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Shifts in the thermal niche of almond under climate change

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Abstract Delineating geographic shifts in crop cultivation under future climate conditions provides information for land use and water management planning, and insights to meeting future demand. A suitability modeling approach was used to map the thermal niche of almond cultivation and phenological development across the Western United States (US) through the mid-21st century. The Central Valley of California remains thermally suitable for almond cultivation through the mid-21st century, and opportunities for expansion appear in the Willamette Valley of western Oregon, which is currently limited by insufficient heat accumulation. Modeled almond phenology shows a compression in reproductive development under future climate. By the mid-21st century, almond phenology in the Central Valley showed ~ 2-week delay in chill accumulation and ~ 1- and ~ 2.5-week advance in the timing of bloom and harvest, respectively. Although other climatic and non-climatic restrictions to almond cultivation may exist, these results highlight opportunities for shifts in the geography of high-value cropping systems, which may influence growers' long-term land use decisions, and shape regional water and agricultural industry discussions regarding climate change adaptation options.

1 Introduction

Climate is a primary control on the geographic distribution of native plants and cultivated crops (Guisan and Zimmermann 2000; Leemans and Solomon 1993). Existing shifts in these distributions have been documented as a result of observed changes in climate (Kelly and Goulden 2008), and future shifts are anticipated as a function of projected climatic changes (Lobell et al. 2006). Although climate change impacts may be mitigated to some extent in

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horticultural settings (e.g., irrigation, frost protection), such efforts may be a greater challenge for perennial crops (Lobell and Field 2011). Not only are perennial crops subject to climate impacts throughout the year and over their decades-long lifespan, but they are also prevented from employing agricultural management decisions used in annual crop systems such as fallowing. Understanding how climate change may alter the geographic distribution of perennial crops provides important information on the viability of future cropping choices, which may inform long-term implications for land use and water management planning, crop yields, and agroeconomics (Lobell et al. 2006).

Climatic drivers behind projected shifts in perennial crop distribution under climate change vary by crop and geography; these climatic drivers may include changes in cold hardiness zone (Parker and Abatzoglou 2016), extreme heat (White et al. 2006), reductions in chill accumulation (Luedeling et al. 2009), and water availability (Machovina and Feeley 2013). Geographic shifts in the potential distribution of cultivated species have been empirically assessed using species distribution models (SDMs) (Machovina and Feeley 2013) and random forest approaches (Moriondo et al. 2013), as well as process-based suitability models (SMs) (e.g., White et al. 2006). While both modeling frameworks have merits and shortcomings, previous work has shown they may produce similar results in modeling the distribution of agricultural crops (Estes et al. 2013; Parker and Abatzoglou 2017). However, unlike SDMs, SMs can provide information on specific climatic limitations and crop phenology, and are not limited by the correlative approach or temporal averaging of environmental conditions. This additional insight is advantageous as information on crop phenology is necessary for plant-pollinator interactions, crop water demands, and farm operations (Webb et al. 2007).

Virtually, 100% of the commercially grown supply of US almonds (*Prunus dulcis*)—and more than 80% of the global supply—is cultivated in California, comprising more than 10% of California agricultural and ranching income (CDFA 2015). Since 1995, almond cropland in California has more than doubled from 1690 to 3600 km^2 (CDFA 2016) as a function of increased demand and high profitability for growers. Almond cropland increased by more than 400 km^2 between 2011 and 2015, a period that coincided with the most severe drought in 1200 years in California (Griffin and Anchukaitis 2014). The relatively high water demands of almonds have resulted in challenges for growers, both in physically maintaining their orchards (Smith 2014) and in navigating public opinion and water politics within the region (Weiser 2015). While increased water demands due to summer heat can be a challenge during drought years, winter warmth can also pose problems for almond production in terms of decreased yields (Lobell and Field 2011) and increased populations of pests (Luedeling et al. 2011b). Previous work has shown that climate change may impact California agriculture by escalating pressure from pests (Luedeling et al. 2011b), shifting perennials northward or upslope to cooler climes (Lobell et al. 2006), and increasing water scarcity (Averyt et al. 2013).

Similar to California, much of the Northwestern United States (NWUS, covering Oregon, Washington, and western Idaho, 42°–49° N, 114°–125° W) has wet winters and dry summers ideal for almond cultivation. Nearly one quarter of the land area in the NWUS is devoted to agricultural production, yielding agricultural commodities valuing more than 17 billion US dollars (USD) and contributing to hundreds of thousands of jobs (Dalton et al. 2013). Broadly, the NWUS is a leader in the US production of perennial fruit and nut crops such as cherries, apples, pears, and hazelnuts, with the value of all regional fruit and nut production in 2016 topping 3.4 billion USD (USDA-NASS 2016).

