. We have included the definition instead the expression 'inner physiological factors'.

Lang, G. A., Early, J. D., Martin, G. C., and Darnell, R. L.: Endo-, para-, and ecodormancy: physiological terminology and classification for dormancy research, HortScience, 22, 371-377, 1987.

p. 1, l. 14: 'accumulating cool temperatures to finish dormancy is unclear (at least in terms of what dormancy this is – I'd most likely associate finishing dormancy with bloom of leaf out, but that also requires heat). No need for "be broken" in quotation marks. This is commonly used and doesn't need to be identified as an odd term (or whatever the purpose of the quotation marks is).

Quotation marks have been removed, and the sentence have been reformulated as follows:
"accumulating chilling temperatures to finish this sort of dormancy".

p. 1, l. 16: I don't think the chilling requirement is different for each variety (which means that no two varieties have the same requirement). They are crop and variety-specific, but not all different.

Yes, the referee is right. We have modified the sentence to avoid this possible misunderstanding, as follows:
"chilling accumulation required to break dormancy depends on specie and variety"

p. 1, l. 28 – p.2, l. 10: irrelevant – delete
We have deleted the sentence.

p. 2, l. 12: income, not wealth
Yes, the referee is right. We have modified the sentence as suggested.

p. 2, several places: for simplicity and reader-friendliness, I recommend replacing 10ˆ6 by 'million'
We have modified the sentence as suggested.

p. 2, ll. 18-19: FAOSTAT doesn't directly provide such values I believe, so it would be important to state how this was determined (also note that there are all kinds of issues with this database). It is also not obvious that this sentence refers to the global scale, since the previous sentence talks about Spain. Overall, this isn't a very relevant statement in a paper that's just on Spain.

In the FAOSTAT /Data/Crops webpage, it is possible to select a crop and gather worldwide data for a particular crop. According to those data, Spain is a major fruit producer in the world and, consequently, studies on Spain are relevant. We have briefly mentioned the process we followed to obtain the showed information from FAOSTAT service in the text.

p. 2, l. 24: I believe the thing trees are sensitive to is frost (not generally cold temperatures)

Yes, the referee is right. We have modified the sentence as suggested.

p. 3, l. 1: 'accumulation of cold periods' is an unfortunate choice of words. Sounds like trees need, say, 5 cold periods to break endodormancy.

Yes, the referee is right. We have reformulated it for making it clear as follows: "the accumulation of time exposed to cold temperatures"

p. 3, l. 3: not all models are based on temperatures between certain thresholds. The Dynamic Model works differently, and even the Utah-type models don't really follow this simple structure.

Yes, the referee is right. We have modified the sentence by removing "all based on the accumulated time with temperatures between certain thresholds".

p. 3, 12: I disagree that the chilling requirement corresponds to conditions where a tree is grown. It may rather correspond to conditions where it evolved/was bred

Yes, the referee is right. We have modified the sentence as follows:

"Each tree species and variety has specific chilling requirements for correct plant development, usually related to the environmental conditions where it evolved or was bred".

p. 3, ll. 13-17: not sure what information is conveyed here. The initial statement is about considering a range, but then the examples are precise values, not ranges. If this is supposed to illustrate intra-specific variation, then please make sure to use the appropriate terminology (not sure what 'crop tree' refers to).

Yes, we understand the referee's point. We have modified the text as follows: "As a result, for a given species a range of estimates of chill accumulation encompassing all varieties has to be considered. For instance, for the apricot varieties considered in Campoy et al. (2012), the estimated accumulated chilling varies between 413 ('Palsteyn' variety) and 1172 ('Orange red' variety) chill hours (chilling hours method). This range is 613-777 when chilling units by Utah method are computed, and 37-64 chill portions when Dynamic method is applied."
Also, we have replaced the expression "crop tree" by "fruit tree" throughout the paper.

p. 4, l. 9 (or elsewhere): Somewhere the authors need to mention the various chill assessments that have already been done by a number of people in a wide range of places.

Yes, the referee is right. We have mentioned the references listed in the answers to major issues (above in this document) in several parts of the text.

p. 4, l. 17: no, the models do not need hourly Tmin and Tmax. They just need hourly temperature, which can be derived (if no other information available) from daily Tmin and Tmax.

Yes, the referee is right. We have modified the sentence as follows:

"The climate variable required by the chilling models used in this study is hourly temperature, which can be derived, when no other information is available, from minimum (Tmin) and maximum (Tmax) temperatures."

p. 4, l. 22: not sure what 'freely distributed' means. Open-access?

We have used the exact term used by the creators of the dataset (http://www.meteo.unican.es/datasets/spain02)
It means that you can download the data with the condition of quoting two references provided. We have clarified it in the text specifying that free downloading is possible.

p. 4, l. 24: is this really an observational dataset?

Yes, it is. The methodology for generating these databases is robust and widely known on climate modelling studies: direct observations are interpolated in a physically-based way to a regular grid to be usable for climate models' comparison purposes. For instance, E-OBS (Haylock et al., 2008) and CRU (Harris et al., 2014) databases were built using this methodology.

Also, please see the link in the previous comment, where the database is described. Also, the quote Herrera et al., 2016 title reads:
*Herrera et. al. (2016) Update of the Spain02 Gridded **Observational** Dataset for Euro-CORDEX evaluation: Assessing the Effect of the Interpolation Methodology. International Journal of Climatology, 36:900–908. DOI: 10.1002/joc.4391.*

We have added the link (http://www.meteo.unican.es/datasets/spain02) in the text.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, Int. J. Climatol., 34, 623-642, 10.1002/joc.3711, 2014.

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P., and New, M.: A European daily high-resolution gridded dataset of surface temperature and precipitation, D20119 pp., 2008.

Herrera et. al. (2016) Update of the Spain02 Gridded Observational Dataset for Euro-CORDEX evaluation: Assessing the Effect of the Interpolation Methodology. International Journal of Climatology, 36:900–908. DOI: 10.1002/joc.4391.

p. 5, l. 15: more details are needed on the temperature generation, especially since the source will be hard to find for most readers. What mathematical functions were used for constructing daily curves? The common method in horticultural studies such as this one is a methodology by Linvill (1990), which is based on a sine curve during the day and logarithmic cooling at night (implemented in the chillR package; Luedeling, 2018). I'd be quite curious to learn how de Wit's method compares with this, but the authors provide insufficient information about their approach.

Yes, we used de Wit's method. MATLAB code has been made available in the supplementary material as requested by the referee.

p. 6, ll. 11-13: The authors compute a mean and then a median. Later in the paper they argue that one should calculate a 10% quantile. Why didn't they do this here?

The objective of this paper as stated in page 4 line 10 is to assess the impact of climate change on temperate fruit tree chilling accumulation Spain. This general objective is better achieved by an averaged indicator, as median and mean. The suggestion of using the 10th quantile was only introduced in page 10, starting from line 20, proposals for further work, consisting in using the EOA index for analysing chances of robust, high confidence, local adaptation. This EOA index needs a threshold definition, for which we propose the 10th quantile (so we do not need nor suggest using it for other purpose than that). This is a refinement of previous assessment of average impact, but we consider this further work out of the scope of the current study.

We have modified the text to make this point clearer.

p. 6, ll. 16-17: As stated above, I'd prefer to have the code made publically available, for full transparency and usefulness.

Please see the Answer#8. Codes have been provided as supplementary material.

p. 6, l. 23: Is the full name of MAPE really 'mean percentage absolute error'? That would seem to lead to the acronym 'MPAE'

Yes, you are right, this is a typo. That line has been changed by "mean absolute percentage error". In other parts of the document (i.e. page 19, line 6) the order is correct.

p. 7, l. 19: 'similarly simulated' is awkward wording

It has been changed to "simulated in a similar way".

p. 7, ll. 23-27: All these models use different units, so they can't be compared (the fact that they're probably all called chill units doesn't make them equivalent). While it's obvious that the Dynamic Model can't be compared to the others (because values are much smaller than for the other metrics), the others are also not comparable!

Yes, we understand that the reader could interpret that the models with the same units could be comparable. We have modified the text to clarify these aspects.

p. 8, l. 27: scenarios were averaged in this study, but we also provided information for determining the impact of climate model and emissions scenario.

We have modified this sentence as follows:

"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; information for determining the impact of climate model and emissions scenario was provided in that study)."

p. 9, ll. 1-2: As stated above, I don't consider it an asset to include outdated models in a study…

Please see Answer#2 to major issues above in this document.

p. 9, l. 22: not sure what 'discrete nature' means. And I also think that this may be an indication that these models are too sensitive for warm places.

We meant discrete as opposite as continuous. We think that the high values of CV are related to the low values of the chilling in absolute terms, which actually is in agreement with referee's suggestion: this might makes these models too sensitive for warm places. We have included this explanation in the discussion.

p. 9, ll. 26: this study didn't 'find' this, it just reported on it. Luedeling et al. (2011) sort of found this.

We have modified this as suggested, using the verb "report".

p. 10, ll. 4: Yes, it would be great to have more datasets, but we actually already have a lot. Rather than call for collecting more data, I'd call for better use of such data for model development and validation.

Probably the referee is right and it is more about data availability and access and less about data existence. At least in the case of Spain, although it is true that there are several works on the subject, there are species/varieties with little data availability and the models developed up to now have important shortcomings. We have specified that the scarcity mentioned in the paper is referred to the available data in Spain, as we rely on referee's knowledge about elsewhere.

p. 10, ll. 11-12: 'crop varieties depending on the RCP' is unfortunate wording. First, crop varieties don't depend on RCP. Second, RCPs are theoretical pathways that not be followed precisely. Better to say something like 'depending on how rapidly GHG emissions can be reduced' or something like that.

Yes, we understand how the sentence could be misunderstood. We have modified it according referee's suggestion.

p. 10, l. 23: not sure what 'low-limit chill requirements' are

We meant the variety with the lower chilling requirement within a given species. We have used that expression to make the sentence more understandable.

p. 10, l. 29: as mentioned above, this is exactly what the Safe Winter Chill metric achieves.

Yes, we are referring to that, we have introduced a quote here (Luedeling et al., 2009)

p. 11, 2-4: It's obvious that RCP8.5 causes greater change, similar to the end vs. middle of century. Doesn't need to be mentioned or should clearly be marked as expected.

Text has been modified as suggested.

p. 11, l. 6: why especially in warm regions? The impact depends not only on chill loss, but also on what is grown there and how much chill it needs.

The text has been modified as follows:

"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 and are cultivated with chilling demanding species, where their reduction may jeopardise the cultivation of some tree crops within the near future."

p. 11, ll. 17-18: confusing sentence.

The text has been modified as follows:

"Such an adaptation would benefit from mitigation, as adaptation is assumed to be more feasible for moderate warming scenarios."

Reference list: It would be so much easier to look through this, if all but the first row of a reference were indented.

The section we has been modified as suggested.

Maps: maps should have a coordinate system, north arrow, scale bar etc.

We have included the suggested information in the corresponding figures.

Fig. 1: I doubt that all the olive data are right. If so, some parts of Spain would be almost exclusively olives.

We have checked the data and they are correct. Source is the Spanish Ministry related to agriculture and official statistics. Jaen province (Andalusia) is the largest area of olive trees in the world. When travelling through it (simply from the highway) you can only see olive trees for kilometres (please see image below).

Source:https://www.google.es/maps/@37.6076977,-4.0473674,3a,60y,283h,73.24t/data=!3m6!1e1!3m4!1sTVFJSEzMRW_Jco1F645SpA!2e0!7i13312!8i6656)

Maps 3-7: very hard to compare changes, which is really the most important part of this paper, if the maps are scattered across various places.

We have rearranged the figures to bring map of change together.

Fig. 5: is the scale used for the change useful.

We have adapted the scale to the new figures, and we have tried to make it useful.

In summary, I think this contribution has potential, since the way the climate data were processed is very robust. But the team should consider adding some chill modelling capacity to the study to make this more convincing. While chill seems like an easy application of a climate change projection framework (it's assumed to just depend on temperature after all), things are actually quite complicated due to the invisibility of chill induced changes, which has precluded the development of convincing models so far. In consequence, there are many models, and most of them are not suitable for studies across climates. If the authors manage to adequately consider this, this manuscript may become publishable.

Thank you for your thoughtful revision. We have addressed the issues summarized by the referee in the answers above. We are convinced that our arguments are correct and sound, but if the editor and both referees ask us to remove some of the chilling models considered, we would be willing to do so.

References:

Balandier, P., Bonhomme, M., Rageau, R., Capitan, F., and Parisot, E. (1993). Leaf bud endodormancy release in peach trees - evaluation of temperature models in temperate and tropical climates. Agricultural and Forest Meteorology 67, 95–113.

Benmoussa, H., Ghrab, M., Ben Mimoun, M., and Luedeling, E. (2017a). Chilling and heat requirements for local and foreign almond (Prunus dulcis Mill.) cultivars in a warm Mediterranean location based on 30 years of phenology records. Agricultural and Forest Meteorology 239, 34–46.

Benmoussa, H., Luedeling, E., Ghrab, M., Ben Yahmed, J., and Ben Mimoun, M. (2017b). Performance of pistachio (Pistacia vera L.) in warming Mediterranean orchards. Environmental and Experimental Botany 140, 76–85.

Benmoussa, H., Ben Mimoun, M., Ghrab, M., and Luedeling, E. (2018). Climate change threatens central Tunisian nut orchards. International Journal of Biometeorology 62, 2245–2255.

Cesaraccio, C., Spano, D., Snyder, R.L., and Duce, P. (2004). Chilling and forcing model to predict bud-burst of crop and forest species. Agricultural and Forest Meteorology 126, 1–13.

Fishman, S., Erez, A., and Couvillon, G.A. (1987a). The temperature dependence of dormancy breaking in plants – computer simulation of processes studied under controlled temperatures. Journal of Theoretical Biology 126, 309–321.

Fishman, S., Erez, A., and Couvillon, G.A. (1987b). The temperature dependence of dormancy breaking in plants - mathematical analysis of a two-step model involving a cooperative transition. Journal of Theoretical Biology 124, 473–483.

Guo, L., Dai, J., Wang, M., Xu, J., and Luedeling, E. (2015). Responses of spring phenology in temperate zone trees to climate warming: A case study of apricot flowering in China. Agricultural and Forest Meteorology 201, 1–7. Linsley-Noakes,

G.C., and Allan, P. (1994). Comparison of 2 models for the prediction of rest completion in peaches. Scientia Horticulturae 59, 107–113. L

invill, D.E. (1990). Calculating chilling hours and chill units from daily maximum and minimum temperature observations. HortScience 25, 14–16.

Luedeling, E. (2012). Climate change impacts on winter chill for temperate fruit and nut production: A review. Scientia Horticulturae 144, 218–229.

Luedeling, E. (2018). chillR: Statistical methods for phenology analysis in temperate fruit trees (R package).

Luedeling, E., and Brown, P.H. (2011). A global analysis of the comparability of winter chill models for fruit and nut trees. International Journal of Biometeorology 55, 411–421.

Luedeling, E., and Gassner, A. (2012). Partial Least Squares Regression for analyzing walnut phenology in California. Agricultural and Forest Meteorology 158–159, 43–52.

Luedeling, E., Zhang, M., and Girvetz, E.H. (2009a). Climatic Changes Lead to Declining Winter Chill for Fruit and Nut Trees in California during 1950–2099. PLoS ONE 4, e6166.

Luedeling, E., Zhang, M., McGranahan, G., and Leslie, C. (2009b). Validation of winter chill models using historic records of walnut phenology. Agricultural and Forest Meteorology 149, 1854–1864.

Luedeling, E., Zhang, M., Luedeling, V., and Girvetz, E.H. (2009c). Sensitivity of winter chill models for fruit and nut trees to climate change. Agriculture, Ecosystems & Environment 133, 23–31.

Luedeling, E., Girvetz, E.H., Semenov, M.A., and Brown, P.H. (2011). Climate Change Affects Winter Chill for Temperate Fruit and Nut Trees. PLoS ONE 6, e20155.

Luedeling, E., Guo, L., Dai, J., Leslie, C., and Blanke, M.M. (2013a). Differential responses of trees to temperature variation during the chilling and forcing phases. Agricultural and Forest Meteorology 181, 33–42.

Luedeling, E., Kunz, A., and Blanke, M.M. (2013b). Identification of chilling and heat requirements of cherry treesâ˘A˘Ta statistical approach. International Journal of Biometeorology 57, 679–689.

Ruiz, D., Campoy, J.A., and Egea, J. (2007). Chilling and heat requirements of apricot cultivars for flowering. Environmental and Experimental Botany 61, 254–263. Zhang, J., and Taylor, C. (2011). The Dynamic Model provides the best description of the chill process on “Sirora” pistachio trees in Australia. HortScience 46, 420–425.

Responses to referee comment [RC2]

Interactive comment on "Chilling accumulation in temperate fruit trees in Spain under climate change" by Alfredo Rodríguez et al.

We thank the reviewer for her thoughtful comments. Our answers are highlighted in green italics.

Alfredo Rodríguez et al. did an extensive and rigorous job on trying to quantify future developments on chilling accumulations for Peninsular Spain and the Balearic islands. They did a major effort in modelling and validation of input data and consider a highly relevant aspect of local fruit production that is vulnerable to climate change (Campoy et al., 2011; Luedeling, 2012). In this sense, and in my opinion, this regional study has its relevance and its place in this journal. This study does also contribute to a better understanding in this domain, by improving the methodology with regards to previous studies through the use of state of the art climate models and scenarios, although it does not stand out for the novelty of the used approaches. To increase the value, that the paper brings to the scientific community as well as to end users, a couple of revisions are suggested below, which, if taken into account, would make this paper more suitable for publication.

We appreciate the referee's comments.

