

MODELING THE THERMAL NICHE FOR PERENNIAL AGRICULTURE UNDER CURRENT AND
FUTURE CLIMATE

A Dissertation

Presented in Partial Fulfillment of the Requirements for the

Degree of Doctorate of Philosophy

with a

Major in Geography

in the

College of Graduate Studies

University of Idaho

by

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May 2017

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ABSTRACT

Delineating locations viable for cultivating perennial crops has implications for economics, land use planning, water management, and food security at local, regional, national, and global scales. Provided that growing season water requirements for commercial perennial crops are typically met through irrigation, understanding the relationship between crop distribution and thermal variables is important for informing current agricultural practices, as well as when considering adaptive measures for climate change. Using almonds as an example, the changing geographies of suitable cultivation locations were examined under current and future climate, providing insight into opportunities cultivation expansion and translocation. One widely used measure of assessing the climatic suitability of a location for crop cultivation is the United States Department of Agriculture Plant Hardiness Zones (HZs), defined by average coldest annual temperatures. Evaluations of changes in winter temperatures showed a warming of the coldest temperatures by the mid-21st century, resulting in a northward shift in HZs across the United States and an expansion in the overwinter survival area for almonds. To address additional thermal constraints on species range, comparisons were made between two empirical species distribution models (SDMs) and a mechanistic model (MM) in modeling the thermal niche of almond. Results suggested that while using agriculturally relevant metrics in SDMs may improve SDM results, where data are available, an MM more effectively captures the interannual climate variability that is important for assessing suitability for cultivating perennials. Consequently, an MM was used to model future almond distribution. Model results showed that warmer mid-century temperatures reduced frost risk and increased annual heat accumulation across the northwestern US (NWUS), where such thermal conditions currently limit almond cultivation. In addition to range expansion, warming temperatures also resulted in a compression of crop development and a shift of crop phenology toward earlier maturation. While factors such as water availability, biotic interactions, and competing land use were not considered here, these results collectively suggest that translocation may be possible. Should non-thermal challenges to cultivation be manageable, geographic diversity in crop cultivation may provide an option for adapting perennial crop production to climate change and provide for economic and food supply stability.

ACKNOWLEDGEMENTS

I would first like to thank my advisor, John Abatzoglou, for his guidance, patience, constructive and fair feedback, and support of my research, my development as a scholar, and my broader career and life pursuits. My appreciation of John's advising style and humor - both in humoring my ideas and in being humorous - made for a rewarding experience that was about as enjoyable as a PhD ought to be. I must also acknowledge my committee members, Paul Gessler, Karen Humes, and Russell Qualls, for their involvement in my degree progression. I am appreciative of their time and energies spent in committee service, and am grateful for their respective roles in an engaging, educating, interesting, and relatively low-stress examination.

Beyond my advisor and committee, I would like to acknowledge Steven Daley-Laursen for his enthusiasm in showing me the ropes of the administrative side of academia, and I would like to thank the faculty and staff involved with the REACCH project for their support and positive feedback on research ideas and extracurricular pursuits. Sanford Eigenbrode and Dianne Daley-Laursen must be acknowledged by name and I am especially grateful for all of Dianne's hard work taking care of funding, payments, scheduling, paperwork, and minutia, allowing me to focus on research and scholarly development.

Taking the science to the people is at the heart of Katherine Hegewisch's work, and I am incredibly grateful for her efforts in translating my research into actionable tools, as well as for her friendship and moral support over these past years. I count myself fortunate to have been part of a lab of both accomplished scientists and superb human beings.

Finally, I must acknowledge others not directly involved with this work but who were no less important to the process: my parents and brother; friends Paige, Sarah, Conni, and Claire; my MoHos, who are in a category unto themselves; and my grandmother, whom I think of often. I owe Mister Gunny lots of treats for his company and daily reminders to get away from the computer. And perhaps most importantly, I owe a debt of gratitude to Tom, whose patience and encouragement have been nearly boundless. Without your support this experience would have been much more difficult and a lot less fun.

This work was made possible through the financial support of the National Institute of Food and Agriculture competitive grant, award number: 2011-68002-30191.

To be interested in food but not in food production is clearly absurd.

–Wendell Berry, *Citizenship Papers*

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CHAPTER 1: INTRODUCTION

Climate Change Impacts on Agriculture

Agriculture in the United States (US) is a multi-billion dollar industry, with farm output alone accounting for roughly 1% of total US gross domestic product (USDA ERS 2016). Orchard crops accounted for nearly 15% of the US agricultural economic sector in 2016 despite accounting for less than 2% of US cropland acreage (USDA ERS 2016; USDA NASS 2012). The bulk of the US fruit and nut crop is produced in California, with the state's orchard crops comprising roughly two-thirds of US total production in 2015 (CDFA 2016).

With wet winters and dry summers, California's Mediterranean climate is coupled with elaborate water infrastructure that allows for widespread irrigation making much of California ideal for cultivating a variety of temperate-region fruit and nut crops. However, recent water shortages associated with the multi-year drought from 2012-2016 in California have had an adverse affect on California orchard production, resulting in yield declines and fallowed land (Bland 2015; Romero 2017; Sofer 2016; Strom 2014). Additionally, warmer winter temperatures have reduced winter chill – a necessary condition for blossom development – in California's Central Valley (Luedeling et al. 2009), and resulted in reductions in Sierra snowpack (Knowles et al. 2006), a critical source for California's irrigation water.

Continued changes in climate are anticipated to produce both positive and negative impacts to agriculture in the US. Warmer growing season temperatures may increase water demand and detrimentally impact some crop yields (Schauberger et al. 2017), and warmer winters may be increasingly problematic for fruit and nut production in California, particularly for crops that require high amounts of winter chill. By contrast, higher atmospheric CO₂ may increase water use efficiency and yields in some crops and locations (Deryng 2016), and agricultural productivity and potential may increase in northerly latitudes as climate change precipitates longer growing seasons and a reduction in early season frost risk (Mueller et al. 2015; Peterson and Abatzoglou 2014). Still, while some benefits may exist for certain crops and locations, climate change is projected to have an aggregate negative impact on the agriculture industry both nationally (Hatfield et al. 2014) and in California, impacting not only yield and grower income (Deschenes 2011; Lobell 2006), but also consumer costs (Strom 2014).

Perennial crops may be particularly impacted by climate change. Unlike annual crops, which can be fallowed in years with unfavorable environmental conditions or replaced with

new varieties in response to climatic change, the adaptive capacity of perennial crops to climate variability and change is more limited. High value orchard crops such as almonds and wine grapes cannot be fallowed and have decades-long life spans, requiring significant capital investment to implement adaptive measures such as planting new varieties or relocating orchards (Hayhoe et al. 2004; Lobell and Field 2011). Numerous studies have addressed the impacts of climate change on perennial fruit and nut crops in California, focusing largely around water availability and challenges associated with increasing temperatures. These studies have shown that warming temperatures can negatively impact yields and market value for perennial crops with chilling hour requirements (Luedeling et al. 2009), and increase the incidence of agricultural pests (Ziter et al. 2012). Warming temperatures in California may also increase in irrigation demand (Mehta et al. 2013) and decrease water supply (Cayan et al. 2008), resulting in increased water scarcity (Averyt et al. 2013) that will increase competition for water among users.

One of the grand challenges facing society in the coming decades is to sustainably feed a growing world population with limited land resources and the additional stressors of changing environmental conditions. All signs point toward a future with increased global caloric demands and a climate different from the one in which modern agriculture has developed. The impacts of climate change on agriculture are multitudinous, spanning land use, water resources management, economics, food security, and public health (Boxall et al. 2009; Lobell et al., 2008; Schmidhuber and Tubiello, 2007). Consequently, it is increasingly important to understand the potential for cultivating crops beyond their current range, particularly for crops that may suffer deleterious effects from climate change in the existing range. Understanding the changing geographies of crop cultivation in a changing climate will be particularly important for perennials given the additional challenges in their cultivation. Ultimately, modeling potential cultivation locations for perennials under future climate scenarios provides a first step toward assessing opportunities for crop translocation, which may prove a viable adaptation approach for agricultural systems impacted by climate change.

Objectives and Overview

It is hypothesized that while climate change may negatively impact perennial fruit and nut cultivation in California, climate change may increase the potential for cultivation in higher altitude and latitude locations. The objectives of this work are to assess the potential geographic shift in thermally suitable cultivation areas for perennials by (1) calculating changes in annual

minimum temperature extremes and subsequent shifts in US Department of Agriculture cold hardiness zones that provide a climatic restriction on perennial crop cultivation, (2) evaluating modeling methods for delineating cultivar thermal niche under for a perennial crop, and (3) determining the geographic potential for cultivating a high value perennial crop under future climate conditions. This dissertation presents work addressing these objectives individually, each written and formatted for publication in refereed journals.

Chapter 2 examines changes in annual coldest daily minimum temperatures (TN_n), which govern overwinter survival rates of natural and cultivated species, relative to mean winter minimum temperatures. Changes in cold hardiness zones, defined by the climatology of these extreme cold temperatures, are also calculated. While shifts in TN_n and cold hardiness zones are broadly applicable to perennial and annual crops and ornamentals, this chapter also examines how these shifts impact three specific fruit and nut crops: Nonpareil almonds, Hayward kiwifruit, and Navel oranges.

Using almonds as a case study, chapter 3 evaluates three methods of modeling perennial crop distribution: a mechanistic model based on published bioclimatic requirements, an empirical model using standard bioclimatic variables, and an empirical model using horticulturally relevant climatic variables. In addition to assessing the ability of each of these models to capture species range, the mechanistic model also elucidates the limiting thermal factors to almond cultivation across the landscape.

Building on chapter 3, the mechanistic model is used to project the future thermal niche of almond under climate change across the western US coastal states. These results are presented in chapter 4 along with an analysis of how almond phenology and the limiting thermal factors to almond cultivation shift over time and space under climate change. This chapter highlights where almonds might continue to thrive, and where thermal conditions may allow for expansion into novel regions.

While each chapter addresses a single objective of the larger work, collectively they address the potential implications of climate change for perennial fruit and nut crops, illustrating the changing geographies of perennial cultivation in a warmer future. As such, chapter 5 provides a brief conclusion to the dissertation, offering a synthesis of the findings and providing final thoughts regarding some of the knowledge gaps that remain and recommendations for future research.

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CHAPTER 2: COLD HARDINESS ZONES AND SUITABLE OVERWINTER RANGES

Published in *Environmental Research Letters*

Parker LE, Abatzoglou JT (2016) Projected changes in cold hardiness zones and suitable overwinter ranges of perennial crops over the United States. *Environmental Research Letters* 11(3):034001

Abstract

Average annual absolute minimum temperatures (TN_n) provide a means of delineating agriculturally relevant climate zones and are used to define cold hardiness zones (CHZ) by the United States Department of Agriculture. Projected changes in TN_n , mean winter minimum temperatures, and CHZs over the conterminous United States (CONUS) were assessed using an ensemble of statistically downscaled daily climate model output through the mid 21st century (2041-2070). Warming of TN_n is on average ~40% greater than that of mean winter minimum temperatures across CONUS, resulting in widespread shifts in CHZs and an average climate velocity of 21.4km decade⁻¹ resulting in widespread shifts in CHZs. These changes enable a geographic expansion of thermally suitable areas for the cultivation of cold-intolerant perennial agriculture including almond, kiwi, and orange crops. Beyond these crops, warming of TN_n has broad implications for food security and biotic interactions.

Introduction

A number of studies have highlighted the importance of both mean and extreme minimum temperatures to ecological systems. For example, monthly average minimum temperatures have been used for habitat mapping (e.g. Ledig *et al.*, 2010), crop yield assessment (e.g. Lobell *et al.*, 2007), and pest monitoring (e.g. Tràn *et al.*, 2007; Paradis *et al.*, 2008). While the distribution of species may not be directly linked to mean annual or monthly temperatures, extreme minimum temperatures have established links to the overwinter survival rates of insects (e.g. Bale, 1996; Stahl *et al.*, 2006) and plants (Alden and Hermann, 1971; Vetaas, 2002). Consequently, extreme minimum temperatures provide constraints on the potential geographic range of natural and cultivated species (e.g. Woodward *et al.*, 2004), and can impact crop yields (e.g. Porter and Gawith, 1999; Gu *et al.*, 2008).

Cold damage to plants may occur at a range of minimum temperatures (T_{\min}) depending on species sensitivity and phenological stage (Sakai and Larcher, 1987; Larcher, 2005). Given the challenges in generalizing plant cold tolerance, the United States Department of Agriculture (USDA) developed cold hardiness zones (CHZ) based on annual minimum T_{\min} (TN_n) averaged over a climatological period. These zones provide guidance for where plants might survive, and are presently used to establish nursery crop insurance standards. A map of cold hardiness zones was first published by the USDA in 1960, and was updated in 1990 (Cathey, 1990) and again in 2012 (Daly *et al.*, 2012). Although other measures of delineating horticulturally relevant climate zones exist, we focus on the USDA hardiness zones because of their ubiquity over the United States (McKenney *et al.*, 2007).

Under climate change scenarios, mean winter temperatures (e.g. Maloney *et al.*, 2014) and extreme minimum temperatures are projected to warm (e.g. Kharin *et al.*, 2013; Sillmann *et al.*, 2013; Wuebbles *et al.*, 2014). Given the importance of cold extremes to species survival and distribution, increased temperatures may allow for the geographic expansion of plants, pests and invasive species into areas where they had previously been thermally limited (e.g. Battisti *et al.*, 2005; Weiss and Overpeck, 2005; Walther *et al.*, 2009). Additionally, annual T_{\min} cold extremes are of interest to a variety of civil sectors including electricity, transportation and infrastructure (e.g. Amato *et al.*, 2005; Larsen *et al.*, 2008).

Improved understanding of projected changes in temperature extremes – including TN_n – have implications for informing climate adaptation approaches for crop cultivation, identifying areas at risk for invasive species expansions, and tracking regions of potential changes in electricity and infrastructure needs. Increases in TN_n under climate change will

result in significant redistribution of biologically relevant thermoclines and subsequent species (e.g. Diffenbaugh *et al.*, 2008). Observed warming in annual average T_{\min} across the coterminous United States (CONUS) has resulted in poleward and altitudinal shifts in thermoclines, with spatially varying climate velocity – that is the speed and direction that a given property migrates with climate change (e.g. Dobrowski *et al.*, 2013). Previous studies have examined changes in the coldest minimum temperatures over the observational record (e.g. Alexander *et al.*, 2006; Brown *et al.*, 2008; Abatzoglou *et al.*, 2014), and those projected over the 21st century using climate models (Diffenbaugh *et al.*, 2008; Sillmann *et al.*, 2013; Abatzoglou and Barbero, 2014). Further, studies have shown larger warming of TN_n relative to maximum T_{\min} in observations (Alexander *et al.*, 2006), and in modeling studies (e.g. Kharin *et al.*, 2013; Sillmann *et al.*, 2013). The warming of these cold extremes in mid- and high-latitude locations has been connected to the reduction in snow and sea ice (e.g. Kharin and Zwiers, 2005; Kharin *et al.*, 2013), as well to the diminished variance in cold-season temperatures resulting from Arctic amplification (e.g. Screen, 2014).

We build on these aforementioned studies by examining TN_n and CHZ projections using an ensemble of global climate model output downscaled to a spatial resolution congruent with contemporary agroclimatic information, evaluating projected changes in TN_n relative to mean winter (December – February) T_{\min} (TN_{DJF}), and calculating the climate velocity of CHZs, TN_n and TN_{DJF} . Further, we complement previous work by examining the impact of projected changes in TN_n on thermally suitable areas for the cultivation of three high market-value perennial fruit and nut crops: Nonpareil almond, Hayward kiwi, and Navel orange.

Data and Methods

We obtained daily T_{\min} data from twenty global climate models (GCMs) participating in the fifth phase of the Climate Model Intercomparison Project (CMIP5) (Taylor *et al.*, 2012) that were statistically downscaled over CONUS using Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown, 2012) for both historical (1950-2005) and future (2006-2099) experiments. Downscaled data were trained using the gridded surface meteorological dataset of Abatzoglou (2013) at a 1/24th degree resolution grid that ensures that quantiles of the downscaled historical GCM period adhere to those of the observed record (1979-2012). The gridded dataset of Abatzoglou (2013) is a hybrid product that bias correct data from the North American Land Data Assimilation System (NLDAS2; Mitchell *et al.*, 2004) with monthly data from the Parameter Regression on Independent Slopes Model (PRISM; Daly

et al. 1994), and exhibits nominal biases for temperature extremes such as TN_n when compared to *in situ* weather stations (i.e., coldest 1% of daily TN had a mean bias of +0.5°C compared to data from Global Historical Climate Network stations). MACA uses an analog approach for mapping GCM fields to observed fields and applies an equidistant quantile mapping bias correction procedure (Li *et al.*, 2010; Pierce *et al.*, 2015) that preserves the differences between future and historical daily temperatures from GCM simulations across quantiles, including TN_n and other extreme values.

Dynamical downscaling using regional climate models (RCM) is arguably better suited for assessing climate extremes modulated by mesoscale land-surface phenomena (e.g., snow-albedo feedback). However, the restricted availability of RCM output from multiple GCMs and the additional statistical bias correction procedures needed for local assessment limited our analysis to the statistically downscaled products. We conduct a complementary analysis to facilitate a comparison between statistically downscaled products used in our analysis and dynamically downscaled results from two RCMs (CanCM4 and RCM4) using a common GCM ensemble member from the second generation Canadian Earth System Model (CanESM2) forced with RCP 8.5 as part of the CORDEX project (Giorgi *et al.*, 2009).

We constrained our analysis to model simulations for the historical period (1971-2000) and mid 21st century period (2041-2070). We chose to assess mid-century projections in TN_n , $TN_{\overline{DJF}}$, and CHZs because of the limited ability for developing meaningful management strategies relevant to end-of-century projections. We primarily focus on future experiments run under Representative Concentration Pathway 8.5 (RCP 8.5) given that inter-model variability exceeds inter-scenario variability for these time horizons (Kharin *et al.*, 2007; Kharin *et al.*, 2013), and emissions trajectories to date have more closely followed RCP 8.5 (Peters *et al.*, 2013).