Though almonds are not currently commercially produced in the NWUS, *Prunus* species (e.g., cherries, peaches, plums) are cultivated on more than 200 km^2 of NWUS cropland and produce nearly 600 million USD in sales (USDA-NASS 2016). Relative to California, the NWUS is a water-rich region with less interannual variability in precipitation and is projected to see less surface water scarcity under future climate (Averyt et al. 2013). Additionally, while warming may increase the vulnerability of some crops currently grown in California (e.g., Kerr et al. 2017), it is projected to lengthen the growing season (Mote et al. 2014), increase overwinter minimum temperature extremes (Parker and Abatzoglou 2016), and increase heat accumulation (White et al. 2006), allowing for the expansion of perennials currently limited by these climatic factors in the NWUS (e.g., Houston et al. 2017).

This study builds on previous work examining shifts in high market-value perennials (e.g., White et al. 2006) by modeling changes in the potential geographic distribution of almonds under future climate. Using the SM of Parker and Abatzoglou (2017), the viability of future almond cultivation is evaluated based solely on thermal variables as almonds in the US are irrigated (Lobell and Field 2011), and other limiting conditions (e.g., soils, pests) may be augmented or controlled in agricultural settings (Yao et al. 2005). We specifically seek to identify how thermal controls on almond cultivation vary spatially and temporally across crop development stages, delineate how climate change will alter the geographic distribution of land suitable to almond cultivation, and assess potential shifts in almond phenology.

2 Data and methods

2.1 Data

Historical maximum temperature (T_{max}) and minimum temperature (T_{min}) for the period 1979–2014 for the Western US [32°–49° N, 114°–125° W (Supplemental Figure 1)] were acquired from the gridded daily surface meteorological (gridMET) dataset of Abatzoglou (2013). The 4-km resolution gridMET dataset provides meteorological data at spatial and temporal scales suitable for both local and landscape-scale ecological and agricultural modeling.

Daily T_{max} and T_{min} data were obtained from 20 global climate models (GCMs) participating in the fifth phase of the Climate Model Intercomparison Project (CMIP5) for the historical (1950–2005) and future (2006–2099) forcing experiments. These data were statistically downscaled to 4-km resolution using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2012), using training data from gridMET to ensure compatibility between the downscaled historical GCM experiments (1950–2005) and the observed record (1979–2012). MACA uses an analog approach to map daily GCM fields to observed fields and applies an equidistant quantile mapping bias correction procedure (Li et al. 2010) that preserves simulated differences in the distribution of variables such as temperatures, including those associated with extreme values. We constrained our analysis to model simulations for the early (2010–2039) and mid (2040–2069) 21st century periods, choosing to assess these periods because of the limited ability for developing meaningful management strategies relevant to end-of-century projections. Further, we focus on future experiments run under Representative Concentration Pathway 4.5 in order to provide a conservative estimate of potential novel cultivation locations. However, given that emissions trajectories to date have more closely followed RCP 8.5 (Peters et al. 2013), we also provide supplementary results from these experiments.

Following Parker and Abatzoglou (2017), almond location data were obtained from the 2015 US Department of Agriculture National Agriculture Statistics Service Cropland Data Layer (CDL) and land cover data from the US Geological Survey Land Cover Institute's MODIS-based Global Land Cover Climatology (LCC). Almond and cropland densities at the 4-km resolution of the climate data were calculated as the proportion of land classified as almond and cropland by the CDL and LCC, respectively; we consider "almond locations" to be those 4-km grid cells with > 1% almond density and cropland to be those 4-km grid cells with > 10% cropland density (Supplemental Figure 1). These data were used exclusively to visualize and analyze output from the SM in the context of existing cropland.

2.2 Modeling almond development

The complex, multi-year development cycle of almond reproduction was simplified for modeling purposes to focus on four stages of development: endodormancy, ecodormancy, flower development, and fruit development. Winter dormancy in many plants consists of two distinct parts; during endodormancy, internal physiological processes prevent development, while during ecodormancy external environmental conditions govern development. Plants accumulate chilling units during endodormancy and enter ecodormancy when the plant's chill threshold has been met, after which floral and fruit development progresses (Covert 2011).

The SM, detailed in Parker and Abatzoglou (2017), is based on physiological requirements and constraints of almond development. The SM utilizes thermal requirements for almond development compiled from the published literature and based on field studies and growth chamber experiments, using conservative thresholds and focusing on the widely grown Nonpareil cultivar where a range of values exist within the literature, or when requirements vary by cultivar (Supplemental Table 1). The SM accounts for the thermal conditions necessary for almond growth (e.g., growing degree day (GDD) accumulation) as well as thermal conditions that would negatively impact reproductive development (e.g., frost damage) throughout all growth stages, and assumes that water requirements are met via precipitation or irrigation. While the SM better accounts for mechanisms throughout crop phenology than SDMs, physiological processes are not detailed as they may be in a fully mechanistic model.

