The risk for insufficient chill accumulation: a climate change perspective for apple and cherry production in the United States

Hossein Noorazar [1], Lee Kalcsits [2], Vincent P. Jones [3], Matthew S. Jones [3], Kirti Rajagopalan [1,*]

[1] Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164, USA; kirtir@wsu.edu, h.noorazar@wsu.edu
[2] Department of Horticulture, Tree Fruit Research and Extension Center, Washington State University, 1100 North Western Avenue, Wenatchee, WA 98801, USA; lee.kalcsits@wsu.edu
[3] Department of Entomology, Tree Fruit Research and Extension Center, Washington State University, 1100 North Western Avenue, Wenatchee, WA 98801, USA; vpjones@wsu.edu, matthew.s.jones@wsu.edu
* Correspondence: kirtir@wsu.edu

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Abstract: Winter chill accumulation is critical for the productivity and profitability of perennial tree fruit production systems. Several studies have quantified the impacts of global warming on risks of insufficient chill accumulation in the warmer tree fruit and nut production regions of the United States (US), such as the Southeast and California, where these risks are currently prevalent. In this work, we focus on the Pacific Northwest US - the largest production area in the US for apples, pears and cherries - and quantify the potential risk of insufficient chill accumulation. Our results highlight large spatial variations in response within the PNW, with northern areas projected to have reduced risks and southern areas projected to have increased risks. In the southern areas, rather than chill accumulation in and of itself, it is the combination of reduced and delayed chill accumulation with likely advancement in spring phenology that lead to production risks. In spite of future reductions to chill accumulation, risks of insufficient chill accumulation seem limited for apple even with advancement of spring phenology. Under the extreme "no climate policy" RCP 8.5 climate projections, the production risks are significant for early blooming crops (e.g. cherries) and varieties with relatively high chill portions requirements (e.g. Sam cherries), necessitating planning for management strategies such as frost protection and chemical management of budbreak to address potential risks which have not historically been a concern in the region. Under less extreme warming outcomes, the PNW tree fruit production systems are likely to remain resilient. Given that the convergence of the fulfillment of chilling requirements and environmental conditions promoting budbreak is where potential risk to perennial tree fruit production exists, future work should focus on understanding, modelling and projecting responses within this convergence space. Additionally, given significant spatial differences across a relatively small geographic range, it is also critical to understand and model these dynamics at a local landscape resolution for regions such as the PNW that faced limited risk historically, but could be exposed to new risks under a warming climate.

Keywords: climate change; chill requirement; global warming, Dynamic Model; tree fruit; apples; cherries

1. Introduction

Winter chill accumulation is as critical as the active growing season for the productivity and profitability of temperate, perennial tree fruit production systems. Specifically, chilling affects emergence from endodormancy, transition to ecodormancy, and the resumption of growth in the spring [1]. While chill accumulation is an important part of crop suitability to a region, commercial varieties have a broad range of chilling requirements that make them suitable for many different regions [2-4]. Currently, insufficient chill accumulation is most important in subtropical tree-fruit growing regions such as Israel, South Africa, Spain, and California where varietal selection can be often based largely on chill requirements [5-10]. While subtropical areas have been the focus for problems related to insufficient chilling requirements, decreased winter chill accumulations related to a warming climate mean that potentially many more regions will face this issue in the near future [2, 3, 6-8, 11-15].

Dormancy for perennial tree fruit species is a time period during the annual cycle where buds remain inactive. In an attempt to establish more accurate terminology to describe the two primary dormant phases during winter, Lang et al. [16] proposed two stages: endo-, and ecodormancy. The Endo- and ecodormancy stages are defined by physiological and environmental inhibitions of regrowth, respectively. The two stages are not discrete, but rather are dynamic in response to environmental stimuli [17]. Dormancy induction in autumn is regulated by either photoperiod, temperature, or a combination of both [18-20]. Once dormancy has been induced, a tree will remain in the endodormant stage until it fulfills its chilling requirement at which point it enters the ecodormant stage when environmental conditions prevent bud break. As climate change advances spring phenology, there is a risk of convergence between the fulfillment of chilling requirements (break of endodormancy) and environmental conditions promoting budbreak (break of ecodormancy).

Within the United States of America (US), the focus of most existing studies on climate change implications for winter chill accumulation are primarily in the warmer tree-fruit production regions such as California and the Southeast where risk of insufficient accumulation currently exists, and large global warming related reductions in chill accumulation can be expected [6-8, 15]. Although temperate tree fruit crops are grown throughout the continental US, the Pacific Northwest region (PNW) is the largest apple, pear, and cherry production region. The PNW accounted for 67% of the US apple production in 2018 with a value of $2.1 billion, and 87% of the US fresh cherry production valued at $470 million (USDA NASS 2018 statistics). Cool wet winters and warm, dry summers of the PNW are ideal for specialty crop production. Irrigation water availability and proximity to processors and markets provide an additional competitive advantage [21]. Therefore, while insufficient chill accumulation is not currently a significant production risk in the PNW, given its position as the largest production area in the US for multiple tree fruit, it is critical to understand future production risks in the PNW under future warming scenarios. Only two studies have addressed climate change in the Pacific Northwest United States (PNW) and those were restricted to two locations [21] or in the larger context of tree fruit production worldwide [3]. These studies did not account for the risk of insufficient chill accumulation risk in the context of likely advancement of spring phenology under warming.

A variety of temperature-based empirical models have been developed to estimate chill accumulation and the transition from endo- to ecodormancy. These include the Chilling Hours Model [22], the Utah Model [23] and the Dynamic Model [24, 25] The Dynamic Model takes into account the positive effect of cool temperatures, the negative effect of high temperatures, the positive effect of moderate temperatures, the effect of moderate temperatures alternating with chilling temperatures, and the time inhomogeneity of chilling negation. The Dynamic Model has been reported to better capture the dynamic nature of the chilling process as compared with other models [2, 12, 26, 27], work for a variety of crops and cultivars [7, 28, 29], and for a variety of climatic regimes [12, 30]. Moreover, the Dynamic Model has been shown to work well in warmer climatic regimes [7, 12, 24]-critical from the point of climate change and a shift to warmer temperature regimes.

This work aims to characterize changing winter-chill accumulation risk in the tree-fruit production regions of the PNW by driving the Dynamic Chilling Portions Model [24, 25] with historical climate and future climate projections. In particular, we consider risk in the context of potential advancement of the timing of bloom, and discuss uncertainties, implications and potential adaptation strategies for the PNW.

2. Methods

2.1 Historical Climate and Future Climate Projections

Historical simulations (1979--2016) were based on the gridded meteorological observations product - GridMET [31]. Future climate projections (2026- 2099) were based on the Coupled Model Intercomparison Project 5 (CMIP5; [32].) which were down-scaled to the 4km resolution based on the Modified Multivariate Adaptive Constructed Analog (MACA) method [33], and subsequently re-gridded to the 1/16 degree (~6km) resolution by linear interpolation for computational efficiency. Nineteen climate projections under two representative concentration pathways (RCPs) were used for a total of 38 projections that captured the range in uncertainty in projections. The 19 models used in this study were bcc-csm1-1, bcc-csm1-1-m, BNU-ESM, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC365, HadGEM2-ES365, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC-ESM-CHEM, MIROC5, MRI-CGCM3, and NorESM1-M. The RCP 4.5 scenario assumed a stabilization or reduction of greenhouse gas emissions starting around mid-century while the RCP 8.5 is an extreme “no climate policy” scenario that assumed increasing emissions until the end of the century and is associated with relatively high temperature increases post mid-century compared with RCP 4.5 [34]. The observed historical data and future climate projections of temperature were assembled as a daily time step and then were then disaggregated into an hourly time step using a sine-logarithmic algorithm [35].