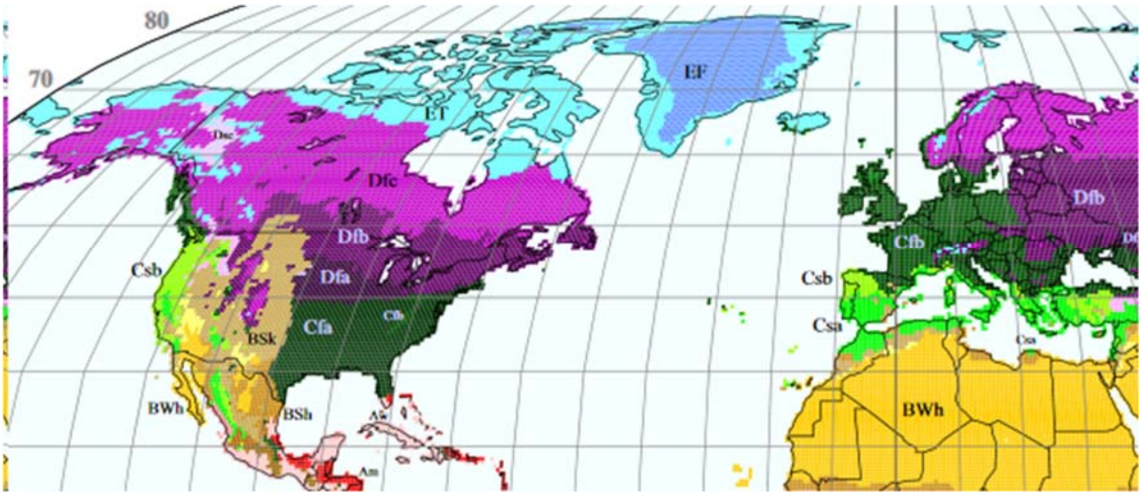
Major remarks regarding the content

With regards to the methodology and scope of the paper, I agree in most points with Eike Luedelings review comment (RC1):

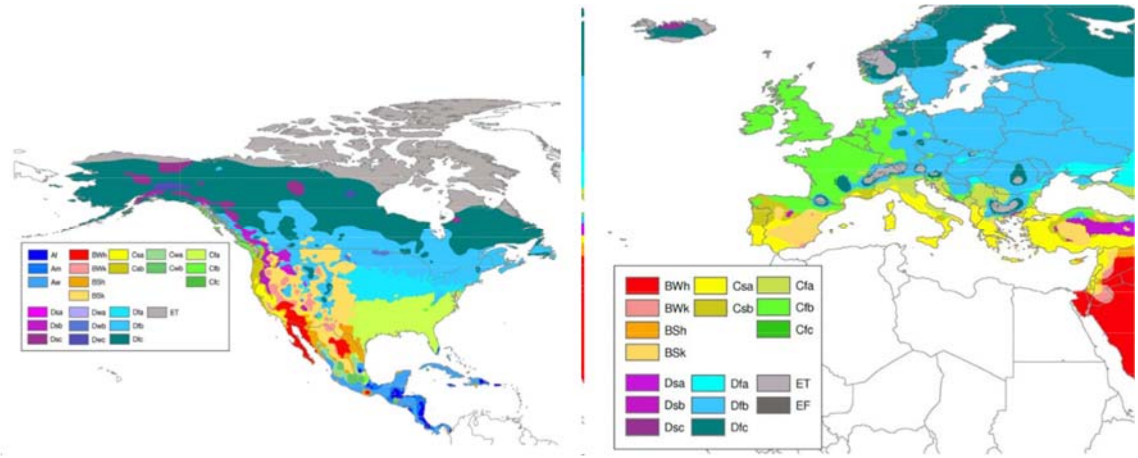
(1) First of all, combining models that have been found to be inadequate (Luedeling, 2012) is not innovative, and the fact that the models were apparently applied without calibration to local conditions is in my eyes the biggest shortcoming of the paper. To my knowledge, there is no evidence that a model that was tested for North Carolina (Latitude range 36.5N-33.8N, Köppen-Geiger classification 'Warm temperate with hot summer climate' (Peel et al., 2007)), can be transferred to Spain (Latitude range 43.5, 36.0, major Köppen-Geiger classification 'Arid steppe cold' climate (Peel et al., 2007)); nor can be safely assumed, that the cultivars in all regions have the same physiology, which is implied by using the same model, despite the mention of this fact on p.3, l. 11.

- *About the comment on combining models, please see Answer#2 to referee 1*
- *About the comment on applying models to other countries without additional adjustment, please see Answer# 4 (and also 2 and to 3) to referee 1, and the references included there.*

*Additionally, we have checked the locations used to develop North Carolina model (Shaltout and Unrath, 1983). The paper says "A chill unit model was developed for 'Starkrimson Delicious' (Malus domestica Borkh.) apples grown under the **wide range of temperature and elevations in North Carolina**", and the locations considered were Wake, Cleveland, Wilkes, Mitchell, Henderson. Looking at the climate at these locations we can see that parts of Spain (northern Spain) actually share the temperature regime with them, which can be checked by looking at the second subindex of the Köppen-Geiger climate classification (a or b, denoting temperature regime, "hot summer" and "warm summer" respectively; see images below from http://koeppen-geiger.vu-wien.ac.at/pdf/kottek_et_al_2006_A4.pdf, and Peel et al., 2007), which are the same for North Carolina and the northern Spain.*



Source: http://koeppen-geiger.vu-wien.ac.at/pdf/kottek_et_al_2006_A4.pdf



Source: Peel et al., (2007)

That is why in answer#4 to referee 1 we proposed: In our case, the main driver is temperature regime; and actually, in the case of North Carolina model for *apples, main production area is North Spain, with climatological characteristics (temperature) more similar to North Carolina than the Spanish average. Accordingly, we have delimited more the concrete area of the apple tree production in the introduction section.*

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633-1644, 10.5194/hess-11-1633-2007, 2007.

Shaltout, A. D., and Unrath, C. R.: Rest completion prediction model for 'Starkrimson Delicious' apples, J. Amer. Soc. Hort. Sci., 108, 957-961, 1983.

(2) At this point of the introduction, a better contextualization and reference for the obtained values would be highly appreciated. Only on p.3, ll. 14-17, an exemplary chilling requirement is given, and this for apricot which is not considered in this study. Without a knowledge of local requirements of apple, olive and vineyard, the severity of the change in chilling units is hard to grasp. Also, with the quoted requirements at hand ("631 chill units [Utah model, 'Palsteyn' variety), the observed difference between models ("less than 500 chill units", p.7 l. 25) can be substantial, and the outcome of Figures 7-8 more alarming than described in the paper. Later, on p.10, ll. 11- 17, exemplary requirements for an apple and an olive variety is given, which are at risk of not being fulfilled according to the 'far future' predictions. For better understanding of the key findings of the paper, more such values should be given.

- *To follow the referee's comment, we have added a table (Table 1)with values for different species showing the range of chilling requirement exhibited by the main varieties. Also, we have removed any comparative comments between methods, following referee's 1 indications.*
- *About the message from Figure 7-8: Even if the impacts are high as pointed by the referee, we wanted to stress that the wide range of chilling requirements exhibited by the varieties of a given species will facilitate adaptation. In most locations, variety change will be enough, and crop change will not be required. We have modified the text to clarify this, using the new table (Table 1) to illustrate it.*

(3) In my opinion, estimations of concrete, crop or variety related shortcomings in chilling have highest relevance for planning applications and various end users, so if this is possible, it would be very interesting to find in this paper indications which zones under cultivation of a given crop will become unsuitable in terms of chilling for major varieties.

We have added some examples in the discussion for the highest vulnerable varieties or those with strongest market influence. We think that going into a deep analysis is *beyond the scope of this paper because 1) We would need to set thresholds. As illustrated by the new table, for a given crop and even just considering the most important varieties we should consider very different thresholds to estimate suitability area; 2) we would need to consider other measurements than the mean, (as the Safe Winter by Luedeling et al. (2009) and use a confidence/robustness index that allow to support any recommendation or conclusion on suitability area.*

Luedeling, E., Zhang, M., and Girvetz, E. H.: Climatic Changes Lead to Declining Winter Chill for Fruit and Nut Trees in California during 1950–2099, PLOS ONE, 4, e6166, 10.1371/journal.pone.0006166, 2009.

(4) Obviously, the diversity of species cannot be fully covered in this paper, but, joining the suggestion of RC1, with open source code and output maps, interested parties could quickly assess these zones following an example. It might be a subject of discussion in this stage of the paper, if these findings would be improved or not by considering the agreement of different chilling models. A priori, there is a major concern with this methodology, that I share with the author of RC1, because of the unjustified comparison of chill units among models and the mentioned inadequacy of some of them.

- *About including open source code in supplementary material, we have agreed to do so, see Answer#8 to referee 1.*
- *About the comment on combining or comparing models, please see Answer#2 to referee 1. In further work, we propose a methodology to assess robustness of the individual model outcomes (as they cannot be put together due to have different units), the EOA index (Rodríguez et al., 2019). Then, the agreement between chill models on the suitable zones for a given variety (as suggested by this referee in her question 2) could be compared by using the EOA values. This development, however, is out of the scope of this paper. We have clarified this in the text.*

Rodríguez, A., Ruiz-Ramos, M., Palosuo, T., Carter, T. R., Fronzek, S., Lorite, I. J., Ferrise, R., Pirttioja, N., Bindi, M., Baranowski, P., Buis, S., Cammarano, D., Chen, Y., Dumont, B., Ewert, F., Gaiser, T., Hlavinka, P., Hoffmann, H., Höhn, J. G., Jurecka, F., Kersebaum, K. C., Krzyszczak, J., Lana, M., Mechiche-Alami, A., Minet, J., Montesino, M., Nendel, C., Porter, J. R., Ruget, F., Semenov, M. A., Steinmetz, Z., Stratonovitch, P., Supit, I., Tao, F., Trnka, M., de Wit, A., and Rötter, R. P.: Implications of crop model ensemble size and composition for estimates of adaptation effects and agreement of recommendations, Agric. For. Meteorol., 264, 351-362, https://doi.org/10.1016/j.agrformet.2018.09.018, 2019.

(5) Potentially reducing the number of models and increasing the documentation (equations, parameters) of the models should help overcome the, in my view, given uncertainty about how the different models can be understood considering the three studied fruit crops mentioned in the paper. In p.5 ll.22-24, the North Carolina model is introduced as being developed for apple trees, the De Melo-Abreu method for olive trees and the Dynamic method for peach trees. I would wish for more elaboration on how these choices have been justified and on how to make use of the findings presented in the Figures 3-8. The codes should be open access, too, since I totally agree with RC1, a research should be reproducible and with the given information this is not of application.

- *About the models used in the study and dealing with uncertainty, please see Answer#2 and 3 to referee 1. Also, a brief history of each model origin, development and applications (references suggested in the Answers#2 and 3 have been included).*
- *About including open source code in supplementary material, we have agreed to do so, see Answer#8 to referee 1.*

Remarks regarding the form

Title

In p.2, ll.1-22, the authors state "Vineyard, apricot trees, olive trees and almond trees could be also included in this last subgroup [of temperate fruits], although some of their climatic requirements are nearer the subtropical fruit trees" p.2,ll 6-7). Bearing this in mind, the mention 'temperate fruit trees' in the title of the paper is in my opinion a bit misleading, although reference handbooks do classify olives and grape as temperate (Schaffer, 2018).

We have removed the word "temperate" from the title, as follows:

"Chilling accumulation in fruit trees in Spain under climate change"

Abstract

The abstract could be more concise and feature more detail about the findings of this study than the context.

We have modified it making it more focused on results.

Introduction

In p.2, ll.1-22: In line with RC1, I consider the description of the classification as too long and can be left out, especially in view of the ambiguity of the classification mentioned above. The section on bias adjustment (p.4 ll.1-9) could be slightly more elaborated, and precise how it is ensured that the change over time of the climate signal is not cancelled out, see also Michelangeli et al. (2009). The transition from this paragraph to the following is a bit sharp. At this point, an overview of similar (regional) studies on chilling requirements would be expected point.

We have removed the classification part. The bias adjustment section have been extended with some details on the methodology, according to the following guidelines:

Bias adjustment is based on a transfer function such that the marginal cumulative distribution function of the adjusted variable matches that of the observations. A complete discussion of the technique, including validation and effect on climate indices can be found in Piani et et al. (2010), Piani et al, (2010b), Dosio and Paruolo (2011), and Dosio et al. (2012), Ruiz-Ramos et al., (2016), Dosio and Fischer, (2018). Dosio (2016) showed that bias-adjustment largely improves the value of present and future threshold-based indices (e.g., the number of frost days): these indices are generally poorly simulated over the present climate, such that the projected climate change may not be reliable.

We have better linked with next paragraph. Also, we have included the references of previous studies (see references included in the Answers to referee 1). Also, we can mention climate change differences when using bias correction methods and cancellation of climate change signal over time (Michelangeli et al, 2009; Casanueva et al., 2018).

Casanueva, A., Bedia, J., Herrera, S., Fernández, J., and Gutiérrez, J. M.: Direct and component-wise bias correction of multi-variate climate indices: the percentile adjustment function diagnostic tool, Clim. Change, 147, 411-425, 10.1007/s10584-018-2167-5, 2018.

*Dosio, A., and Paruolo, P.: Bias correction of the ENSEMBLES high-resolution climate change projections for use by impact models: Evaluation on the present climate, Journal of Geophysical Research Atmospheres, 116, 10.1029/2011JD015934, 2011.*https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2011JD015934

Dosio, A., Paruolo, P., and Rojas, R.: Bias correction of the ENSEMBLES high resolution climate change projections for use by impact models: Analysis of the climate change signal, Journal of Geophysical Research Atmospheres, 117, 10.1029/2012JD017968, 2012.

Dosio, A.: Projections of climate change indices of temperature and precipitation from an ensemble of bias-adjusted high-resolution EURO-CORDEX regional climate models, Journal of Geophysical Research: Atmospheres, 121, 5488-5511, doi:10.1002/2015JD024411, 2016.

Dosio, A., and Fischer, E. M.: Will Half a Degree Make a Difference? Robust Projections of Indices of Mean and Extreme Climate in Europe Under 1.5°C, 2°C, and 3°C Global Warming, Geophys. Res. Lett., 45, 935-944, 10.1002/2017GL076222, 2018.

Michelangeli, P. A., Vrac, M., and Loukos, H.: Probabilistic downscaling approaches: Application to wind cumulative distribution functions, Geophys. Res. Lett., 36, 10.1029/2009GL038401, 2009.

Piani, C., Haerter, J. O., and Coppola, E.: Statistical bias correction for daily precipitation in regional climate models over Europe, Theoretical and Applied Climatology, 99, 187-192, 10.1007/s00704-009-0134-9, 2010.

Piani, C., Weedon, G. P., Best, M., Gomes, S. M., Viterbo, P., Hagemann, S., and Haerter, J. O.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models, Journal of Hydrology, 395, 199-215, 10.1016/j.jhydrol.2010.10.024, 2010.

Ruiz-Ramos, M., Rodríguez, A., Dosio, A., Goodess, C. M., Harpham, C., Mínguez, M. I., and Sánchez, E.: Comparing correction methods of RCM outputs for improving crop impact projections in the Iberian Peninsula for 21st century, Clim. Change, 134, 283-297, 10.1007/s10584-015-1518-8, 2016.

Materials and methods

Regarding the selection of models and scenarios, although hardly done in literature, the choice of models could be better justified using methodologies as in (Mendlik and Gobiet, 2016), since there is evidence of high sensitivity of climate model selection (Wilcke and Bärring, 2016). However, the authors chose the two reasonable scenarios (RCP 4.5 and RCP 8.5), allowing for consistent comments on importance of mitigation in context of actual discussion. Key equations of the chilling models should be provided in the additional material. In the main text a comment on the validation of the models should be given, in the view of their applicability on future time series.

The ensemble of climate models contains 10 members, which was the whole set of models available. Additionally, Figure 3 is meant prove that our inputs are robust. To take into account the referee's concern we have included the following (bold) text in the corresponding section:

"..... 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). ***Due to the complex orography of the Iberian Peninsula and its remarkable climatic diversity (CLIVAR-Spain, 2010), no additional systematic selection was performed to reduce the number of RCM ensemble members (e.g., Mendlik and Gobiet, 2016). A thorough analysis in this sense would imply decomposing the Iberian Peninsula into several climatic sub-regions (Wilcke and Bärring, 2016) and would derive into a much more complex process to potentially improve***

already robust results. *The outputs of the EUR-11 ensemble for two RCPs were considered: 1) +4.5 W/m2 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/m2 (RCP8.5).”*

CLIVAR-Spain: Climate in Spain: past, present and future. Regional climate change assessment report, Ministerio de Ciencia e Innovación (España), Ministerio de Medio Ambiente y Medio Rural y Marino (España) 978-84-614-8115-6, www.clivar.es, 2010.

Mendlik, T., and Gobiet, A.: Selecting climate simulations for impact studies based on multivariate patterns of climate change, Clim. Change, 135, 381-393, 10.1007/s10584-015-1582-0, 2016.

Wilcke, R. A. I., and Bärring, L.: Selecting regional climate scenarios for impact modelling studies, Environ. Modell. Softw., 78, 191-201, https://doi.org/10.1016/j.envsoft.2016.01.002, 2016.

Results

With regards to the CV, MAPE and IQR, the classes > 20, >0.4... are in my view not informative enough. Also, in section 3.1, the MAPE values are declared as problematic above 20% for few grid points, without mentioning until how high they stretch. Thus, no conclusion can be made if the computation for these grid points can be trusted at all.

High MAPE values can be related also to the low values of the chilling accumulation in those areas, and therefore it does not mean that necessarily the projections cannot be trusted at all. It means that we should be more careful when interpreting the results. Nevertheless, we have marked somehow the areas in the plots where values were greater than 20%. Also, we have chosen a more understandable, representative classes for the figures, and the top end has been specified.

Discussion

The difference between the two researched scenarios could be expressed more clearly (p.10, ll.11-19).

We have introduced a sentence here discussing the main difference found between results obtained for each RCPs.

References

I join the request made in RC1 for indented references. In the text, the reference in p.3, l.29 should be revised.

Format change has been made within the limits of the journal instructions.

The mentioned reference has been checked and corrected.

Figures

As stated in RC1, all figures need to be presented with a scale bar, north arrow, and (due to inconsistency between figures) the reference system. Preferably all maps would be shown in the same projection (or the stretch of the figures should be revised). The layout of subfigures could be optimized so as to allow for bigger figures. If the decision will be taken to not report on all models, this could be of great improvement of the readability.

- *We have modified the figures as suggested. Layout has been revised to allow the figures to be as large as possible, although this kind of composite figures are quite common in climate and impact publications (e.g. see https://www.meteo.unican.es/es/view/publications)*

- *On the models to be reported: Please see our answers above. We are convinced that our arguments are correct and sound, but if the editor and both referees ask us to remove some of the chilling models considered, we would be willing to do so.*

Figure 1 shows a good overview of land use in Spain for the reader, exposing major growing areas for the considered crops. Values seem reasonable from my experience. However, the choice of the color map is unfortunate, <1%, which could be conceptually be negligible, is very hard to distinguish from the higher classes. I suggest to revise the classification to a lower number of classes, 5 being preferred. A clarification is needed whether the map shows the percentage from the total area or from area classified as cropland.

We have modified the figure 1 as suggested. We have specified that the percentage refers to the total area.

Figure 2 features a useful example output of the analysis, but it was not justified that this is a representative example. The most reliable model would have been preferred, the Dynamic model was judged as best performing (Luedeling, 2012). In subplot B, over the years, the chilling units decrease, a trend line could be interesting, next to the mean. Subplot C should highlight which model is used for subplots A and B. In subplot D, neighboring grid points expose substantial differences in this mountainous terrain. With regards to the shortcomings mentioned in mountains areas, a further study could envision a more focused analysis on those areas.

The example was considered representative for two reasons, 1) because it shows the general procedure followed for each cell to obtain an individual outcome from the climate ensembles, illustrating how the methodology aggregated yearly information and projections using different climate models, 2) to explain how the initial and final chilling accumulation dates are calculated, and this is particularly important for the Utah-based methods considered in the study as warm temperatures sometimes negatively contribute to chilling accumulation. This is not the case of the Dynamic model where only positive increases of chilling accumulations are added up, being the purpose of the cited figure of illustrating one of the Utah-based methods, more complicated to explain in that sense. So Dynamic model is not as useful as the others to illustrate this.

The text has been changed to further explain the need of this figure and the footnote has been modified to clarify that all subplots refer to the same model.

We agree with the referee's suggestion that a further study more focused on mountainous areas would be very much interesting from the scientific point of view. However, our priority was to focus in main productive areas that are usually at lower regions.

Regarding Figures 3 -8 and as mentioned above, classes such as >20 are little informative. In this line, it would be of great value if the maps could either exclude or highlight less reliable outcomes. This could be done by keeping grid points white, or, if readability is not compromised, with a hatched overlay. From visual comparison, there seems to be a substantial part of the apple cultivation shown in Figure 1 in coastal and mountainous areas, those reported as with comparatively high errors.