TN_n for each winter-centric year was calculated from November – March, along with $TN_{\overline{DJF}}$. We calculated 30-year averages of TN_n and $TN_{\overline{DJF}}$ for each model for both the historic and mid 21st century time periods and considered both multi-model ensemble averages, as well as the ensemble 25th and 75th percentiles to assess intermodel variability. The climate velocities of multimodel mean TN_n and $TN_{\overline{DJF}}$ between historical and mid 21st century were calculated using a distance-based velocity algorithm (Hamann *et al.*, 2015). This algorithm determines the shortest distance between locations with analog climates and divides by the number of years between the two climate periods to provide the climate velocity in units of km yr^{-1} . We calculated both forward (i.e. current-to-future) and backward (future-to-current) velocities of

the ensemble average temperature and report the minimum of the two velocities as a conservative estimate.

The multi-model mean of 30-year average TN_n values were also used to define CHZs. Hardiness zones range from -51.1° to 21.1°C with each zone spanning 5.6°C and being comprised of half-zones A and B, each covering a 2.8°C range. Projected changes in CHZs and the velocity of CHZ shifts were also calculated. While CHZ projections may be useful for assessing climate change impacts on crop cultivation, we utilize minimum temperature thresholds (TN_{CROP}) for dormancy as a means of examining how projected changes in TN_n may expand thermally suitable areas for crop survival. We chose to examine the impacts of projected changes in TN_n on Nonpareil almonds, Hayward kiwis, and Navel oranges because of their relatively high market value. These cultivars also provide examples across a range of hardiness threshold temperatures, from -25°C for Nonpareil almonds (Janick and Moore, 1996), to -12°C for Hayward kiwifruit (Strik, 2005), to -4.4°C for Navel oranges (Fake and Norton, 2012). Using the multi-model mean TN_n for both the historical and mid-century periods, we calculated the percent area over CONUS with TN_n values above TN_{CROP} . Additionally, to provide a more conservative measure of potential changes in crop cultivation area, we also assessed the percent suitable land area where at least 80% of the models showed $TN_n > TN_{\text{CROP}}$.

Results

Ensemble average projected increases in $TN_{\overline{\text{DJF}}}$ range from 1.7°C in the southeastern US to more than 5°C in the Upper Midwest and northern Great Plains (Figure 2.1a). While the spatial pattern of warming for $TN_{\overline{\text{DJF}}}$ resembled that seen in TN_n , the magnitude of warming of the latter was more acute across a majority of CONUS (Figure 2.1b). The ensemble average TN_n warming ranged from 1.8°C to more than 7°C warming, yielding a 40% greater increase compared to $TN_{\overline{\text{DJF}}}$ when averaged over CONUS. This results in an additional 2°C of warming of TN_n over $TN_{\overline{\text{DJF}}}$ across a broad region of the Midwestern US, Great Lakes and interior northwestern US (Figure 2.1c). This asymmetric warming was found for all downscaled GCMs across much of the northern half of the United States from the Great Plains to the Atlantic Ocean, as well as for much of the Intermountain West. Conversely, fewer GCMs showed differential warming across portions of the southern United States, the Rocky Mountains, and portions of the Southwest including California and Arizona (Supplemental Figure 2.S1). Intermodel variability, represented by 25th and 75th percentiles of projected increases in TN_n

and $TN_{\overline{DJF}}$ across models (Supplemental Figure 2.S2), was largest over the northern US and the northern Rocky Mountains of Idaho and Montana, for $TN_{\overline{DJF}}$ and TN_n , respectively.

The velocity of TN_n also varied spatially (Figure 2.2a). The mean (median) estimate of the speed of TN_n over CONUS was 21.4km decade⁻¹ (16.2km decade⁻¹), albeit with substantial spatial heterogeneity as seen in prior assessments of climate velocity (e.g., Dobrowski et al., 2013; Loarie *et al.*, 2009). The fastest speed of TN_n was found over the northern Great Plains and Midwestern US due to large increases in TN_n coupled with a weak spatial gradient in TN_n , while slow speeds were found along the West Coast, in the Southwest, and in coastal Florida. By comparison, the velocity of projected $TN_{\overline{DJF}}$ was less than TN_n , with a mean (median) of 15.6 km decade⁻¹ (12 km decade⁻¹) and with similar spatial patterns (Figure 2.2b). As an artifact of the spatial bounds of our data, forward-looking climate velocities have no analog climates within CONUS for parts of the Northern Plains and more localized areas in the Rocky Mountains and the Northeast (Supplemental Figure 2.S3). Backward-looking velocities show analog climates over 95% of locations and differ from forward-looking velocities, particularly over the topographically complex Western US.

As CHZs are calculated from average TN_n , those locations showing the largest warming of TN_n also exhibited the largest projected increases in CHZs (e.g. from zone 5 to 6). Cold hardiness zones of downscaled GCM data from historical runs (Figure 2.3a) were similar to published CHZs from observational records (e.g. Daly *et al.*, 2012). A comparison of ensemble mean TN_n downscaled from historical runs and TN_n calculated using daily PRISM data from 1981-2010 showed absolute biases < 1.5°C over CONUS, with a mean bias of +0.1°C, suggesting reasonable agreement. Mid-century CHZ projections showed northward and upward shifts in existing zones (Figure 2.3b), with a mean (median) shift over CONUS of ~93km (~56km) by the mid 21st century. Nearly all (98%) of CONUS exhibited an increase in CHZ (i.e. toward warmer absolute minimum temperature) using the multi-model mean, and no location saw a decrease in CHZ. Similar changes in CHZ were projected by the mid 21st century using RCP 4.5 forcing (Supplemental Figure 2.S4).

Warming TN_n (and consequent shifting CHZs) resulted in an increase in land area with sufficiently warm temperatures for overwinter survival of crops. Over the historical period, approximately 24% and 5% of CONUS had sufficiently warm TN_n for overwinter survival of oranges and kiwifruit, respectively (Figures 2.4a,c). Mid 21st century projections of TN_n would enable an expansion of land with suitable overwinter temperatures to approximately 37% and 9% of CONUS for kiwifruit and oranges, respectively; the extent of TN_{CROP} for oranges expanded

northward along coastal areas and kiwi expanded northward from its historical range (Figures 2.4b,d). The majority (~74%) of CONUS showed multi-model mean $TN_n > TN_{CROP}$ for almonds over the historical period (Figure 2.4e), expanding into the north central plains and covering ~93% of CONUS by the mid 21st century (Figure 2.4f). A more conservative approach, where at least 80% of the models have $TN_n > TN_{CROP}$, shows comparable results: the percent land area suitable for crop survival over the historical (future) period was ~73% (~90%) for almonds, ~23% (~32%) for kiwi, and ~5% (~8%) for oranges.

Similar patterns of warming are evident across the statistically and dynamically downscaled data, however changes in TN_n and TN_{DJF} are more heterogeneous in the dynamically downscaled outputs (Supplemental Figure 2.S5). The spatial correlation of changes in TN_n (TN_{DJF}) between the downscaled data and the RCMs were 0.80 (0.87) for RCM4, and 0.83 (0.88) for RCA4. The raw GCM output, statistically downscaled data, and both RCMs show amplified warming of the TN_n versus TN_{DJF} over the majority of CONUS. Whereas the RCMs highlight heterogeneous warming in the topographically complex western United States, the inter-RCM variability is quite large.

Discussion and Conclusions

The mechanisms responsible for the amplified warming of TN_n are likely a function of Arctic amplification and land-atmosphere interactions. The Arctic and interior Canada are primary air mass source regions for cold air outbreaks over CONUS that typically result in TN_n . Observed amplification in warming rates over high latitude landmasses and the poles versus the mid-latitudes has contributed to an increase in the temperature of cold air masses that have impacted CONUS over the second half of the 20th century (Walsh *et al.*, 2001; Hanks and Walsh, 2011). Huybers *et al.*, (2014) showed a pattern of decreased variance of the coldest 5% of TN in DJF with warming TN_{DJF} on an interannual basis in observations, which supports the amplified warming of TN_n . Continued amplified warming rates of source regions for cold air outbreaks likely contribute to the larger warming rate of TN_n versus TN_{DJF} . While changes in atmospheric circulation with climate change have been hypothesized to increase the potential for cold air outbreaks (e.g. Francis and Vavrus, 2012), decreases in temperature variance as a result of climate change would reduce the potential for cold air outbreaks (e.g. Schneider *et al.*, 2015; Screen, 2014). Changes in snow cover and depth can also increase warming rates as the high albedo and thermal emissivity of snow cover helps promote exceptionally cold temperatures.

Consequently, projected declines in snowfall (Lute *et al.*, 2015) and snow depth (e.g. Salathé *et al.*, 2008) may locally alter the radiative balance and contribute to differential rates of warming (e.g. Dyer and Mote, 2006). However, Abatzoglou and Barbero (2014) and Gao *et al.* (2015) noted that extreme cold air outbreaks including all-time record low temperatures may occur under a warmer climate, though with reduced duration and spatial extent.

Climate velocity may shape the distribution of ecological zones and resident species (Loarie *et al.*, 2009). As TN_n has a direct link to species viability, we suggest that the climate velocity of such metrics is important for changes in range shifts in agricultural and natural ecosystems. While their methodology for calculating climate velocities differs from that used here, Dobrowski *et al.* (2013) showed similar patterns in the velocity of mean T_{min} over the 20th century, though our mean projected velocities of TN_n are greater than the average velocity of mean T_{min} in that study. The greater velocity of TN_n versus $TN_{\overline{DJF}}$ suggests a hastened rate of change that may be important for planning and adaptation efforts, and in fact the velocity of change may be more important for some adaptation efforts than the magnitude of the change itself.

It is important to note the uncertainty in the projection of extremes in GCM data and associated statistical downscaling that may not fully capture the mesoscale land-surface feedbacks that can modify warming of temperature extremes. Statistically and dynamically downscaled products for a common GCM ensemble member generally show similar patterns in TN_n and $TN_{\overline{DJF}}$, but localized magnitudes differ. The heterogeneity exhibited in the dynamically downscaled products (e.g. over the western US) likely highlight regions where snow-albedo feedbacks are captured by RCMs (e.g. Salathé *et al.*, 2008; Pepin *et al.*, 2015). In this respect, RCMs may help to unveil changes occurring at local scales that are not adequately resolved using statistical approaches. However, the influence of snow-albedo feedbacks is contingent upon accurately simulating snowcover changes. The differences in magnitude and spatial heterogeneity of the change in TN_n and $TN_{\overline{DJF}}$ between the RCMs examined here indicate the challenges in refining the magnitude of change at local scales. Likewise, the lack of ensemble GCM-RCM combinations and the potential for GCM biases to propagate into RCM simulations currently limit a comprehensive analysis suitable for research of this sort. However, coordinated experiments such as CORDEX (Giorgi *et al.*, 2009) can better elucidate uncertainty that arises through downscaling approaches as well as highlight value-added downscaling from RCMs on changes in TN_n that may help refine our results.

The increase in TN_n and subsequent shifts in CHZs projected for mid-century periods supports previous work on changing thermal suitability envelopes. For example, the analysis of Lobell *et al.* (2006) on perennial crops over California showed favorability for future crop development at higher latitudes or elevations. Similarly, Olesen *et al.* (2007) project an expansion in thermal suitability zones for maize production over Europe during the 21st century. While our analysis does not consider other factors (e.g. heat tolerance thresholds, chilling hour requirements, water availability, competing land use) that govern where crops can be cultivated, warming of TN_n may provide opportunities for crop production in regions that are currently thermally limited by cold extremes. However, there are many caveats to the potential for crop expansion with respect to warming TN_n . For the perennials examined here that are either early blooming or highly sensitive to frost damage, commercial cultivation occurs almost exclusively in areas where TN_n is much warmer than TN_{CROP} and there are few studies providing thorough examination of threshold temperatures for cold hardiness (Janick and Moore, 1996). It should be noted that the TN_{CROP} values used in this study are temperatures that would severely damage or kill crops during overwinter dormancy; during other phenological stages, crops may be at higher risk for damage from less extreme cold temperatures. Further, while these threshold temperatures may be tolerated during dormancy for a few hours, many hours below TN_{CROP} would result in increased damage or mortality (Fake and Norton, 2012). Additionally, tolerance may decrease on nights with little wind when radiative heat loss can cool plant tissues below the ambient air temperature (Johnson, 2011).

Warming TN_n and projected shifts in CHZs have implications for agricultural and natural vegetation, land management, the energy sector and infrastructure. In addition to cultivated crops, native and invasive species and pests may also see geographic expansion, resulting in additional challenges for agricultural land managers as well as those managing forests, rangelands and other natural resources (e.g. Noss, 2001). Moreover, an increase in TN_n may also have economic impacts. Provided that the greatest electrical demands for heating occur during the coldest temperatures, the anticipated reductions in heating demand assessed from projected changes in TN_{DJF} may be augmented further with greater rates of warming of TN_n (Scott and Huang, 2007; Mideksa and Kallbekken, 2010). In addition to lowered heating costs, further economic impacts of warming TN_n include the reduced cost of transportation infrastructure repairs as warmer T_{min} extremes reduce thermal stress on asphalt and damage from frost heaves (e.g. Mills and Andrey, 2002).

The differential warming exhibited between changes in mean and extreme minimum winter temperatures highlights the importance of assessing both means and extremes in understanding potential impacts of climate change. Through utilizing daily projections to illustrate results with direct implications for climate change impacts, we show the benefit in revisiting previous studies whose analyses were limited temporally and spatially by previously unavailable downscaled daily data, and suggest that for applied purposes statistically downscaled products may be preferable to RCMs for multi-member ensemble studies. Finally, although the caveats presented above highlight the need for additional research to more fully account for the role of climatological factors governing crop survival, our results show promise for geographic expansion of thermally limited cultivars under climate change.

Acknowledgements

This research was funded through award #2011-68002-30191 from USDA National Institute of Food and Agriculture. We appreciate the constructive feedback from three anonymous reviewers that helped improve the quality of the manuscript.

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Figures

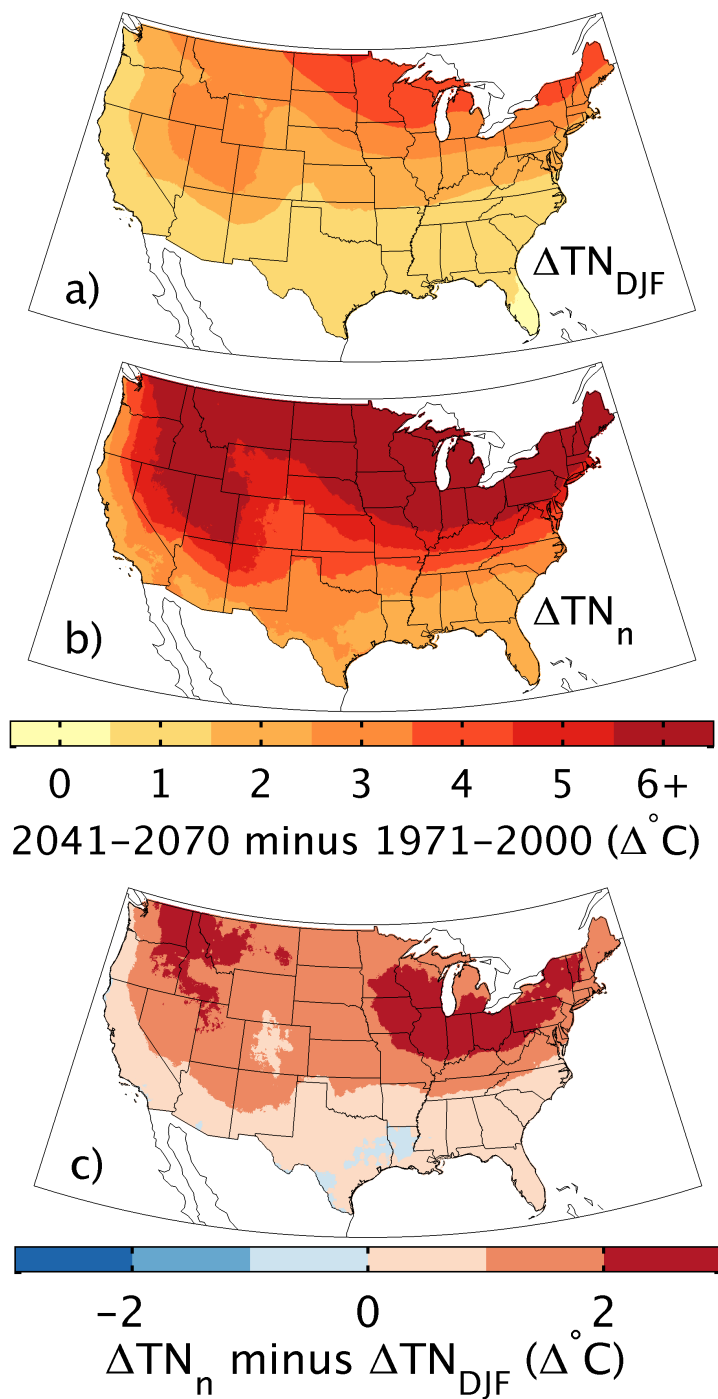


Figure 2.1 Projected ensemble averages of (a) mid-century warming in TN_{DJF} over CONUS (b) mid-century warming in average TN_n and (c) the difference in warming of TN_n and warming of TN_{DJF}

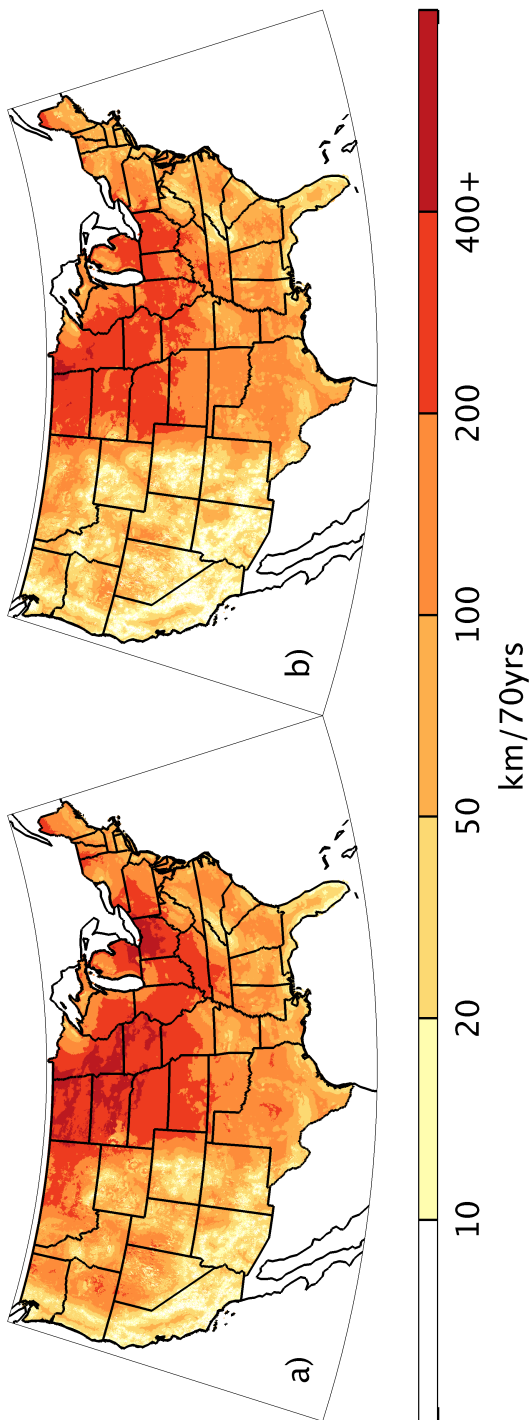


Figure 2.2 Estimated climate velocity of (a) TNn and (b) TN_{DJF} defined as the minimum of the forward and backward looking calculations