2.2 Dynamic Model

The Dynamic Model [24, 25] computes chill accumulation in units referred to as “chill portions” (CP). Chill accumulation is considered a two-step process. The first step is a reversible intermediary process where chill accumulates under low temperatures (a bell curve between -2°C and 13°C with optimal accumulation around 6°C), with no accumulation under -2°C, and potential for a negative accumulation by exposure to higher temperatures. The negation is a complex process that depends on the level, duration and cycle of exposure to high temperatures and only occurs during the intermediary process. Accumulation during this time can also be enhanced by exposure to moderately high temperatures (13°C - 16°C) alternating with lower temperatures such as in a diurnal cycle. Once the intermediate accumulation threshold is surpassed, chill accumulation increases by a unit called a chill portion unit. The accumulated chill portion units are conserved and cannot be reversed, and the intermediate level is set back to zero. Further details can be found in [24, 25].

The Dynamic Model implementation we used was provided as part of the chillR package for the R software [36]. The Dynamic Model runs on an hourly temperature time series. The daily temperature inputs from Section 2.1 were converted to hourly temperatures by a function in the chillR package that was based on [35]. We used a simulation time frame of September 1st to March 31st.

2.3 Bloom Phenology Model

While the focus of this work is on chill accumulation, we also use a bloom phenology model to consider chill accumulation in the context of bloom phenology advancements. We used the bloom phenology model used in the Washington State University Tree Fruit Decision Aid System (DAS) [37]. This model was developed based on experimental observations of bloom at nine field sites between 2010 and 2014 and corresponding temperature observations. The bloom curve was estimated at multiple locations and years by choosing a 1m long branch with 50-100 flower buds present on 10 different trees per block per cultivar and evaluated the number of flowers open at each visit with 2-3 visits per week. Temperatures used to estimate heat units came from Daymet [38] for each location and year. Heat unit accumulations started from 1 January of each year, and the heat units were calculated using the equations of [39], which fits a sine wave to the maximum and minimum temperatures and calculates the area under the curve for heat unit accumulation. A 5.5°C lower temperature threshold and a 25.3°C upper temperature threshold with a vertical cutoff was used. Here, we used the phenology model parameters for the Cripps Pink cultivar as representative of apples. For this cultivar, the timing of 50% bloom completion is projected based on a cumulative normal distribution with a mean and standard deviation of 436.61 and 52.58 heat units respectively. A bloom phenology model for cherry trees was not available. Because cherry trees typically bloom about 2 weeks earlier than apple trees in this region, we shifted the Cripps Pink bloom time by two weeks to represent cherry bloom time.

2.4 Chill Portion Requirements

Chill portion requirements are species- and cultivar-specific [2, 3]. In order for the analysis to be applicable to a range of different tree-fruits as well as cultivars, we consider chill portion requirement thresholds from 20 to 75 at intervals of 5 chill portions. This is based on the range of values compiled through literature reviews by [2] and [40]. Specific to PNW, some of the known minimum chill portions requirements [41,42] are listed in Table 1 and they fall within the 20-75 chill portions range considered in this analysis.

Table 1. Chill Portions accumulation requirements for some commonly grown varieties in the PNW.

	Cultivar	Minimum CP requirement
Sweet Cherry	Brooks	37
	Lapins	35
	Rainier	45
	Sam	70
Apple	Golden Delicious	50
	Gala	50-55

3. Results and Discussion

The results present regional spatial maps of average results and focus on four representative locations spread across the PNW (Figure 1) to highlight temporal aspects and the spread of results from the the 19 climate models.

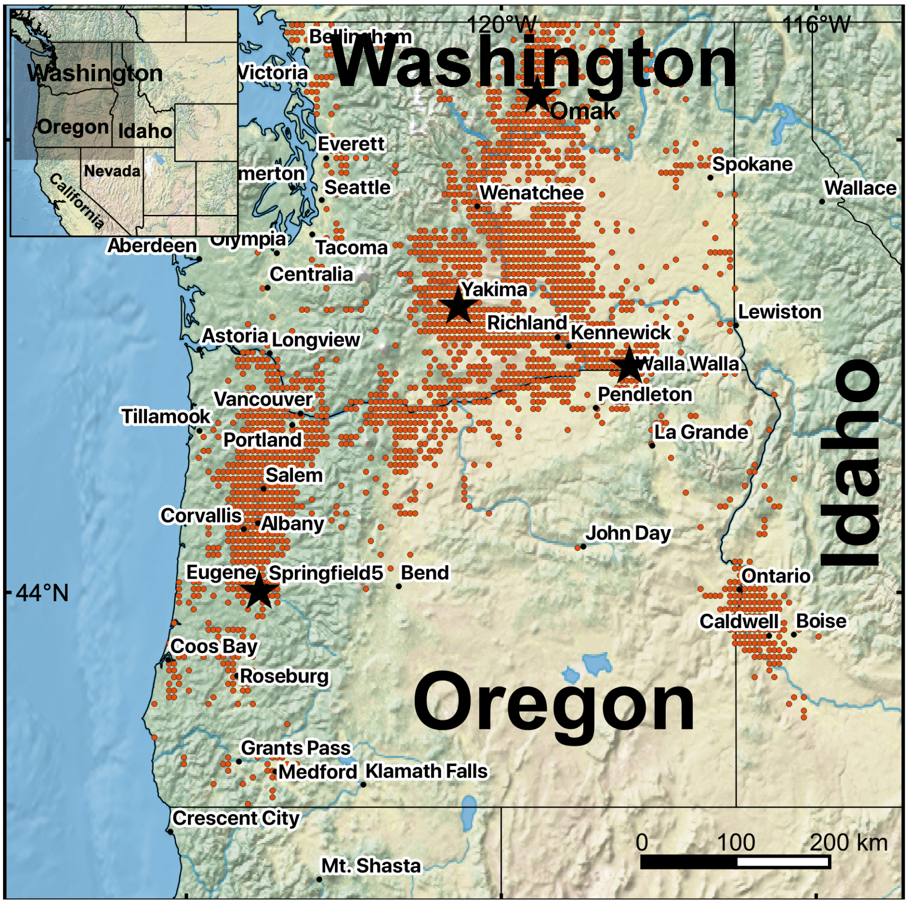

Figure 1. Map of the study domain. Red dots correspond to apple, cherry, pear growing areas that were simulated. Stars correspond to four locations (Omak, Yakima, Walla Walla, Eugene) across the study domain that we selected to highlight specific time series details.

3.1 Chill Portions Accumulation

3.1.1 Chill Portions Accumulation

Historically, the southern tree fruit growing areas of the Willamette Valley in Oregon State accumulated the most, and the northern parts of Washington State accumulated the least chill portions (CP) units (Figure 2). The apparent contradiction in the warmer areas (Willamette Valley) having the most CP units and the colder areas having the least is a function of the way CPs are defined where temperatures lower than -2°C result in no CP accumulations. With climate change, modeled CP accumulations increased in the relatively colder northern parts of Washington state but decreased in other regions, with larger differences for the RCP 8.5 scenario. By the end of the century, in a switch from historical conditions, the northern parts of Washington state were projected to accumulate more CP than the other regions in this study (Figure 2).