Using daily T_{max} and T_{min}, the SM modeled the requirements for sustaining and advancing almond development at an annual time step (November 1–October 31), with each year simulated independently (Fig. 1). The SM begins each year of almond development on November 1, a proxy for the onset of endodormancy and the industry standard start date for chill accumulation (Covert 2011), and tracks the timing of almond development each year. Beginning with 1 November, the SM accumulates chill and records the day of the year on which the required chill portion is accumulated (CPday). We use the Dynamic Model for calculating chill accumulation, which allows warm temperatures to cancel the effects of cool temperatures in chill accumulation and has been shown to be more accurate than other chilling models (Luedeling and Brown 2011). The SM begins accumulating GDD on CPday and tracks the timing of subsequent phase thresholds as defined by cumulative GDD. While harvest may commence as soon as 100% hull split is reached, we account for some drying time on the tree, as is common in orchard management practices. Using observations from the Chico, California

Regional Almond Variety Trial (RAVT, Connell et al. 2010), we calculated an average of 12 days between 100% hull split and harvest, which is hereafter used in the SM as the threshold for harvest timing. This differs from harvest requirements of Parker and Abatzoglou (2017). Experiments showed that this modified measure of harvest timing increased viability, particularly in locations that fail to reach the GDD thresholds used to define harvest in Parker and Abatzoglou (2017) (Supplemental Figure 2).

Each growth stage of each year has the opportunity for failed development due to extreme cold, a lack of chill, insufficient heat accumulation, or frost; failure is treated as a binary variable. The SM treats all failure scenarios equally, and failure during any development stage results in an unviable year for almond cultivation. A suitable year is one in which thermal requirements are met across all crop stages. The species viability index (SVI) was calculated as the proportion of suitable years to total years for almond cultivation. The SVI can be used to facilitate comparisons across space and between time periods. Likewise, the SVI for each individual thermal requirement was calculated to highlight the limiting thermal conditions for almond development.

We calculated the SVI for each model for the contemporary, early, and mid-21st century periods. Results calculated using gridMET for 1979–2014 were comparable to multi-model mean results over contemporary model years 1971–2000; we hereafter use observed gridMET results for the contemporary period. The SVI for individual models were averaged to determine the multi-model mean SVI. Early and mid-21st century projections focused on multi-model mean SVI. However, we supplemented this by tabulating the number of models (out of 20) that had high viability (SVI ≥ 0.8) to provide a visualization of the robustness of results across models. Projections are considered robust to intermodel variability when at least 16 of the 20 models agree there is high viability. We argue that information on locations with high viability is likely to be of greater practical interest to growers who may be risk averse, and further argue that intermodel agreement would help elucidate areas most likely to be thermally suitable for almond cultivation. SVI analysis was refined to locations with current cropland

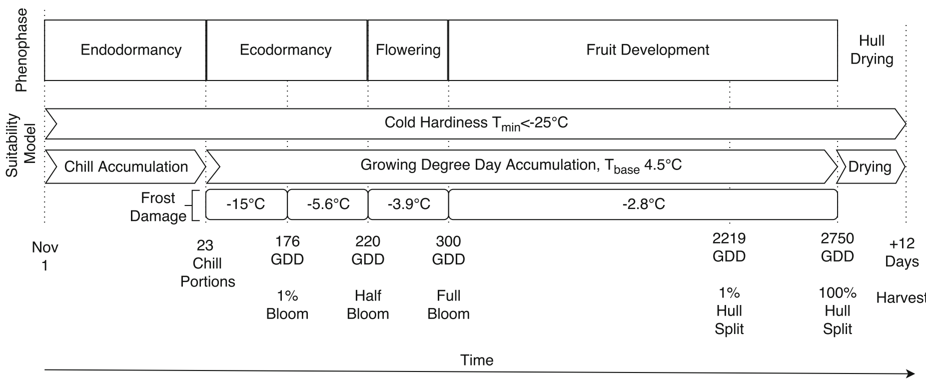


Fig. 1 Schematic of the suitability model (SM) described in the study of Parker and Abatzoglou (2017). Phenological stages of endodormancy, ecodormancy, flower development, fruit development, and hull drying are shown for reference. For each phenophase, the SM assesses the thermal conditions needed for phenological advancement, utilizing known threshold values for chill accumulation, growing degree days (GDD), and cold damage based on daily minimum temperatures (T_{min}). If T_{min} falls below − 25 °C at any time during the year or if T_{min} falls below frost damage thresholds, which vary by phenostage, the year is considered unviable. Likewise, years with insufficient chill or GDD accumulation are also considered unviable, as are years without sufficient drying time due to delayed maturation

density > 10% to highlight suitability in locations most practical for cultivation. The density of cropland within each suitable 4-km grid cell was then multiplied by the area of each grid cell (16 km^2) to yield the areal extent of thermally suitable cropland in square kilometers.