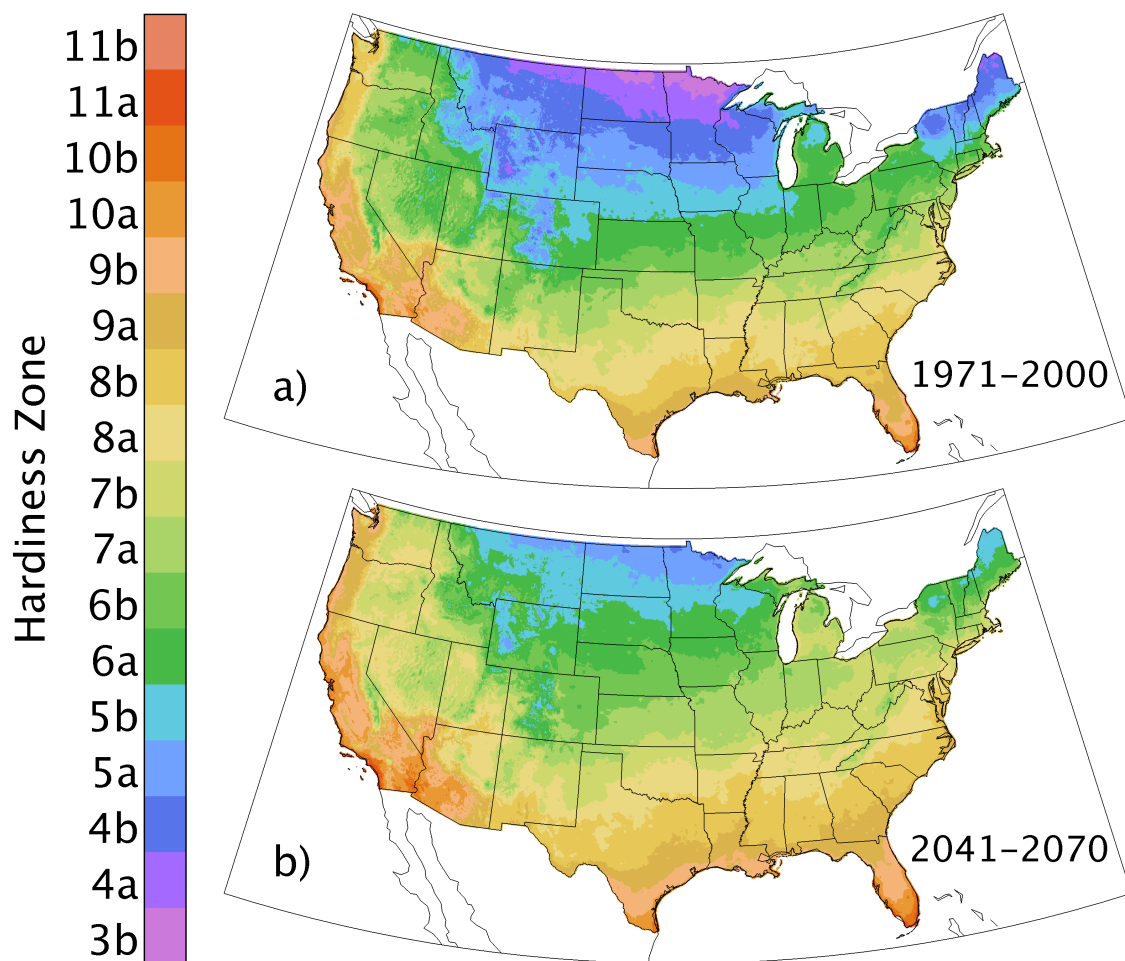


Figure 2.3 (a) Cold hardiness zones as defined by the multi-model mean of TN_n averaged over the period 1971-2000. (b) Cold hardiness zones as defined by the multi-model mean of TN_n over the period 2041-2070, showing shifts in hardiness zones over the majority of CONUS

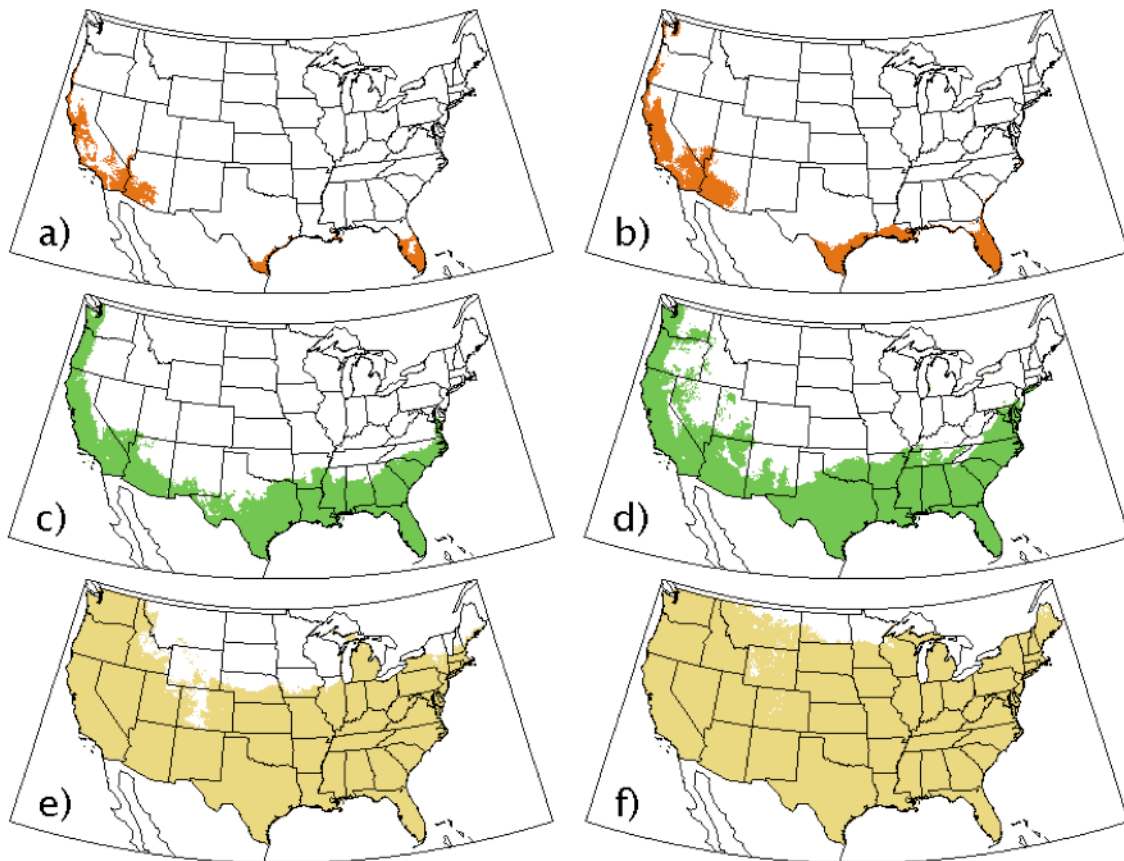
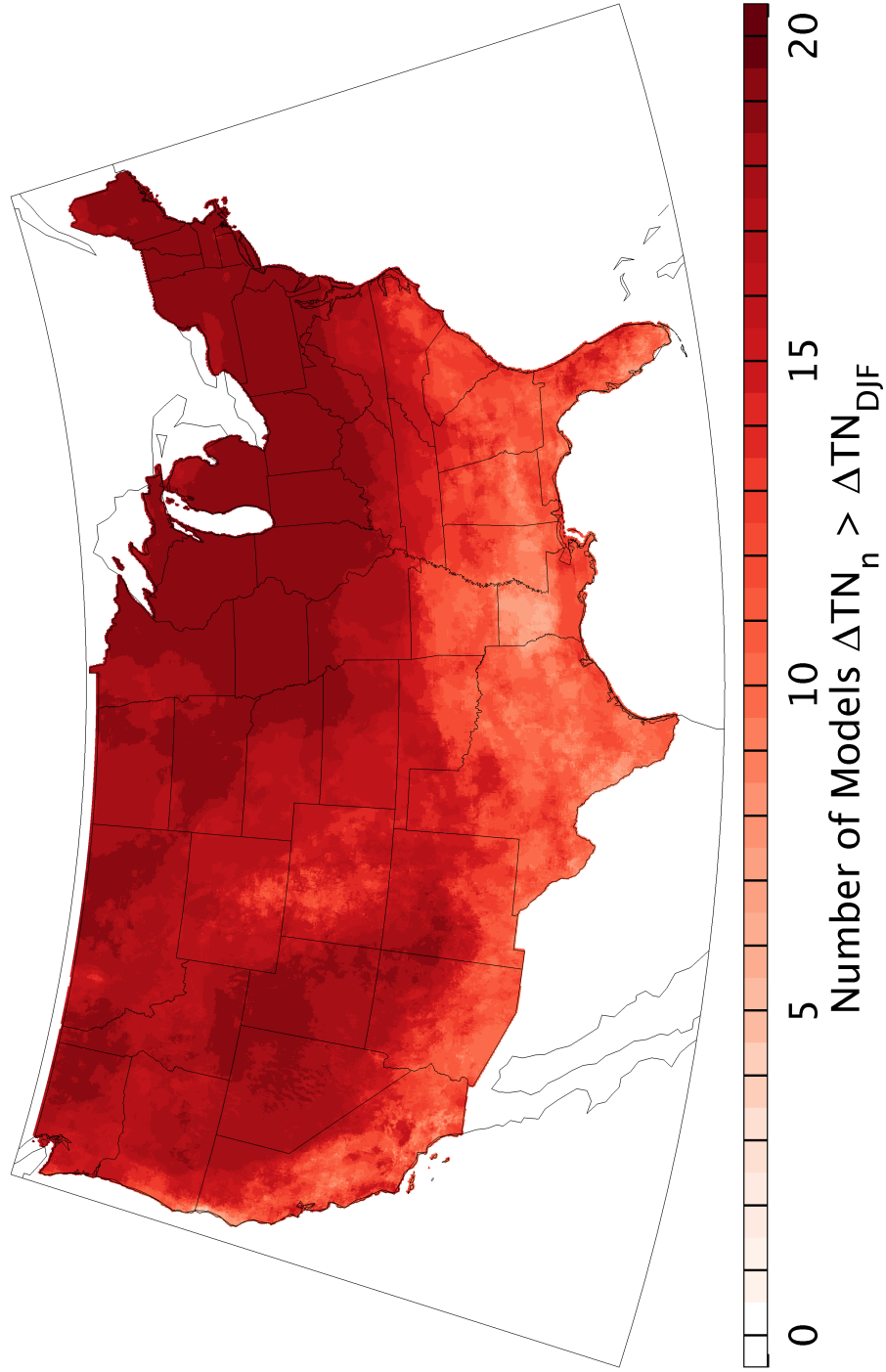
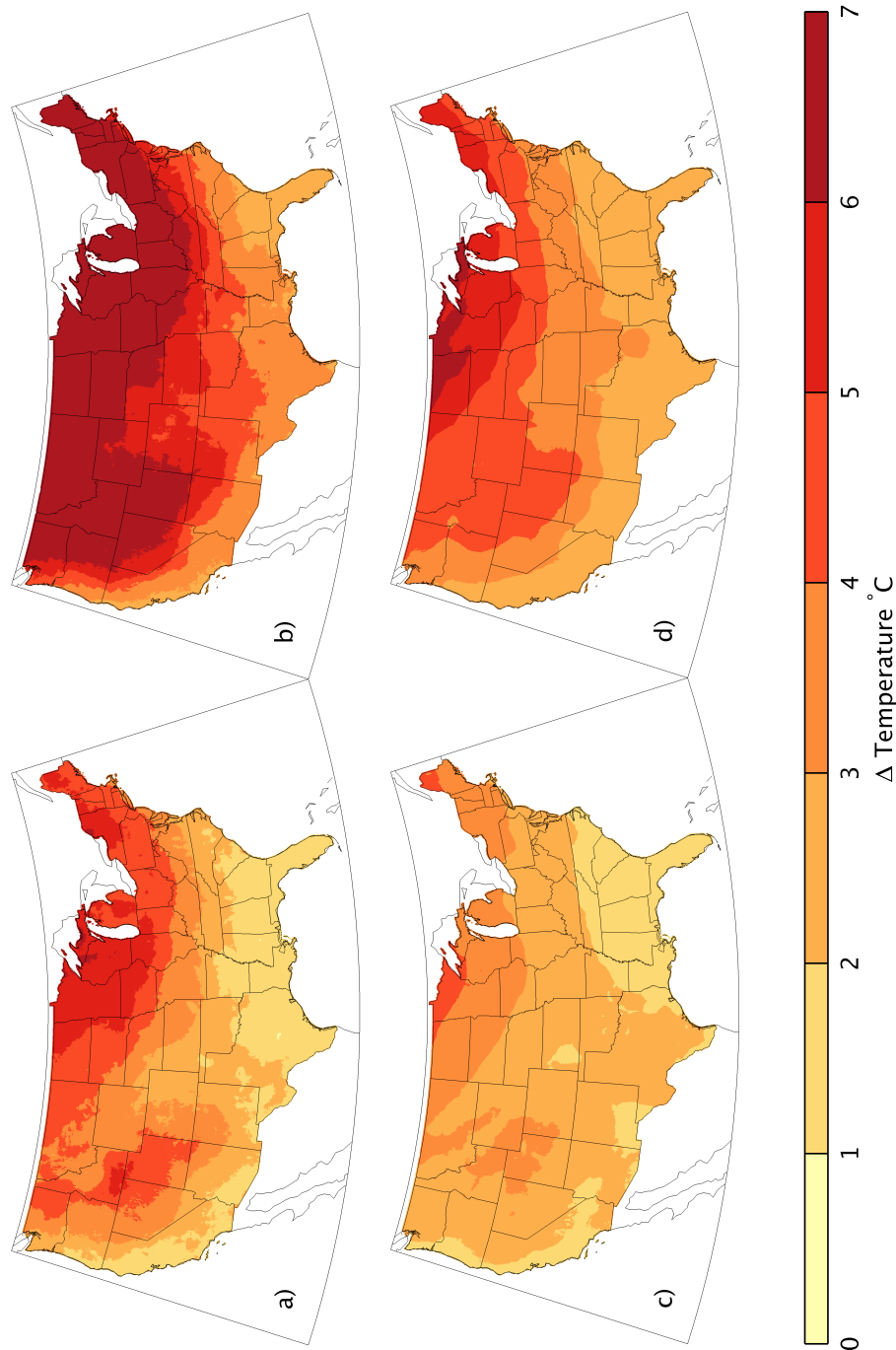


Figure 2.4 Shaded areas are those where the ensemble average $TN_n > TN_{CROP}$ for: (a) oranges over the period 1971-2000 (b) oranges over the period 2041-2070 (c) kiwifruit over the period 1971-2000 (d) kiwifruit over the period 2041-2070 (e) almonds over the period 1971-2000 (f) almonds over the period 2041-2070