As answered above, we have chosen a more understandable, representative classes for the figures, and we have highlighted the areas >20 in these figures to facilitate interpretation.

Technical comments (additionally to those mentioned in RC1, to which I fully agree):

* P.2 l. 26 delete 'it

We have deleted it.

* P.2 l.18, production, not productivity (if productivity is meant, the reference i.e. area should be specified, and I agree it is not relevant in this paper, rather give the importance of other fruits in Spain, ideally with national statistics rather than FAOSTAT)

Yes, the referee is right, we have changed it in the revised version.

* P.3 l.34, add 'among other regions'

The referee's suggestion has been included in the revised version.

* P.5 l.23 inconsistent usage of Dynamic model / Dynamic method

The referee's suggestion has been included in the revised version, using Dynamic model throughout the paper.

* P.8 l.10, specify where the biggest change occurred

We have specified it in the revised version.

* P.9 l.16, Mediterranean','

The referee's suggestion has been included in the revised version.

* P.9 ll.17-18 reformulate

The referee's suggestion has been included in the revised version as follows:

"In light of the results, our hypothesis is that the stations in these areas are poorly represented by the interpolated Spain02 dataset."

* P.9.l.21 a warmer scenario

The referee's suggestion has been included in the revised version.

* P.9 ll.28-29 'Nonetheless, few tree crops are grown [...]' – have these areas also be found as potential new cropping areas?

Yes, at the lower part of the mountains, but the affected areas would be relatively small. That is why in our view improving the estimations for these areas would be interesting of course but not a priority.

* P.10 l.17 are you comparing this value (469 chilling units, according to the De Melo-Abreu method) with all outputs? It should only be compared to the output of the analysis using the same method, which, in the case of the far future under RCP8.5, where the map shows mainly values between 500-1000 chill units in the area coinciding with olive cropping.

The comparison is established only between results from the same models. We have stressed this in the revised version as it is a key point. it seems that it was not clear *enough. Also, we have specified more the region we are referring to (red areas in Figure 8, first column, third row).*

Thank you for your thoughtful revision. We have tried to address all the issues you raised. We are convinced that our arguments are correct and sound, but if the editor and both referees ask us to remove some of the chilling models considered, we would be willing to do so.

References

Campoy, J.A., Ruiz, D., Egea, J., 2011. Dormancy in temperate fruit trees in a global warming context: A review. Sci. Hortic. 130, 357–372. https://doi.org/10.1016/j.scienta.2011.07.011

Luedeling, E., 2012. Climate change impacts on winter chill for temperate fruit and nut production: A review. Sci. Hortic. 144, 218–229. https://doi.org/10.1016/j.scienta.2012.07.011

Mendlik, T., Gobiet, A., 2016. Selecting climate simulations for impact studies based on multivariate patterns of climate change. Clim. Change 135, 381–393. https://doi.org/10.1007/s10584-015-1582-0

Michelangeli, P.-A., Vrac, M., Loukos, H., 2009. Probabilistic downscaling approaches: Application to wind cumulative distribution functions. Geophys. Res. Lett. 36. https://doi.org/10.1029/2009GL038401

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the KoÂ´lppen-Geiger climate classiïnˇA¸cation. Hydrol Earth Syst Sci 12.

Schaffer, B., 2018. Handbook of Environmental Physiology of Fruit Crops: Volume I: Temperate Crops, 1st ed. CRC Press. https://doi.org/10.1201/9780203719299

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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 chilling temperatures to finish this sort of dormancy~~accumulating cool temperatures to finish dormancy ("be broken")~~. The accumulation of cool temperatures according to specific rules is called chilling accumulation, and each tree species and variety has specific chilling requirements for correct plant development~~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 purpose, 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 ~~method~~models for calculating chilling accumulation, and the results for each model were individually ~~were~~ compared for the 2021–2050~~near~~ and 2071-2100~~far~~ future periods under both RCPs. These results project a generalised reduction in chilling accumulation regardless of the RCP, future period or chilling calculation ~~method~~model used, with higher reductions for the 2071-2100 period ~~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 where the crop is currently grown, ~~,~~ 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.~~

Olive and vineyard data are included now

Growing fruit trees is an important source of ~~wealth~~ income for farmers. Spain is one of the largest producers of fruits and vegetables in Europe, with 7437 million euros from 7.4~~$\cdot 10^{6}$~~ million t of exported fruits in 2017 (FEPEX, 2018) from a total fruit production of ~~11.24~~23.17~~$\cdot 10^{6}$~~ million 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 million~~$\cdot 10^{6}$~~ ha), followed by vineyard (0.94 million~~$\cdot 10^{6}$~~ ha), almond (0.58~~$\cdot 10^{6}$~~ million ha), citrus (0.26~~$\cdot 10^{6}$~~ million ha) and peach trees (0.09~~$\cdot 10^{6}$~~ million 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~~production, one of the most important groups of fruit trees are the temperate trees, accounting for approximately 48% of the total world fruit production according to FAOSTAT (2018). In Spain, ~~temperate~~ fruit trees are concentrated mainly on the east coast, along the river valleys of the coast, especially in the Ebro and Jucar valleys; specifically, apples are found mainly in the ~~North~~North-West and North-East of Spain and peaches are found mainly in North-East and South-East of Spain. 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~~frost. 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 time exposed to cold temperaturesthe 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 evolved or was bredEach 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 methodmodels, such as those mentioned above. As a result, for a given species a range of estimates of chill accumulation encompassing all varieties has to be considered. For instance, for the apricot varieties considered inAs 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 between 413 ('Palsteyn' variety) and 1172 ('Orange red' variety) chill hours (chilling hours model). This range is 613-777 when chilling units by Utah model are computed, and 37-64 chill portions when Dynamic model is applied.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 et al., 2009a; Luedeling 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, as demonstrated by recent projects such as the Coupled Model Inter-comparison Project phase 5 (~~Coupled Model Inter-comparison Project phase 5~~CMIP5; Taylor et al., 2012)~~.~~ or in studies such as Luedeling et al. (2011) in which GCMs were used for analysing the climate change impact on chilling accumulation. However, ~~their~~ the coarse horizontal resolution of GCMs (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 among other regions.

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. The bias adjustment technique used here is based on a transfer function such that the marginal cumulative distribution function of the adjusted variable matches that of the observations. A complete discussion of the technique, including validation and effect on climate indices can be found in Piani et al. (2010a), Piani et al. (2010b), Dosio and Paruolo (2011), Dosio et al. (2012), Ruiz-Ramos et al. (2016), and Dosio and Fischer (2018). Through the use of transfer functions ~~(e.g. Piani et al., 2010a; Piani et al., 2010b), temperature biases from RCMs are~~, 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). Dosio (2016) showed that bias-adjustment largely improves the value of present and future threshold-based indices (e.g., the number of frost days): these indices are generally poorly simulated over the present climate, such that the projected climate change may not be reliable. Although it is known that bias-adjustment can affect climate change signal at some extent (see e.g. Casanueva et al., 2018 for the quantile mapping method), these techniques are considered a valid alternative to apply on climate model outputs to crop models, especially suitable for handling regions of complex orography (Maraun and Widmann, 2018), as it is the case of Spain.

~~.Luedeling et al. (2011)~~The impact of climate change in global chilling accumulation by using GCMs climate projections was analysed in Luedeling et al. (2011), although the coarse resolution does not allow extracting practical recommendations for Spanish farmers. With higher resolution, Luedeling et al. (2009a), performed an analysis focused on the California region, and there are some other studies in other regions of the world (see Table 3 in~~Luedeling et al., 2011~~ Luedeling, 2012), but their results are still difficult to apply for helping in decision making in Spain. In addition, recent studies working with multi-crop model ensembles suggest that ensemble results tend to improve as the number of ensemble members increases. For instance, in Martre et al. (2015) the errors decreased when ~~as~~ the ensemble members increased, with little decrease beyond 10 members. This debate was analysed from the statistical point of view in Wallach et al. (2018). More common are the multi-climate model ensembles, as the one used by Gabaldón-Leal et al. (2017), who worked with an ensemble of climate models of 12 bias-adjusted members, and applied the de Melo-Abreu model to analyse impact of climate change for olive trees in southern Spain.

The usefulness of the studies that combine~~appl~~ chilling models ~~to~~and climate projections to quantify the future impact relies upon the availability of chill assessments where the chilling requirements of different crops and varieties have been analysed. There are a number of such assessments in a wide range of locations: for example, for estimating the chilling requirements in Murcia, Spain, using the Utah and Dynamic models, for apricots (Campoy et al., 2012; Ruiz et al., 2007; Viti et al., 2010) and for sweet cherry cultivars (Alburquerque et al., 2008), or in Gerona, Spain, using the Dynamic model for apple trees (Funes et al., 2016); and in other places than Spain, several studies have been conducted using the mentioned chilling models (see e.g. Aybar et al., 2015; Benmoussa et al., 2017a; Benmoussa et al., 2017b; Marra et al., 2017; Miranda et al., 2013; Razavi et al., 2011; Sawamura et al., 2017). Even the Chilling Hours Model, which is the oldest method to estimate winter chill accumulation and~~-~~ considers all hours with temperatures ranging from 0 to 7.2 ºC equally effective, is still widely used (see e.g. Londo and Johnson, 2014 and Houston et al., 2018 for grapevine or AEMET, 2018 for analysing the risk of frost in Spain).

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 periods. For that purpose, a suite of four chilling accumulation models (each one individually considered and studied) were used by applying 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.~~. To our knowledge, no other previous study provides high-resolution projections of chilling accumulation for the whole peninsular Spain and the Balearic Island by using four bias adjusted climate ensembles (one per chilling model) of 10 members (10 RCMs).

2 Material and methods

2.1 Observed and simulated climate data sets

The climate variable required by the chilling models used in this study is hourly temperature, which can be derived, when no other information is available, from minimum (Tmin) and maximum (Tmax) daily temperatures.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 2005 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, the 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 is available for downloading (http://www.meteo.unican.es/datasets/spain02) and is freely distributed for research purposes. It- 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 1S). 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). Due to the complex orography of the Iberian Peninsula and its remarkable climatic diversity (Bladé et al., 2010), no additional systematic selection was performed to reduce the number of RCM ensemble members (e.g., Mendlik and Gobiet, 2016). A thorough analysis in this sense would imply decomposing the Iberian Peninsula into several climatic sub-regions (Wilcke and Bärring, 2016) and would derive into a much more complex process to potentially improve already robust results. 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 future periods (-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

The EUR-11 climate models' outputs were not directly used by the models but first, the~~Once~~ bias adjustment process was performed, and hourly data was~~had been~~ prepared from the bias adjusted data.~~,~~ Then four different ~~method~~models were used to estimate chilling over Peninsular Spain and the Balearic Islands:~~. Several methods wereThe four considered models were:~~ the Utah ~~method~~model (Richardson et al., 1974) originally developed for peach trees, and two of its adaptations (Richardson based models, RbM); the North Carolina ~~method~~model (Shaltout and Unrath, 1983) developed for apple trees, and the ~~method~~model specifically developed by De Melo-Abreu et al. (2004) for olive trees. T~~, and t~~he Dynamic ~~method~~model (Fishman et al., 1987b), also developed for peach trees, was considered. ~~Methods~~ Models based on the Utah ~~method~~model 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~~model, which was developed based on Redhaven and Elberta peach varieties grown in Utah, ~~–~~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. We used the weights from Richardson et al. (1974), which are the most used, but other versions with modified chilling accumulation values for different ranges exist.

The North Carolina ~~method~~model is an adaptation of the Utah ~~method~~model where temperature ranges have been adjusted for apple trees. Specifically, it was developed for Starkrimson Delicious apple variety under a wide range of temperature and elevations corresponding to five locations in North Carolina (Shaltout and Unrath, 1983). The North of Spain, orographically complex and where most of the national apple production is concentrated, includes regions with similar temperature regimes to which the model was developed (see e.g. Kottek et al., 2006; Peel et al., 2007). An example of a current application of the model can be found in the elaboration of apple frost risk maps (http://www.nrcc.cornell.edu/industry/apple/apple.html) by the Northeast Regional Climate Center from USA administration, implemented by the University of Cornell.

The De Melo-Abreu et al. (2004) model, consisting in a generalisation and simplification of the Utah model applied to olive, showed good performance. Model development was based on 15 olive cultivars grown in four locations (Cordoba and Mas Bové in Spain and Santarém and Elvas in Portugal). It consists onapplied 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). Recently, thise model has been applied in Northwest Argentina (Aybar et al., 2015) with satisfactory results.

The Dynamic model was developed for Israeli weather conditions, and incorporates detailed bud responses to temperature based on experimental data with peach trees (Erez et al., 1990). The 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. For the implementation of this model, the equations and standard parameters available in Luedeling and Brown (2011) have been followed (see Code 1S in suppl. mat.).

Results from different chilling models -were treated as separated ensembles (when combined with climate projections), and therefore they were not averaged nor directly compared in absolute terms but they were interpreted individually. The chilling period was calculated separately for each chilling model, year, member of the EUR-11 ensemble and grid cell. Fig. 2 describes the process for generating the chilling maps for understanding the whole process followed in each cell, from the self-regulating period calculation, to the aggregation procedure followed for years and climate models. 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. This chilling accumulation for the Dynamic model is much easier to calculate (because the chilling portions accumulation do not decrease) (and for this reason a chilling model different than the Dynamic model was chosen to illustrate the process in Fig. 2). 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 for calculating chilling accumulation with the four models, for the hourly temperature estimation and for the computation of chilling accumulation period are available by contacting the authors andas supplementary material (Codes 1S to 9S) and can be used 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 absolute percentage ~~absolute~~ error (MAPE) between AEMET-based and Spain02-based chilling units calculated with the four chilling ~~method~~models 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 ~~method~~models.

Then chilling projections were computed with the four ~~method~~models and for the 2021–2050~~NF~~ and 2071-2100~~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~~for every chilling model. 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 ~~method~~models 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 (those grid cells are highlighted in diagonal lines in the rest of plots to stress that results should not be considered there). 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 (Fig~~s~~. 3b~~, 4a~~) was taken as the chilling accumulation simulated by the EUR-11 ensemble. Inter-annual variability of chilling accumulation was ~~similarly simulated~~simulated in a similar way when using Spain02 and the EUR-11 ensemble, with small differences for the De Melo-Abreu and Dynamic ~~method~~models in the southern half of Spain (Fig. 1S in suppl. mat.).

As simulated by EUR-11, the four ensembles estimated higher chilling accumulation in the North of Spain, as expected by the cooler conditions in that part of the country. In general, the spatial pattern of chilling accumulation is similar for the different chilling models used (Fig. 3b). ~~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~~4a) was, in general, lower than 20% for most of the grid cells whatever chilling ~~method~~model was considered. The Dynamic ~~method~~model presented the lowest results with maximum CV values for some points of the South coast of the Iberian Peninsula. The De Melo-Abreu ~~method~~model showed CV values similar to the Dynamic ~~method~~model with the exception of the mountainous regions where the CV was higher. Finally, the Utah and North Carolina ~~method~~models 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~~4b) was lower than 5 chilling portions for the Dynamic model and lower than 100 chilling ~~units (or 5 chilling portions for the Dynamic method)~~units for all ~~four~~ Utah, North Carolina and de Melo-Abreu chilling models ~~and~~ in 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 median of the four EUR-11 based ensembles show a general decrease of chilling units and portions over all simulated areas for both the 2021–2050~~NF~~ and 2071-2100~~FF~~ periods under both RCPs~~, as expected~~ (Figs. ~~5a~~5b, ~~6a~~5d, ~~7a~~ 6b and ~~8a~~6d), being more pronounced by the end of the century, as expected. Under RCP4.5, a decrease of up to 30 chill portions in the Dynamic model based ensemble and up to 600 chill units ~~(and up to 30 chill portions in the Dynamic method)~~for the rest of the chilling ensembles is projected for the 2021–2050 period~~NF~~ (Fig. 5b). A slightly higher but similar decrease is projected under the RCP8.5 scenario in the 2021–2050 period~~NF~~ (Fig. ~~6b~~5d). In the 2021–2050 period~~NF~~ under both RCP scenarios, and in 2071-2100 period~~FF~~ under RCP4.5 scenario, the change was fairly spatially homogenous (Figs. 5b, 5d and 6b). However, in 2071-2100 period~~FF~~ under RCP8.5 scenario an agreement among the chilling model ensembles points that the largest chilling accumulation changes are projected for the North and North-West coast and for the South-East coast of Spain, with decreases larger than 60 chilling portions calculated with the Dynamic model and larger than 1200 chilling units calculated with the Utah, North Carolina and de Melo-Abreu models (Fig. 6d).

~~CV and IQR~~ CV values (Fig~~s~~. ~~5c, 5d, 6c, 6d~~7) are similar for the 2021–2050 period~~NF~~ between RCP4.5 and RCP8.5 and for all chilling model--based ensembles, with the Utah and North Carolina ~~method~~based ensembles~~models~~ presenting higher CV values than the De Melo-Abreu and Dynamic ~~method~~ones~~models~~. ~~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).~~

In the 2071-2100 period~~FF~~, b~~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). B~~oth climate model inter-annual variability and uncertainty ~~inter-annual variability and climate model uncertainty~~ (~~CV and IQR~~CV and IQR, respectively, see Figs. 7 and 8), in general, increase with respect to the NF period~~NF~~ for every model ensemble~~method~~; both are higher in the RCP8.5 scenario. As found in the NF period~~NF~~, the Utah and North Carolina chilling model--based ensembles ~~method~~presented higher CV ~~and IQR~~ values than the De Melo-Abreu and Dynamic ~~method~~ones. The IQR obtained is larger for the 2071-2100 period~~FF~~ and RCP8.5 scenario, as expected.

To illustrate the consequences of these projections, we can analyse the mean number of compromised seasons in four representative productive locations for some common varieties of apple, olive and peach trees (Table 1). All the crops and varieties used in the example would be severely compromised in the 2071-2100 period and RCP8.5 scenario at the selected locations, so adaptation would be mandatory for that period. However, at Murcia, adaptation would be required from now on.

On the other side, the analysis shows how some varieties (peach Sunlite and Flavortop at Buñol, East of Spain) may offer resilience until mid of the century.

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; in addition information for determining the impact of climate model and emissions scenario was provided in that study). 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~~model 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 methodmodels considered; therefore, comparison with previous results was not possible for these methodmodels.~~

Our work has similar findings than other studies performed in other parts of the globe;~~,~~ for example, Darbyshire et al. (2013), who analysed the impact of the future warming on winter chilling in Australia concluding that adaptation will be necessary in many locations, at least at some extent, within the next 50 years. Also, a negative impact of climate change on chilling accumulation was found, as expected, in another region with Mediterranean climate, California, in Luedeling et al. (2009a), showing that adaptation would be difficult for some crops under some scenarios. This would be also the case in Brazil (Wrege et al., 2010). According to these studies, adaptation for some tree crops appears to be much more difficult in other parts of the world than we found in this study for Spain.

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 ~~method~~models 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. In light of the results, our hypothesis is that the meteorological stations in these areas are poorly represented by the interpolated Spain02 data set~~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 2071-2100 period~~FF~~ and for the warmer scenario~~s. 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.~~. These high CV values, particularly for Utah and North Carolina models, could be related to the low values of chilling accumulation in absolute terms, which might become these models too sensitive for warm places.

Uncertainty was also higher in some mountainous regions, where chill increases are found for warmer climate projections for both the Utah and ~~De~~ de Melo-Abreu model-based ensembles~~methods~~. At first glance contradictory, this is explained by the temperature thresholds used in the ~~method~~models and is in agreement with the results reported by Luedeling et al. (2011) ~~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.