Finally, we highlight phenological changes to development timing in current almond-growing regions in California, defined as those 4-km grid cells with high (> 40%) almond density.

3 Results

Over the contemporary period, the SM showed high viability (SVI ≥ 0.8) over California's Central Valley, and much of the Mojave and Sonoran deserts. By contrast, no land in the NWUS had high SVI over the contemporary period. Frost and insufficient heat accumulation have been the primary limiting factors for almond cultivation outside of current almond-growing locations (Fig. 2, Supplemental Figure 3).

Under both RCP 4.5 and RCP 8.5 scenarios, multi-model mean suitability in California's Central Valley remained high (≥ 0.8) in the early 21st century period. Much of the NWUS remained unsuitable under RCP 4.5 (RCP 8.5) by the early 21st century, with only ~ 2000 km^2 (~ 3700 km^2) of the region showing SVI ≥ 0.8 in pockets of southwestern Oregon and the northern Willamette Valley (individual model results are presented in Supplemental Figures 4–5). More substantial changes were noted for the mid-21st century period. While suitability increased over northwestern California and remained unchanged in the Central Valley, declines in suitability were evident along the southern California coast and in southeastern California, where chill accumulation declined. Across the NWUS, ~ 23,000 km^2 (~ 49,000 km^2) of the region showed SVI ≥ 0.8 for the mid-21st century period, with high suitability west of the Cascades. Increased suitability is shown to result from reduced frost risk between the onset of ecodormancy and 1% bloom and additional heat accumulation required for nut maturation, with the relative influence of factors varying geographically.

Heat accumulation and frost during bloom onset remain primary thermal constraints for viability across much of the NWUS into the mid-21st century. Under RCP 4.5 (RCP 8.5), ~ 137,500 km^2 (~ 190,000 km^2) of total NWUS land area showed high suitability for mid-21st century frost at 1% bloom; similarly, ~ 85,200 km^2 (~ 229,300 km^2) of the NWUS showed high suitability (SVI ≥ 0.8) for 100% hull split GDD accumulation, both substantial increases over contemporary suitability (Supplemental Tables 2-3, Supplemental Figure 6).

Individual models show strong agreement of high SVI for both early and mid-21st century periods over California's Central Valley (Fig. 3, Supplemental Figure 5). By contrast, more uncertainty was apparent for regions of potential expansion of almond cropland, including over the NWUS where fewer than 7% (10%, RCP 8.5) of locations with high multi-model mean SVI at the mid-21st century showed robust agreement across models (≥ 16 of 20 models).

Over the contemporary period, the SM showed ~ 35,860 km^2 of suitable cropland over the Western US, with ~ 34,950 km^2 of suitable croplands in California and no suitability in the NWUS. We further restrict our analysis of projected changes in almond thermal suitability to current agricultural lands and areas of robust model agreement of high SVI. Model projections for the early 21st century using RCP 4.5 (RCP 8.5) show a