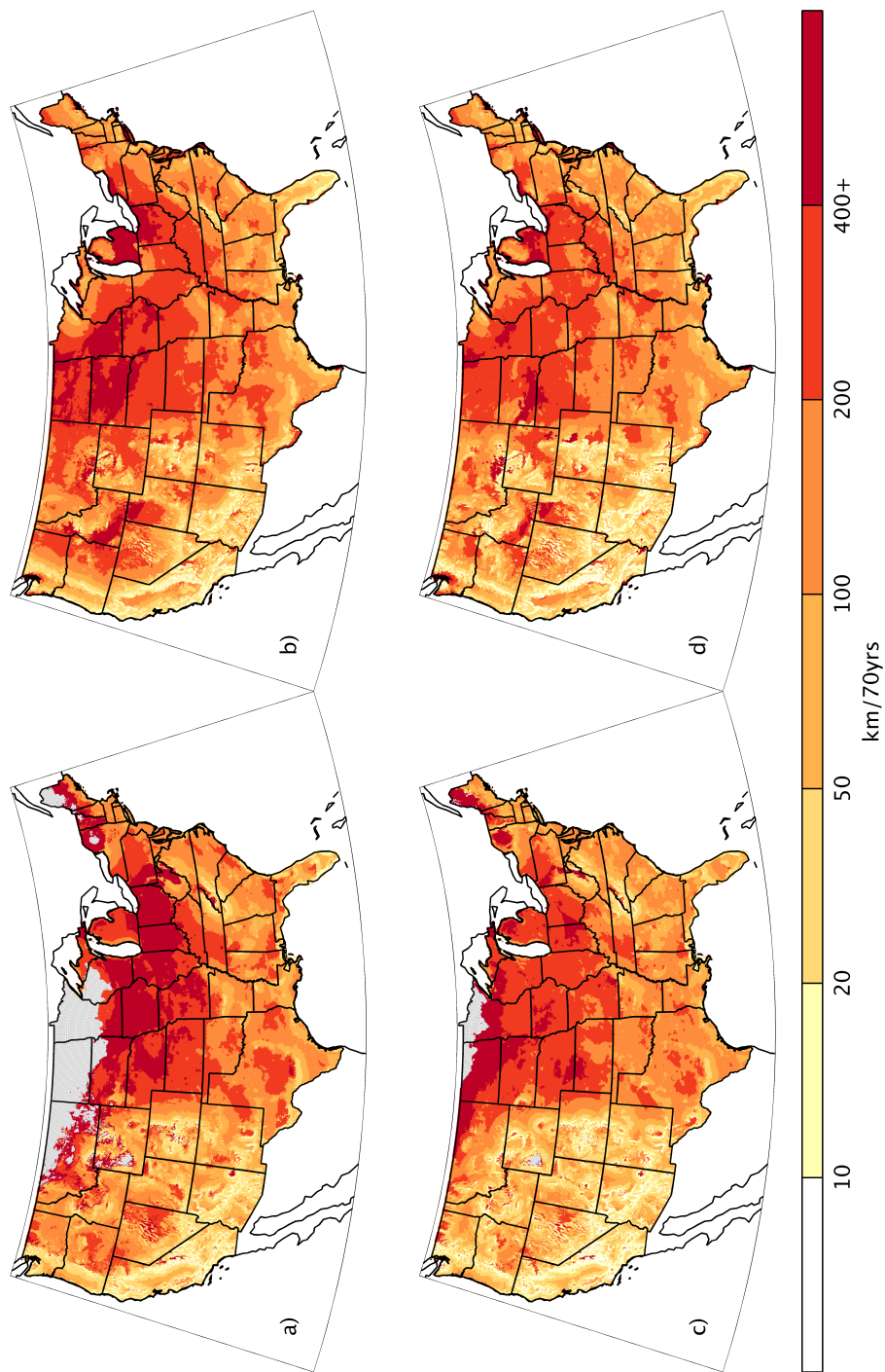
Supplemental Figures



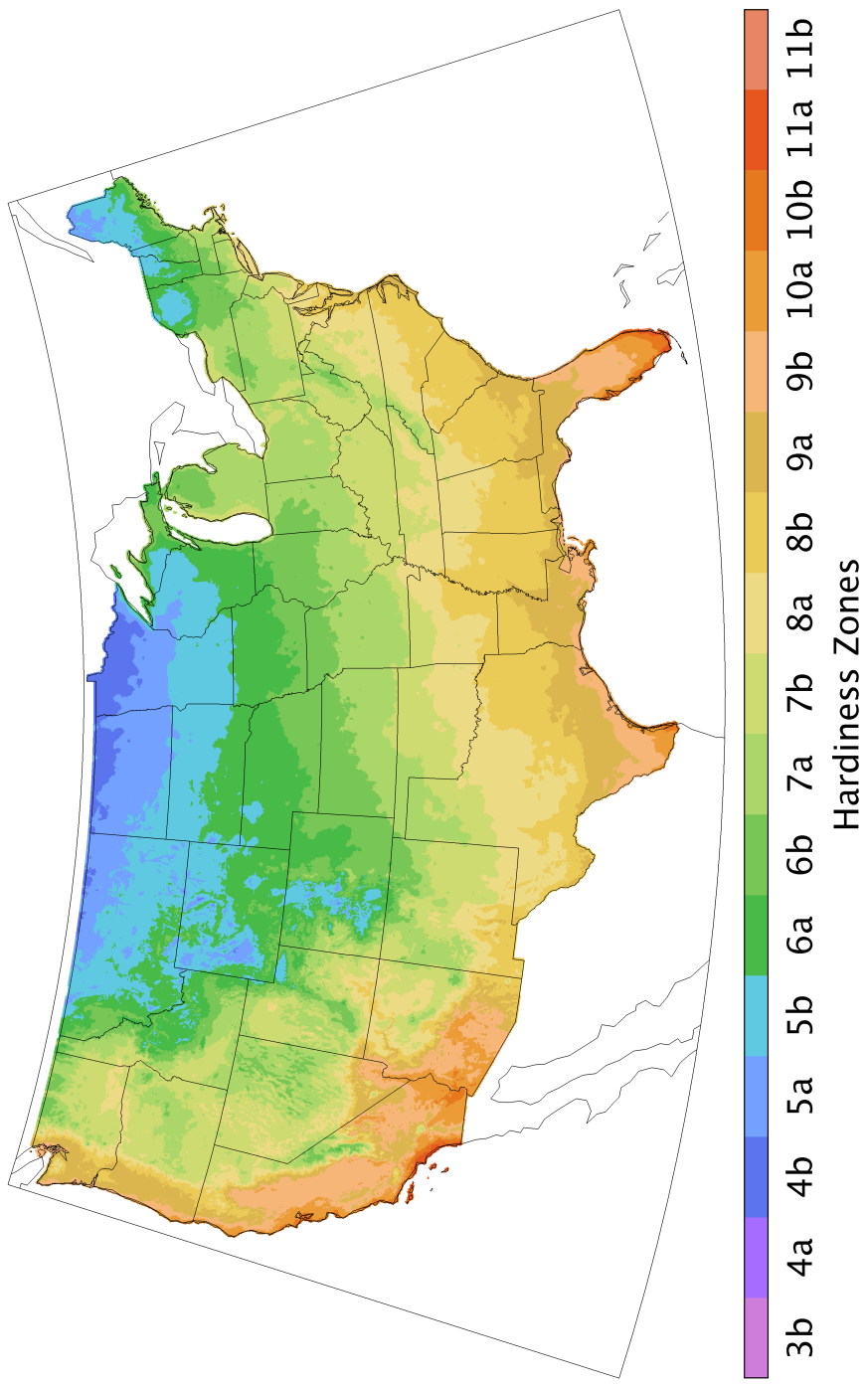
Supplemental Figure 2.S1 The number of models that showed larger warming of annual minimum T_{min} than mean winter minimum temperatures



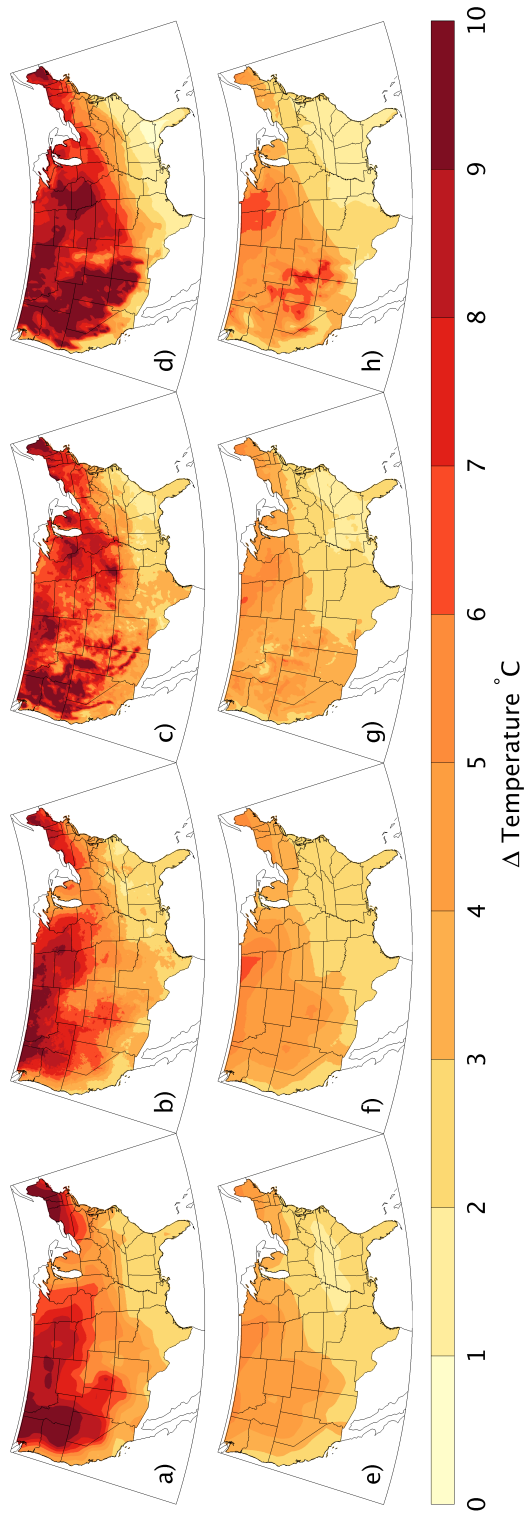
Supplemental Figure 2.S2 Top row: The ensemble (a) 25th and (b) 75th percentile projected change in TN_{DJF} . Bottom row: The ensemble (c) 25th and (d) 75th percentile projected change in TN_{DJF}



Supplemental Figure 2.S3 Climate velocities for (a) TN_n forward looking, (b) TN_n backward looking, (c) TN_{DJF} forward looking, (d) TN_{DJF} backward looking. Grey areas within CONUS indicate regions where no climate analog was found within the dataset (i.e. the climate analog exists outside of CONUS)



Supplemental Figure 2.S4 Cold hardiness zones at mid-century (2041-2070) under RCP 4.5



Supplemental Figure 2.S5 Top row: change in TN_n for (a) CanESM2 GCM (b) MACA (c) RCM4 (d) RCA Bottom row: change in TN_n for (e) CanESM2 GCM (f) MACA (g) RCM4 (h) RCA

CHAPTER 3: COMPARING MECHANISTIC AND EMPIRICAL APPROACHES TO MODELING CROP NICHE

Forthcoming in *International Journal of Biometeorology*

Parker LE, Abatzoglou JT (2017) Comparing mechanistic and empirical approaches to modeling the thermal niche of almond. *International Journal of Biometeorology*.

Abstract

Delineating locations that are thermally viable for cultivating high-value crops can help to guide land use planning, agronomics, and water management. Three modeling approaches were used to identify the potential distribution and key thermal constraints on almond cultivation across the southwestern United States (US), including two empirical species distribution models (SDMs) – one using commonly-used bioclimatic variables (Traditional SDM) and the other using more physiologically relevant climate variables (Nontraditional SDM) – and a mechanistic model (MM) developed using published thermal limitations from field studies. While models showed comparable results over the majority of the domain, including over existing croplands with high almond density, the MM suggested the greatest potential for the geographic expansion of almond cultivation, with frost susceptibility and insufficient heat accumulation being the primary thermal constraints in the southwestern US. The Traditional SDM over-predicted almond suitability in locations shown by the MM to be limited by frost, whereas the Nontraditional SDM showed greater agreement with the MM in these locations, indicating that incorporating physiologically relevant variables in SDMs can improve predictions. Finally, opportunities for geographic expansion of almond cultivation under current climatic conditions in the region may be limited, suggesting that increasing production may rely on agronomical advances and densifying current almond plantations in existing locations.

Introduction

Climate plays an important role in shaping the geographic distribution and survival rates of organisms, both on natural and cultivated lands (Guisan and Zimmermann 2000; Leemans and Solomon 1993). While adverse climate impacts can be mitigated to some extent in horticultural settings (e.g. irrigation), climate is an important factor in determining the geographic distribution of crops. This is particularly notable for perennial crops, which, unlike annuals, are subject to climate conditions year-round and whose decades-long life spans limit adaptation efforts such as fallowing (Lobell and Field 2011). Understanding the viability of cropping choices – from both an agricultural and economic perspective – across a geographic region is important for addressing food security challenges under both present day conditions, as well as in the coming decades under climate change and increased global caloric demands (Lobell et al. 2008).

Modeling potential geographic ranges of croplands using biophysical environmental predictors can elucidate crop viability through space and time. However, agricultural research has typically used mechanistic models (MMs) that focus on modeling crop yield in a predefined geographic area rather than the potential geographic distribution of a crop. These models attempt to capture relationships between environmental cause and phenological effect, realized from agronomic studies (Dourado-Neto et al. 1998). Widely used agricultural MMs vary in their specifics, though each use input data on weather, soils, and crop phenology to simulate crop production (Stöckle et al. 2003). However, the ability to use MMs may be limited by the availability of environmental input data, the capability to accurately parameterize the model, stationarity assumptions when extrapolating MMs in time and space, and computational expense (Challinor et al. 2009).

Though MMs have been used to identify species range (Buckley et al. 2010), species distribution models (SDMs) are a more common method for estimating the geographic niche of an organism. SDMs are an empirical approach that have been used to determine the potential range of native species (Vetaas 2002), assess the possible advancement of invasive species (Jiménez-Valverde et al. 2011), and estimate the impact of climate change on species distributions (Pearson and Dawson 2003). SDMs utilize a sample of observed locations of a given species and co-located environmental data to model the species' potential geographic range. Despite their utility, there are a number of limitations and criticisms of SDMs. For example, SDMs overlook biotic interactions and species adaptation (McKenney et al. 2007; Guisan and Zimmermann 2000), and assume species-environment equilibrium, implying that

species absence is purely a function of uninhabitability (Araújo and Pearson 2005). Additionally, SDMs typically use climatological means and bioclimatic variables that may not be mechanistically related to biological viability, and fail to account for the impact of extremes on species prevalence (Woodward et al. 2004).

Whereas both modeling approaches have their merits and shortcomings, SDMs may be more suited to native species whose growing conditions are not managed. Still, some studies have utilized SDMs to address the impact of climate and climate change on managed crops, including some perennial species (Pocle et al. 2014). Further, while SDMs differ in their approach from MMs (i.e. correlative vs. process basis), previous work has shown that modeling frameworks can produce similar results in projecting both distribution and productivity in agricultural settings (Estes et al. 2013).

This study compares the results of an MM and two SDMs for modeling the viability of cultivating *Prunus dulcis* (almond) across the southwestern United States by exclusively considering thermal factors. Following Hijmans and Graham (2006), we consider the MM to be a more accurate representation of the potential distribution to which we compare two SDMs. One SDM is developed using a common approach for selecting thermal variables (Porfirio et al. 2014). The other SDM selects thermal variables that more directly relate to the physiological requirements for a species (Dilts et al. 2015; Zimmermann et al. 2009). Although other environmental factors such as precipitation and soils are commonly included in such models, we focus solely on temperature variables as virtually all commercially grown almonds in the US are irrigated (Lobell and Field 2011), and cultivated systems may have the capacity to augment soils and biotic conditions that would otherwise be limiting (Yao et al. 2005). Although others have undertaken similar studies examining annual crops (Estes et al. 2013), this study is novel in that it considers a perennial cultivar subject to interannual climate variability.

Almonds are an important agricultural commodity and have a significant impact on regional water resources. California's Mediterranean climate is ideal for almond cultivation and enables the state to produce essentially all of the commercially grown US almond supply and more than 80% of the global supply, adding \$11 billion US dollars in revenue to the California economy (Almond Board of California 2015). Likely as a result of the reported health benefits of almond consumption (Tan and Mattes 2013), global almond demand has increased; coupled with high profitability for growers, increased almond demand has led to a doubling of almond acreage in California since 1995 (US Department of Agriculture 2016). Despite the relatively high water demands of almonds, newer (since 2010) orchards have principally replaced

annuals with higher water demand, potentially reducing agricultural water demand (Howitt et al. 2015); however, the inability to fallow perennials and the increasing water demand of orchards as they age may offset these initial reductions.

The objective of this study is to address the ability of MMs and SDMs to model the potential geographic distribution of thermally suitable land for almond cultivation under present-day climatic conditions across the southwestern US. To this end, we endeavor to (1) identify key thermal controls on almond range across the region, (2) determine how well SDMs capture the thermal niche of almond as compared to the MM, (3) assess the value of incorporating physiologically relevant variables in SDMs, and (4) assess the potential for an expansion of thermally suitable land for almond cultivation across the southwestern United States. Given the current increase in almond plantations and climatic water stress precipitated by drought in California (Williams et al. 2015), the geography of suitable almond habitat has implications for land use, agricultural water demands, and economics.

Data and Methods

a. Data

i. Climatological Data

Daily maximum and minimum temperature (T_{\max} , T_{\min}) for the period 1979 – 2014 for the southwestern US [32° – 42° N, 114° – 125° W (Figure 3.1)] were acquired from the gridded surface meteorological dataset (METDATA) of Abatzoglou (2013). METDATA was created using two datasets: hourly data at ~12km resolution from the North American Land Data Assimilation System Phase 2 (NLDAS-2, Mitchell et al. 2004), and monthly data at ~4km resolution from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly et al. 2008). The resulting 4km resolution gridded daily dataset provides meteorological data at spatial and temporal scales suitable for both local and landscape scale ecological and agricultural modeling.

ii. Species Presence Data

Almond location data were obtained from the 2015 United States Department of Agriculture National Agriculture Statistics Service (USDA-NASS) Cropland Data Layer (CDL). While CDL almond location data is available dating back to 2007, 2015 provides the greatest extent of almond acreage due to the recent increase in cultivated almond cropland (Lobell and

Field 2011). The CDL maps the location of more than 100 crop categories across the US at 30m resolution based on spectral signatures from satellite imagery that have been classified using a manual training process (Boryan et al. 2011). Despite inherent limitations of satellite-derived proxies, the CDL provides the most current and the highest spatial resolution publicly available data for crop occurrence. Only almond locations in California were used as occurrence data given that CDL data show that 99.97% of cultivated almond cropland in 2015 was in California. Nearly 5500km² were classified as almond in the 2015 California CDL. An almond crop density map was generated by calculating the proportion of land classified as almond by the CDL at the 4km resolution of the climate data.

b. Almond Phenology

Almond phenology is a complex, multi-year cycle wherein the bud development of the subsequent year's crop coincides with the development of the current year's crop, vegetative bud development, the differentiation to reproductive buds, the development of almond flowers, and the maturation of almond nuts (Covert 2011). We simplified almond phenology and focused on four stages of reproductive development based on the availability and consistency of information from agronomic literature: endodormancy, ecodormancy, flower development, and hull split.