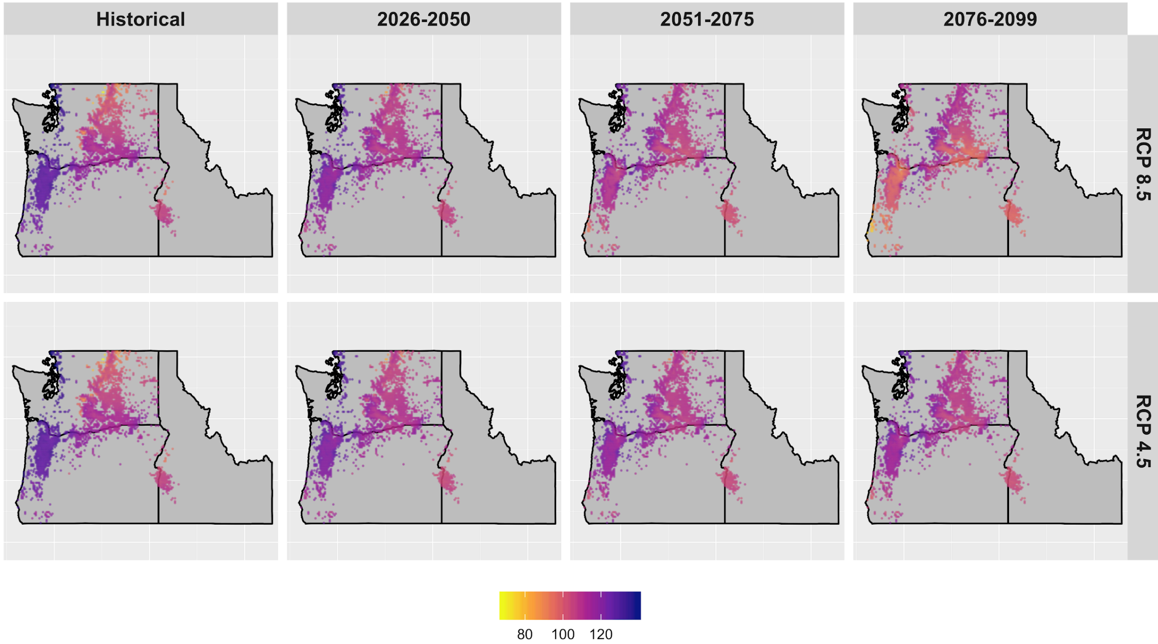

Figure 2. Average CP accumulation between September 1st and March 31st for different time frames under multiple climate models. First the accumulated CP by March 31st is computed for each location, year and model. Then for each location, the median of these values is taken over the years within each time window. Finally, the mean of these median values is taken over the 19 climate models. Results are shown for the RCP 8.5 and 4.5 scenarios.

3.1.2 Magnitude of Change

Our simulations showed both increases and decreases across relatively short geographical ranges (Figure 3). For the RCP 8.5 scenario, CP accumulation was generally projected to change by +/- 25% for most areas with some coastal areas showing decreases larger than 40% (Figure 3). The changes are smaller in magnitude for the RCP 4.5 scenario, especially after 2050. However, it should be noted that for all regions, by the end of the century, the average over all 19 climate models accumulated more than 80 CP by March 31st even under the more extreme RCP 8.5 scenario. These levels of CP accumulation are above the range of minimum chilling requirements identified for different tree fruit species and cultivars in the PNW. This suggests that there is limited risk of insufficient chill accumulation. This is in contrast to [21] who quantified the risk for insufficient chill accumulation for two locations in the PNW; Corvallis (close to Eugene) and Wenatchee (close to Yakima). The differences reported are likely because [21] is based on the chill accumulation model of Baldocchi and Wong [6] while we used the Dynamic Model. Models that do not account for dynamic conditions have shown exaggerated responses to warming compared to the Dynamic Model whose response may be better able to capture changes to chilling conditions [8, 12] However, the general direction of change in Corvallis/Eugene is consistent across both studies. While [21] does not consider locations in northern Washington state, increases in chill accumulation in these colder regions are consistent with those reported by [26] in their global study which highlights changes in the Okanagan Valley in Canada which is just north of the Omak region in northern Washington state.

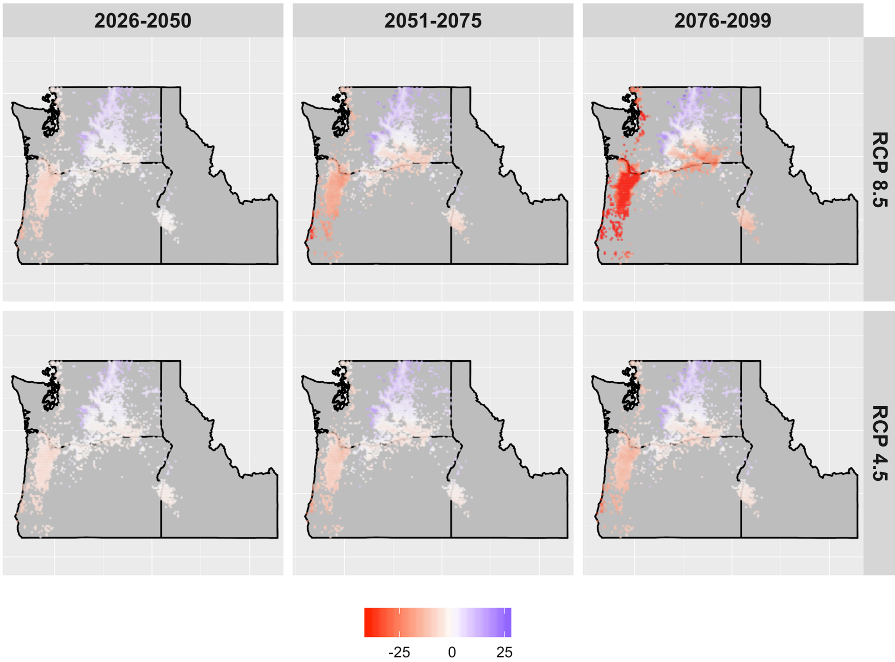

Figure 3. Percentage differences of CP accumulation between projections and historical observations; In this plot, for a given location and model, we computed the median of CP accumulation across years in three future time periods. Then, the differences between these projections and historical observations were computed. Then, we computed the median of percentage differences over the 19 climatic models. Chill seasons start on September 1st and end on March 31st. Results are shown for the RCP 8.5 and 4.5 scenarios.

3.1.3 Time Series Evolution of CP Accumulation and Spread Across Models

Figure 4 shows the time series evolution of changes in CP as well as the spread across models for the four representative locations highlighted in Figure 1 (black stars). In all four locations, there was a considerable spread in accumulated CP under the two different climate change scenarios. Across locations, there were differences in the rate of change over time. CP was projected to increase slightly in Omak until approximately mid-century and then minimally increase after that point (Figure 4). For other regions in southern Washington State and Oregon, CP was projected to decrease at a nearly linear rate until the end of the century (Figure 4). This was particularly true for the southwestern location in Eugene, Oregon. While there is a large spread across models, most models indicated meeting minimum CP requirements in all locations. There are just a couple of climate models that indicate a risk of not meeting minimum CP requirements for species and cultivars with high CP requirements (above 70 CP), especially in Oregon State (Eugene) and southeastern Washington State (Walla Walla) towards the end-of-century. The end-of-century minimum and maximum projected CP accumulation for Eugene (RCP 8.5) across the nineteen models were 56.4 and 119.2 chilling portions, respectively. For Omak, the minimum and maximum CP accumulations were 80.7 and 122.5 CP, respectively.