Ideally, a site-specific calibration would be desirable for any simulation exercise. However, when data are not available for the targeted area, a common practise is to extend models' application to locations where the conditions are similar with those where the model was calibrated. For example the Utah model is applied without site-specific calibration in locations different than Utah (e.g. Alburquerque et al., 2008 for cherries in Spain, Razavi et al., 2011 for peach and apricot in Iran, or Sawamura et al., 2017 for peach in Japan). However, it is important to stress that these models were developed, more than for specific locations, for specific tree species (see materials and methods section). In addition, a current practice is to use the chilling models against phenological data of a specific species, generally for several varieties, and obviating that the model was fitted for a different crop, assuming that there are not differences among species (e.g. Alburquerque et al., 2008; Benmoussa et al., 2017a; Benmoussa et al., 2017b; Elloumi et al., 2013; Funes et al., 2016; Prudencio et al., 2018). In our work, we have prioritized the adjustment parameters made to the Utah model (Richardson et al., 1974) for different species (apple, which became North Carolina model; and olive, which became de Melo-Abreu model), under the hypothesis that the model would perform better if fitted to the behaviour of each species than if the model was used with the parameters established for peach.

However, uncertainty from the chilling models themselves remains. There are several studies (e.g. Benmoussa et al., 2017a; Luedeling et al., 2009b; Ruiz et al., 2007; Zhang and Taylor, 2011) indicating that the Dynamic Model (DM) exhibits a higher accuracy than the RbM, but at the same time, the reported improvement in those studies is very small (e.g. Ruiz et al., 2007), and they also report varieties and locations where RbM models perform better. Also, some studies claim that there is not a significant difference between models performance; for instance, in Alburquerque et al. (2008) differences between DM and Utah model were not found when estimating chilling requirements for cherry cultivars in Spain, or in Ruiz et al. (2007) chilling requirements of the evaluated apricot cultivars were very homogeneous according both to the Utah and Dynamic models, also in Spain. Both Utah and Dynamic models still have room for improvement in terms of accuracy as found (among other chilling models) in Luedeling (2012). In the same study, the DM was recommended for warm regions. However, -DM did not show good performance in the Tunisian -warm climate Sfax region estimating chilling requirements for pistachios (Benmoussa et al., 2017b), and despite of providing better chilling estimates than other models for almonds in the same Sfax region, the DM showed some shortcomings indicating that is not well adapted to that climate (Benmoussa et al. (2017a). In view of all these evidences, we cannot conclude that DM is a better model for Spain in general terms and therefore four different chilling models were considered in this study.

To improve the existing models, and while functional understanding of dormancy process progresses (Campoy et al., 2011), more experimental data, whose availability is limited in Spain, should be generated to improve the chilling simulation, not only because of the differences between locations, but mainly due to the huge uncertainty related to the species and variety requirements. 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. A fix period could become eventually meaningless in Spain in a climate change context, causing inconsistencies when the cold period is clearly shifted at the end of the century. This self-regulating calculation period approach has been considered for chill models because of the lack of reliable physiological markers and the inefficacy of fixed dates to account for the seasonal climate variability (Measham et al., 2017). According to Marra et al. (2017) a self-regulating algorithm approach to calculate the starting date, similar than the one used here, allowed a significant improvement compared to a fix date. Also, results in Measham et al. (2017) show a larger variability in the chilling portions accumulation using a fix date approach than a self-regulating one, as some chilling portions were excluded due to a late initial date. However, some studies found chilling responsive periods not covering the full winter season (e.g. Guo et al., 2015; Luedeling et al., 2013). Nevertheless, having in mind this possible chilling accumulation overestimation, the use of a self-regulating method makes the chilling projections comparable across periods (i.e. baseline, 2021–2050 and 2071-2100 periodsNF and FF) and RCPs. 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 2071-2100 period~~FF~~ for some crop varieties depending on how rapidly greenhouse gasses emissions evolve. The main difference between the two studied RCPs, consisting in a larger reduction of chilling accumulation in RCP8.5, is projected to be more accentuated in 2071-2100 period~~FF~~, as expected. According with the chilling requirements and the example on the number of compromised seasons (see Table 1), this severe scenario could cause, f~~F~~or example, that the broadly cultivated Golden Delicious apple variety which requires 1050 chill units (measured with the North Carolina ~~method~~model~~; Hauagge and Cummins, 1991~~),~~ but our results show that those chilling requirements will not be obtained~~ had difficulties in fulfilling its chilling requirements under a RCP8.5 scenario in the Ebro valley (see Fig. 2Sa in suppl. mat.), 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~~ estimated with the De Melo-Abreu ~~method~~model~~; De Melo Abreu et al., 2004~~) in that region~~,~~ in the 2071-2100 period~~FF~~ under the RCP8.5 scenario, according to the projected chilling accumulation values (see Fig. 2Sb in suppl. mat.). 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). In the case of the widely grown Redhaven peach variety, with requirements of 813 chilling units (estimated with the Utah model) and 73 chilling portions (estimated with the Dynamic model), in the 2071-2100 period~~FF~~ under the RCP8.5 scenario, a lack of chilling requirement accumulation is projected by both Utah and Dynamic model-based ensembles ~~models~~according to the projected chilling accumulation values (see Figs. 2Sc and 2Sd in suppl. mat.), at the South-West and East of Spain, also including large regions of Murcia, Valencia and the Balearic Islands, which are zones with a currently high peach production. The high number of compromised seasons would lead to a change of variety in these areas, which despite of these important impacts, would be enough in most locations to adapt to the projected chilling accumulation under future conditions. In general, for all tree crops considered here, there are some varieties with low chilling requirements with adaptation potential;~~,~~ for example Anna apple variety (218 chilling units measured with the North Carolina model, Hauagge and Cummins, 1991), Aprilglo peach variety (8 chilling portions and 150 chilling units measured with the Dynamic and Utah models respectively, Erez, 2000) or Arbequina olive variety (339 chilling units measured with the de Melo-Abreu model, Table 1).

Further work to advance towards more accurate projections of chilling sums, while new experimental data are generated, would be to analyse the ~~probabilities~~ confidence 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~~the variety with the lower chilling requirement within a given 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 would be a refinement of the current impact assessment, and it sh~~w~~ould ~~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. 2071-2100 period~~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, for example, considering the threshold for a variety to meet the “safe winter chill” requirements at a specific location and time (Luedeling et al., 2009a). ~~i.e. that a variety meets its chill requirements at a specific location and time at 90% likelihood.~~By doing this, suitable zones for a given variety could be calculated.

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

A winter chill reduction may threaten the viability of some crop varieties, especially in some areas that already have a low number of chilling units and are cultivated with chilling demanding species, where their reduction may jeopardise the cultivation of some varieties within the 2021–2050 period~~near future~~.

An ~~attempt to~~ improvement of chilling projections was accomplished ~~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, and then applying four chilling models ~~and~~ using an evolving chilling period onset. At our current knowledge, such an assessment by four independent ensembles has not previously been done. T~~As a result, t~~he 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, as adaptation is assumed to be more feasible for moderate warming scenarios.~~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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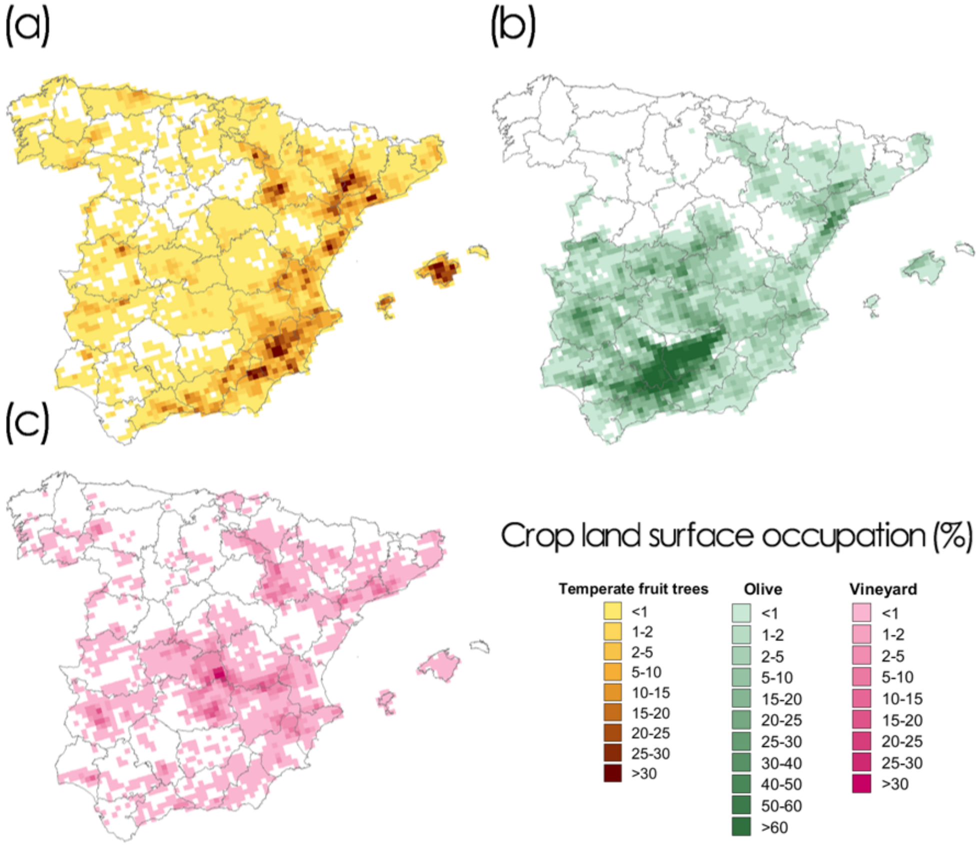

(a)
(b)
(c)
Crop land surface occupation (%)
Temperate fruit trees
<1
1-2
2-5
5-10
10-15
15-20
20-25
25-30
>30
Olive
<1
1-2
2-5
5-10
15-20
20-25
25-30
30-40
40-50
50-60
>60
Vineyard
<1
1-2
2-5
5-10
10-15
15-20
20-25
25-30
>30

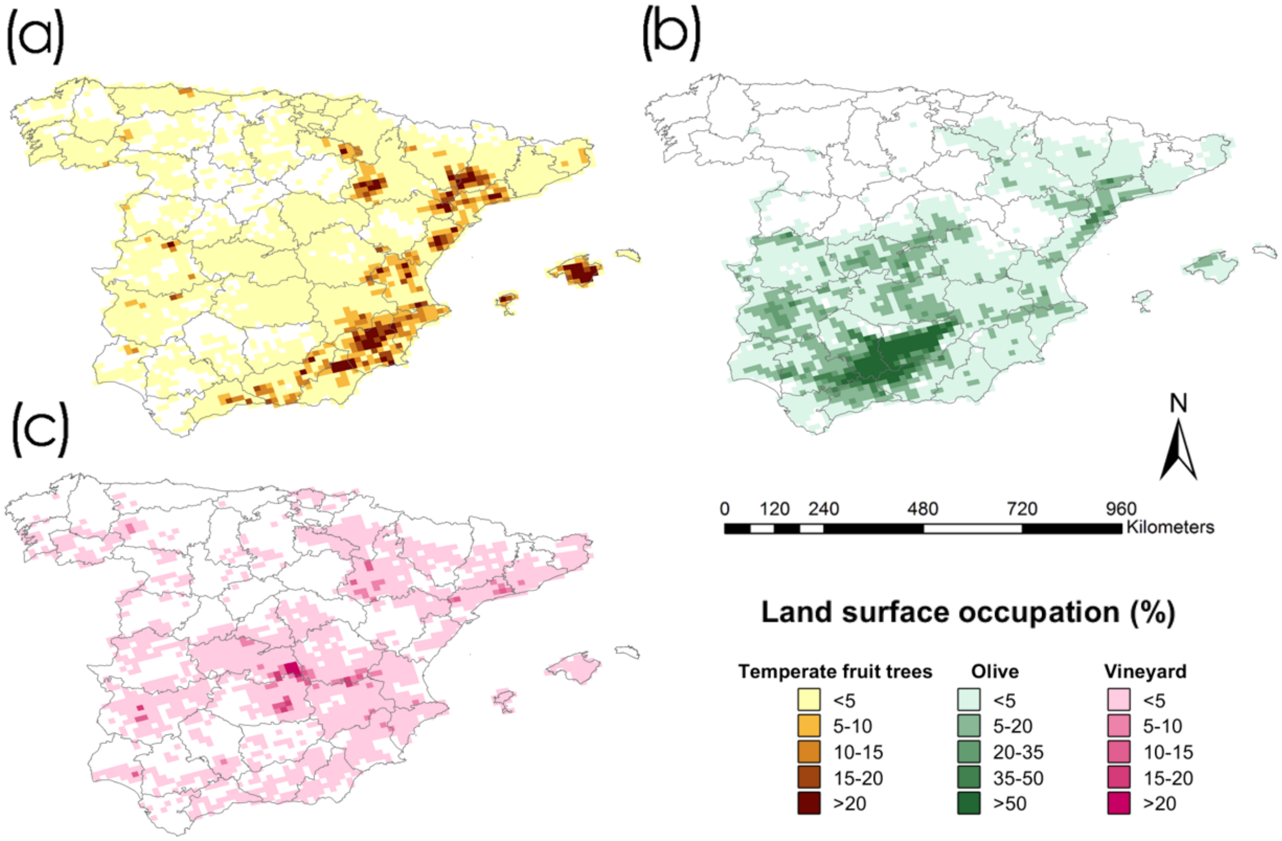
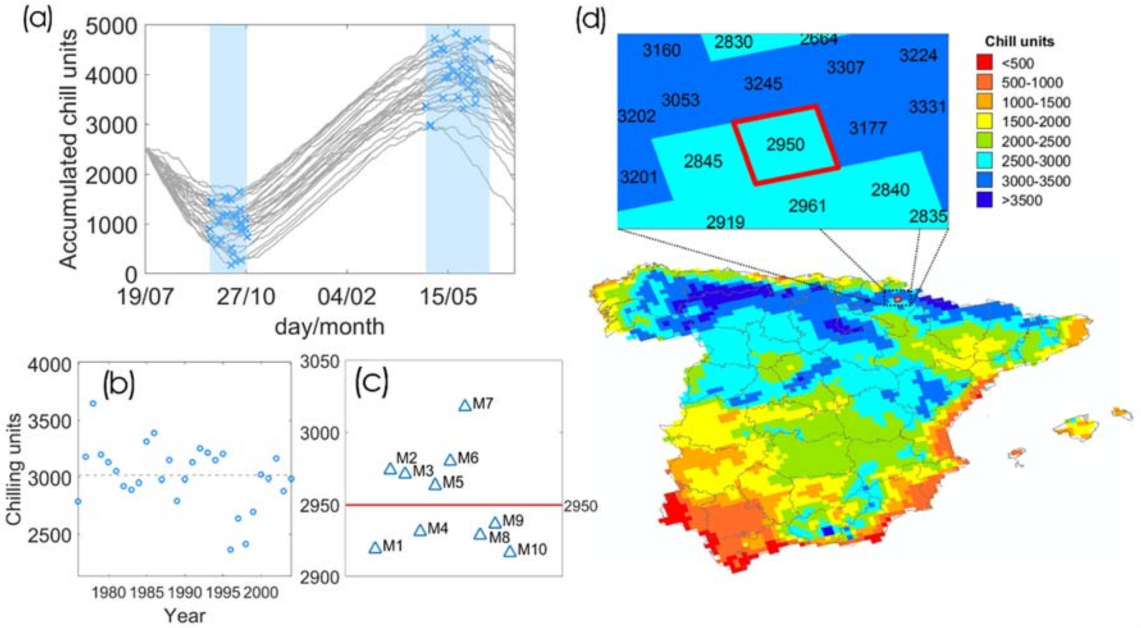


Figure 1. Percentage of land surface occupation (from the total cell area) for temperate fruit trees (orange colour tones, plot a), olive (green colour tones, plot b) and vineyard (pink colour tones, plot c) in 2011. Maps were created with the information available from the Spanish Soil Occupation Information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



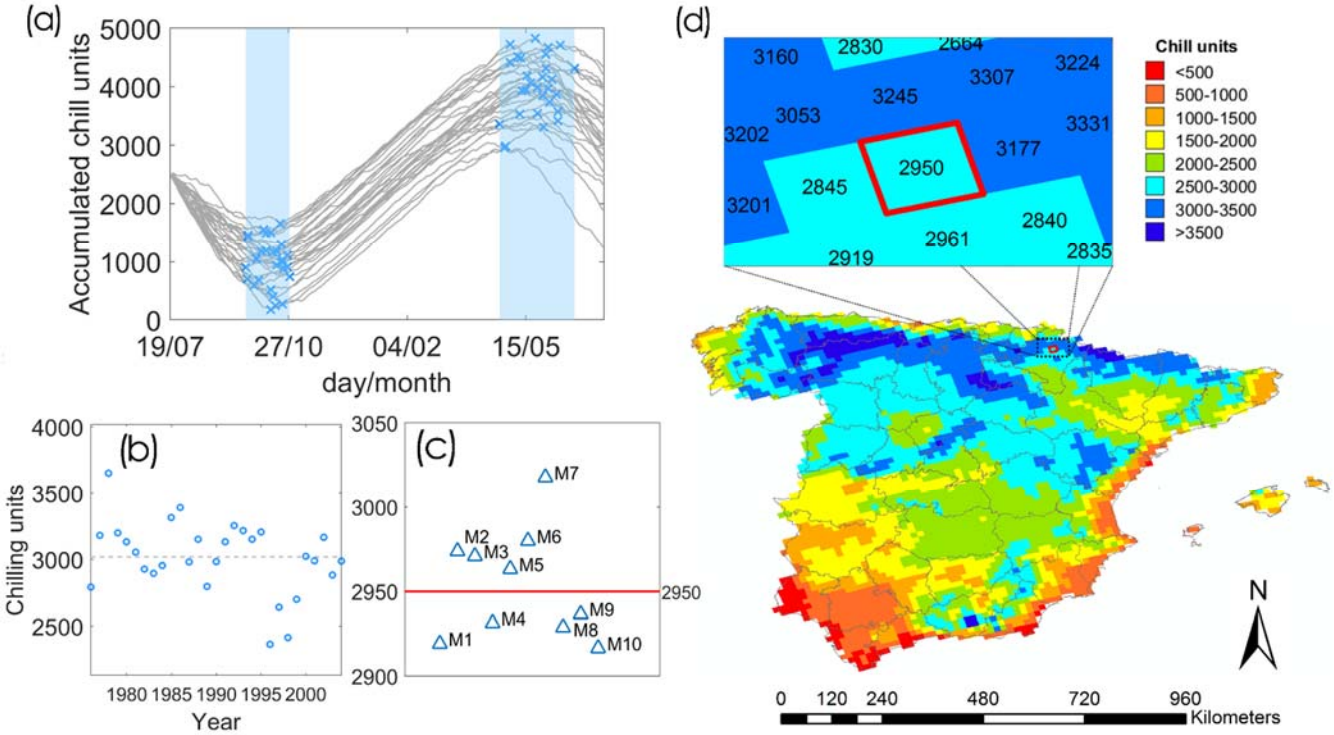
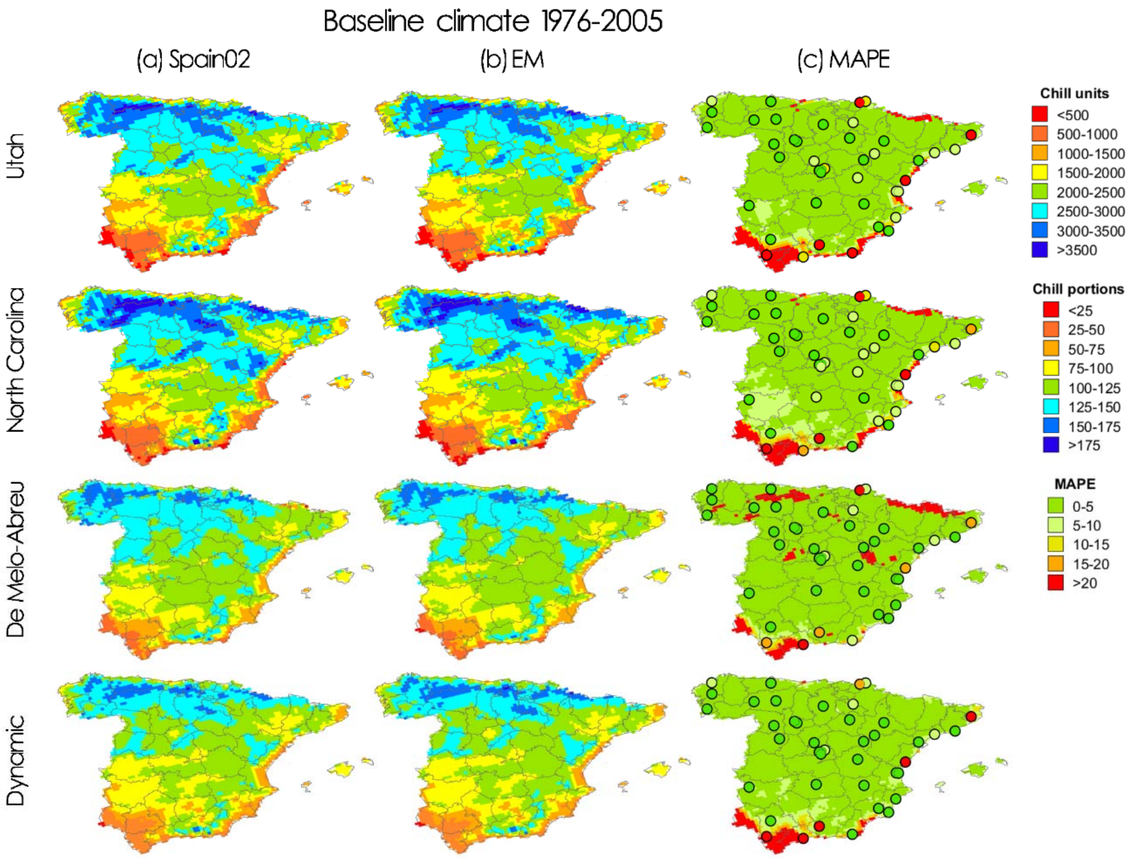