Endodormancy is a period during which almonds trees are dormant and flower buds are prevented from emerging to prevent cold damage. Chill begins to accumulate during endodormancy (Covert 2011), and the completion of chill accumulation signals the beginning of ecodormancy, a period during which internal physiology no longer limits growth. Growth remains limited by environmental conditions during ecodormancy. The accumulation of heat (e.g., growing degree days, GDD) during ecodormancy allows for floral buds begin to emerge. Ecodormancy ends when approximately 50% of the flowers have bloomed, and flower development continues until sufficient cumulative GDD allows the crop to reach 100% bloom. Fruit development continues during the months after bloom as GDD continue to accumulate (Covert 2011). Hull split occurs when the hull separates from the shell and is the final stage of fruit development. Although harvest does not occur until 100% of the tree's hulls have split, continued GDD accumulation is needed to advance the tree from the start of hull split to harvest, and growers may alter water and pest management practices beginning at 1% hull split (UCIPM 2016).

c. Mechanistic Model

i. Thresholds for Almond Development

The mechanistic model (MM) was conceptualized as a biophysical approach to delineating the thermal niche for perennial crops. The MM considers the thermal requirements for almond reproductive development compiled from published literature, which are based on field observations and growth chamber experiments (Table 3.1). We applied conservative thresholds for crop suitability when a range of values was identified in the literature, and used values for the Nonpareil cultivar when a range of values was provided for different cultivars as it is the most widespread almond varietal grown in California. For example, while published data offer a wide range of temperatures that could result in varying levels of frost damage during flower development, we used frost temperature thresholds that result in ~20% damage (Snyder and Melo-Abreu 2005). GDD values for 1% bloom were not established in the literature and were calculated using phenology data from the Regional Almond Variety Trials (RAVT, University of California 1996-2006); cumulative GDD at 1% bloom was found to be 80% of that at 50% bloom. Similarly, GDD for hull split and harvest were calculated using phenology data from Connell et al. (2010). When accounting for GDD in crop phenology, we used low GDD thresholds during flowering stages to best assess frost risk in early bloom, whereas we used the average of the published GDD ranges during later stages of development (i.e. nut and harvest stages). The MM focuses solely on the thermal requirements for almond development and assumes that water needs can be met throughout development. This assumption also eliminates a need to account for heat stress, which is physiologically a function of water stress due to increased evaporative demand coupled with limited water supply rather than a direct response to ambient air temperature (David Doll, personal communication).

The MM accounts both for the conditions necessary for growth, as well as the conditions that would halt the growth cycle or result in crop damage, including cold hardiness, chilling requirements, heat accumulation requirements, and frost damage during ecodormancy, flowering, and nut development (Connell et al. 2010; Janick and Moore 1996; Rattigan and Hill 1986). The MM examines a total of 13 thermal requirements throughout crop development each year. A year is considered to be unviable for almond cultivation if any of the 13 thermal requirements are not met. Details of these thermal requirements are highlighted as follows:

1. Cold Hardiness

Cold hardiness temperature thresholds, defined by the annual coldest daily minimum temperature (T_{N_n}), provide constraints on the potential geographic range of both natural and cultivated species, and have a direct link to the thermal viability of species (Parker and Abatzoglou 2016). We employed an absolute cold hardiness threshold temperature of -25°C (Janick and Moore 1996) to define suitable locations for over winter survival, and assessed over winter survival on an annual basis.

2. Chill Accumulation

We utilized the Dynamic Model (Fishman et al. 1987) for calculating chill portions (CP) as it has been shown to be a more accurate approach for calculating chill accumulation (Luedeling and Brown 2011). CP were calculated from the equations provided in Luedeling et al. (2009b) after temporally disaggregated daily data to hourly data using a modified sine curve model (Linville 1990). We calculate cumulative CP between November 1 and March 31, covering the common period for chill accumulation for almonds (Covert 2011).

3. Growing Degree Days

Heat accumulation is a key driver of crop development and is commonly used to estimate crop phenology (e.g. timing of maturation). Heat accumulation is commonly measured as GDD above a crop-specific base temperature threshold (T_{base}). Following McMaster and Wilhelm (1997), we define GDD as:

$$GDD = \begin{cases} \frac{T_{max} + T_{min}}{2} - T_{base}, & \frac{T_{max} + T_{min}}{2} > T_{base} \\ 0, & \frac{T_{max} + T_{min}}{2} \leq T_{base} \end{cases}$$

where $T_{base} = 4.5^{\circ}\text{C}$ (Rattigan and Hill, 1986).

Although previous work has suggested that growing degree hours (GDH) may provide a more accurate measure of heat accumulation than GDD, differences in accuracy vary between species and location, and the temporal disaggregation of daily data to hourly data to estimate GDH can contribute to uncertainty (Roltsch et al. 1999). We hereafter used GDD as a proxy for heat accumulation as GDD have successfully predicted development rates in several *prunus* species, including almond (Zavalloni et al. 2006), and are a more common means of computing heat accumulation when daily summarized weather data are available. Bloom timing from our model using GDD compared favorably with field study data from the RAVT, with modeled

bloom occurring within ± 6 days of observed bloom timing on average, with the modeled bloom timing typically occurring earlier than observed consistent with the conservative nature of selected GDD phenology thresholds. Similarly, nut development rates compared favorably with field study data from Connell et al. (2010), which showed a Nonpareil nut maturation date 23 - 25 days after the onset of hull split; our model showed a mean nut maturation date of 24 days after the onset of hull split in locations with $>1\%$ almond density. The MM uses GDD to both assess crop maturation as well as track crop phenology in order to assess other thermal requirements, namely frost damage. Specifically, the MM uses GDD accumulation beginning November 1 in order to determine whether sufficient heat accumulates – irrespective of sufficient chill accumulation – for reaching phenology stages of 1%, 50%, and 100% bloom, 1% and 100% hull split, and harvest. Separately, the MM uses GDD accumulation beginning at the onset of ecodormancy in order to track the timing of almond maturity, which is used to determine frost susceptibility.

4. Frost Damage

Crops are susceptible to frost damage throughout their reproductive cycle, with damage-causing temperature thresholds (T_{frost}) rising throughout the progression of crop development. The MM assesses frost damage for ecodormancy through harvest and defines frost-induced development failure when a development stage has at least one day where $T_{\text{min}} < T_{\text{frost}}$. Frost damage was calculated for each phenological stage from 1% bloom to 100% hull split. GDD was used to determine the timing of transition between each stage, and each frost damage assessment was for the period ending with the given stage. For example, frost damage for 1% bloom occurs only if $T_{\text{min}} < T_{\text{frost}}$ for any day between the end of endodormancy and the date on which the 1% bloom GDD threshold is met. Frost damage for individual phenostages was only calculated for regions and years where sufficient CP and GDD were met. In subsequent results, we report the fraction of years during which frost damage occurred of the years in which it was calculated.

ii. Modeling Almond Development

The MM (Appendix A) used the thresholds outlined in Table 3.1 to model the thermal requirements for almond development for each year (November 1 – October 31) over the 35-year period (November 1979 – October 2014). The MM provides for the opportunity for failed development at each growth stage and year, which is treated as a binary variable. However, the true impact to crop yield – or viability – varies across development stage. For example, failure

to meet the frost damage threshold values used in the MM results in 20% crop damage, while failure to meet the CP and GDD accumulation threshold values may result in reduced crop quality and yield (Luedeling et al. 2009a), and deficiency in meeting cold hardiness requirements results in tree mortality (Janick and Moore 1996). The MM treats failure during any development stage as an unviable year for almond cultivation without explicitly modeling crop yield. By considering each year independently, this approach may better account for the influences of interannual climate variability on almond cultivation and can be used to assess the percent of years with suitable conditions. Additionally, the MM highlights the specific thermal attributes that limit consistent crop development across geographic regions.

d. Species Distribution Model (SDM)

While multiple empirical methods for SDM exist, we used a maximum entropy method (MaxEnt, version 3.3.3; Phillips et al. 2006). Although Phillips et al. (2006) highlight some of the limitations of presence-only species distribution modeling and the MaxEnt method specifically, work by Aguirre-Gutiérrez (2013) showed that MaxEnt performs well relative to other empirical species distribution modeling methods.

The statistical mechanics of the MaxEnt solution are detailed in Elith et al. (2011). Briefly, MaxEnt utilizes geolocated species presence data in concert with environmental data (e.g. climate, soils) to quantify the species' environmental niche as defined by the probability of species occurrence. MaxEnt randomly selects locations from a pre-defined geographic domain where species presence is unknown. Referred to as background points, the spatial scope of these locations can influence MaxEnt output and performance (Elith et al. 2011). It has been recommended that background points be chosen only from locations accessible to the species of interest (Merow et al. 2013). Consequently, we limited the geographic domain of the training data to 4-km grid cells where >10% of the cell is classed as cropland by the 30-m resolution USGS Land Cover Institute's MODIS-based Global Land Cover Climatology (henceforth, cropland) (Broxton et al. 2014) (Figure 3.2a). Experiments confirmed that these restrictions on background point locations improved model function.

Previous SDM studies have utilized combinations of bioclimate variables – typically climate normals – as environmental data in modeling species habitat (McKenney et al. 2007). We considered two sets of climate variables (Table 3.2). One set, hereafter referred to as Traditional, was based on variables common in SDM literature and the BioClim dataset (Hijmans et al. 2005), calculated using the 1979-2014 climatologies from METDATA.

The second set of climate variables, hereafter referred to as Nontraditional, was based on 1979-2014 averages of the variables used in the MM. We define frost probability (FP) as the percent of years that experienced with $T_{\min} < T_{\text{frost}}$ between the end of ecodormancy and 1% hull split, during which time frost damage concern among growers is highest. Finally, to avoid over-fitting the model and ostensibly utilize the more suitable locations for almond cultivation in our presence data, presence locations were restricted to 4km cells with >1% almond density (Figure 2b). While the model was trained over the cropland background, the model was projected over the full domain.

Following Phillips and Dudík (2008), we utilized MaxEnt's default settings, detailed in Merow et al. (2013), with the exception of the model features wherein we restricted MaxEnt to linear and quadratic features to produce models that are more easily interpreted and provide a better reflection of general species-environment relationships (Syfert et al. 2013). Using a random subsample of 20%, we completed 100 replicated runs for both the Traditional and Nontraditional models. We used the area under curve (AUC) from the receiver operating curve (ROC) as a measure of model performance. The maximum AUC is defined as:

$$AUC = 1 - \frac{\infty}{2}$$

where ∞ is the fraction of pixels covered by or containing the species (Aguirre-Gutiérrez 2013; Phillips et al. 2006). Unlike many ecological applications where ∞ is unknown, here the fraction of background pixels (cropland>10%) with almond density >1% is 0.35, making the maximum AUC for our models 0.83.

The MaxEnt training process tracks the contribution of environmental variables to model fit and provides a measure of variable importance as the percent contribution of each variable. MaxEnt's logistic output provides an estimate of the probability of occurrence of a species at a location, which we use as a measure of the thermal suitability of that location. Finally, to facilitate a more direct comparison with the results of the MM, we normalized MaxEnt output by dividing the logistic output by the median value over almond occurrence locations with >1% density and capping values at 1. We refer to this value as the species viability index (SVI), and compare this with the ratio of suitable years to total years for almond cultivation as simulated by the MM.

e. Caveats

Although we consider the MM to be a more accurate representation of the potential distribution (Hijmans and Graham 2006), neither the MM nor the SDMs provide definitive

predictions of where almonds can be successfully cultivated. First, the models do not differentiate between those locations where the physical and legal infrastructure for irrigation exists and where it does not. Secondly, the models do not differentiate between regions with and without competing land use, or suitable soils or topography. Thirdly, errors in parameterization in the MM could lead to poor accuracy in prediction (Buckley et al. 2010). For example, our conservative estimates of temperature and GDD thresholds may under-predict suitability in some locations, and published frost damage thresholds are primarily meant to serve as guidelines rather than definitive measures of critical temperature (Snyder and Melo-Abreu 2005). Finally, biotic interactions between the species, pests, pollinators, and climate are not explicitly considered, but are likely important for almond cultivation (Polce et al. 2014).

Results

a. Mechanistic Model

The MM showed the highest SVI values over California's Central Valley, Central Coast, and the deserts of southeastern California, southern Nevada, and western Arizona (Figure 3.3a). Approximately one third of the domain had high suitability (SVI > 0.8) whereas ~57% of the domain had low suitability (SVI < 0.5). The MM showed strong agreement for subdomain locations with >1% almond density as 99.6% of these locations had high suitability for almond cultivation, indicating that the model performs well compared to independent records of species presence.

The fraction of years with suitable thermal conditions for each development stage of the MM is shown in Figure 4. This figure elucidates the limiting thermal variables for almond cultivation across space and over the almond phenological cycle. While the majority (>96%) of the domain had sufficiently warm TN_n (suitability in >80% of years), portions of southern California failed to consistently meet CP requirements, a key limiting factor to almond cultivation. Frost damage and GDD accumulation were the primary limiting factors to suitability over higher elevation regions of California and Nevada. Although model results show diminished frost risk during later development stages, nearly one third of the domain experienced development failure due to frost between the onset of heat accumulation and 1% bloom in a majority of years. Further, ~40% of the domain lacks sufficient GDD accumulation to reach maturation and would not be viable in a majority of years even if frost were not a risk.

b. Species Distribution Models

The Traditional (Nontraditional) SDM had an average AUC value of 0.744 (0.741). AUC results for both models were stable across the 100 replicated runs, with standard deviations <0.01. The AUC value of 0.74 would equal a normalized AUC of 0.89 given that the maximum AUC for our models was 0.83, and thus indicates that the models performed well over the training data. The Traditional and Nontraditional SDMs showed 25% and 18% of the domain to have high suitability (SVI>0.8) for almond cultivation, respectively (Figure 3.3b,c). The Traditional SDM showed highest SVI values over the northern and southern portions of the Central Valley, the Mojave Desert, southern Nevada and northwestern California. By comparison, the extent of high suitability in the Nontraditional SDM was reduced in the Sacramento-San Joaquin Delta to the south of the City of Sacramento, in the Mojave Desert, and in southern Nevada, and the model showed little or no suitability in northwestern California.

MaxEnt results showed that TN_{month} and TX_{month} provided the highest percent contribution to model gain for the Traditional model, while FP and TN_{DJF} contributed the most to model gain for the Nontraditional model (Table 3.3). Figure 5 shows response curves for these variables, illustrating their respective impact on almond suitability independent of other model variables. Response curves for the Traditional model showed an optimum in TN_{month} near 2°C, with Gaussian shaped decline for values to -4°C and +7°C. Similarly, the variable response curve for TX_{month} was Gaussian shaped, with an optimum near 37°C. Nontraditional SVI exhibited a unimodal response to TN_{DJF} with an optimum near ~2.5°C, while the response curve for FP showed an optimum at 0 with declines at higher values of FP.

c. Model Comparison

We compared the three modeling approaches by mapping the difference in SVI across the domain (Figure 3.6). Average model differences were minimal (<0.1) for areas with current almond density >1%. Both SDMs generally under-predicted SVI relative to the MM in regions to the west of the Central Valley, with the largest differences near the San Francisco Bay area, the Salinas Valley, the Central Coast, and in the Transverse Ranges north of the Los Angeles Basin. Conversely, the Traditional SDM predicts higher SVI than the MM for the Sierra foothills, the Klamath Mountains of northwestern California, and the periphery of the Mojave Desert. The Traditional SDM had higher suitability ($SVI_{\text{TRADITIONAL}} - SVI_{\text{MM}} > 0.1$) for ~15% of the domain. However, of the locations where the Traditional SDM showed high suitability and the MM did not, 37% incurred frost damage between anthesis and 1% hull split in at least 20% of years. By

comparison, the Nontraditional model showed little area (<3% of the domain) with high suitability (SVI>0.8) where the MM did not also have high suitability.

Secondly, we assessed the mean SVI simulated by each model over croplands binned by almond density (Figure 3.7). Across all almond densities, the MM showed a higher mean SVI than the SDMs. As almond density increases, differences between the MM and SDMs generally decrease, with all models showing very high mean suitability (SVI>0.9) for croplands with almond densities >0.5%. All models showed low average suitability over croplands where almonds are not currently cultivated. However, over croplands without current almond cultivation, high suitability (SVI >0.8) was found in 42%, 10%, and 11% for the MM, Traditional SDM, and Nontraditional SDM, respectively. The MM shows these locations to be predominantly in the greater Sacramento and San Francisco Bay Areas, and along the California-Arizona border, while the SDMs show high suitability areas scattered throughout the Central Valley and the Sierra Foothills east of Sacramento (Supplemental Figure 3.S1).

Discussion

The MM showed frost during ecodormancy was a primary thermal constraint to almond cultivation over the broadest spatial extent of the domain, supporting previous research showing frost damage between bud swell and anthesis to be a key limiting factor in almond cultivation around the world (Miranda et al. 2005). Further, while the MM primarily highlights higher elevation regions as being most susceptible to frost, some reduction in SVI in lower elevation valleys, at scales finer than the 4-km resolution of our data, may occur as a function of localized cold air drainage (Dobrowski et al. 2009). However, it should be noted that because the MM accounts for almond failure when $T_{\min} < T_{\text{frost}}$, some locations with moderate or low SVI may have higher suitability using less conservative thresholds for T_{frost} , if willing to accept the risk of associated yield declines with frost damage, or if using frost protection measures. Further, later blooming cultivars may mitigate frost damage risk; consequently, the development of late-blooming cultivars is a principal goal in almond breeding (Sorkheh et al. 2009).

Like MMs, SDMs can provide insight into the potential distribution of perennial agriculture such as almonds. In previous work in ecology, agroecology, and ecological modeling (Estes et al. 2013; Hijmans and Graham 2006), SDMs have been shown to produce broadly comparable spatial predictions to MMs (Estes et al. 2013). Our results show that the MM, though designed to produce a conservative model of almond suitability, projects a larger extent

of highly suitable lands than do the SDMs, and the most significant differences between the models existed for locations where the current species is absent. These differences are likely a function of the correlative approach used by MaxEnt, which is better able to predict suitability in locations most similar to current almond locations; consequently, the SDMs appoint or restrict suitability as a function of the training data rather than true environmental limitations driven by physiology (Hijmans and Graham 2006). Further, the statistical output provided by MaxEnt (e.g. variable contribution and variable response curves) are also driven by the correlative modeling approach and may not reflect the true importance of or physiological response to the bioclimatic variables incorporated in the model. Though Estes et al. (2013) found SDMs to be a superior approach for modeling maize distribution compared to a MM given that SDMs provide comparable results and require less effort, as a perennial crop, almonds must survive on decadal rather than annual timescales and are thus subject to climate variability that is not captured well by SDMs. Although SDM results may be improved by using physiologically relevant variables, and modeling methods such as MaxEnt provide statistical analysis that can be useful for improving model performance through variable selection and experimentation, MMs are not limited by the biases implicit in a correlative approach and are more capable of accounting for climate variability. Still, that the SDMs projected a more conservative spatial extent of suitability may indicate a weakness in the strictly thermal approach of the MM.