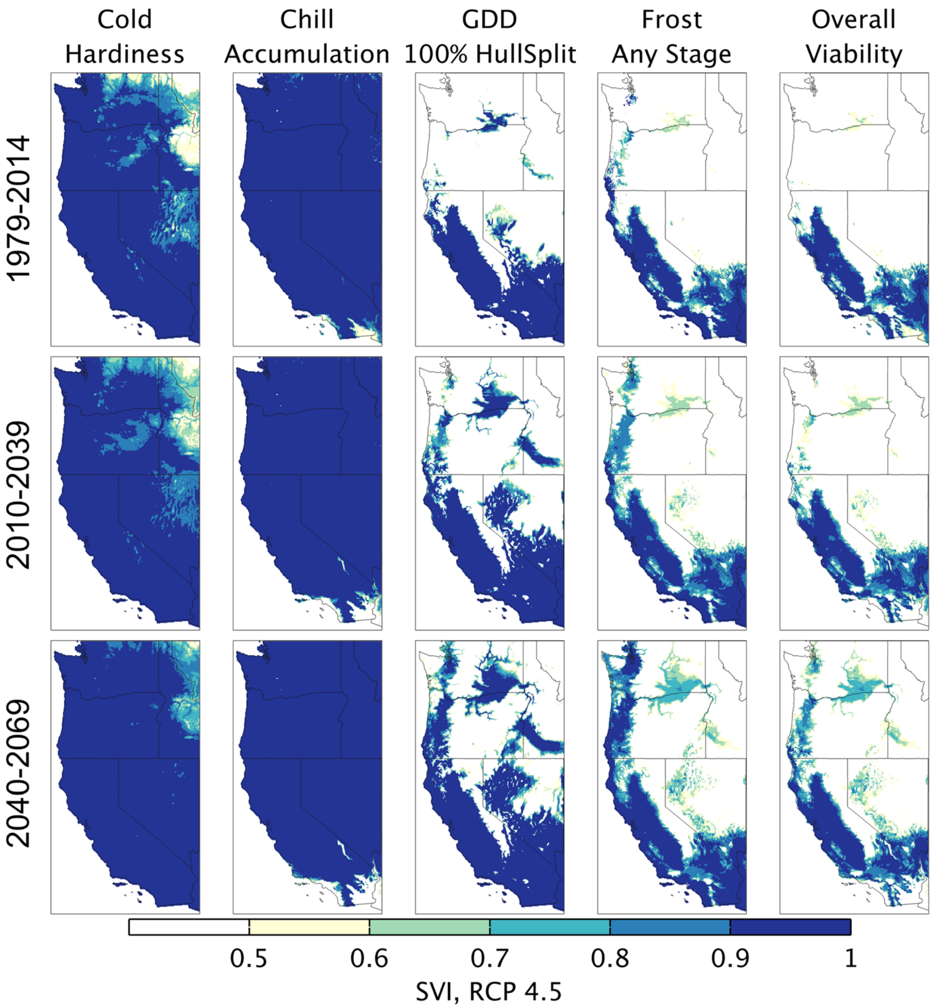


Fig. 2 Multi-model mean species viability index (SVI) for individual thermal suitability factors and (far right) overall suitability over the contemporary (top), early- (middle), and mid-21st century (bottom) periods. Frost SVIs reflect the percent of years without frost damage at any time between ecodormancy onset and 100% hull split. Areas with SVI < 0.5 are masked out

contraction of thermal suitable cropland area across the Western US by ~1279 km^2 (~1275 km^2), primarily in southern California and along the California-Arizona border, and slight expansion by 66 km^2 (145 km^2) in localized areas of northern California and along the Central Coast. Although an additional contraction of 380 km^2 (895 km^2) of southern California cropland occurs by the mid-21st century, ~34,200 km^2 (~33,700 km^2) of California cropland remained thermally viable to almond cultivation into the mid-21st century, including all of California's primary almond-growing locations. Additionally, opportunities for expansion by the mid-21st century exist over ~1025 km^2 (~4750 km^2) of current NWUS croplands, primarily in the Rogue, Umpqua, and Willamette valleys (Fig. 4, Supplemental Table 4, Supplemental Figure 8).