Figure 2. Methodological example: Chilling accumulation calculation process using the North Carolina chilling model in a particular location (42.86ºN, 1.57ºW) for the 1976–2005 period, for a single location and chilling model. Plot a) shows the initial

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).



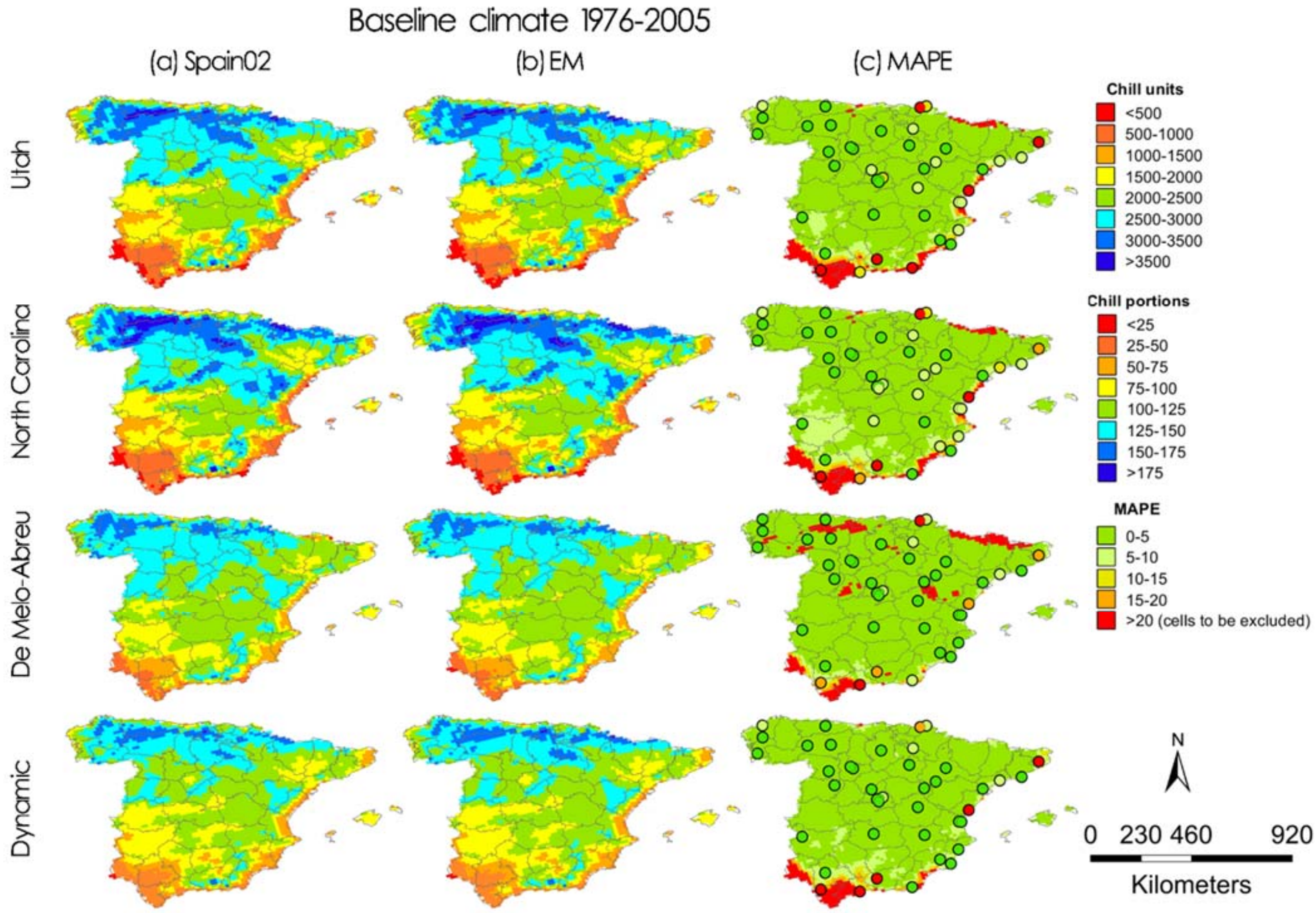
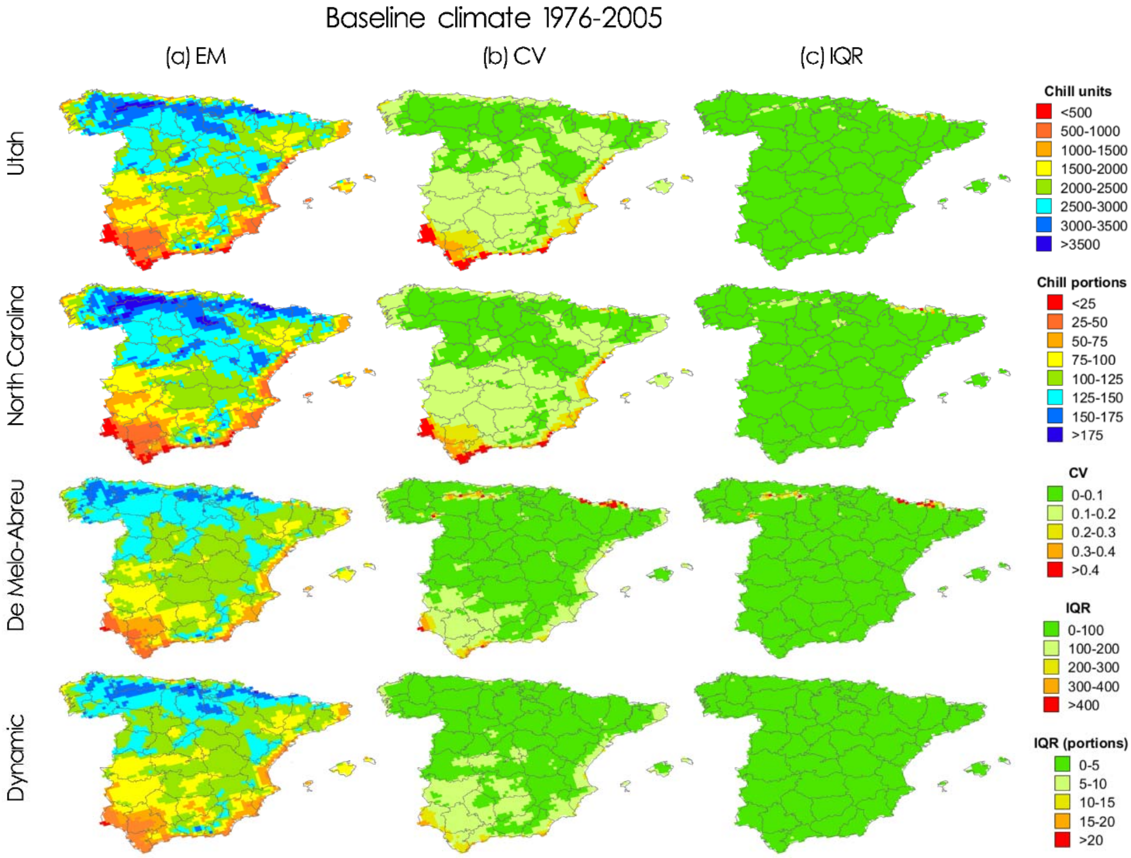


Figure 3. Evaluation of the chilling accumulation units for the baseline period (1976–2005). For each chilling ~~method~~model (rows), the map of the 30-year mean chilling sums calculated with the observational data set Spain02 (first column) and the map of medians of the 30-year mean chilling sums of 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). Cells with MAPE values greater than 20 (in red) are not considered as reliable results. 95th percentile MAPE values for each model were 25.8 (Utah), 23 (North Carolina), 25.9 (de Melo-Abreu) and 14.2 (Dynamic).



Baseline climate 1976-2005
(a) EM
(b) CV
(c) IQR
Utah
North Carolina
De Melo-Abreu
Dynamic
Chill units
<500
500-1000
1000-1500
1500-2000
2000-2500
2500-3000
3000-3500
>3500
Chill portions
<25
25-50
50-75
75-100
100-125
125-150
150-175
>175
CV
0-0.1
0.1-0.2
0.2-0.3
0.3-0.4
>0.4
IQR
0-100
100-200
200-300
300-400
>400
IQR (portions)
0-5
5-10
10-15
15-20
>20

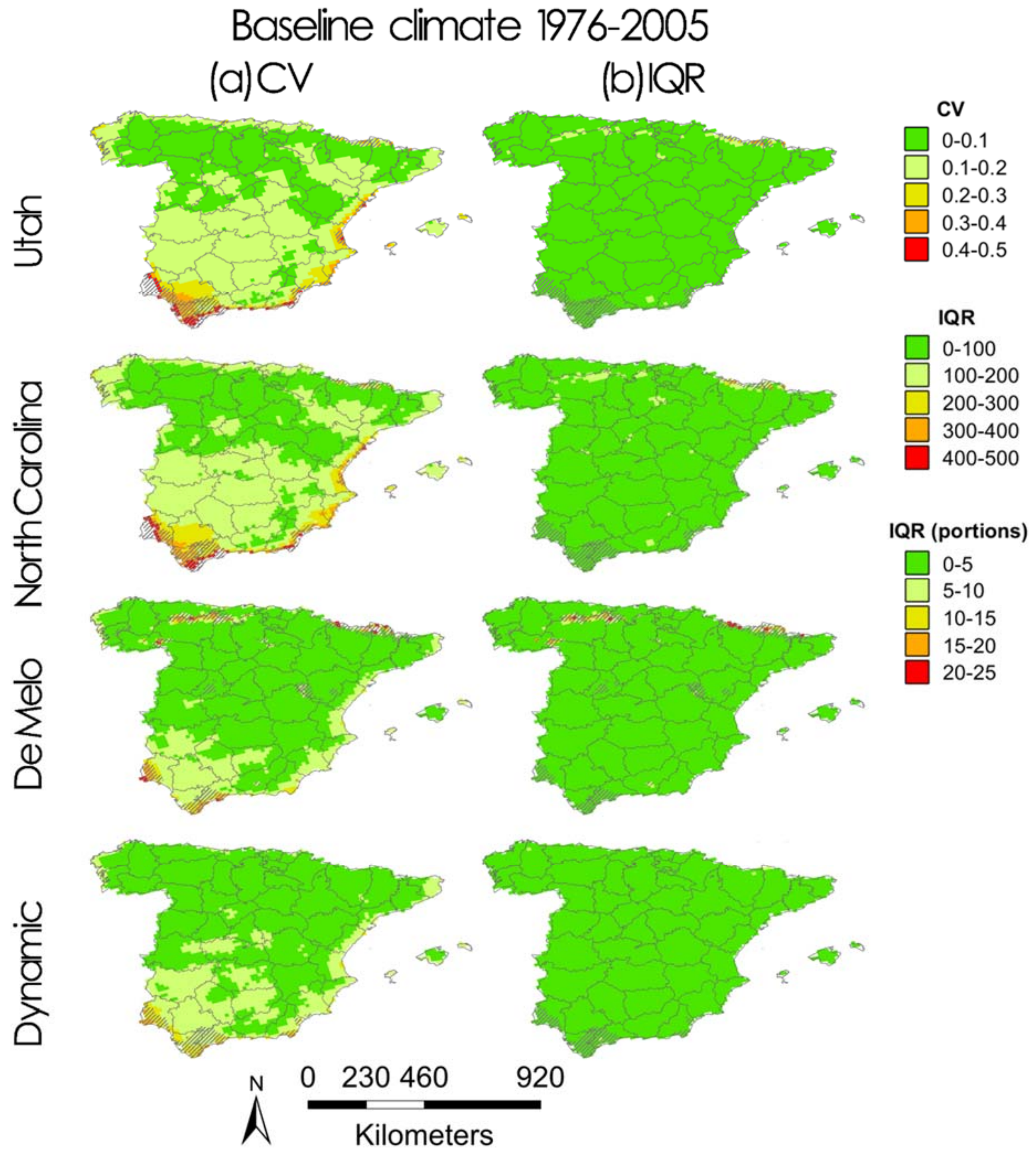
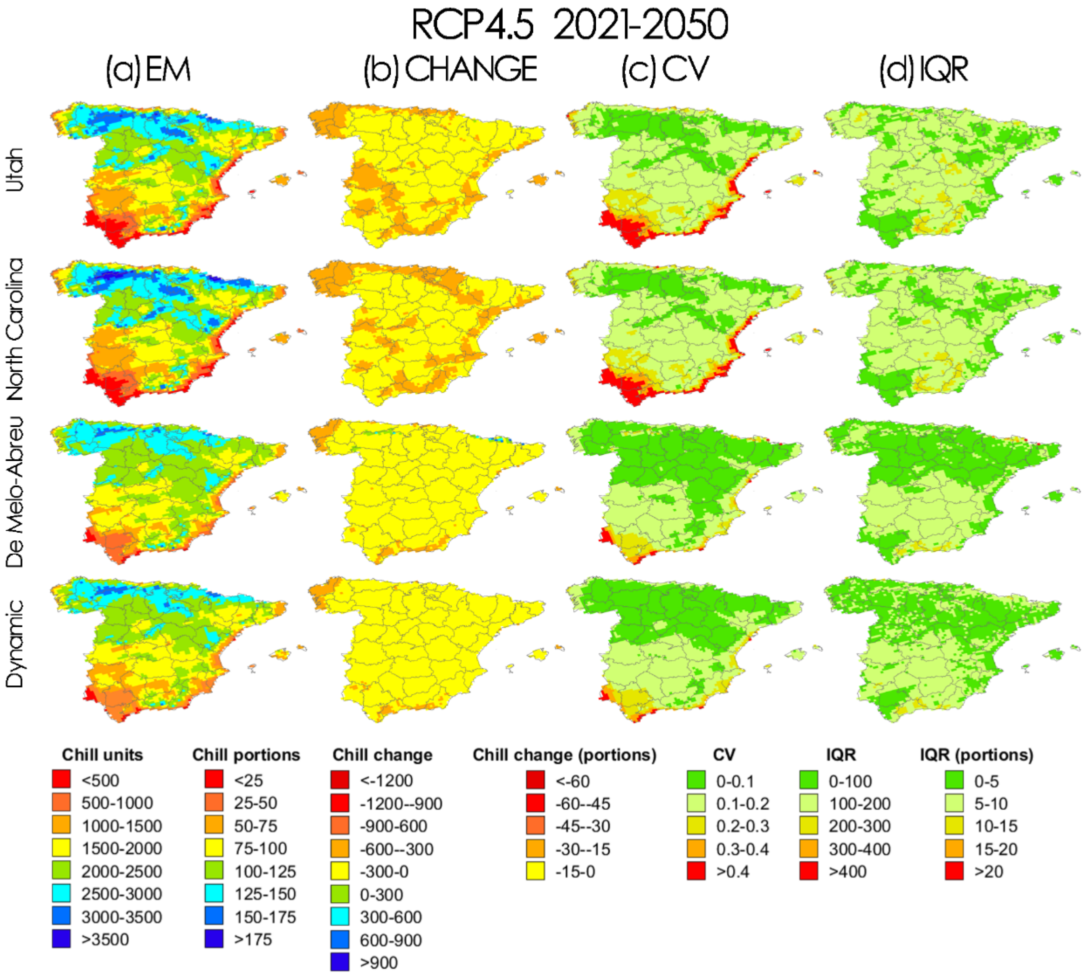
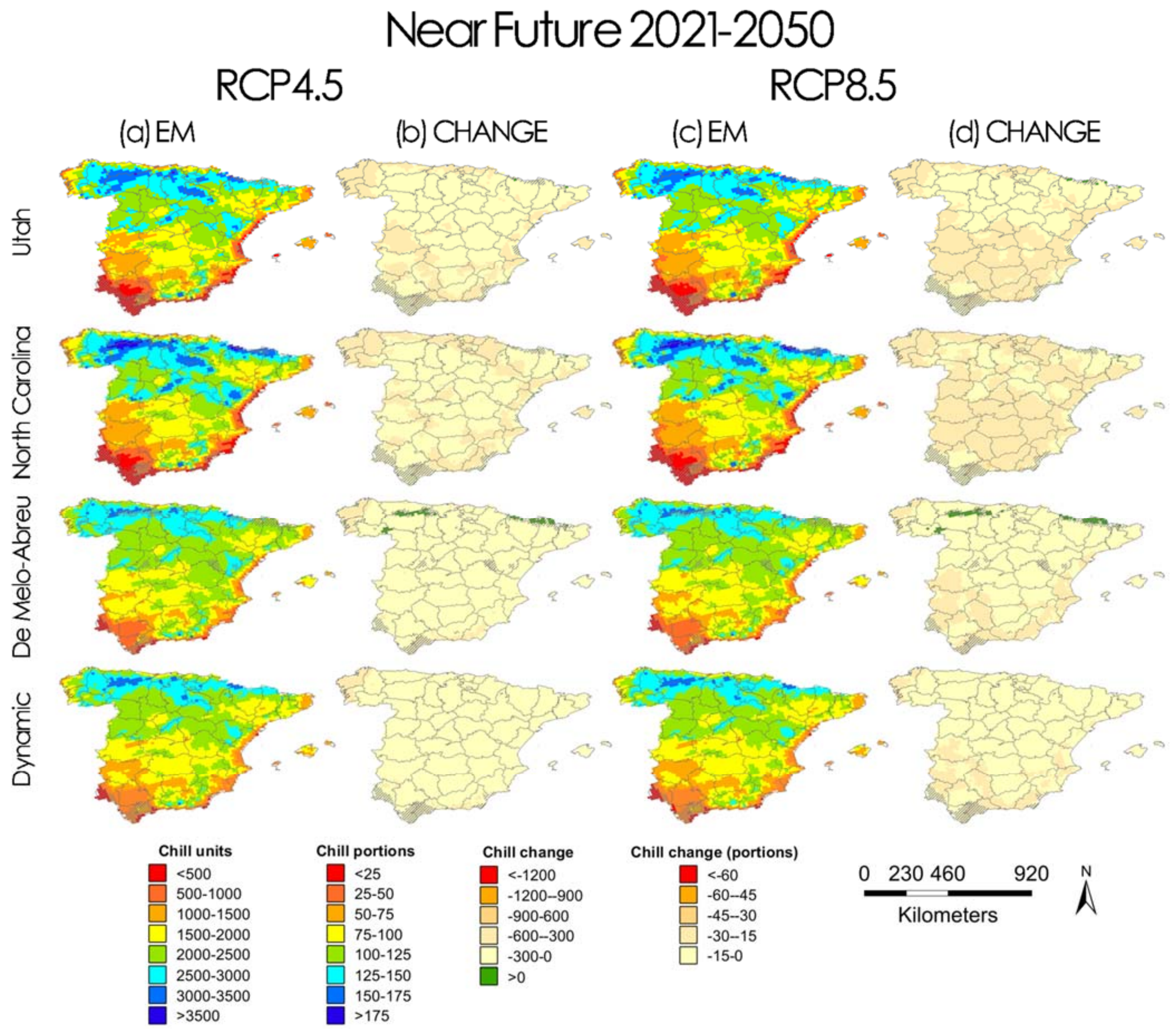