Although attempts were made to address some aspects of climate variability through the use of non-traditional variables (e.g. frost probability) in one SDM, similar to previous findings (Dilts et al. 2015; Estes et al. 2013), the use of non-traditional variables did not significantly improve model performance as measured by AUC; however, disparities in SVI between the SDMs were evident in regions at risk for frost. The Traditional SDM over-predicted suitability in locations shown by the MM to be limited by frost, indicating that the model does not sufficiently capture the processes (e.g. climate extremes and variability) responsible for restricting species viability in these regions (Zimmerman et al. 2009). Conversely, the Nontraditional SDM under-predicted suitability in some of these locations, suggesting that the Nontraditional model's frost tolerance may be overly restrictive. The more conservative geographic range of almond cultivation simulated by the Nontraditional model, and the relative absence of high suitability in locations shown by the MM to be limited by frost, indicate that these variables may be preferred over their Traditional counterparts. Further, the use of non-traditional variables provides insight to almond viability response to changes in

mechanistically-relevant variables that are more directly related to agricultural productivity (Hatfield et al. 2014), may be of greater interest to almond growers and others in the agricultural industry (Crane et al. 2010), and may improve explanations of changes in almond distribution in response to climatic changes (Dilts et al. 2015).

Results from all three models show areas of high suitability outside of the current extent of almond cropland, suggesting potential for expanding almond plantations across the Southwest; however, the spatial patterns of potential expansion highlight a number of caveats. High suitability for almond cultivation is modeled for much of the Mojave Desert; however, our models do not account for water availability (e.g. precipitation or the physical and legal infrastructure required for irrigation), thus widespread expansion into such regions is likely to be limited as almond orchards require year-round watering (Johnson and Cody 2015). Additionally, our results do not account for non-climatic restrictions to almond cultivation, such as current land use and socio-economic factors. Many of the high suitability locations outside of the Central Valley occur on Federal or State owned lands and therefore are not available for commercial expansion of almonds. Further, there may be limited opportunity for expansion on existing croplands where almonds are not currently present. For example, while existing croplands to the north of San Francisco (i.e. in Napa Valley) show high suitability for almond cultivation, these locations are currently cultivated with wine grapes and a variety of other high-value crops that are unlikely to be replaced by almond plantations. Finally, we do not account for any sociological or economic considerations that influence growers' management decisions, including grower risk tolerance and cost of cultivation versus profitability (Rougoor et al. 1998).

Though the high species viability simulated by all models over the Central Valley elucidates the geographic hotspot for almond cultivation, divergence in model agreement on potential geographic expansion over existing cultivated lands may give pause to continued expansion of almond orchards in the southwestern US. While increasing almond density in areas already successfully growing the crop may provide a means to increase production, challenges may arise given the potential limitations (climatic, physical, legal, and political) in providing sufficient water for the crop's high water demand. Consequently, although our model results suggest that the geographic expansion of almond in the Southwest may be limited under current climate conditions, both mechanistic and empirical distribution models may be useful in projecting the potential suitability of almond cultivation under future climate. However, given the limitations of the correlative approach of SDMs, we suggest that using an MM is

preferable when biophysical limits are known, and that MMs are further advantageous when seeking to understand the physiological mechanisms driving distribution, and/or when assessing opportunities for translocation (Kearney and Porter 2009).

Finally, whereas our results suggest the geographic range is primarily limited by frost risk and insufficient heat accumulation under current climate, the impact of warming temperatures may impact winter chill requirements, and water limitations may become a larger issue across the southwestern US (Luedeling et al. 2009a,b; Averyt et al. 2013). Such prospective changes make it increasingly important to understand the geographic potential for cultivating high value crops beyond their current range, and the strengths and limitations of the modeling techniques used to delineate a cultivar's fundamental niche.

Acknowledgements

We are appreciative of the almond expertise provided by David Doll, and the feedback on early versions of the manuscript from Amber Kerr and Kripa Jagannathan. This research was supported by the National Institute of Food and Agriculture competitive grant, award number: 2011-68002-30191. We appreciate the constructive feedback from three anonymous reviewers that helped improve the quality of the manuscript.

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Tables

Table 3.1 Phenological thresholds used in the MM and their sources

Stage	Model Threshold	Published Range	Source
Cold Hardiness	-25°C		Janick and Moore (1996)
Chill Portions	23	23 - 30	Covert (2011)
GDD Base Temperature	4.5°C		Rattigan and Hill (1986)
1% Bloom GDD	176 (80% of 50% bloom GDD)		RAVT, University of California (1996-2006)
1% Bloom Frost	-15°C (undefined damage %)	-15 – -20°C	Janick & Moore (1996)
50% Bloom GDD	220	220 – 370	Published Range: Covert (2011)
50% Bloom Frost	-5.6°C (20% damage)	-6.5 – -3°C (up to 50% damage)	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)
100% Bloom GDD	300	300-500	Janick and Moore (1996)
100% Bloom Frost	-3.9°C (20% damage)	-5.6 - -2.2°C (up to 75% damage)	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)

1% Hull-Split GDD	2219	~1900 - 2550	Based on Connell <i>et al.</i> (2010)
1% Hull-Split Frost	-2.8°C (19% damage)	-2.8 - -0.5°C (up to 50% damage)	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)
100% Hull-Split GDD	2750	~2390 - 3100	Based on Connell <i>et al.</i> (2010)
100% Hull-Split Frost	-2.8°C (19% damage)	-2.8 - -0.5	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)
Harvest GDD	3032	~2760 - 3530	Based on Connell <i>et al.</i> (2010)

Table 3.2 Climatological variables used in the traditional and nontraditional SDMs

Traditional SDM Variables	Nontraditional SDM Variables
Average annual temperature (T_{ann})	Average annual growing degree-days (GDD)
Average annual diurnal range (T_{diurnal})	Average annual freeze-free days (FFD)
Average annual temperature range (T_{range})	Average frost probability during bloom (FP)
Average minimum temperature of the coldest month (TN_{month})	Average annual coldest minimum temperature (TN_n)
Average maximum temperature of the warmest month (TX_{month})	Average annual warmest maximum temperature (TX_x)
Average temperature of the coldest quarter (T_{DJF})	Average minimum temperature of the coldest quarter (TN_{DJF})
Average temperature of the warmest quarter (T_{JJA})	Average maximum temperature of the warmest quarter (TX_{JJA})

Table 3.3 The relative contribution for each variable in the Traditional and Nontraditional species distribution models (SDM)

Variable	Percent Contribution
<i>Traditional SDM</i>	
TN _{month}	63.3
TX _{month}	23.9
T _{diurnal}	10.6
T _{DJF}	1.7
T _{ann}	0.4
T _{range}	0.1
T _{JJA}	0.1
<i>Nontraditional SDM</i>	
FP	42.2
TN _{DJF}	30.1
TX _x	10.8
TX _{JJA}	7.3
FFD	4.8
GDD	4.7
TN _n	0

Figures

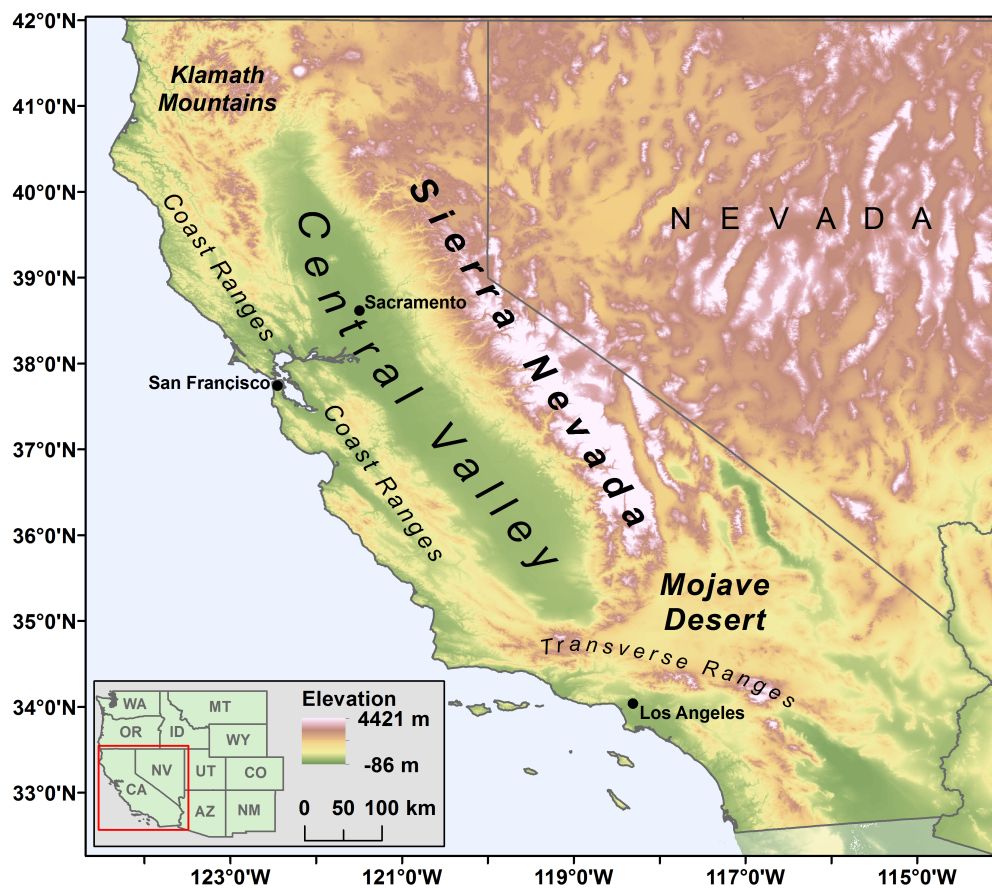


Figure 3.1 Overview of the study area, including names of prominent geographic features and cities

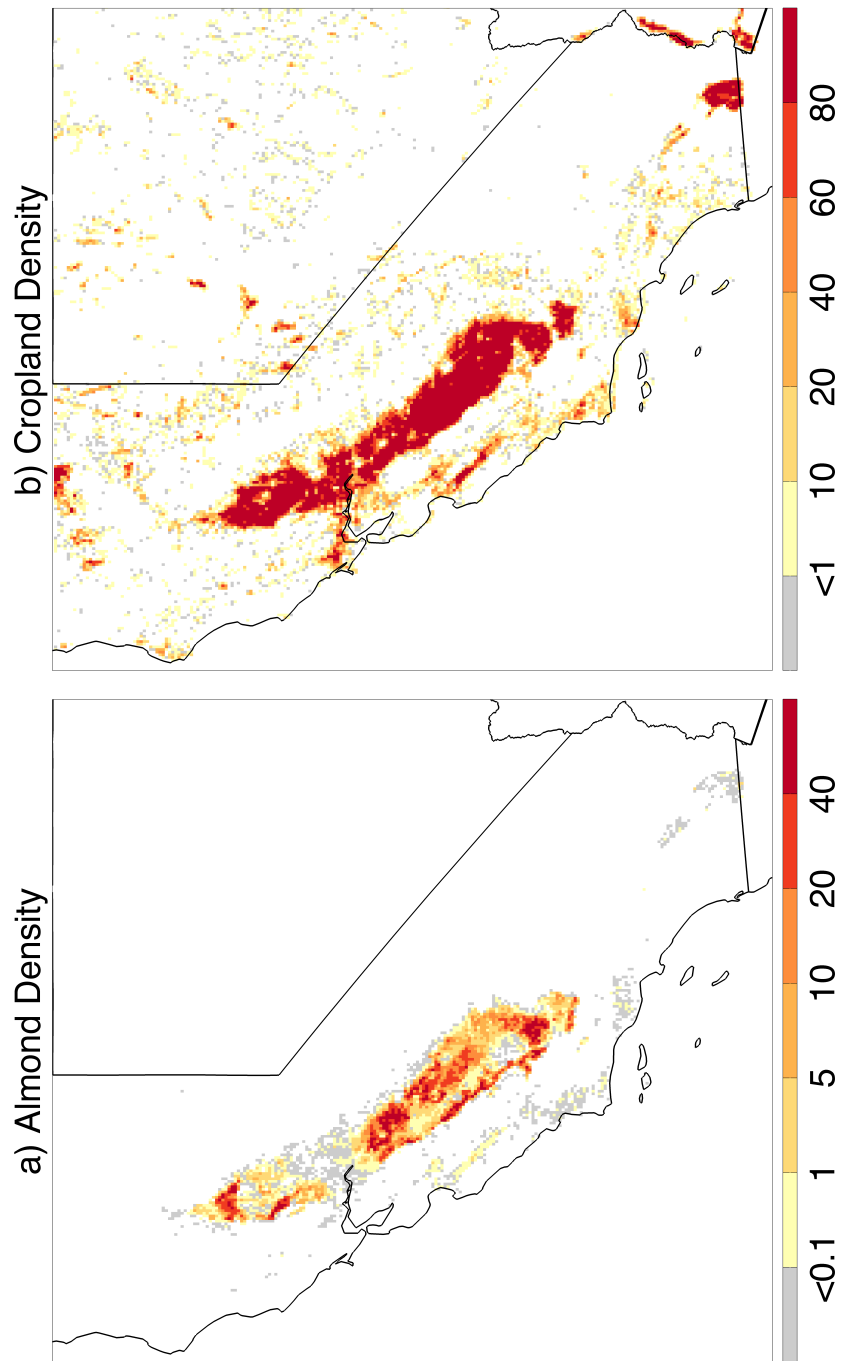


Figure 3.2 Almond (a) and cropland (b) locations and their relative densities on a 4-km grid

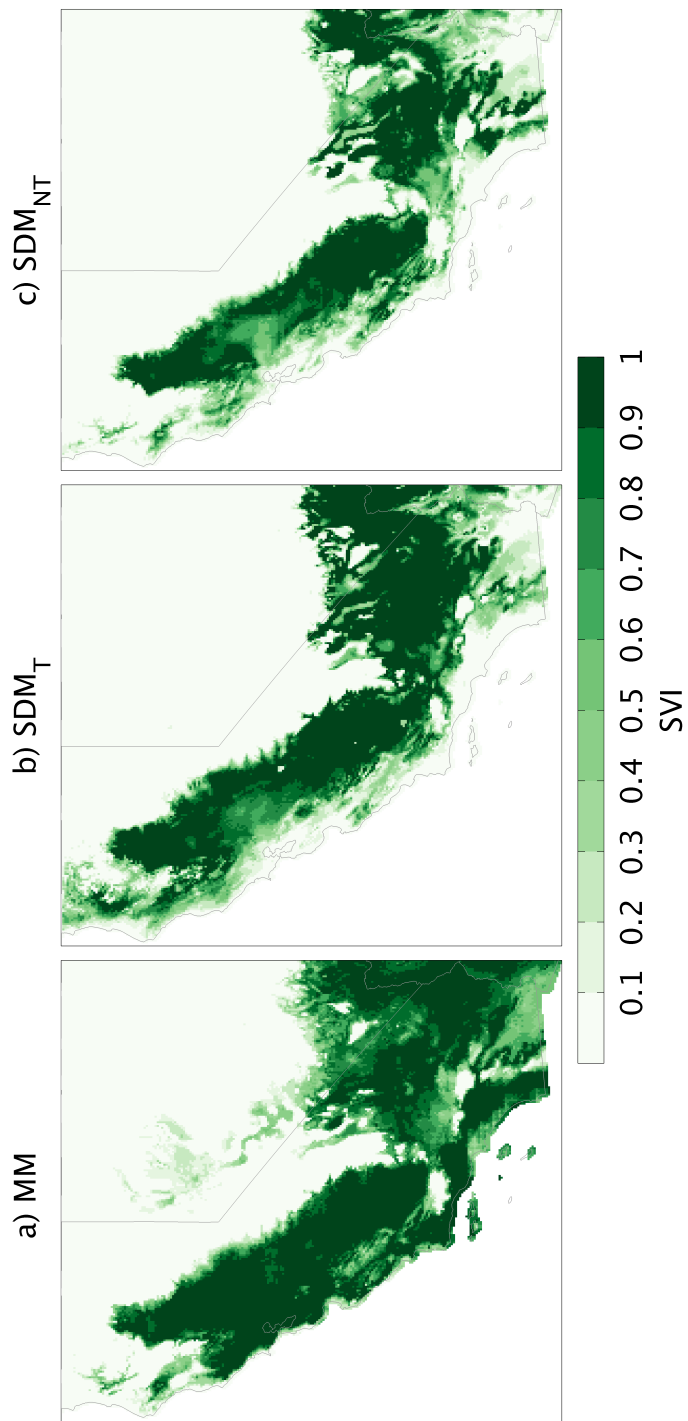


Figure 3.3 Species viability index (SVI) for (a) Mechanistic Model (MM), (b) Traditional species distribution model (SDM_T), and (c) Nontraditional species distribution model (SDM_{NT})