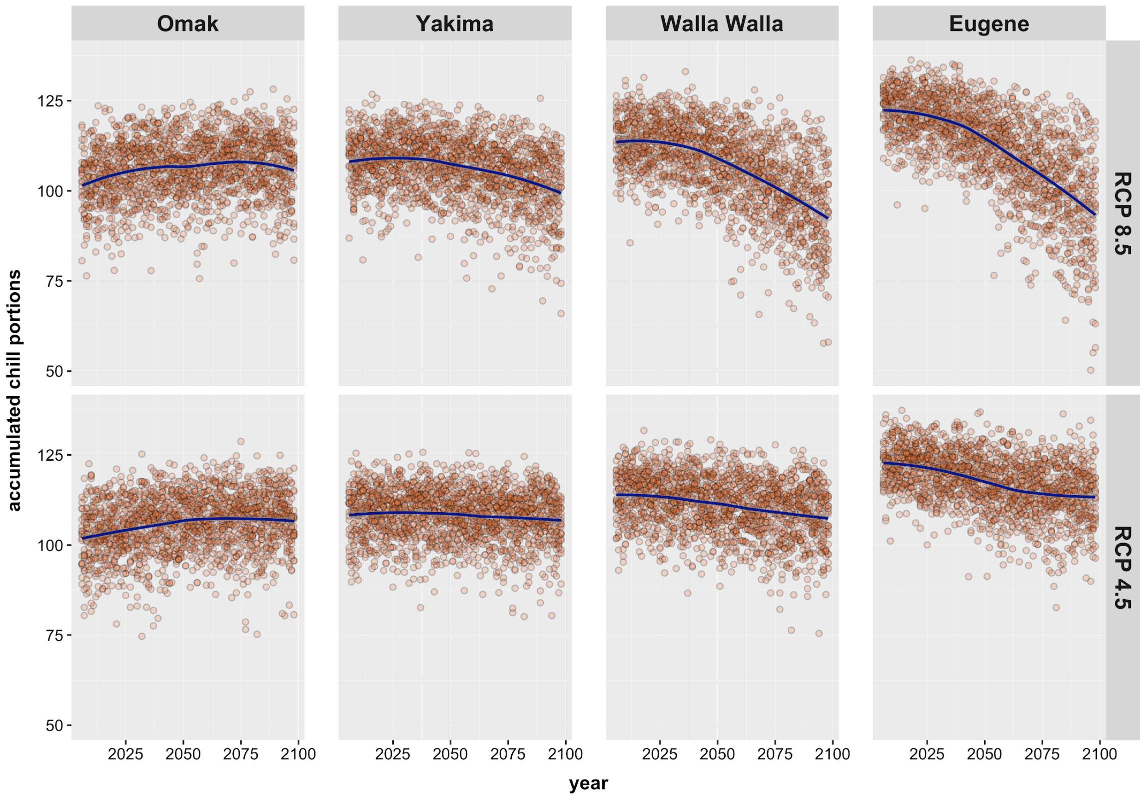

Figure 4. Time series evolution of CP accumulation (September 1- March 31st) in Omak, Yakima, Walla Walla, and Eugene for the RCP 4.5 and 8.5 scenarios. The range for a given year corresponds to the 19 climate models.

3.1.4 Reasons for Simulated Changes

To highlight the factors producing regional differences discussed above, Table 2 provides the fraction of total hours (%) spent in different temperature ranges as relevant for the Dynamic Model (see Section 2.2, and references [24, 25] for the simulation time frame of September 1st to March 31st. The increasing trend in CP accumulation for northern Washington State (Figs. 3 and 4) can be attributed to the models projecting significantly less time (-19%) with exposure to very cold temperatures (less than -2°C) which do not accumulate CP, and more time (7%) with exposure to a range of temperatures where CP accumulate. In contrast, other regions see decreases in the relative time of exposure to temperatures conducive to chill accumulation (-18% for Eugene). This, coupled with CP negating effects of temperatures outside the optimum range of -2 to 13 C, contributed to more rapid decreases in CP accumulation for the warmer southern regions. Table 3 provides information similar to Table 2 except limits the timing for CP accumulation from September 1 to December 31. Model runs for Northern Washington state (Omak) did not indicate increases in relative time of chilling exposure in this time frame (1% in Table 3 as compared with 7% in Table 2), indicating that most of the increases in CP accumulation observed for this region will likely take place during the later part of the winter season.

Table 2. The relative fraction of time (%) spent within specific temperature intervals between September 1st and March 31st. These intervals correspond to differing effects on CP accumulation in the Dynamic Model. The results are for the RCP 8.5 scenario.

		< -2°C	**-2°C - 13°C**	**13°C - 16°C**	**>16°C**
Omak	Historical	23.9	61.6	5.1	9.4
	RCP8.5(2076-2099)	4.9	68.8	7.3	19
	Difference	-19	7.1	2.3	9.6
Yakima	Historical	17.6	65.8	6	10.6
	RCP 8.5 (2076-2099)	4.5	65.2	9	21.2
	Difference	-13.1	-0.7	3.1	10.7
Walla Walla	Historical	9.4	71.3	7.1	12.3
	RCP 8.5 (2076-2099)	1.7	61.3	11.8	25.3
	Difference	-7.7	-9.9	4.6	13
Eugene	Historical	2.1	79.7	7.5	10.7
	RCP 8.5 (2076-2099)	0.3	62	14.4	23.3
	Difference	-1.8	-17.7	6.9	12.6

3.2. Timing of Accumulation of Various Chill Portions

In general, most areas other than the northern region (e.g., Omak) see a projected delay in the timing of when different CP thresholds will be met (Figure 5). For the end of the century, models consistently projected that Eugene, Oregon had a one-month delay in the timing of a range in CP thresholds being met, compared with historical timings, and a little more than a 2-week delay for mid 21st century projections. For northern Washington State (Omak), models projected a delay in the timing for chilling fulfillment for the lower CP thresholds and an advancement for the greater CP thresholds with a reversal at thresholds around 45 CP in late December. This occurs because increased exposure to temperatures optimal for chill accumulation is in effect only after January (see discussion around Tables 2 and 3 in section 3.1). Even for central Washington State (Yakima), we can see that earlier delays are compensated later in the season with a shrinking delay. This, again, points to the wide variation in the response to warming within this tree fruit production region.

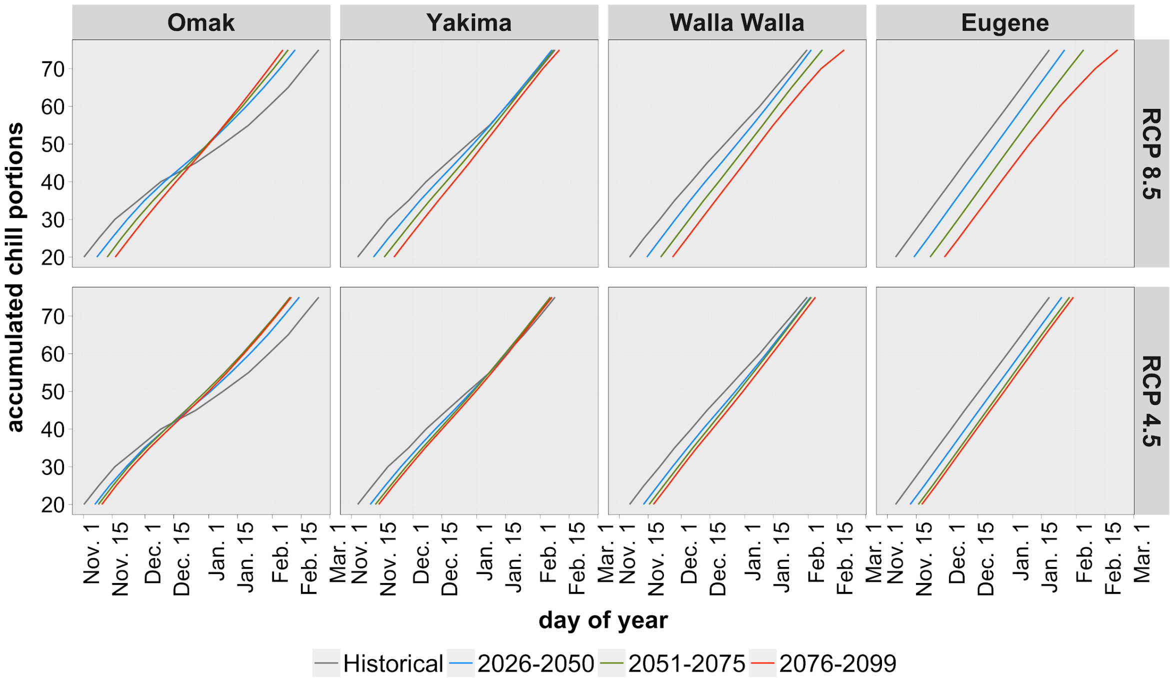

Figure 5. Day of the Year a given range CP accumulation thresholds (20 to 75 CP) are met. The range encompasses minimum CP requirements for the range of tree fruit species and cultivars grown in the region. These are average Day of the Year values across years and averaged across the 19 climate models.

Table 3. The relative fraction of time (%) spent within specific temperature intervals between September 1st and December 31st. These intervals correspond to differing effects on CP accumulation in the Dynamic Model. The results are for the RCP 8.5 scenario.