Figure 4. Maps of ~~chilling accumulation,~~ inter-annual variability and uncertainty results for the baseline period (1975–2005). For each chilling ~~method~~<u>model</u> (rows), ~~the median of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (first column) and~~ the 10 EUR-11 ensemble members' mean coefficient of variation (CV, expressed per unit) of the 30-year period (~~second~~ <u>first</u> column) and the ensemble's interquartile range (IQR<u>, measured in chill units or chill portions respectively</u>) of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (~~third~~ <u>second</u> column). <u>Grid cells with mean absolute percentage</u>

error (MAPE, %) values from the validation phase higher than 20 are not considered as reliable results and are highlighted in diagonal lines.

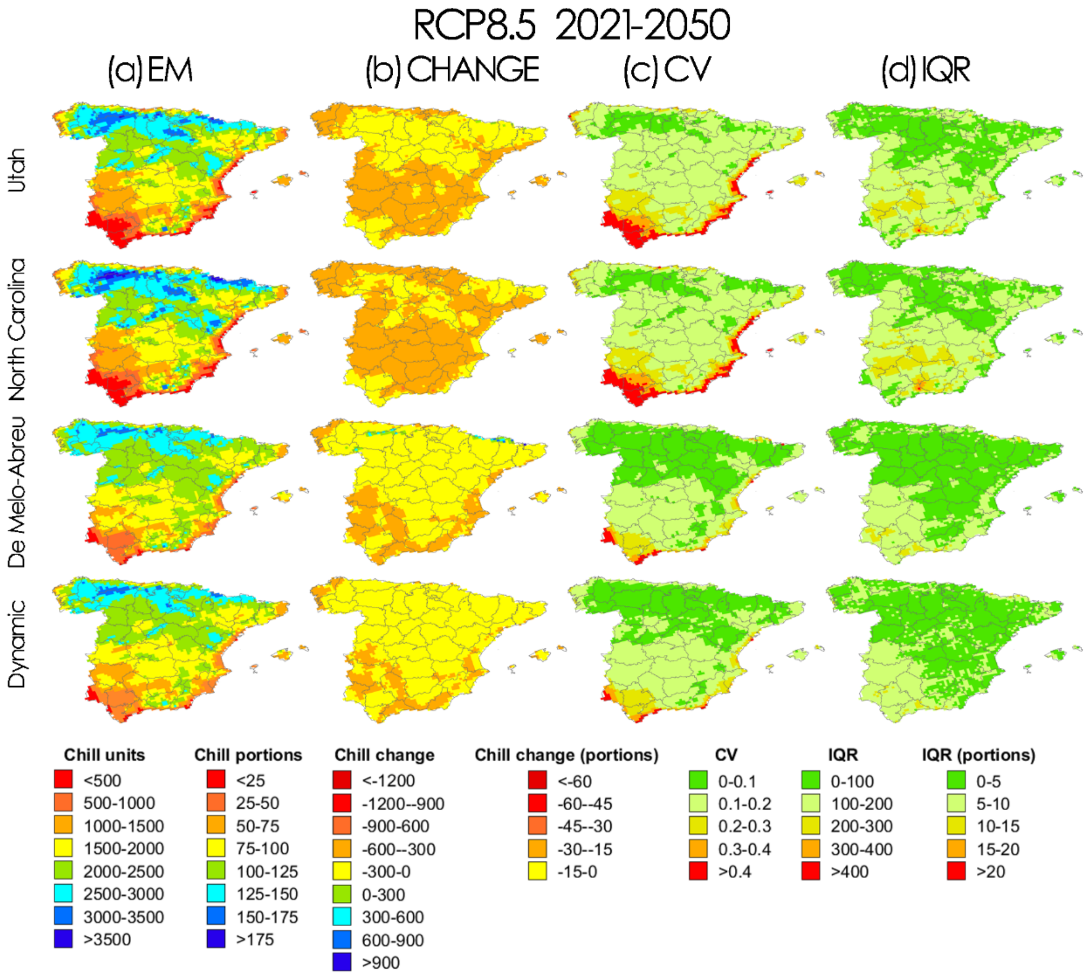




~~**Figure 5. Maps of chilling accumulation, inter-annual variability and uncertainty results for RCP4.5 scenario in the NF (2021-2050). For each chilling method (rows), the median of the 30-year mean chilling sums of the 10 EUR-11 ensemble members (first column), change in chilling accumulation with 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 5. Maps of chilling accumulation in the ~~NF (~~2021-2050 period~~)~~. For each chilling model (rows), the median of the 30-year mean chilling sums of the 10 EUR-11 ensemble members and change in chilling accumulation with respect to the baseline period, for RCP4.5 scenario (first and second column respectively) and RCP8.5 scenario (third and fourth column respectively). Grid cells

with mean absolute percentage error (MAPE, %) values from the validation phase higher than 20 are not considered as reliable results and are highlighted in diagonal lines.



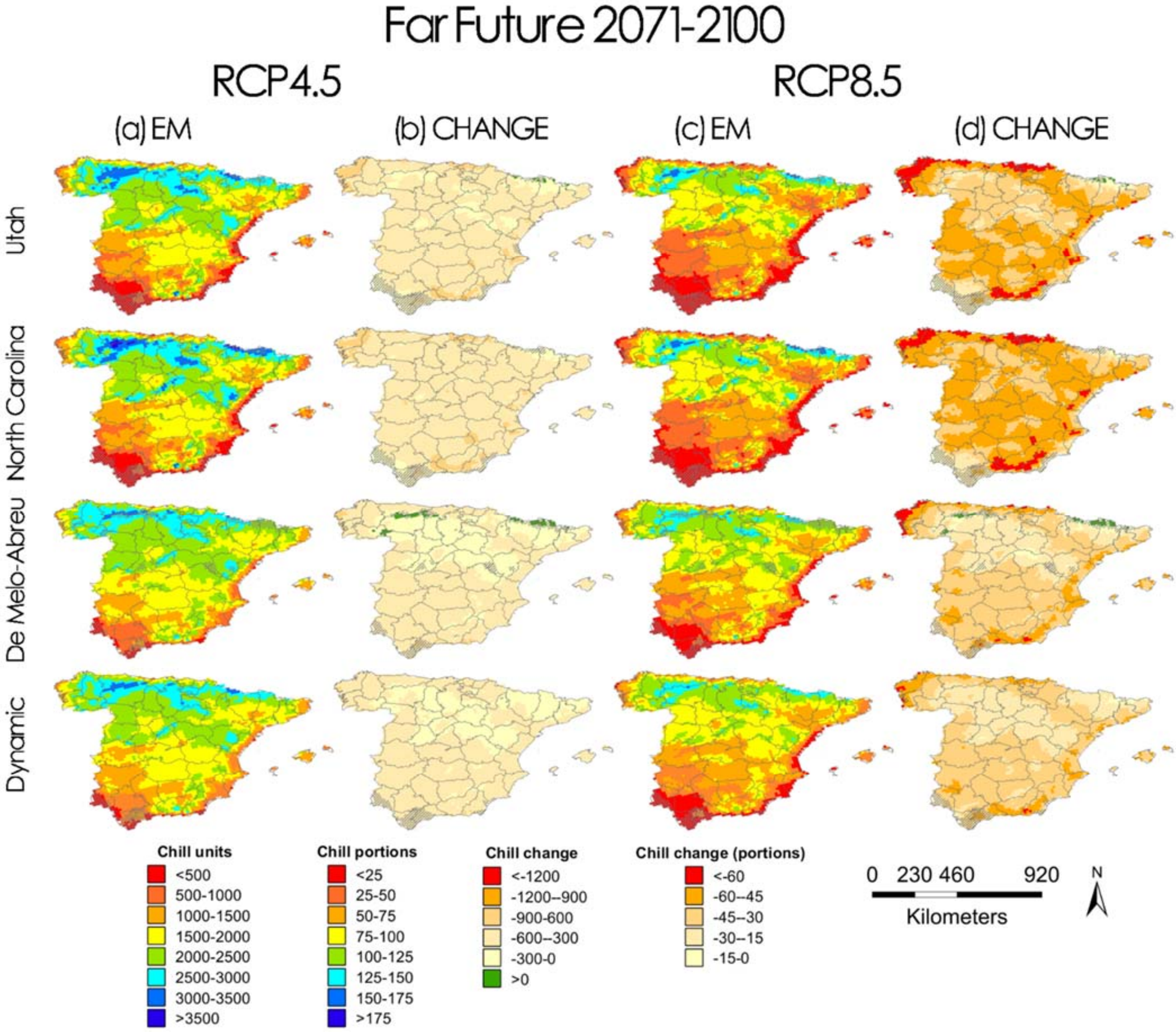
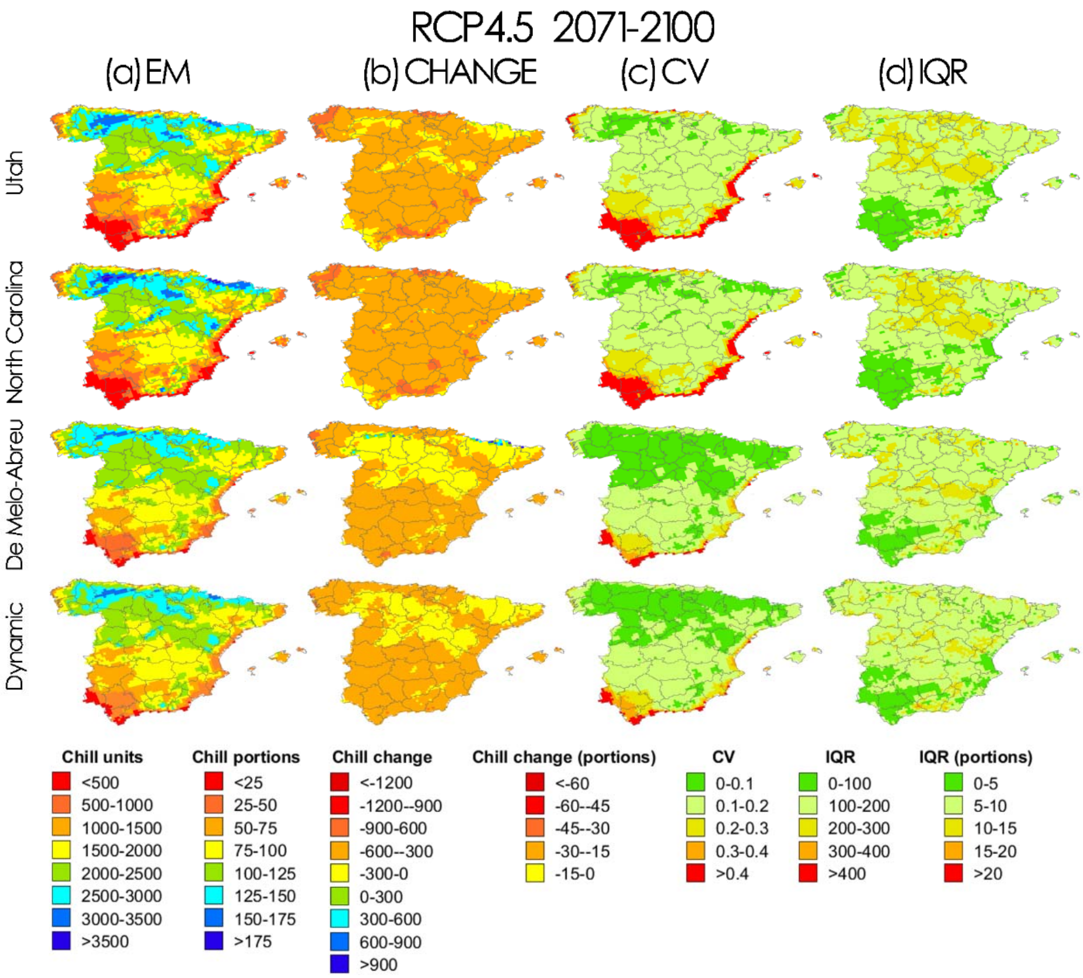
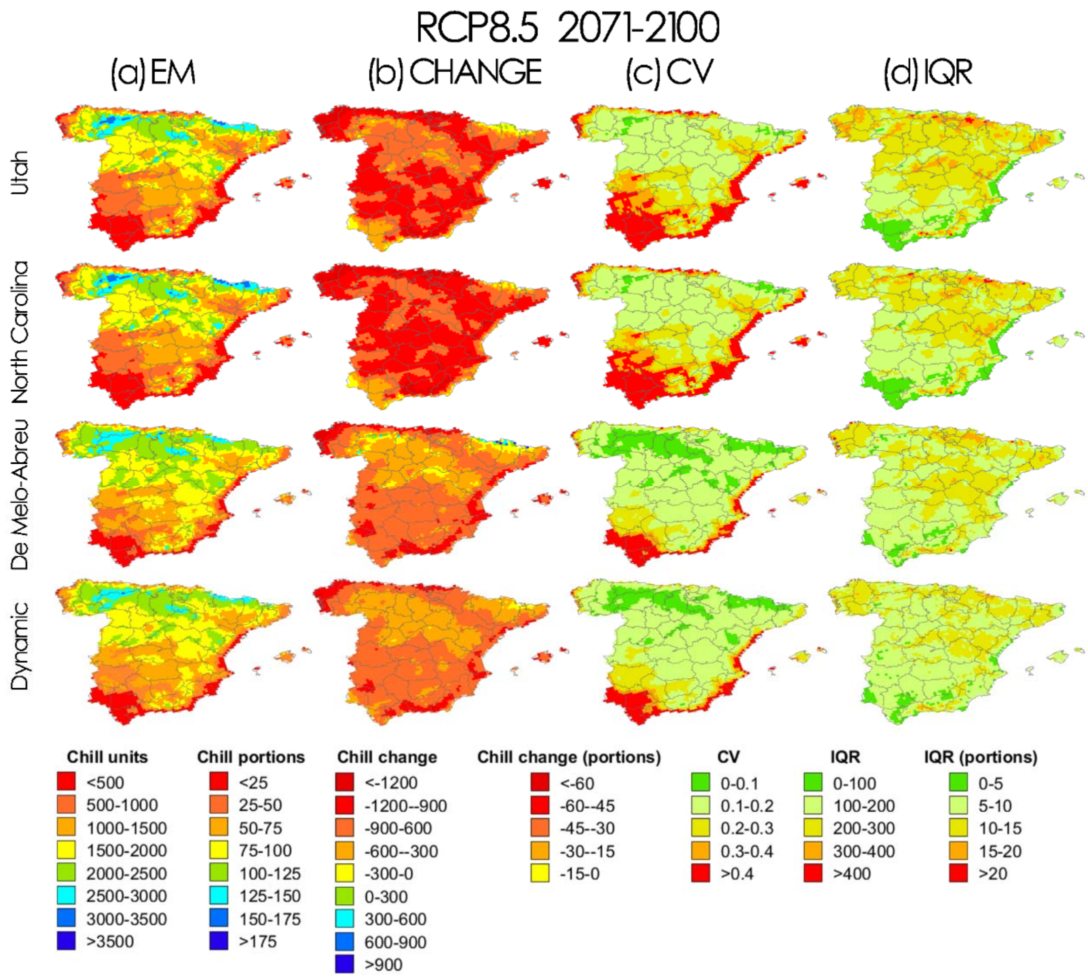


Figure 6. Same as Fig. 5 but for ~~the RCP8.5~~the ~~FF (~~2071-2100 period~~)~~.