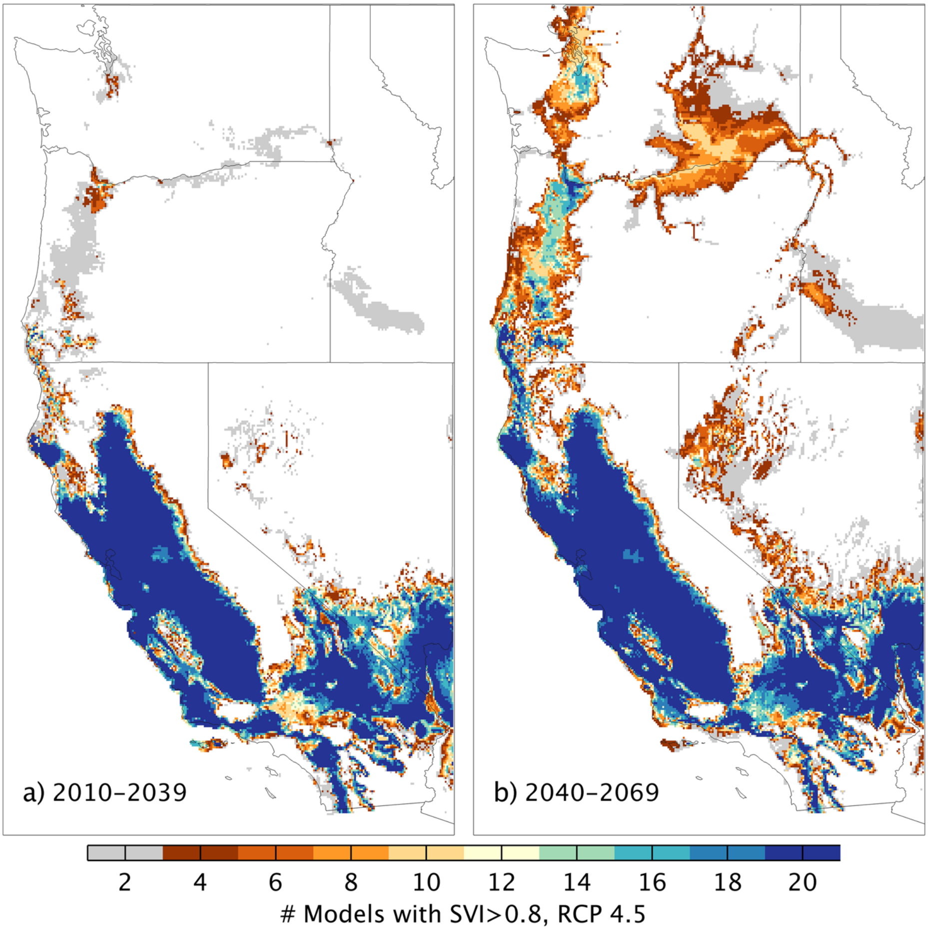
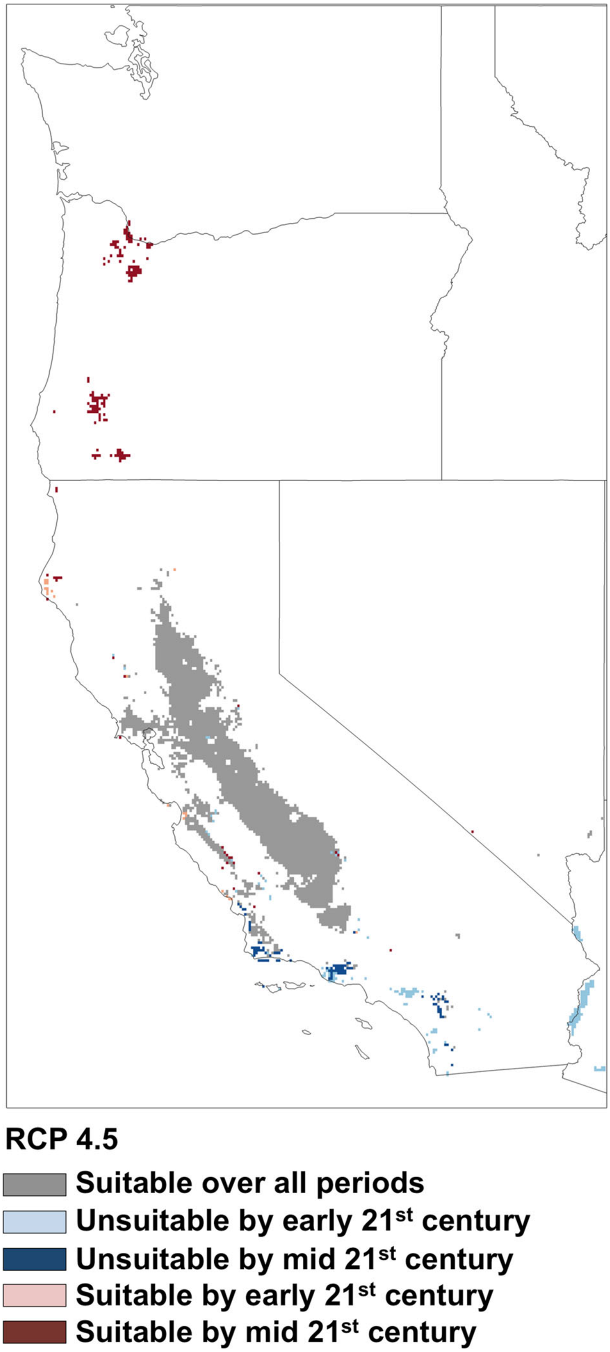


Fig. 3 Number of models showing high suitability (SVI ≥ 0.8) out of 20 models over the **a** early and **b** mid-21st century periods for RCP 4.5

Changes in the timing of almond development were shown to vary by phenostage and location (Fig. 5). In general, warming resulted in a delay in chill accumulation while phenology in all other phases advanced, thereby compressing the almond reproductive cycle. Relative to contemporary phenology in California's primary almond-growing regions, chill accumulation occurred approximately 13 days later by the mid-21st century. Conversely, all other development stages occurred earlier in the year in these locations (Supplemental Table 5). For example, average 50% bloom and maturation (100% hull split) in current almond-growing locations occurred ~6 and ~19 days earlier by the mid-21st century, respectively. Mid-21st century ecodormancy onset and bloom timing over NWUS locations with high mid-21st century SVI were comparable to current timing in primary almond-growing regions in California. However, mid-21st century nut maturation over these highly suitable locations in the NWUS was delayed by 43 days relative to historical maturation dates in California's primary almond-growing regions.


RCP 4.5
Suitable over all periods
Unsuitable by early 21st century
Unsuitable by mid 21st century
Suitable by early 21st century
Suitable by mid 21st century