		< -2°C	-2°C - 13°C	13°C - 16°C	>16°C
Omak	Historical	19.5	57.8	7.1	15.6
	RCP 8.5 (2076-2099)	4.5	58.6	8.6	28.4
	Difference	-15.1	0.9	1.4	12.8
Yakima	Historical	16.3	59.2	7.5	16.9
	RCP 8.5 (2076-2099)	4.6	55.7	9.4	30.3
	Difference	-11.7	-3.6	1.9	13.3
Walla Walla	Historical	8.2	62.9	9.1	19.8
	RCP 8.5 (2076-2099)	1.6	51.4	11.5	35.5
	Difference	-6.6	-11.4	2.4	15.7
Eugene	Historical	1.7	72.1	9.4	16.9
	RCP 8.5 (2076-2099)	0.3	51.4	15	33.4
	Difference	-1.5	-20.7	5.6	16.5

Although there was no observed risk for chilling requirements being met for cultivars with chilling requirements of less than 70 CP by March 31st, the timing of the fulfillment of chilling thresholds can have implications for locations where spring phenology occurs earlier. These delays can have significant implications for tree fruit production, through affecting the dormancy cycle both in terms of altering the heat accumulation required for emerging from dormancy, and timing of bloom. Furthermore, chilling past the minimum chilling threshold for tree fruit species has been shown to reduce thermal heat unit requirements for bud break in the spring [43-47].

3.3. Effect of changes in the timings of the first frost event and bloom

The results, discussed above, consider a simulation time frame of September 1st to March 31st for historical and future climate simulations. However, there could be changes to the initiation of the dormancy period and chill accumulation under warming. There are large gaps in our knowledge of the process that triggers initiation of dormancy [20, 48]. While for many species, photoperiod is the primary elicitor for dormancy induction and is a function of latitude and day of the year, for tree fruit species, exposure to freezing temperatures is necessary to initiate chill accumulation [49]. The implication is that results discussed earlier are conservative and a delay in the first frost date under climate change (Figure 6) may possibly delay chill accumulation as well. This could lead to lower accumulations than noted above, potentially elevating, albeit by small amounts, the risk for insufficient chill accumulation.

Under warming, accelerated heat accumulation can advance the timing of bloom. When chill requirements are not met before bloom, the result is non-uniform budbreak which has severe implications for fruit production. There are significant effects of insufficient chilling that increases flower bud abscission, reduces flower quality and fruit set, and affects both fruit and vegetative growth and development [50]. Since accumulated CP can strongly vary across tree fruit species and cultivar, we look at the time series of chill accumulation and bloom time in conjunction for cherries and apples and a medium (45 CP; Figure 7) and high (75 CP; Figure 8) minimum CP requirement.

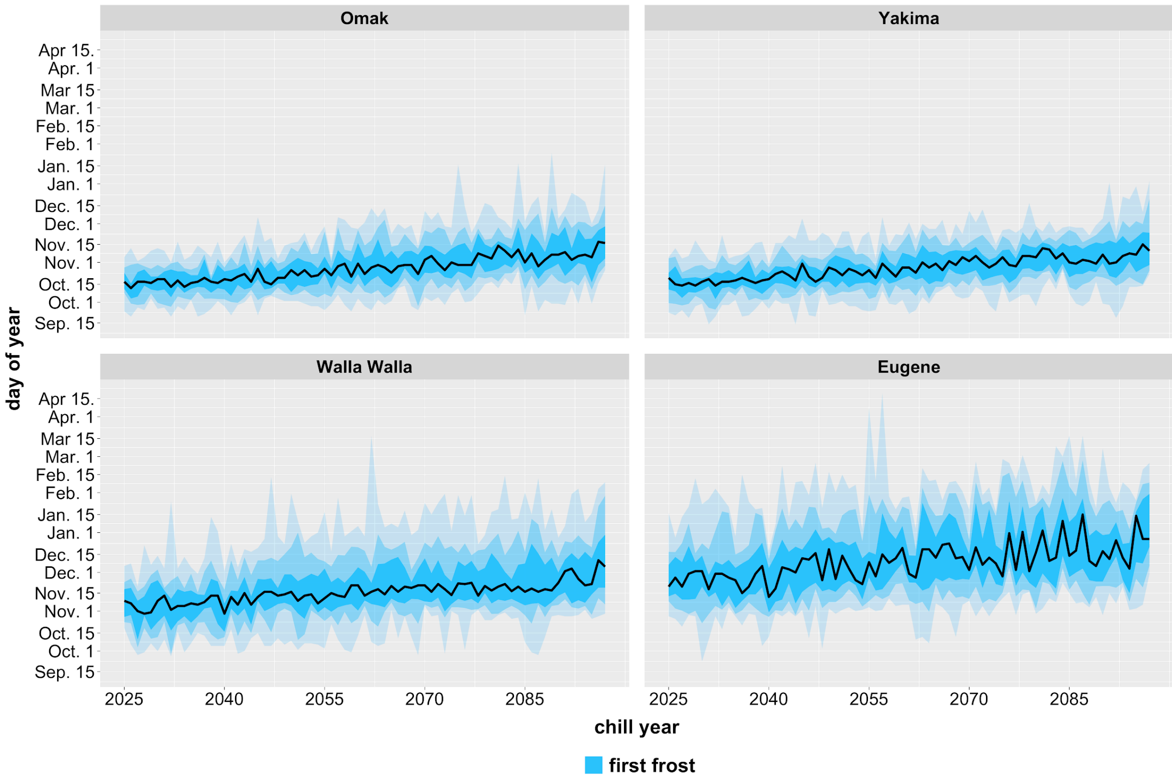

Figure 6. First frost day for Omak, Eugene, Walla Walla and Yakima as per RCP 8.5. The spread in each year corresponds to the 19 models. Different shades of blue envelop the 25th to 75th percentile, 10 to 90th percentile, and the full range of the first day of frost, respectively.