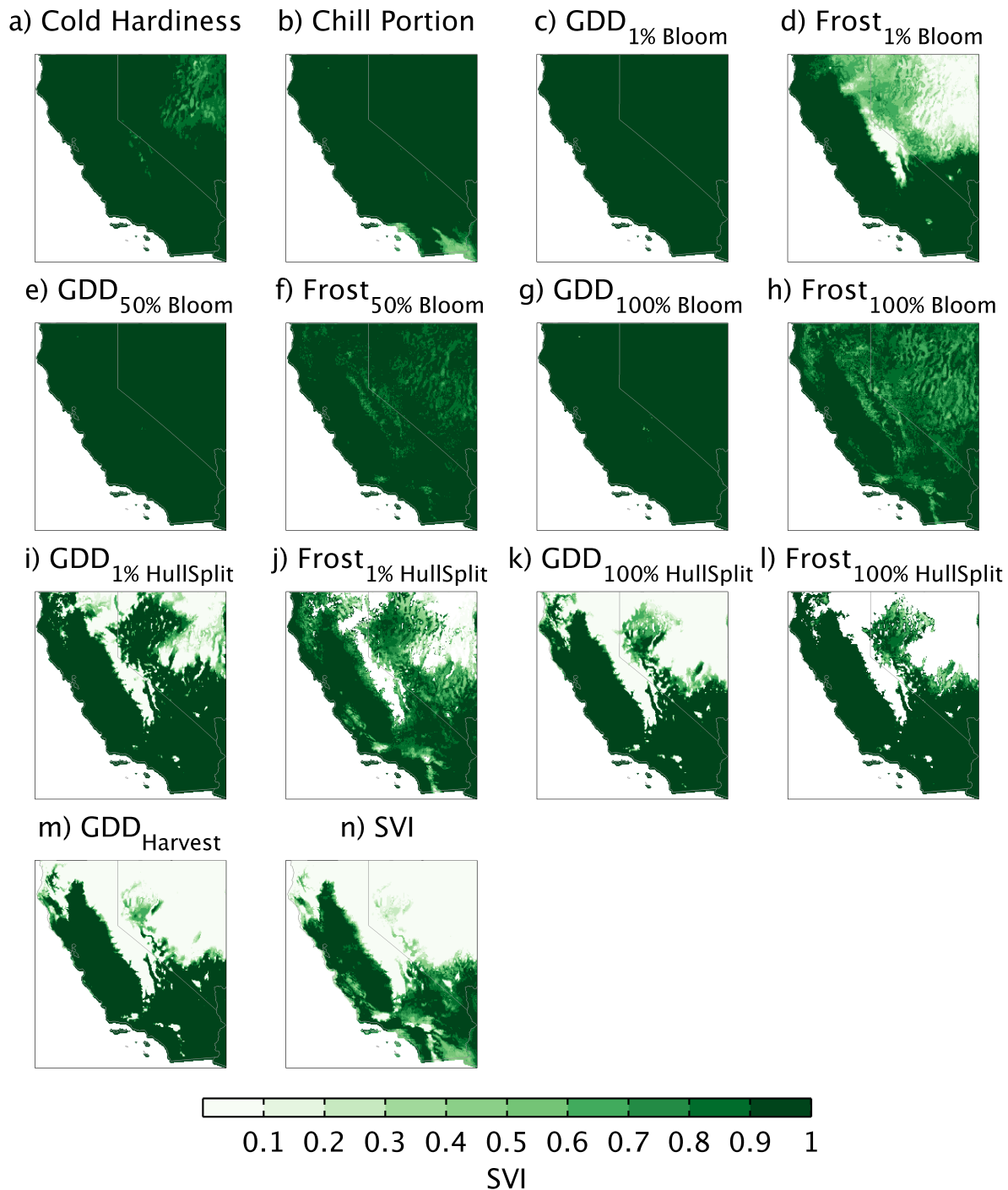


Figure 3.4 Mechanistic model SVIs for each development stage. SVIs for cold hardiness, chill portion, and GDD accumulation are calculated independently. SVIs for frost damage require the determination of the start and end dates of the development stage and so cannot be calculated independently. Consequently, SVIs for frost damage reflect the fraction of years in which CP and GDD requirements were met and frost did not occur

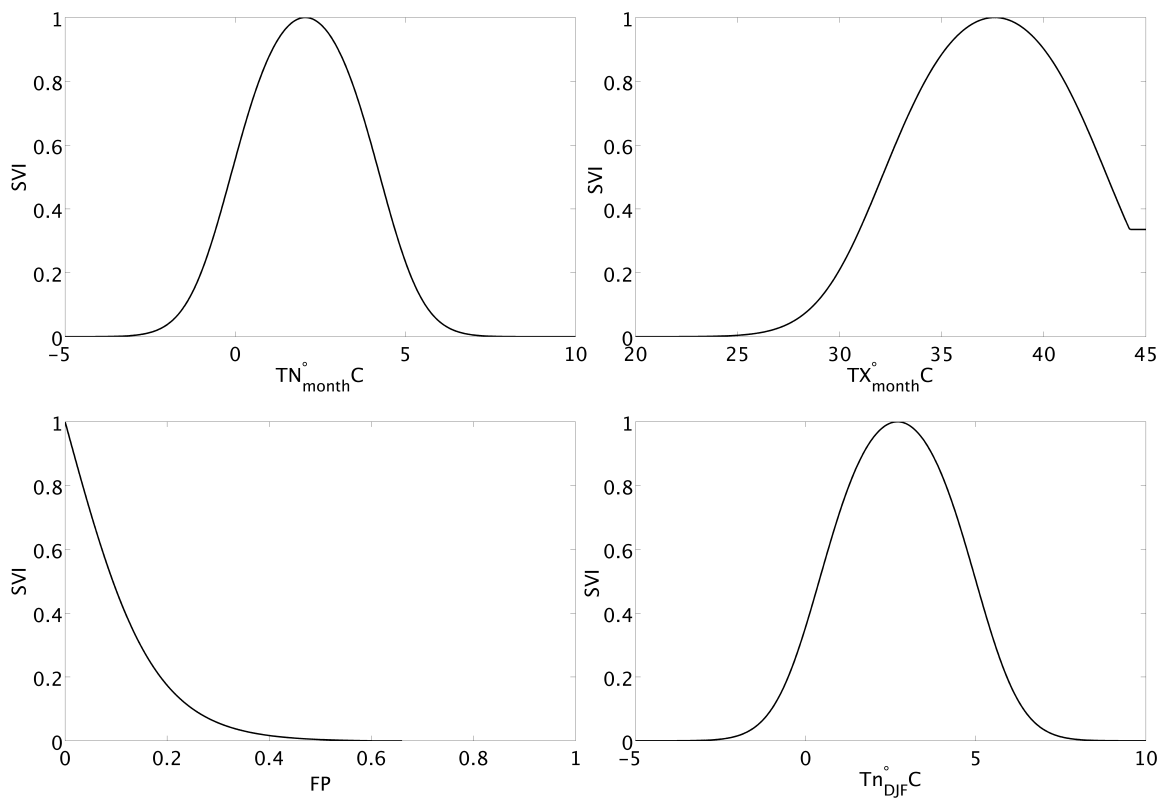


Figure 3.5 Environmental variable response curves for the Traditional (top row) and Nontraditional (bottom row) species distribution models

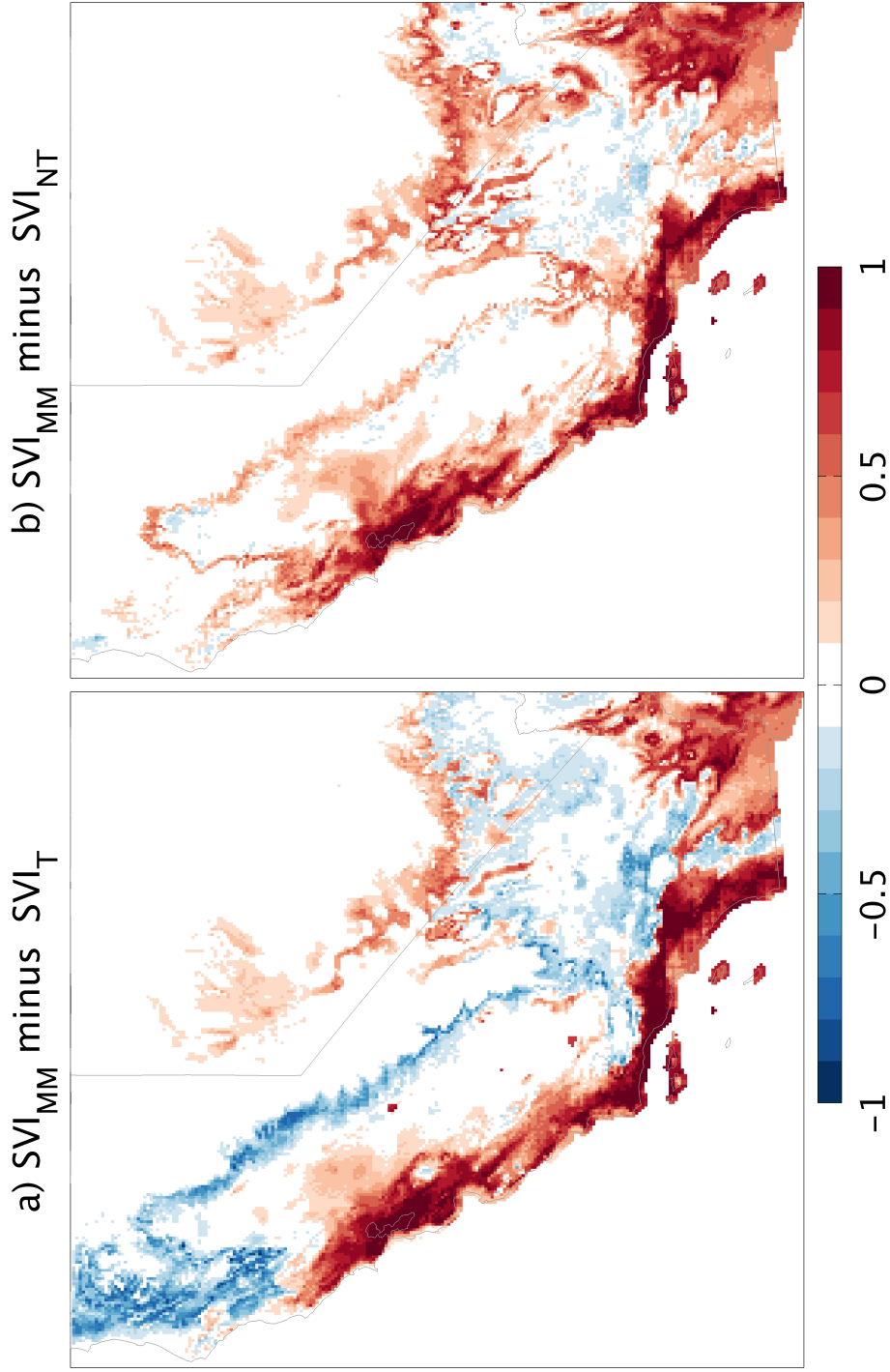


Figure 3.6 SVI differences between the mechanistic model and the (a) Traditional (SDM_T), and (b) Nontraditional (SDM_{NT}) species distribution models. Red hues indicate that the species distribution model under-predicted SVI relative to the mechanistic model, while blue hues indicate that the species distribution model over-predicted SVI relative to the mechanistic model. In order to highlight areas of more significant model disagreement, differences in SVI of ± 0.1 are masked with white

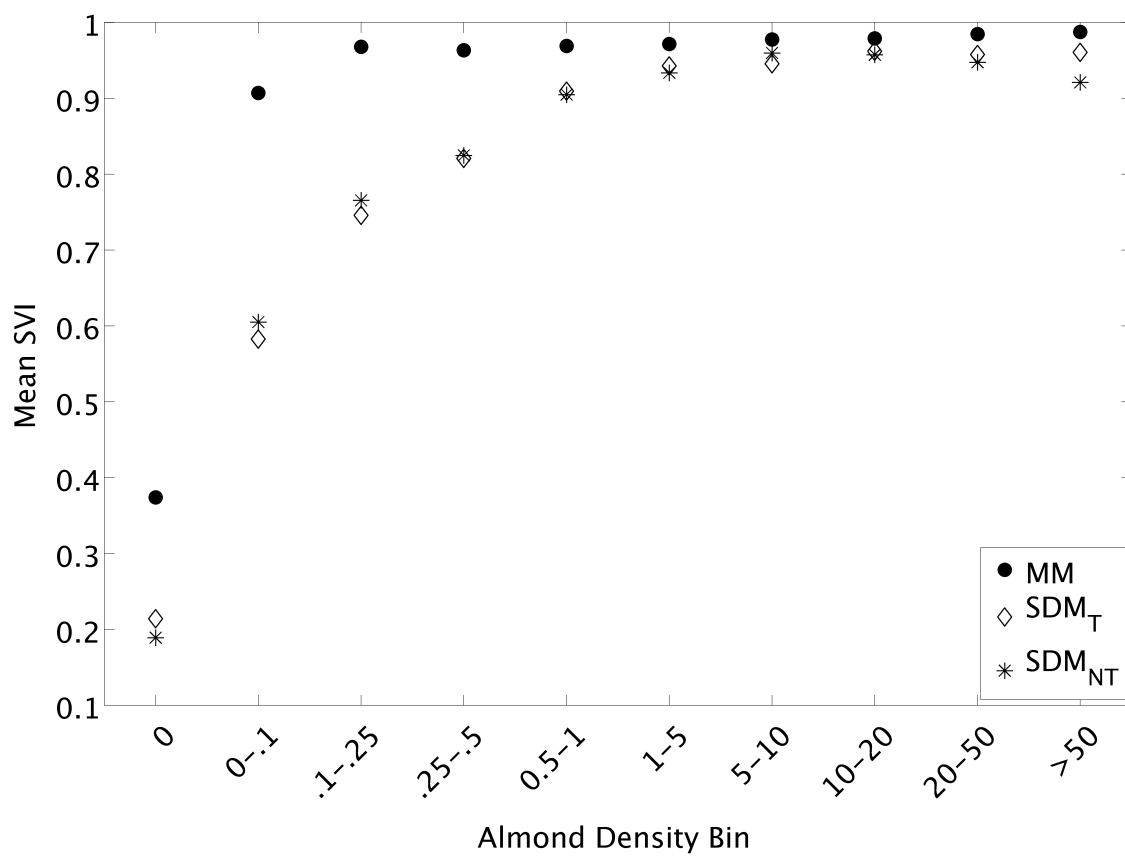
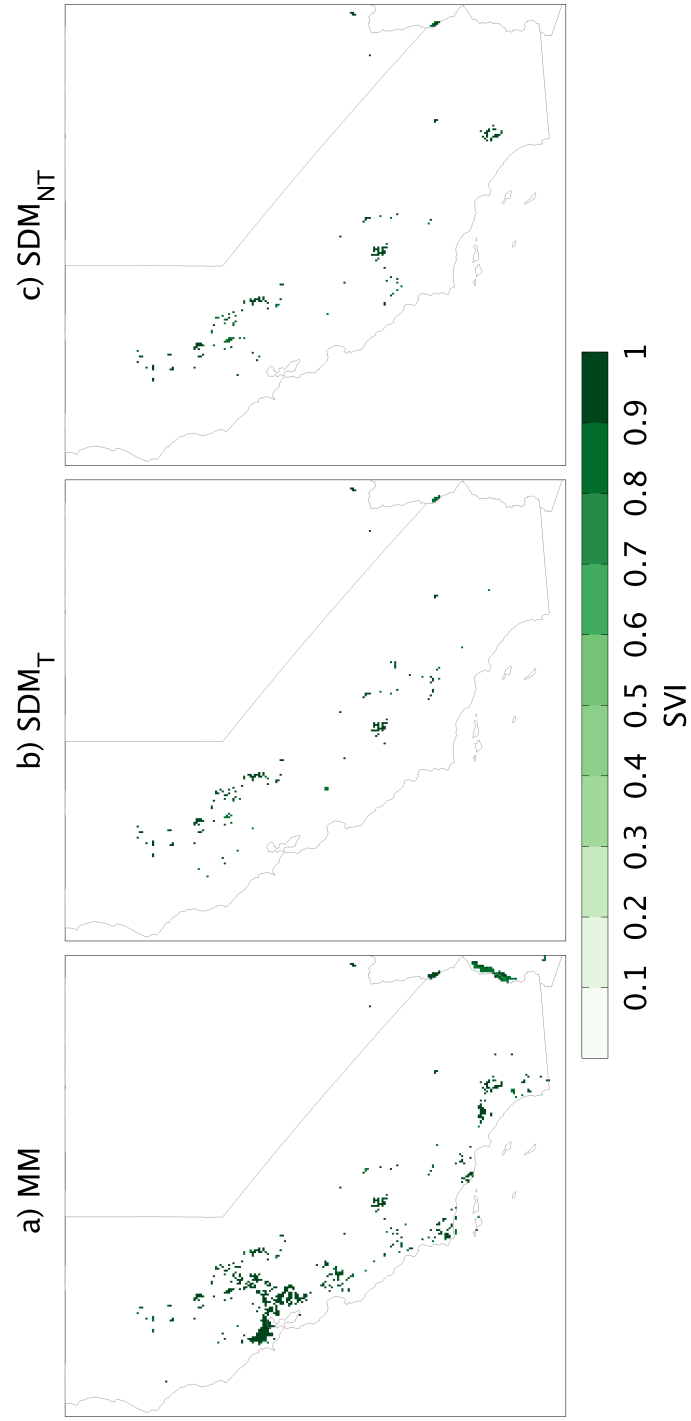


Figure 3.7 Mean SVI values, binned by almond density, for croplands

Supplemental Figures



Supplemental Figure 3.S1 Cropland (>10% density) locations without current almond cultivation shown to have SVI >0.8 for (a) the mechanistic model (MM), (b) the Traditional species distribution model (SDM_T), and (c) the Nontraditional species distribution model (SDM_{NT})

CHAPTER 4: SHIFTS IN THE THERMAL NICHE OF ALMOND UNDER CLIMATE CHANGE

As submitted to *Climatic Change*

Abstract

Delineating how climate change may shift where high-value crops such as almonds can be cultivated provides information for land use and water management planning, and insights to the economic and production considerations necessary to meet consumer demand. A suitability modeling approach was used to map the thermal niche of almond cultivation and the timing of phenological development across the western United States (US) through the mid-21st century. The Central Valley of California remained thermally suitable for almond cultivation in the mid-21st century and opportunities for expansion of the thermal niche for almonds occurred in the northwestern US (NWUS) over the early and mid 21st century, with most of the expansion covering more than 6900-km² of existing croplands in the Willamette Valley of western Oregon, which is currently limited by insufficient heat accumulation. The primary constraints on almond thermal suitability throughout the mid 21st century for other agricultural regions in the NWUS were frost damage and insufficient heat accumulation. Advancement in the timing of crop maturation was modeled across the region, compressing the growing season for almonds. Almond phenology in the Central Valley showed an approximately 2-week delay in chill accumulation and ~1- and ~3-week advance in the timing of bloom and harvest, respectively. Although other climatic and non-climatic restrictions to almond cultivation may exist in the NWUS, 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.

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 function 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 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 constrained by the impracticality of employing agricultural decisions used in annual crops such as fallowing. Understanding how future climate changes 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 chilling hours (Luedeling et al. 2009), water availability (Pollock 2015), and increased aridity (Machovina and Feeley 2013). Geographic shifts in the potential distribution of cultivated species have been empirically assessed using correlative species distribution models (SDMs) (Machovina and Feeley 2013) and random forest approaches (Moriondo et al. 2013), as well as assessed using process-based suitability models (SMs) (Morin et al. 2008; White et al. 2006). While both modeling frameworks have merits and shortcomings, previous work has shown they can 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 crop phenology and climatic limitations specific to individual phenostages, and are not limited by the correlative approach or temporal averaging of environmental conditions. This additional insight into crop phenology is advantageous considering that synchronous phenological timing is necessary for plant-pollinator interactions, and that changes in development timing may influence crop water demands and farm operations (Webb et al. 2007).