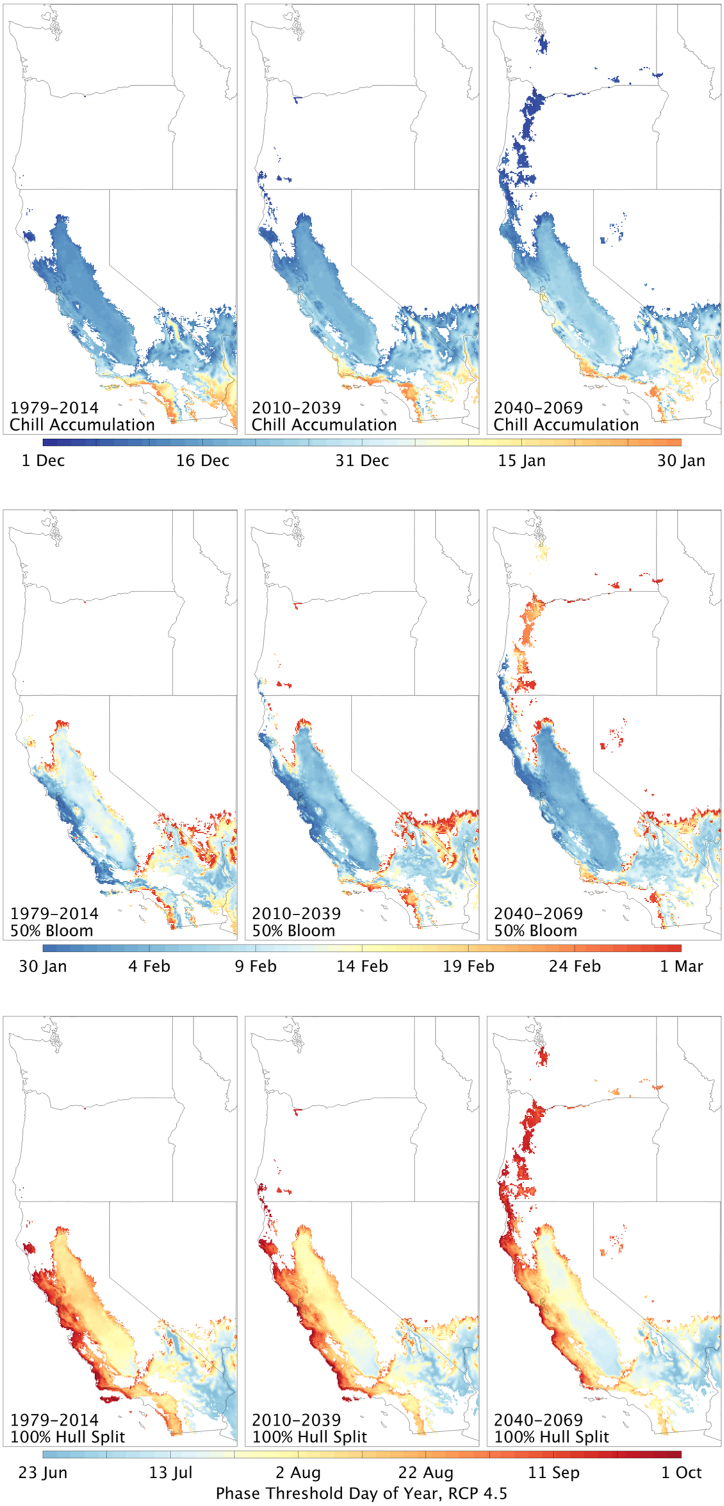
◀**Fig. 4** Expansion and contraction of the high suitability (SVI ≥ 0.8) range of almond over locations with current cropland densities > 10% for RCP 4.5. Expansion is defined as those areas with robust (≥ 16 of 20 models) high suitability; contraction is defined as those areas without robust high suitability. Gray indicates high suitability over all periods, light blue indicates a contraction of almond range by the early 21st century, dark blue indicates a contraction of almond range by the mid-21st century, light red indicates an expansion of almond range by the early 21st century, and dark red indicates an expansion of almond range by the mid-21st century

4 Discussion

Frost damage is known to be a primary limitation to almond cultivation, particularly early-season frost damage occurring between bud swell and anthesis (Miranda et al. 2005). This was reflected in the SM results for the contemporary period across much of the study area outside of where almonds are currently produced. Insufficient heat accumulation has also been a limiting factor to almond cultivation, in addition to other horticultural crops, across the Western US (Sykes et al. 1996). These two thermal constraints wane across areas that have historically been unsuitable to almond cultivation by the mid-21st century, in line with projections of increased annual heat accumulation (White et al. 2006) and decreased risk false spring frost damage (Allstadt et al. 2015). Greater viability may occur where growers have a higher tolerance for risk or the ability to mitigate frost damage (e.g., wind turbine use); conversely, estimated thermal suitability for frost damage may be reduced where cultivation occurs in microclimates subject to cold air drainage at scales finer than those used here. However, as these changes are dependent on methodological choices, care should be taken in interpreting modeled declines in frost risk (Darbyshire et al. 2016; Mosedale et al. 2015).

While declines in frost risk have been shown to have positive effects on crop productivity (Lobell and Gourdji 2012) and could be expected to have a similar effect on almond yield, declines in winter chill may have detrimental effects on crop yields (Luedeling et al. 2009). Although the low chill requirements of Nonpareil almond limit SVI reductions over current almond cultivation locations, mild winters can result in delayed bloom, unevenly timed hull split and harvest, and result in challenges for orchard management (Doll 2013). Further, chill accumulation above the plant's required amount may have a negative impact on yield (Pope et al. 2015), indicating another caveat to the potential northward expansion of almond orchards.