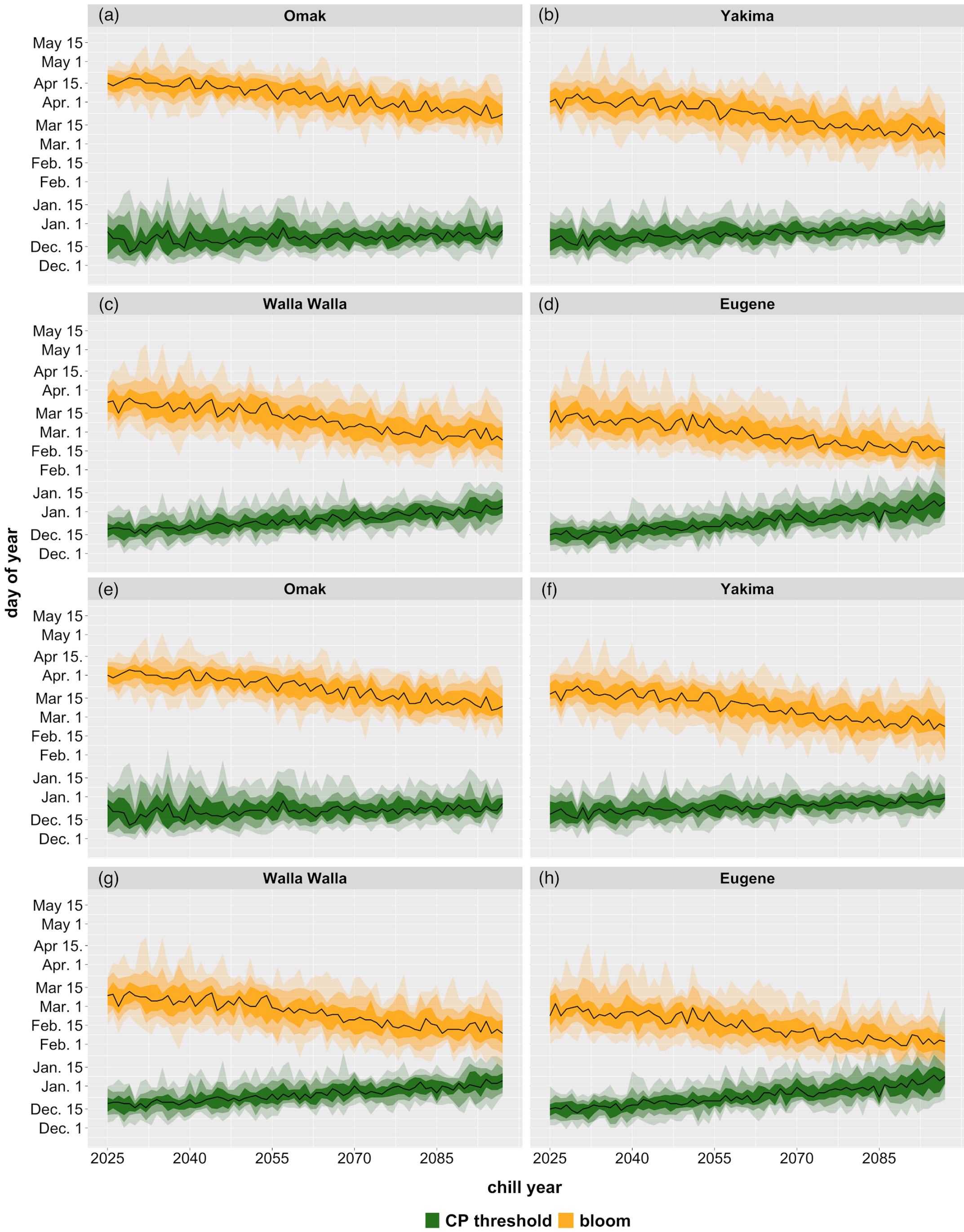

Figure 7. Day of the year for timing of 50% bloom and medium CP accumulation (45 CP) for Omak, Eugene, Yakima, and Walla Walla for RCP 8.5. Parts (a) through (d) correspond to apples and parts (e) though (h) correspond to cherries. The orange part corresponds to the timing of bloom and the green part corresponds to timing of CP accumulation. The spread corresponds to the 19 climate models.

There is a significant variability across climate models producing a wide range in model projections for bloom and CP accumulation. However, for species/cultivars with medium CP requirements, (e.g. Golden Delicious apple) the clouds for bloom and CP accumulation do not converge until the end of the century (except for select extreme climate model projections for cherries in Eugene), indicating no apparent risk for insufficient chill accumulation in the PNW for species/cultivars with medium CP requirements (Figure 7). In contrast, for cultivars with high CP requirements (Figure 8), when advancement of bloom time is considered, significant risk of insufficient chill accumulation is introduced past mid-century in Eugene and Walla Walla and some climate models indicate introduction of risk in Yakima as well. Post mid-century, more than 50% of model projections indicate an onset of bloom before minimum CP requirements have been met (Figures 8 and 9). In spite of uncertainties, it is possible that past mid-century, cultivation of species/cultivars with high CP requirements (e.g. 'Sam' Sweet Cherries) in these areas may require interventions to alleviate these risks.

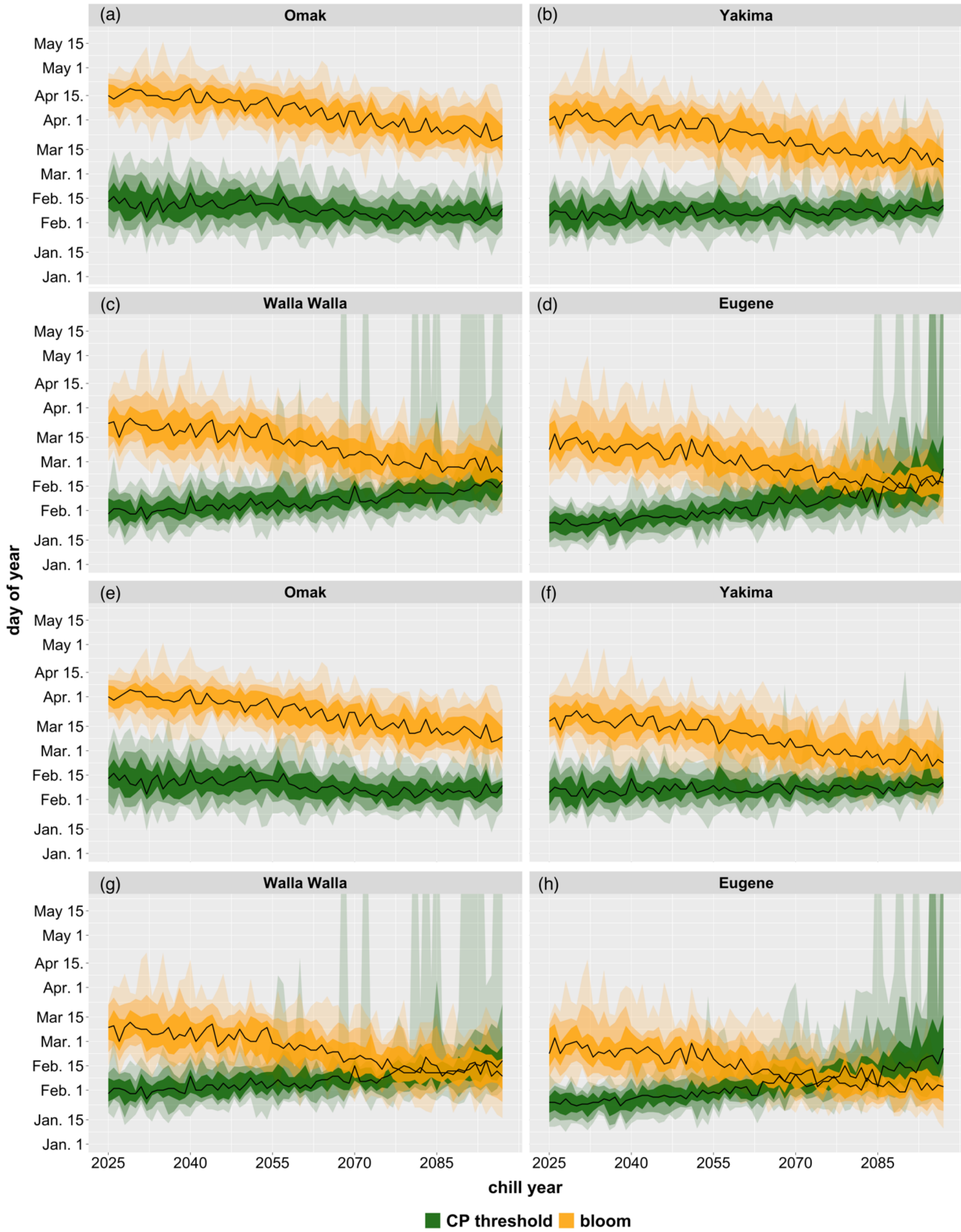

Figure 8. Day of the year for timing of 50% bloom and high CP accumulation (75 CP) for Omak, Eugene, Yakima, and Walla Walla for RCP 8.5. Parts a) through d) correspond to apples and parts e) though f) correspond to cherries. The orange part corresponds to the timing of bloom and the green part corresponds to timing of CP accumulation. The spread corresponds to the 19 climate models.

The high spread in CP accumulation corresponds to years when a CP of 75 was not met and the day of the year was set to 365 days from the simulation start of September 1st.