RCP4.5 2071-2100
(a) EM
(b) CHANGE
(c) CV
(d) IQR
Utah
North Carolina
De Melo-Abreu
Dynamic
Chill units
<500
500-1000
1000-1500
1500-2000
2000-2500
2500-3000
3000-3500
>3500
Chill portions
<25
25-50
50-75
75-100
100-125
125-150
150-175
>175
Chill change
<-1200
-1200--900
-900-600
-600--300
-300-0
0-300
300-600
600-900
>900
Chill change (portions)
<-60
-60--45
-45--30
-30--15
-15-0
CV
0-0.1
0.1-0.2
0.2-0.3
0.3-0.4
>0.4
IQR
0-100
100-200
200-300
300-400
>400
IQR (portions)
0-5
5-10
10-15
15-20
>20


RCP8.5 2071-2100
(a) EM
(b) CHANGE
(c) CV
(d) IQR
Utah
North Carolina
De Melo-Abreu
Dynamic
Chill units
<500
500-1000
1000-1500
1500-2000
2000-2500
2500-3000
3000-3500
>3500
Chill portions
<25
25-50
50-75
75-100
100-125
125-150
150-175
>175
Chill change
<-1200
-1200--900
-900-600
-600--300
-300-0
0-300
300-600
600-900
>900
Chill change (portions)
<-60
-60--45
-45--30
-30--15
-15-0
CV
0-0.1
0.1-0.2
0.2-0.3
0.3-0.4
>0.4
IQR
0-100
100-200
200-300
300-400
>400
IQR (portions)
0-5
5-10
10-15
15-20
>20

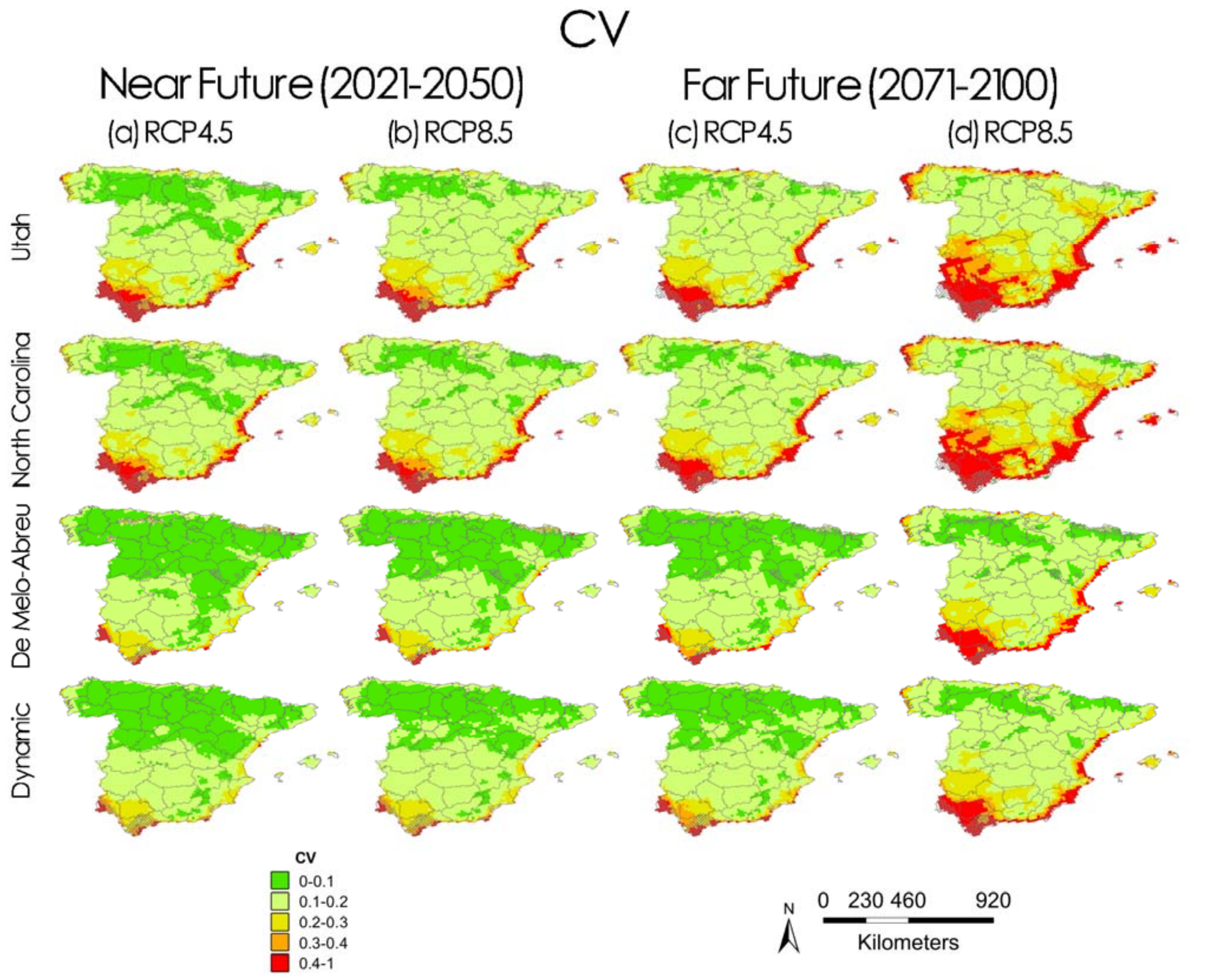
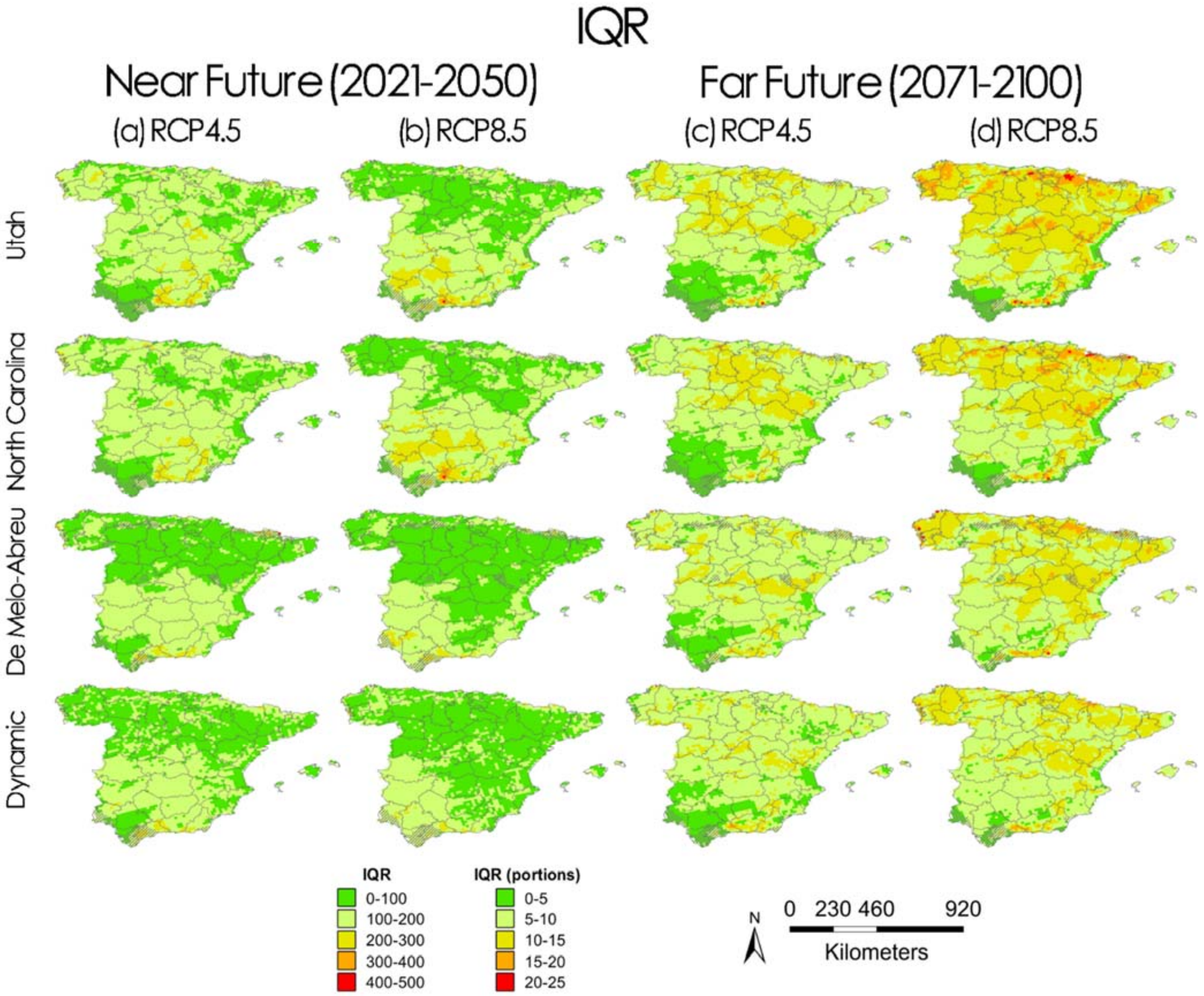


Figure 7. Maps of inter-annual variability results calculated with the 10 EUR-11 ensemble members' mean coefficient of variation (CV, expressed per unit) of the 30-year period. For each chilling model (rows), for RCP4.5 and RCP8.5 scenarios in the ~~NF (~~202~~0~~1-2050 period~~)~~ (first and second column respectively) and in the ~~FF (~~2071-2100 period~~)~~ (third and fourth column respectively). Grid cells with mean absolute percentage error (MAPE, %) values from the validation phase higher than 20 are not considered as reliable results and are highlighted in diagonal lines.

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



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

Figure 8. Maps of uncertainty results calculated with the ensemble's interquartile range (IQR) of the 30-year mean chilling sums of the 10 EUR-11 ensemble members. For each chilling model (rows), for RCP4.5 and RCP8.5 scenarios in the ~~NF (~~2020~~0~~1-2050~~)~~ period (first and second column respectively) and in the ~~FF (~~2071-2100 period~~)~~ (third and fourth column respectively). Grid cells with mean absolute percentage error (MAPE, %) values from the validation phase higher than 20 are not considered as reliable results and are highlighted in diagonal lines.

Table 1. Chilling requirements gathered from the existing literature for some of the main varieties of apple, olive and peach trees, using different chilling calculation models: North Carolina (chilling units), Dynamic (chilling portions), Utah (chilling units) and De Melo-Abreu (chilling units). Values were rounded to the nearest integer value. Mean value was calculated when values for the same variety were found in more than one source. Mean number of seasons (out of 29) for the studied periods where chilling requirements are compromised at the indicated location.

Tree crop	Chilling model	Variety	Chill requirements (units/portions) and source(s)	Mean number of compromised seasons					
				Location	1976-2005	2021-2050		2071-2100	
						RCP4.5	RCP8.5	RCP4.5	RCP8.5
Apple	North Carolina	Royal Gala	1049 [b]	Lleida (NE Spain (41º35'N, 0º41'E)	0	0.7	0.7	3.1	19.9
		Golden Delicious	1050 [a]		0	0.7	0.7	3.1	19.9
		Granny Smith	1057 [a, b]		0	0.7	0.8	3.1	20.3
		Fuji	1077 [a]		0	0.7	0.8	3.5	20.6
Olive	De Melo-Abreu	Arbequina	339 [d]	Almonte (SW Spain, 37º13'N, 6º27'W)	0	0.4	0.4	3.2	17.6
		Picual	469 [d]		0	1.6	3.3	6.6	23.6
		Hojiblanca	494 [d]		0	2	3.5	7.4	25.1
Peach	Dynamic	Sunlite	33 [e]	Buñol (E Spain, (39º22'N, 0º48'W)	0	0	0	0.4	7.9
		Flavortop	38 [c, e]		0	0	0	0.5	11.4
		Fantasia	42 [c, e]		0	0.3	0	1.9	15.1
		Redhaven	73 [c, f]		2.3	14.2	18	24	28.6
Peach	Utah	Sunlite	536 [e]	Murcia (SE Spain, (37º56'N, 1º10'W)	0.8	9.8	11.3	17.6	27.7
		Flavortop	657 [c, e]		2.7	14.6	16.9	23.7	28.6
		Fantasia	683 [c, e]		3.1	15.2	17.8	24.2	28.6
		Elberta	790 [g]		6.9	20.8	21.6	25.8	28.6
		Redhaven	813 [c, g]		7.7	21.9	22.5	26.2	28.6

[a] Hauagge and Cummins (1991) [b] Cook et al. (2017) [c] Erez (2000) [d] De Melo-Abreu et al. (2004) [e] Linsley-Noakes and Allan (1994) [f] Roman et al. (1998) [g] Richardson et al. (1974)

The following supplements accompany the article

Chilling accumulation in ~~temperate~~ fruit trees in Spain under climate change

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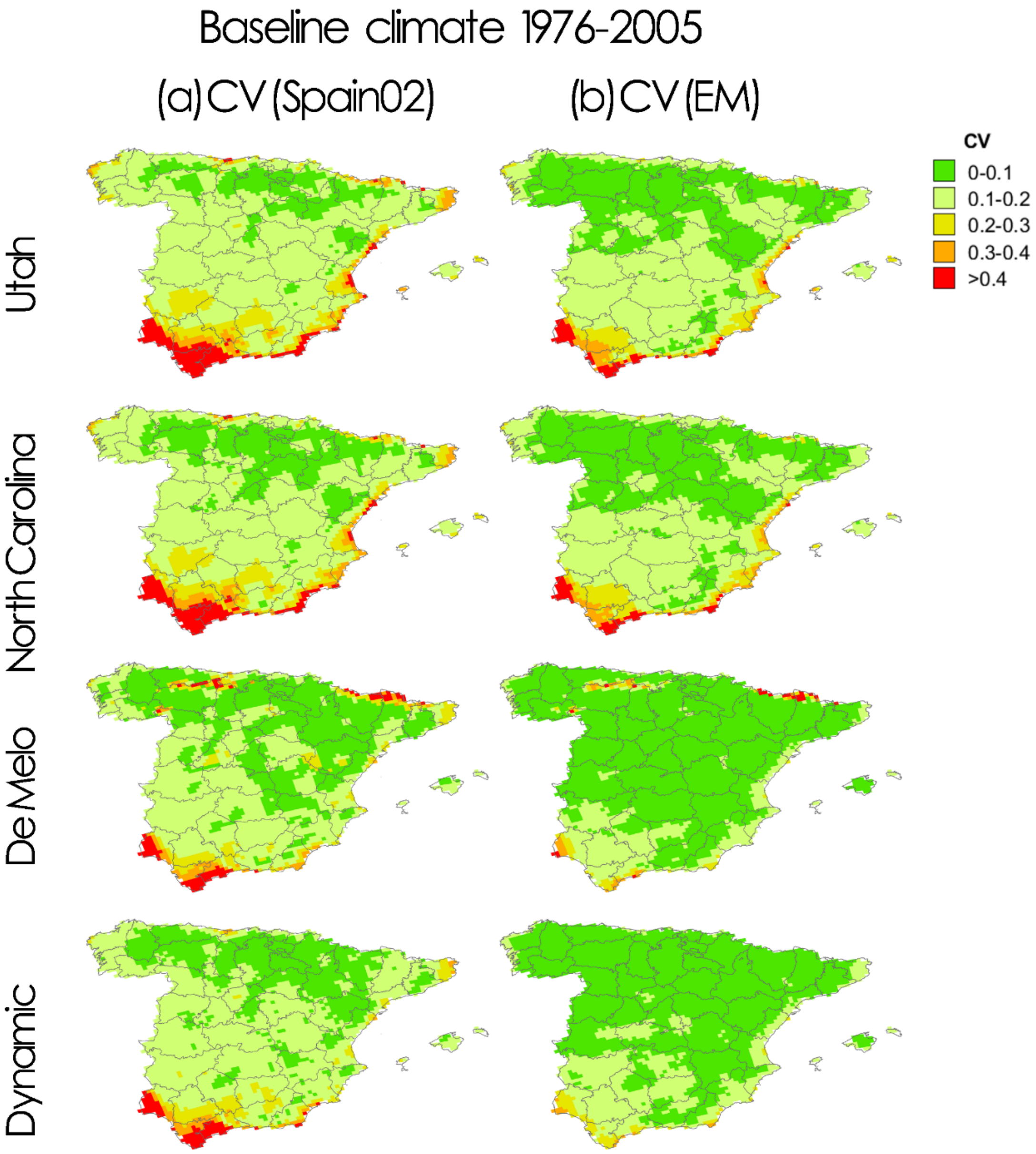
Table 1S. CMIP5/CORDEX EUR-11 bias-adjusted simulation matrix. CORDEX EUR-11 RCMs (Giorgi and Gutowski, 2015) and CMIP5 GCMs (Taylor et al., 2012) used (all r1i1p1/v1 ensemble/downscaling). Grey cells indicate the GCM-RCM combinations selected. The Institute ID of each model is provided in bold italics. Daily maximum and minimum temperatures were retrieved from the Earth System Grid Federation (ESGF) servers.

Bias-corrected CMIP5/CORDEX EUR-11 GCM/RCMs	**CNRM-CM5** ***CNRM-France***	**EC-EARTH** ***ECMWF-European***	**IPSL-CM5A-MR** ***IPSL-France***	**HadGEM2-ES** ***Met Office-UK***	**MPI-ESM-LR** ***MPI-Germany***
CCLM4-8-17 ***CCLM community-International***	grey			grey	grey
REMO2009 ***MPI-Germany***					grey
RCA4 ***SMHI-Sweden***	grey		grey	grey	
RACMO22E ***KNMI-Netherlands***		grey			
ALADIN53 ***CHMI-Czech Republic***	grey				
WRF331F ***IPSL-France***			grey		



Baseline climate 1976-2005
(a) CV (Spain02)
(b) CV (EM)
CV
0-0.1
0.1-0.2
0.2-0.3
0.3-0.4
>0.4
Utah
North Carolina
De Melo
Dynamic

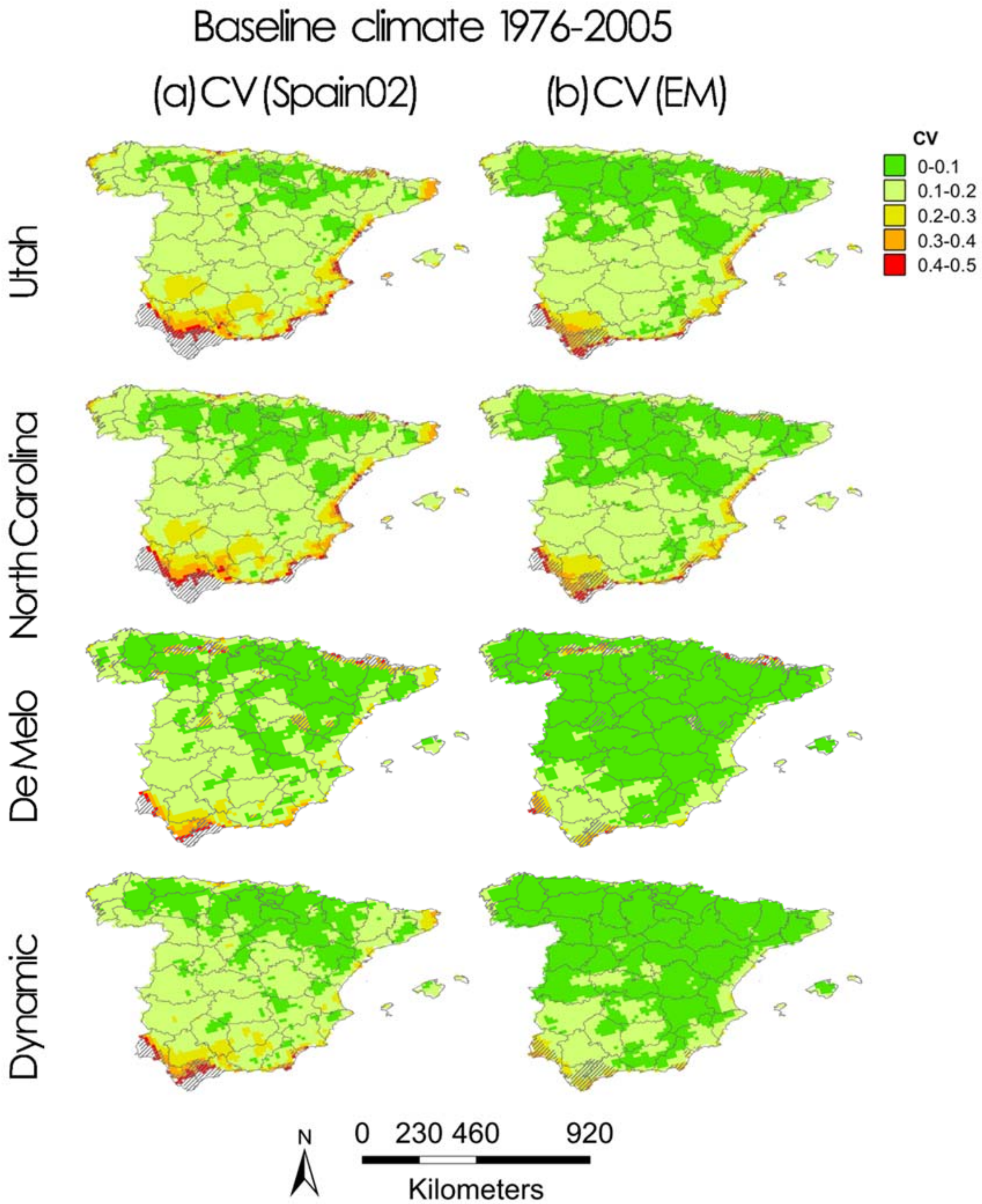


Figure 1S. Comparison of chilling accumulation inter-annual variability for the baseline period (1975–2005). For each chilling method (rows), the coefficient of variation (CV, expressed per unit) of the chilling accumulation calculated with the observational data set Spain02 (first column) and with the 10 EUR-11 ensemble members' mean CV of the 30-year period (second column). Grid

cells with mean absolute percentage error (MAPE, %) values from the validation phase higher than 20 are not considered as reliable results and are highlighted in diagonal lines.