The broad patterns of northward expansion of thermal suitability for almond cultivation are in line with other research that has shown geographic expansion of crops under climate change (e.g., Machovina and Feeley 2013; Moriondo et al. 2013). Beyond shifting the geographies of the thermal niche of almond, climate change is projected to alter almond phenology. Although previous research has detailed the challenges in accurately capturing phenology under climate change (e.g., Chuine et al. 2016; Luedeling et al. 2009; Pope et al. 2014), particularly during the flowering phase, the phenological shifts modeled by the SM support previous studies showing observed (Chmielewski et al. 2004) and modeled (Allstadt et al. 2015; Webb et al. 2007) advancements in crop phenology. While the advancement of almond phenology may allow for the completion of the development cycle in portions of the NWUS, the earlier development of almonds in California may result in a mismatch between tree and pollinator phenology, with potentially deleterious effects on both plant and pollinator populations (e.g., Memmott et al. 2007). Similarly, warming temperatures may also cause declines in crop quality, as high temperatures in the month following bloom have been associated with decreased fruit size in *Prunus* species (Lopez et al. 2007).


1979–2014
Chill Accumulation
2010–2039
Chill Accumulation
2040–2069
Chill Accumulation
1 Dec
16 Dec
31 Dec
15 Jan
30 Jan
1979–2014
50% Bloom
2010–2039
50% Bloom
2040–2069
50% Bloom
30 Jan
4 Feb
9 Feb
14 Feb
19 Feb
24 Feb
1 Mar
1979–2014
100% Hull Split
2010–2039
100% Hull Split
2040–2069
100% Hull Split
23 Jun
13 Jul
2 Aug
22 Aug
11 Sep
1 Oct
Phase Threshold Day of Year, RCP 4.5

◀ **Fig. 5** The timing of three representative phenostages—chill accumulation (top row), 50% bloom (middle row), and 100% hull split (bottom row)—over the contemporary, early, and mid-21st century periods for RCP 4.5. Areas with multi-model mean SVI < 0.8 for each time period are masked out

Given that current almond locations remain thermally suitable into the mid-21st century, California's future water limitations (Seager et al. 2013) may motivate exploring the feasibility of almond cultivation in other regions. The NWUS will likely remain more water secure than California with continued climate change (Averyt et al. 2013). However, climate change may lead to water challenges in the NWUS, with decreased snowpack, earlier runoff, increased summer evaporative demands (Mote et al. 2014), and more frequent summer drought conditions (Marlier et al. 2017). Irrigated agriculture is sensitive to physical water availability and to legal institutions that govern water distribution; consequently, irrigated agriculture may see losses in crop revenue with declines in physically and legally available water (Xu et al. 2014). Further, in locations where almonds might replace crops with lower water requirements, almond plantations could exacerbate water resources challenges.

Beyond water challenges, there may be further limitations to almond cultivation in novel, thermally suitable locations. The shifting geographies of almond suitability may pair with similar niche shifts in—and increased resiliency of—agricultural weeds, pests, and disease, and increased competition for water and nutrient resources. Such changes in biotic interactions may alter orchard management practices and increase reliance on chemical controls, which may have detrimental environmental impacts (Pimentel et al. 1992). Further, the economic costs of crop translocation could be considerable. Crop range expansion or translocation requires appreciable capital and may have significant impacts on regional income (Luedeling et al. 2011a). Beyond crop production, additional costs would be incurred in transporting crops to centralized processing and distribution facilities. Finally, some sociological considerations such as culture and grower risk tolerance and unfamiliarity with new cropping systems are likely to govern the reality of almond cultivation in novel regions.

5 Conclusions

This study highlights some of the possibilities and limitations the almond industry may face under climate change by applying a suitability model to assess the geographic distribution of thermally viable almond cultivation locations in coming decades. We find that cropland in the northern Willamette may become thermally suitable to almond cultivation by the mid-21st century and that virtually all of California's current almond plantations remain thermally suitable. However, these results do not provide a singular answer for the future of the almond industry. The SM focuses on the Nonpareil varietal and does not consider alternative varietals and rootstocks that may be better suited to novel climates (e.g., lower heat requirements for maturation). Nor does the SM account for non-thermal factors governing cultivation, such as water availability, pollinator phenology, competing land use, economic considerations, or grower risk tolerance. Such important lingering questions highlight the need for further research in order to provide a clear and actionable picture for growers regarding environmental suitability and production potential for almonds. Still, recognizing that novel cultivation locations for high-value orchard crops may exist within the lifetime of orchards planted today has implications for long-term land use and water management planning and provides additional insight to inform future development.

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