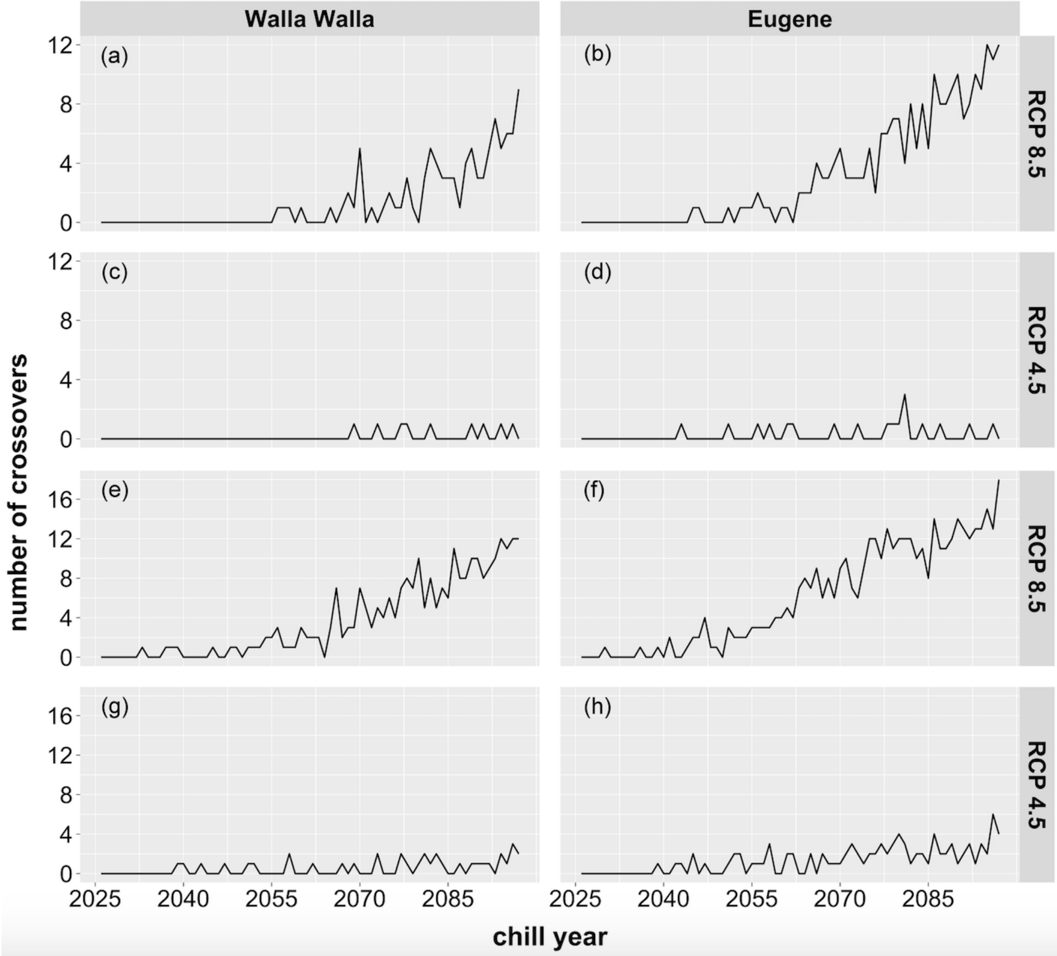

Figure 9. Number of climate models (out of a possible 19) showing a convergence between 50% bloom and 75 chill portions accumulation for Walla Walla and Eugene. Parts a) through d) correspond to apples and parts e) though f) correspond to cherries.

4. Conclusions

The tree fruit producing areas of the Pacific Northwest United States experience large spatial variations in the response of chill accumulation to climate change. Moving north, there is a general trend from decreasing chill accumulation to minimal change then to increasing chill accumulation in response to climate change. The key factors contributing to differential responses within the PNW can also vary by region, with more exposure to optimal temperatures likely contributing to changes in the northern areas and chill negation due to higher temperatures contributing to projected changes in other areas.

While delayed and reduced chill accumulation in and of itself does not pose as much of a threat to tree fruit production in the PNW, a combination of delayed and reduced chill accumulation along with likely advancement in bloom time introduces risks of insufficient chill accumulation under the extreme “no climate policy” RCP 8.5 future climate scenario. This is especially true for southeastern regions of Washington State and parts of Oregon, as well as for tree fruit species and cultivars with relatively earlier bloom and high chill portions requirements (e.g. Sam cherries) and likely not as much of a concern for apple varieties. Even though northern Washington State has less risk of insufficient accumulation, other warmer regions of the PNW with potential future risk of insufficient chill accumulation for some cultivars will likely continue as key production regions given their competitive advantage in terms of faster time to market. These regions would need to plan for management strategies such as overhead irrigation, and chemical management of budbreak (with increased production costs) to address potential risks. Adaptation strategies such as overhead irrigation face other obstacles such as availability of irrigation water. Irrigation water rights typically come with a specified season of use, and if future early season evaporative cooling is outside the current permitted season of use, it would require an approval subject to examination that such a change does not adversely affect another water right holder with a higher priority to the use of water. There is limited projected risk under the RCP 4.5 scenario with less extreme temperature increase projections.

The advancement of bloom could be overestimated in our results given the possibility that delayed chilling can counteract advancement of flowering [43-47], and this dynamic nature of heat requirement for bloom is not considered in our results. However, results indicate that in spite of such a counteraction, parts of the region are likely to face production risks, especially for early blooming cherry varieties with high chill portions requirements. Additionally, the bloom model was an empirical model developed based on historical data in the PNW. Extrapolating it to future warming conditions outside the range the data used to build the model creates uncertainties around the stability of the model under different climates [44]. A similar uncertainty also exists for the Dynamic Model, although it has been evaluated with success in different parts of the world including warmer temperature regimes such as in California--closer to temperature regimes expected in the PNW in the future--giving greater confidence in its application from a climate change perspective.

Significant gaps in our biological understanding of the winter dynamics and dormancy processes in tree fruit create uncertainty in quantifying the response under climate change [3, 44, 51]. Given the potential for increased risk of insufficient chill accumulation in the PNW - one of the prominent tree fruit production regions of the United States - efforts by the scientific community to address these knowledge gaps will be critical for identifying appropriate adaptation or mitigation strategies. Future modeling efforts must also account for the risk of convergence between the fulfillment of chilling requirements (breaking of endodormancy) and environmental conditions promoting budbreak (break of ecodormancy). It is under these conditions where risk to perennial tree fruit production exists and needs to be better understood, modeled, and projected. Given the significant spatial differences across a relatively small geographic range, it is also critical to understand, model and project these dynamics at a local landscape resolution.

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References

1. Saure, M.C. Dormancy Release in Deciduous Fruit Trees. Horticultural Reviews; John Wiley & Sons, Ltd, 2011; pp. 239–300 ISBN 978-1-118-06073-5.

2. Darbyshire, R.; Measham, P.; Goodwin, I. A crop and cultivar-specific approach to assess future winter chill risk for fruit and nut trees. Climatic Change 2016, 137, 541–556.
3. Luedeling, E.; Girvetz, E.H.; Semenov, M.A.; Brown, P.H. Climate Change Affects Winter Chill for Temperate Fruit and Nut Trees. PLOS ONE 2011, 6, e20155
4. Samish RM, Lavee S. The chilling requirement of fruit trees. Publication of the Natl. Univ. Inst. Agr. 1962; 511:372-88.
5. Alburquerque, N.; García-Montiel, F.; Carrillo, A.; Burgos, L. Chilling and heat requirements of sweet cherry cultivars and the relationship between altitude and the probability of satisfying the chill requirements. Environmental and Experimental Botany 2008, 64, 162–170.
6. Baldocchi, D.; Wong, S. Accumulated winter chill is decreasing in the fruit growing regions of California. Climatic Change 2008, 87, 153–166.
7. Luedeling, E.; Zhang, M.; Girvetz, E.H. Climatic Changes Lead to Declining Winter Chill for Fruit and Nut Trees in California during 1950–2099. PLOS ONE 2009, 4, e6166.
8. Luedeling, E.; Zhang, M.; Luedeling, V.; Girvetz, E.H. Sensitivity of winter chill models for fruit and nut trees to climatic changes expected in California's Central Valley. Agriculture, Ecosystems & Environment 2009, 133, 23–31.
9. Luedeling, E.; Zhang, M.; McGranahan, G.; Leslie, C. Validation of winter chill models using historic records of walnut phenology. Agricultural and Forest Meteorology 2009, 149, 1854–1864.
10. Ruiz, D.; Campoy, J.A.; Egea, J. Chilling and heat requirements of apricot cultivars for flowering. Environmental and Experimental Botany 2007, 61, 254–263.
11. Farag, A.A.; Khalil, A.; Hassanein, M.K. Chilling requirement for deciduous fruits under climate change in Egypt. Res J Agric Biol Sci 6(6):815–822.
12. Luedeling, E. Climate change impacts on winter chill for temperate fruit and nut production: A review. Scientia Horticulturae 2012, 144, 218–229.
13. Midgley, S.J.E.; Lötze, E. CLIMATE CHANGE IN THE WESTERN CAPE OF SOUTH AFRICA: TRENDS, PROJECTIONS AND IMPLICATIONS FOR CHILL UNIT ACCUMULATION. Acta Hortic. 2011, 1127–1134.
14. Wrege, M.S.; Caramori, P.H.; Herter, F.G.; Steinmetz, S.; Reisser Júnior, C.; Matzenauer, R.; Braga, H.J. IMPACT OF GLOBAL WARMING ON THE ACCUMULATED CHILLING HOURS IN THE SOUTHERN REGION OF BRAZIL. Acta Hortic. 2010, 31–40.
15. Parker, L.E.; Abatzoglou, J.T. Warming Winters Reduce Chill Accumulation for Peach Production in the Southeastern United States. Climate 2019, 7, 94.
16. Lang, G.A. Early, J.D. Martin, G.C. Darnell, R.L. Endodormancy, Paradormancy, and Ecodormancy—Physiological Terminology and Classification for Dormancy Research. Hortscience, 22, 371-377.
17. Fuchigami LH, Weiser CJ, Kobayashi K, Timmis R, Gusta LV. A degree growth stage (GS) model and cold acclimation in temperate woody plants. Plant cold hardiness and freezing stress. Mechanisms and crop implications. 1982;2:93-116.
18. Heide, O.M. Interaction of photoperiod and temperature in the control of growth and dormancy of Prunus species. Scientia Horticulturae 2008, 115, 309–314.
19. Kalcsits, L.A.; Silim, S.; Tanino, K. Warm temperature accelerates short photoperiod- induced growth cessation and dormancy induction in hybrid poplar (Populus × spp.). Trees 2009, 23, 971–979.
20. Tanino, K.K.; Kalcsits, L.; Silim, S.; Kendall, E.; Gray, G.R. Temperature-driven plasticity in growth cessation and dormancy development in deciduous woody plants: a working hypothesis suggesting how molecular and cellular function is affected by temperature during dormancy induction. Plant Mol. Biol. 2010, 73, 49–65.