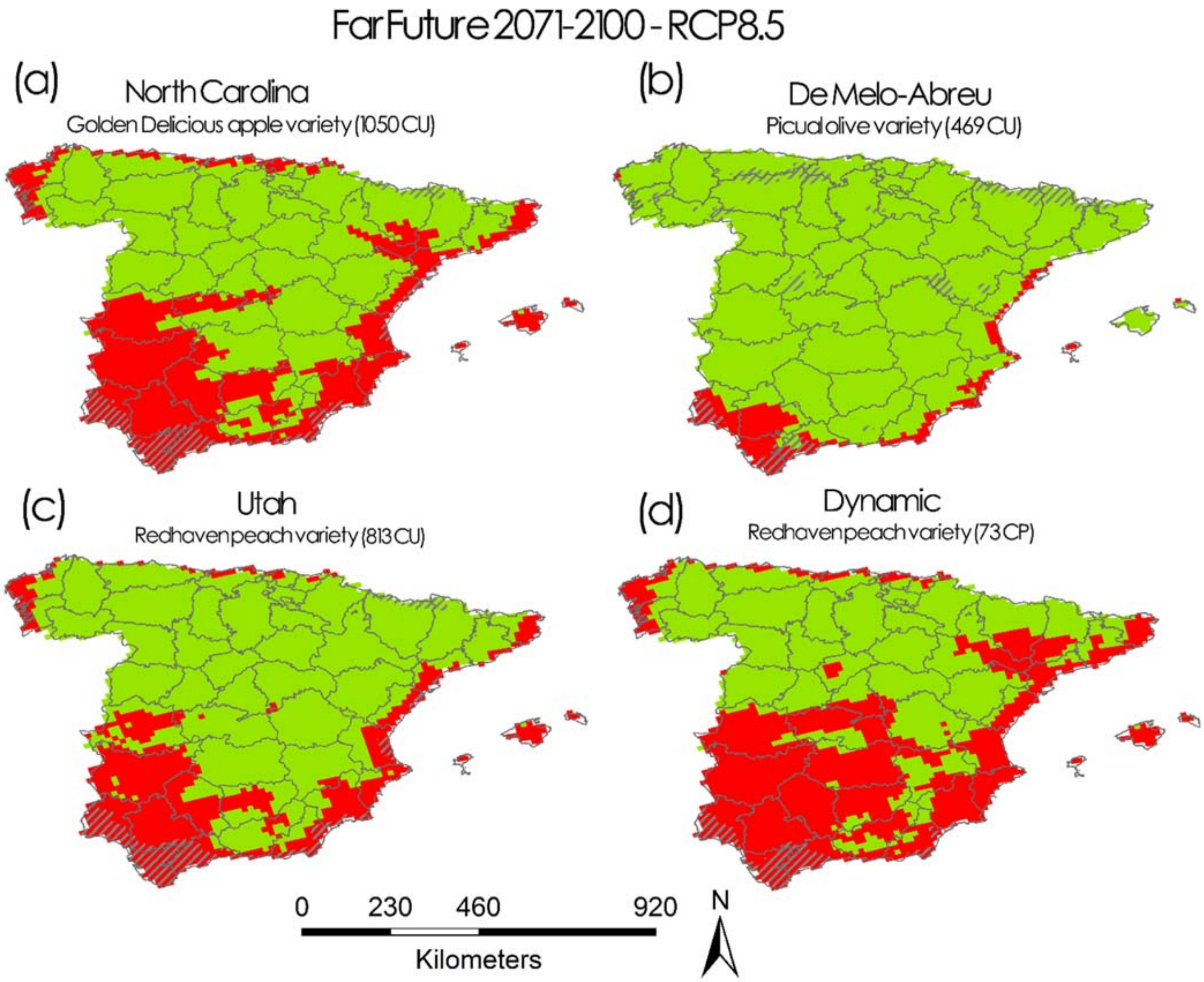


Figure 2S. Map of areas with chilling accumulation, in the 2071-2100 period and for RCP8.5 scenario, projected to be higher (green grid cells) or lower (red grid cells) than 1050 chilling units (chilling requirements estimated for Golden Delicious apple variety with the North Carolina model, plot a), than 469 chilling units (chilling requirements estimated for Picual olive variety with the De Melo-Abreu model, plot b), than 813 chilling units (chilling requirements estimated for Redhaven peach variety with the Utah model, plot c) or than 73 chilling portions (chilling requirements estimated for Redhaven peach variety with the Dynamic model, plot d). Grid cells with mean absolute percentage error (MAPE, %) values from the validation phase higher than 20 are not considered as reliable results and are highlighted in diagonal lines.

Code 1S. Function *chill_portions* MATLAB code, for calculating the chilling portions accumulated by the Dynamic model (Fishman et al., 1987a; Fishman et al., 1987b), with the standard parameters and the equations following Luedeling and Brown (2011)

```
function [delt] = chill_portions(t,time)

% Julian day to cut between seasons
DIA_CORTE = 186;

% See the "cuts" now in hourly approach
pos = [1];
for i=min(time(:,1)):max(time(:,1))
   x = time(:,1) == i;
   aux = find(x);
   aux = aux((DIA_CORTE-1)*24+1:end);
   if ~isempty(aux)
       pos = [pos aux(1)];
   end
end

% Constants
e0 = 4153.5;
e1 = 12888.8;
a0 = 139500;
a1 = 2567000000000000000;
slp = 1.6;
tetmlt = 277;
aa = a0/a1;
ee = e1-e0;

tk = t+273.15;
ftmprt = slp*tetmlt*(tk-tetmlt)./tk;
sr = exp(ftmprt);

xi = sr./(1+sr);
xs = aa*exp(ee./tk);

ak1 = a1*exp(-(e1./tk));
inters = zeros(size(ak1));
intere = zeros(size(ak1));
delt = zeros(size(ak1));
portions = zeros(size(ak1));


for i=1:length(inters)
    if ismember(i,pos)
        inters(i)=0;
        delt(i)=0;
```

```
        portions(i) = 0;
    else
        if intere(i-1)<1
            inters(i) = intere(i-1);
        else
            inters(i) = intere(i-1)*(1-xi(i));
        end

    end
    intere(i)= xs(i)-(xs(i)-inters(i))*exp(-ak1(i));

    if ~ismember(i,pos)
        if intere(i)<1
            delt(i) = 0;
        else
            delt(i) = xi(i)*intere(i);
        end
        portions(i) = delt(i) + portions(i-1);
    end

end


end
```

Code 2S. Function *utah* MATLAB code, for calculating the chilling units according to the Utah model (Richardson et al., 1974)

```
function [ct] = utah(temperature)

ct = zeros(length(temperature),1);


%if 1.4<Temperature<=2.4
x = temperature>1.4 & temperature<=2.4;
ct(x) = ct(x)+0.5;

%if 2.4<Temperature<=9.1
x = temperature>2.4 & temperature<=9.1;
ct(x) = ct(x)+1;

%if 9.1<Temperature<=12.4
x = temperature>9.1 & temperature<=12.4;
ct(x) = ct(x)+0.5;

%if 12.4<Temperature<=15.9 multiplies by 0

%if 15.9<Temperature<=18
x = temperature>15.9 & temperature<=18;
```

```
ct(x) = ct(x)-0.5;

%if Temperature>18
x = temperature>18;
ct(x) = ct(x)-1;
```

Code 3S. Function *north_caroline* MATLAB code, for calculating the chilling units according to the North Caroline model (Shaltout and Unrath, 1983)

```
function [ct] = noth_caroline(temperature)

% North Caroline model (from Shaltout and Unrath 1983, pg 959)

ct = zeros(length(temperature),1);
%if -1.1=<Temperature, zero contribution

%if -1.1<Temperature<=1.6
x = temperature>-1.1 & temperature<=1.6;
ct(x) = ct(x)+0.5;

%if 1.6<Temperature<=7.2
x = temperature>1.6 & temperature<=7.2;
ct(x) = ct(x)+1;

%if 7.2<Temperature<=13
x = temperature>7.2 & temperature<=13;
ct(x) = ct(x)+0.5;

%if 13<Temperature<=16.5, zero contribution

%if 16.5<Temperature<=19
x = temperature>16.5 & temperature<=19;
ct(x) = ct(x)-0.5;

%if 19<Temperature<=20.7
x = temperature>19 & temperature<=20.7;
ct(x) = ct(x)-1;

%if 20.7<Temperature<=22.1
x = temperature>20.7 & temperature<=22.1;
ct(x) = ct(x)-1.5;

%if 22.1>Temperature
x = temperature>22.1;
ct(x) = ct(x)-2;
```

Code 4S. Function *melo_abreu* MATLAB code, for calculating the chilling units according to the de Melo-Abreu model (De Melo-Abreu et al., 2004)

```
function [ct] = melo_abreu(temperature)

% Model 1 for Olives (Melo-Abreu, fig. 1 and section 3.1.)

ct = zeros(length(temperature),1);

%Define constants
%To: optimum temperature for chilling (ºC)
To=7.3;
%Tx: breakpoint temperature (ºC)
Tx = 20.7;
%a: chilling units nullify when temperature is above Tx
a = -0.56;

%if 0<Temperature<=To
x = temperature>0 & temperature<=To;
ct(x) = ct(x)+temperature(x)/To;

%if To<Temperature<=Tx
x = temperature>To & temperature<=Tx;
ct(x) = ct(x) + 1 - (temperature(x)-To)*(1-a)/(Tx-To);

%if Temperature>Tx
x = temperature>Tx;
ct(x) = ct(x) + a;
```

Code 5S. Function *hour_temp* MATLAB code for calculating hourly temperature from maximum and minimum daily temperatures following the de Wit et al. (1978) approach.

```
function [thour,time] = hour_temp(Tmax,Tmin,dates,lat)

% Calculates the temperature for each hour of the day taking into account
% the maximum and minimum temperatures

% Input parameters
    % Tmax: vector with maximum temperatures for each day
    % Tmin: vector with minimum temperatures for each day
    % dates: vector with the date for each row
    % lat: latitude of the cell

% Output parameters
    % thour: temperature for each hour
    % time: vector with the date and time for each row
```

```
%constants
hour_col = 4;
day_col = 3;
month_col = 2;
year_col = 1;

%creates the array of days, with values from 1 to 366
d = zeros(length(dates),1);
for i =1 : length(dates)
    %it restarts the count with each new year
    if(dates(i,month_col)==1 && dates(i,day_col)==1)
        d(i) = 1;
    else
        d(i) = d(i-1)+1;
    end
end

%creates Tmax_aux and Tmin_aux, as auxiliar variables for calculations
Tmax_aux = zeros(length(Tmax)+1,1);
Tmax_aux(1) = Tmax(1);
Tmax_aux(2:end) = Tmax;
Tmin_aux = zeros(length(Tmin)+1,1);
Tmin_aux(end) = Tmin(end);
Tmin_aux(1:(end-1)) = Tmin;

% gets the sunrise hour (tr) for each day (d)
[tr] = sunrise_time(d,lat);

% creates the array for saving hour temperatures
thour = zeros(23,length(d));
hour = zeros(23,length(d));
years = zeros(23,length(d));
months = zeros(23,length(d));
days = zeros(23,length(d));

%gets the temperature of all days for each hour (0-23)
for t=0:23

    %if t<tr
    x = find (t<tr);
    if ~isempty(x)
        thour(t+1,x) = (Tmax_aux(x) + Tmin(x))/2 + ...
            (Tmax_aux(x)-Tmin(x))/2.*cos(pi*(t+10)./(tr(x)+10));
    end
    %if t>=tr && t<14
    x = find(t>=tr & t<14);
    if ~isempty(x)
    thour(t+1,x) = (Tmax(x) + Tmin(x))/2 - ...
        ((Tmax(x)-Tmin(x))/2).*cos(pi*(t-tr(x))./(14-tr(x)));
    end
```

```
    %if t>=14 && t<24
    if t>=14
        thour(t+1,:) = (Tmax + Tmin_aux(2:end))/2 + (Tmax-
Tmin_aux(2:end))/2.*cos(pi*(t-14)./(tr+10));
    end
    hour(t+1,:) = t*ones(length(d),1);
    years(t+1,:) = dates(:,year_col);
    months(t+1,:) = dates(:,month_col);
    days(t+1,:) = dates(:,day_col);
end

%transforms the thour array into a vector
thour = thour(:);
time = zeros(length(thour),6);
time(:,year_col) = years(:);
time(:,month_col) = months(:);
time(:,day_col) = days(:);
time(:, hour_col) = hour(:);
```

Code 6S. Function *sunrise_time* MATLAB code for calculate the sunrise time for each day from latitude

```
function [h] = sunrise_time(d,Lat)

% calculates the sunrise time for each day (d) taking
% into account the latitude

% Input parameters
    % d: matrix with the days of year
% Output parameters
    % h: sunrise time for each day in the input matrix

%D: day of year in degrees
D = 360*d/365;
%dec: declination in degrees
dec = -23.5*cosd(D+9.865);
%w: angle at sunrise in degrees
w=acosd(-tand(Lat)*tand(dec));
%h: solar time in hour
h = 12-w/15;
```

Code 7S. Function *calculate_period* MATLAB code for calculate initial and final chilling accumulation periods used for all chilling models but the Dynamic one.

```
% This function takes the chilling accumulation and checks the “area”
% that would remain taking the maximum values (relatives). It is like if we
```

```
% trace a horizontal line, see where it intersects and we fill the
% resulting area. The biggest area is the chosen one. Then, the minimum
% is identified as the one laying in that region.

function [ pos_minimo, pos_maximo ] = calculate_period(d)

acc = d;
dlen = length(d);

% Remove the first part where only go down
baja = 1;
c = 0;
while baja>0
   c = c + 1;

   % If arrives to the end means it never went down
   if c == dlen
      c = 1;
      baja = 0;
      break;
   end

   % Does not go down
   if d(c+1)>d(c)
       baja = 0;
   end
end
for i=1:(c-1)
  d(i) = NaN;
end


x = isnan(d);
numnan = length(d(x));
d = d(~x);


% ListaEnlazada is just a linked list data structure
CORTEs = ListaEnlazada();
MAXs = ListaEnlazada();
AREAs = ListaEnlazada();

anterior = d(1);
for i=2:(dlen-numnan)-1

      if is_maximum(d,i)>0

        POs = find_left_cut(acc,d(i),i+numnan);

        corte = 1;
        if length(POs)>0
```

```
    % Remove the same point
    for j=1:length(POs)
       if POs(j)==(i+numnan)
           POs(j) = NaN;
       end
    end
    x = isnan(POs);
    POs = POs(~x);

    if length(POs)==0
        corte = 1;
    else
        posaux = POs;
        for aa=1:length(POs)
           pini = POs(aa);
           pfin = i+numnan;

           aux = acc(pini:pfin);
           aux = max(aux);

           % It does not count because it cut the graph
           if acc(pini)<aux
              x = posaux == POs(aa);
              posaux = posaux(~x);
           end
        end
        POs = posaux;

        dist = POs-(i+numnan);

        x = dist == min(dist);
        corte = POs(x);
        if length(corte)>1
            corte = corte(1);
        end
    end
end

p1 = corte;
p2 = i+numnan;

area = 0;
for j=p1:p2
   area = area + abs(max(d(i),acc(j))-min(d(i),acc(j)));
end

% Add to the end of the linked list
MAXs.insertaFinal(i+numnan);
CORTEs.insertaFinal(p1);
CORTEs.insertaFinal(p2);
AREAs.insertaFinal(area);
```

```
        close all
    end

    anterior = d(i);
end


% Get number matrix from linked list
MAXs = MAXs.getMatrizNumerica();
CORTEs = CORTEs.getMatrizNumerica();
AREAs = AREAs.getMatrizNumerica();

if length(MAXs)>0

    x = AREAs == max(AREAs);
    p = find(x);
    if length(p)>0
        p=p(1);
    end

    % Search for the minimum
    posmin = CORTEs((p-1)*2+1);
    minim = acc(CORTEs((p-1)*2+1));
    for j=(CORTEs((p-1)*2+1)):(CORTEs((p-1)*2+2))
        if acc(j)<minim
            minim = acc(j);
            posmin = j;
        end
    end

    pos_minimo = posmin;
    pos_maximo = MAXs(p);

else
    pos_minimo = NaN;
    pos_maximo = NaN;
end

end
```

Code 8S. Function *is_maximum* MATLAB code, auxiliary for *calculate_period* function

```
% Given an array with values, it tell us if the value in the position i is a
% relative maximum. It will be considered also maximum if it is the last one of
% a series of the same values

function r = is_maximum( d, i )
```

```
if i<=1
    r = 0;
    return;
end

ok = 0;
if i==length(d)
    ok = 1;
else
    if d(i)>d(i+1)
        ok = 1;
    end
end

% If its the last one or is bigger than the next one it can be maximum
if ok>0
   if d(i)>d(i-1)
       r = 1;
       return;
   end
   aux = i;
   while d(aux) == d(i)
       aux = aux - 1;
   end
   if d(i)>d(aux)
       r = 1;
       return;
   else
       r = 0;
       return;
   end

else
    r = 0;
    return;
end


end
```

Code 9S. Function *find_left_cut* MATLAB code, auxiliary for *calculate_period* function

```
% It finds the positions x where the plot intersects with the horizontal line y = v
% (only cuts at the left of x) y = f(x)

function [ POs ] = find_left_cut(d,v,x)

POs = ListaEnlazada();
for i=1:length(d)-1
```

```
    if  (d(i) > v && d(i+1) < v) || ...
              (d(i) < v && d(i+1) > v)
          POs.insertaFinal(i);
          POs.insertaFinal(i+1);
    else
          if d(i) == v
            POs.insertaFinal(i);
          else if d(i+1) == v
            POs.insertaFinal(i+1);
              end
          end
    end
end

% Delete repeated
POs = POs.eliminaRepetidos();

aux = x-1;
while aux>0 && d(aux)==d(x)
     posaux = POs.posiciones(aux);
     posaux = posaux.getMatrizNumerica();
     posaux = posaux(1);

     % Delete element in position posaux
     POs.eliminaN(posaux);
     aux = aux - 1;
end

% Convert to numerical matrix and we left only the left ones
POs = POs.getMatrizNumerica();
xxx = POs<x;
POs = POs(xxx);
```

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