21. Houston, L.; Capalbo, S.; Seavert, C.; Dalton, M.; Bryla, D.; Sagili, R. Specialty fruit production in the Pacific Northwest: adaptation strategies for a changing climate. Climatic Change 2018, 146, 159–171.
22. Bennett, J. Temperature and bud rest period: Effect of temperature and exposure on the rest period of deciduous plant leaf buds investigated. Hilgardia 1950, 4, 11–16.
23. Richardson EA, EA R, SD S, DR W. A model for estimating the completion of rest for "Redhaven" and "Elberta" peach trees, 1974.
24. Erez A, Fishman S. The dynamic model for chilling evaluation in peach buds. In IV International Peach Symposium 465 1998 Jun 22 (pp. 507-510).
25. Erez, A.; Fishman, S.; Linsley-Noakes, G.C.; Allan, P. The dynamic model for rest completion in peach buds. Acta Hortic. 1990, 165–174.
26. Luedeling, E.; Brown, P.H. A global analysis of the comparability of winter chill models for fruit and nut trees. Int J Biometeorol 2011, 55, 411–421.
27. Linsley-Noakes, G.C.; Allan, P. Comparison of two models for the prediction of rest completion in peaches. Scientia Horticulturae 1994, 59, 107–113.
28. Miranda, C.; Santesteban, L.G.; Royo, J.B. Evaluation and fitting of models for determining peach phenological stages at a regional scale. Agricultural and Forest Meteorology 2013, 178–179, 129–139.
29. [29] Zhang, J.; Taylor, C. The Dynamic Model Provides the Best Description of the Chill Process on 'Sirora' Pistachio Trees in Australia. HortScience 2011, 46, 420–425.
30. Pérez, F.J.; Ormeño N, J.; Reynaert, B.; Rubio, S. Use of the Dynamic Model for the Assessment of Winter Chilling in a Temperate and a Subtropical Climatic Zone of Chile. Chilean journal of agricultural research 2008, 68, 198–206.
31. Abatzoglou, J.T. Development of gridded surface meteorological data for ecological applications and modelling. International Journal of Climatology 2013, 33, 121–131.
32. Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. An Overview of CMIP5 and the Experiment Design. Bull. Amer. Meteor. Soc. 2012, 93, 485–498.
33. Abatzoglou, J.T.; Brown, T.J. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 2012, 32, 772–780.
34. van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F.; et al. The representative concentration pathways: an overview. Climatic Change 2011, 109, 5.
35. Linvill, D.E. Calculating Chilling Hours and Chill Units from Daily Maximum and Minimum Temperature Observations. HortScience 1990, 25, 14–16.
36. Eike Luedelin. chillR: Statistical Methods for Phenology Analysis in Temperate Fruit Trees. 2019. https://CRAN.R-project.org/package=chillR.
37. Jones VP, Borghi S, Jones MS, Chambers U. WSU-Tree Fruit Decision Aid System. Washington State University. 2020 https://decisionaid.systems. Last accessed August 1st 2020.
38. Thornton, M.M., Thornton, P.E., Wei, Y., Vose, R.S. and Boyer, A.G., 2017. Daymet: Station-Level Inputs and Model Predicted Values for North America, Version 3. ORNL DAAC, Oak Ridge, Tennessee, USA.
39. Baskerville, G.L.; Emin, P. Rapid Estimation of Heat Accumulation from Maximum and Minimum Temperatures. Ecology 1969, 50, 514–517.
40. Crop Chilling Requirements. Available online: http://fruitsandnuts.ucdavis.edu/Weather_Services/chilling_accumulation_models/CropChillReq/2020 (Last accessed April 1, 2020)

41. Erez, A. Bud Dormancy; Phenomenon, Problems and Solutions in the Tropics and Subtropics. In Temperate Fruit Crops in Warm Climates; Erez, A., Ed.; Springer Netherlands: Dordrecht, 2000; pp. 17–48.
42. Díez-Palet, I.; Funes, I.; Savé, R.; Biel, C.; de Herralde, F.; Miarnau, X.; Vargas, F.; Àvila, G.; Carbó, J.; Aranda, X. Blooming under Mediterranean Climate: Estimating Cultivar-Specific Chill and Heat Requirements of Almond and Apple Trees Using a Statistical Approach. Agronomy 2019, 9, 760.
43. Okie WR, Blackburn B. Increasing chilling reduces heat requirement for floral budbreak in peach. HortScience. 2011;46(2):245-52.
44. Darbyshire, R.; Webb, L.; Goodwin, I.; Barlow, E.W.R. Challenges in predicting climate change impacts on pome fruit phenology. Int J Biometeorol 2014, 58, 1119– 1133.
45. Campoy, J.A.; Ruiz, D.; Cook, N.; Allderman, L.; Egea, J. High temperatures and time to budbreak in low chill apricot 'Palsteyn'. Towards a better understanding of chill and heat requirements fulfilment. Scientia Horticulturae 2011, 129, 649–655.
46. Pope, K.S.; Da Silva, D.; Brown, P.H.; DeJong, T.M. A biologically based approach to modeling spring phenology in temperate deciduous trees. Agricultural and Forest Meteorology 2014, 198–199, 15–23.
47. Martínez-Lüscher, J.; Hadley, P.; Ordidge, M.; Xu, X.; Luedeling, E. Delayed chilling appears to counteract flowering advances of apricot in southern UK. Agricultural and Forest Meteorology 2017, 237–238, 209–218.
48. Maurya, J.P.; Bhalerao, R.P. Photoperiod- and temperature-mediated control of growth cessation and dormancy in trees: a molecular perspective. Ann. Bot. 2017, 120, 351–360.
49. Heide, O.M.; Prestrud, A.K. Low temperature, but not photoperiod, controls growth cessation and dormancy induction and release in apple and pear. Tree Physiol. 2005, 25, 09–114.
50. Atkinson, C.J.; Brennan, R.M.; Jones, H.G. Declining chilling and its impact on temperate perennial crops. Environmental and Experimental Botany 2013, 91, 48–62.
51. Richardson, A.D.; Keenan, T.F.; Migliavacca, M.; Ryu, Y.; Sonnentag, O.; Toomey, M. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. Agricultural and Forest Meteorology 2013, 169, 156–173.