Virtually 100% of the commercially grown supply of US almonds – and more than 80% of the global supply – are cultivated in California, comprising more than 10% of California agricultural and ranching income (CDFA 2015). Since 1995, almond acreage in California has

more than doubled from 1,690-km² to 3600-km² (US Department of Agriculture 2015) as a function of increased demand – likely due to reported health benefits of almond consumption (Tan and Mattes 2013) – and high profitability for growers (US Department of Agriculture 2015). Almond acreage increased by more than 400-km² 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 and the inability to fallow perennials has 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 such as navel orangeworm (Luedeling et al. 2011b). Previous work has shown that climate change may escalate the pressure from pests (Luedeling et al. 2011b), shift perennials northward or upslope to cooler climates (Lobell et al., 2006), and increase water scarcity in California (Averyt et al. 2013), indicating that the climate-related challenges facing growers today will persist into the future.

Similar to California, much of the northwestern United States (NWUS) has wet winters and dry summers ideal for almond cultivation. Nearly one quarter of the land area in the NWUS (Oregon, Washington, and Idaho) is devoted to agricultural production, contributing to hundreds of thousands of jobs and accounting for 3% of regional GDP (Dalton et al. 2013). Broadly, the NWUS is a leader in 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 topping \$4.3 billion US dollars (USD) (US Department of Agriculture 2015). Though almonds are not currently commercially produced in the NWUS, existing NWUS *prunus* species (e.g. cherries, peaches, plums) are cultivated on more than 200-km² of cropland and produce more than \$540 million USD in sales (US Department of Agriculture 2015). 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 than California (Averyt et al. 2013). Additionally, while warming may prove challenging for some California crops, 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 in the NWUS (White et al. 2006), allowing for the expansion of perennials currently limited by these climatic factors.

This study builds on previous work examining shifts in high market-value perennials (White et al. 2006) by modeling changes in the potential geographic distribution of the

perennial species *Prunus dulcis* (almond) under future climate. We utilize the SM of Parker and Abatzoglou (2017) to evaluate the viability of almond cultivation 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). Specifically, the objectives of this work are to delineate how climate change will alter the geographic distribution of agricultural land suitable to almond for the early- and mid-21st century, identify how thermal controls on almond cultivation vary spatially and temporally, and assess potential shifts in phenological timing of almond development.

Data and Methods

a. Data

Historical maximum and minimum temperature (T_{\max} , T_{\min}) for the period 1979 – 2014 for the western US [32° – 49° N, 114° – 125° W (Figure 1)] were acquired from the gridded surface meteorological dataset (METDATA) of Abatzoglou (2013). METDATA was created using two datasets: hourly data at $\sim 12\text{km}$ resolution from the North American Land Data Assimilation System Phase 2 (NLDAS-2, Mitchell et al. 2004), and monthly data at $\sim 4\text{km}$ resolution from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly et al. 2008). The resulting 4km resolution gridded daily dataset provides meteorological data at spatial and temporal scales suitable for both local and landscape scale ecological and agricultural modeling.

Statistically downscaled daily T_{\max} and T_{\min} data were obtained from twenty global climate models (GCMs) participating in the fifth phase of the Climate Model Intercomparison Project (CMIP5) for the historical (1950-2005) and future forcing (2006-2099) experiments. Data were statistically downscaled using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2012) using training data from METDATA to ensure compatibility between the downscaled historical GCM experiments (1950-2005) and the observed record (1979-2012). We constrained our analysis to model simulations for the early (2010-2039) and mid (2040-2069) 21st century periods. We chose 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 8.5 (RCP 8.5) given that inter-model variability exceeds inter-scenario

variability for these time horizons (Kharin et al. 2013), and emissions trajectories to date have more closely followed RCP 8.5 (Peters et al. 2013). Finally, as SM results calculated using METDATA were comparable to multi-model mean results over the historical model years 1971-2000, we focus on the observed METDATA from 1979-2014 for the contemporary SM runs.

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 crop and cropland densities at the 4km 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 4km grid cells with >1% almond density and cropland to be those 4km grid cells with >10% cropland density (Figure 1). These data were not used in the SM but rather were used to visualize and analyze output from the SM in the context of existing cropland.

b. Modeling Almond Development

The multi-year development cycle of almonds (Covert 2011) was simplified for modeling purposes to focus on four stages of reproductive development: endodormancy, ecodormancy, flower development, and hull split. The SM, detailed in Parker and Abatzoglou (2017), utilizes thermal requirements for almond development compiled from published literature and based on field studies and growth chamber experiments; where a range of values for thermal requirements exist within the literature, or when requirements vary by cultivar, the SM uses conservative threshold values and focuses on the Nonpareil cultivar as it is the most widely grown commercial varietal (Supplemental Table 1). The SM begins each year of almond development on November 1, a proxy for the onset of dormancy and the industry standard start date for chill portion accumulation (Covert 2011). The MM 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), but assumes that water requirements can be met throughout all growth stages via precipitation or irrigation.

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, over the historical (1979-2014), early, and mid-21st century periods. Each growth stage of each year has the opportunity for failed development, which is

treated as a binary variable though the impact to crop yield (or species viability) varies by growth stage. For example, temperatures below the cold hardiness threshold for almonds may result in tree mortality, whereas temperatures below frost thresholds may result in ~20% crop damage. The SM treats these scenarios equally, as failure during any development stage results in an unviable year for almond cultivation. Over each period of study, the proportion of suitable years to total years for almond cultivation is referred to as the species viability index (SVI), which 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. SVI was calculated for each model and time period. We focus on multi-model mean SVI, or the average SVI calculated separately for each model. However, we also assess the robustness of results across models as measured by the number of models with high SVI (SVI >0.8) for each location and time period. High SVI was selected because locations projected to have high future viability are likely to be of greater practical interest to growers and resource managers. Finally, we refined our SVI analysis to those locations with current cropland density >10% in order to highlight suitability in those locations most accessible for cultivation.

In addition to determining the overall suitability for almond cultivation, the SM also tracks almond phenology for each year. Beginning with 1 November, the SM accumulates chill and records the day of the year on which the required CP is accumulated (CPday). The SM begins accumulating GDD on CPday and records the day of the year cumulative GDD reach 1% bloom, 50% bloom (anthesis), 100% bloom, 1% hull split, and 100% hull split thresholds. While additional time on the tree is recommended for almonds after 100% hull split to encourage drying and ease the harvest process, harvest may commence as soon as 100% hull split is reached. Delay in almond harvest after 100% hull split can impact crop quality due to impacts from naval orangeworm, mold, and rain (Connell et al. 2010, Niederholzer 2012). However, to account for some drying time on the tree, as is common in orchard management practices, we estimated the number of days post-hull split to measure harvest timing using observations from the Chico, California Regional Almond Variety Trial (RAVT, Connell et al. 2010). These data suggest an average of 12 days between 100% hull split and harvest, hereafter used in the SM rather than the GDD accumulation threshold for harvest timing as in Parker and Abatzoglou (2017). Experiments showed that this measure of harvest timing increased overall viability, particularly in NWUS locations with milder summer temperatures that fail to reach harvest GDD thresholds (Supplemental Figure 1). We assess the phenology of almond development in

the NWUS by examining the timing of phenostages, with a particular focus on areas shown to be suitable for almond cultivation. We further calculated changes to development timing in primary almond growing regions, defined as those 4km grid cells with high (>40%) almond density; we constrain our analysis in this manner in order to highlight phenological changes in those areas with high production.

Results

a. Climatic Controls on Almond Development

Spring frost and heat accumulation for nut maturation (100% hull split) have historically been the primary limiting factors for almond cultivation across much of the western US outside of current almond locations, including the NWUS (Figure 2, left). While frost risk increased during the final stage of nut maturation in western Oregon for early 21st century model runs, frost risk during bud swell decreased across the inland NWUS where it had historically been a limiting factor for cultivation. Further, warming temperatures by the early 21st century increases heat accumulation necessary for nut maturation across the western NWUS and in the inland agricultural regions of the Columbia Plateau and Snake River Plain (Supplemental Figure 2a). By the mid-21st century, large increases in SVI were shown across the NWUS resulting from reduced frost risk and increased GDD (Supplemental Figure 2b). Although suitability for individual thermal factors increased across the NWUS under future climate scenarios, heat accumulation necessary to reach 100% hull split and frost during bloom onset remain primary thermal limitations, with 65% and 71% of the NWUS showing SVI <0.8 for 100% hull split GDD accumulation and frost at 1% bloom, respectively (Figure 2, right). Thermal suitability remains largely unchanged in California's Central Valley in current almond locations under future climate projections; however, results showed that reduced chill accumulation was primarily responsible for overall SVI reduction in SVI in parts of southern California (Supplemental Figure 2b).

b. Changes in the Geographic Distribution of SVI

Over the historical period, the SM showed high (>0.8) SVI values over California's Central Valley, and across the deserts of southern California, southern Nevada, and western Arizona, as shown in Parker and Abatzoglou (2017). By contrast, no land in the NWUS had high SVI over the historical period (Figure 3a). However, changes in the suitability of individual

thermal factors resulted in shifts in overall SVI for both early and mid-century periods. Suitability in California's Central Valley remained high (>0.8) in the early 21st period with increased SVI for portions of southeastern and northwestern California. However, significant declines in suitability were evident over extreme southeastern California along the Arizona and Mexico borders where chill accumulation declined. The NWUS remained unsuitable, with only 0.56% of the region showing SVI >0.8 in localized areas of southwestern Oregon and the northern Willamette Valley by the early 21st century (Figure 3b). Mid 21st century thermal conditions were no longer suitable in extreme southeastern California and along the southern California coast; however, suitability increased over northwestern California and remained unchanged in the Central Valley. Across the NWUS gains in suitability were seen for mid-century period, with nearly 50,000-km² across the NWUS showing SVI >0.8 (Figure 3c).

Multi-model mean results showing high SVI were largely robust across models for both early and mid-21st century periods over California (Supplemental Figure 3). Models showed broad agreement of high SVI over the Central Valley, and at least 80% of models showed high SVI over $>99\%$ current almond cultivation locations for both future periods. However, these results were less robust over the NWUS where fewer than 50% of locations with high multi-model mean SVI at mid-century showed agreement across at least 16 of the 20 models. Approximately 3000-km² of land showed high SVI across all models including around 300-km² of current cropland in the northern Willamette Valley, highlighting this area as a hotspot for potential future almond cultivation.

When restricting our analysis of high SVI to current croplands across the domain, results showed that $\sim 34,000$ -km² of California cropland remained thermally viable into the mid-21st century, including the $\sim 4,200$ -km² of current almond plantations. By the early 21st century, suitable almond cropland area contracted by $\sim 1,060$ -km² in southern California and along the California-Arizona border, and expanded by ~ 600 -km² in localized areas in Oregon and northern California. Although an additional 630-km² of southern California croplands were unviable by the mid-21st century, opportunities for expansion by the mid-21st century exceeded range contraction, with more than 6,500-km² of current NWUS croplands becoming viable, including virtually all of the Willamette Valley (Figure 4).

b. Shifts in Phenological Timing

Changes in the timing of almond development were projected for climate change scenarios, with the degree of change varying by phenostage and location (Figure 5). In general,

the date at which chill accumulation requirements were met occurred later with warming, while warming allowed for advancement in phenology in all other phases thereby compressing the almond reproductive cycle. Relative to historical phenology in California's primary almond growing regions, ecodormancy onset (chill accumulation) was modeled to occur approximately 5 and 14 days later by the early and mid-21st century, respectively. Conversely, all other development stages occurred earlier in the year in these locations. Average 50% bloom dates showed the least change in timing by mid-century in California's primary almond growing locations, occurring approximately 6 days and 1 day earlier by the early and mid 21st century, respectively. Maturation (100% hull split) dates in these locations were modeled to occur approximately 10 days and 19 days earlier by the early and mid-21st century, respectively. Finally, phenological timing over NWUS croplands with high suitability at mid-century was compared to historical timing over California's primary almond cultivation locations. Ecodormancy onset and bloom timing over these NWUS locations were comparable to current timing in primary almond growing regions, with mid-century ecodormancy onset occurring 10 days earlier, and 50% bloom dates occurring 10 days later by the mid-21st century. However, mid-21st century nut development over the NWUS remained delayed relative to historical timing over California's primary almond growing regions, with NWUS locations reaching maturity 37 days later.

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 historical period across much of the study area outside of where almonds are currently produced. Insufficient heat accumulation was also shown to be a historically limiting factor to almond cultivation across the western US, and has similarly been linked to plant distribution and crop cultivation restrictions (Sykes et al. 1996). These two thermal constraints wane across areas that have historically been unsuitable to almond cultivation by the mid-century, in line with projections of decreased spring frost risk (Allstadt et al. 2015) and increased annual heat accumulation (White et al. 2006). Higher SVI may occur where growers have a higher tolerance for risk or the ability to mitigate frost damage (e.g. wind turbine use); conversely, SVI for frost damage may be reduced where cultivation occurs in microclimates subject to cold air drainage at scales finer than the 4-km data used here. 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 are projected to 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).

The broad patterns of potential expansion of thermal suitability for almond cultivation in the NWUS are in line with other research that 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. The phenological shifts modeled by the SM support previous research showing observed (Chmielewski et al. 2004) and modeled (Webb et al. 2007) advancements in crop phenology. Further, paralleling the SM phenology results, other studies examining changes in plant and crop phenology have shown a compression of crop development over the growing season, spatial variability in the magnitude of phenological change, and a greater magnitude of change for later phenostages (Allstadt et al. 2015; Webb et al. 2007). While the advancement of almond phenology may allow for the completion of the development cycle in portions of the NWUS, 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 (Mommott et al. 2007). Similarly, the warming temperatures that result in phenological advances 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).

Given that current almond locations remain thermally suitable into the mid-21st century, California's future water limitations (Seager et al. 2013) may be a driver for developing almond cultivation in the NWUS. However, climate change may lead to water challenges in the NWUS as well, with decreased snowpack, earlier runoff, and increased summer evaporative demands (Mote et al. 2014). Such impacts on water availability and irrigated agriculture are sensitive to legal institutions governing water distribution, and irrigated agriculture may see losses in crop revenue as a function of climate change and subsequent declines in water supply (Xu et al. 2014). Further, in locations where almonds might replace crops with lower water requirements, the high water needs of almonds could exacerbate these water resources challenges. Still, increased water use efficiency from rising levels of atmospheric carbon dioxide may curb such potential water shortages and despite potential water resource limitations in the

NWUS, it will likely remain a water secure region relative to California under climate change (Averyt et al. 2013).

In addition to potential water challenges in the NWUS, further limitations to almond cultivation in thermally suitable locations may exist. 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 (Cavagnaro et al. 2006; McDonald et al. 2009); such changes in biotic interactions may alter orchard management practices and increase reliance on chemical controls, which may have detrimental environmental impacts (Pimentel 1992). Further, the economic costs of crop translocation could be considerable. Crop range expansion or translocation requires significant capital and – in the case of translocation – 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.

Although the thermal niche for almonds expanded into the NWUS and the northern Willamette was identified as a hotspot for potential almond cultivation under climate change, that the SM does not account for non-thermal factors governing cultivation potential highlights the need for further research in order to provide a clear and actionable picture for growers regarding environmental suitability and production potential for almonds in novel regions. However, recognizing that thermally-suitable novel cultivation locations for high-value orchard crops are projected to exist within the lifetime of orchards planted today may guide long-term land use and water management planning at the farm and regional scale, inform future development, and perhaps assuage some concerns regarding crop supply and cost.

Acknowledgements

This research was supported by the National Institute of Food and Agriculture competitive grant, award number: 2011-68002-30191.

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Figures

Almond Densities and Existing Croplands

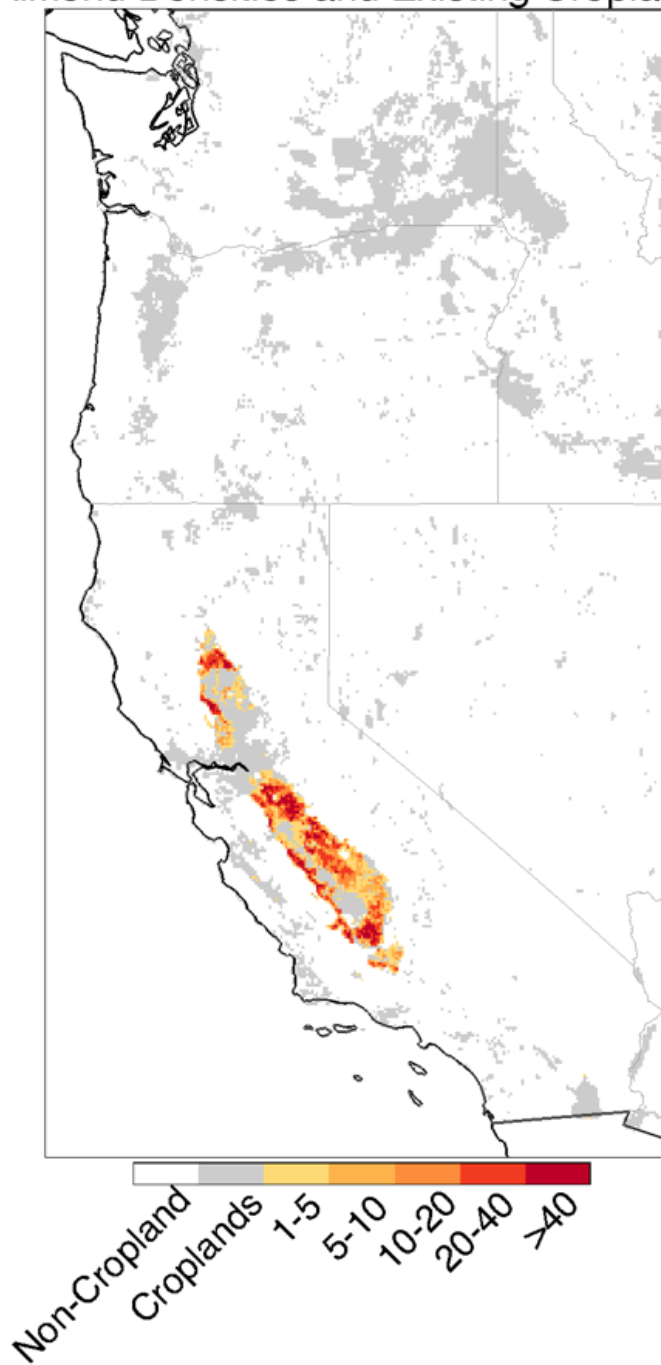


Figure 4.1 Overview of study area. Grey areas indicate locations with relative cropland densities >10% on a 4-km grid. Yellow to red hues indicate almond density of locations with >1% cultivation density

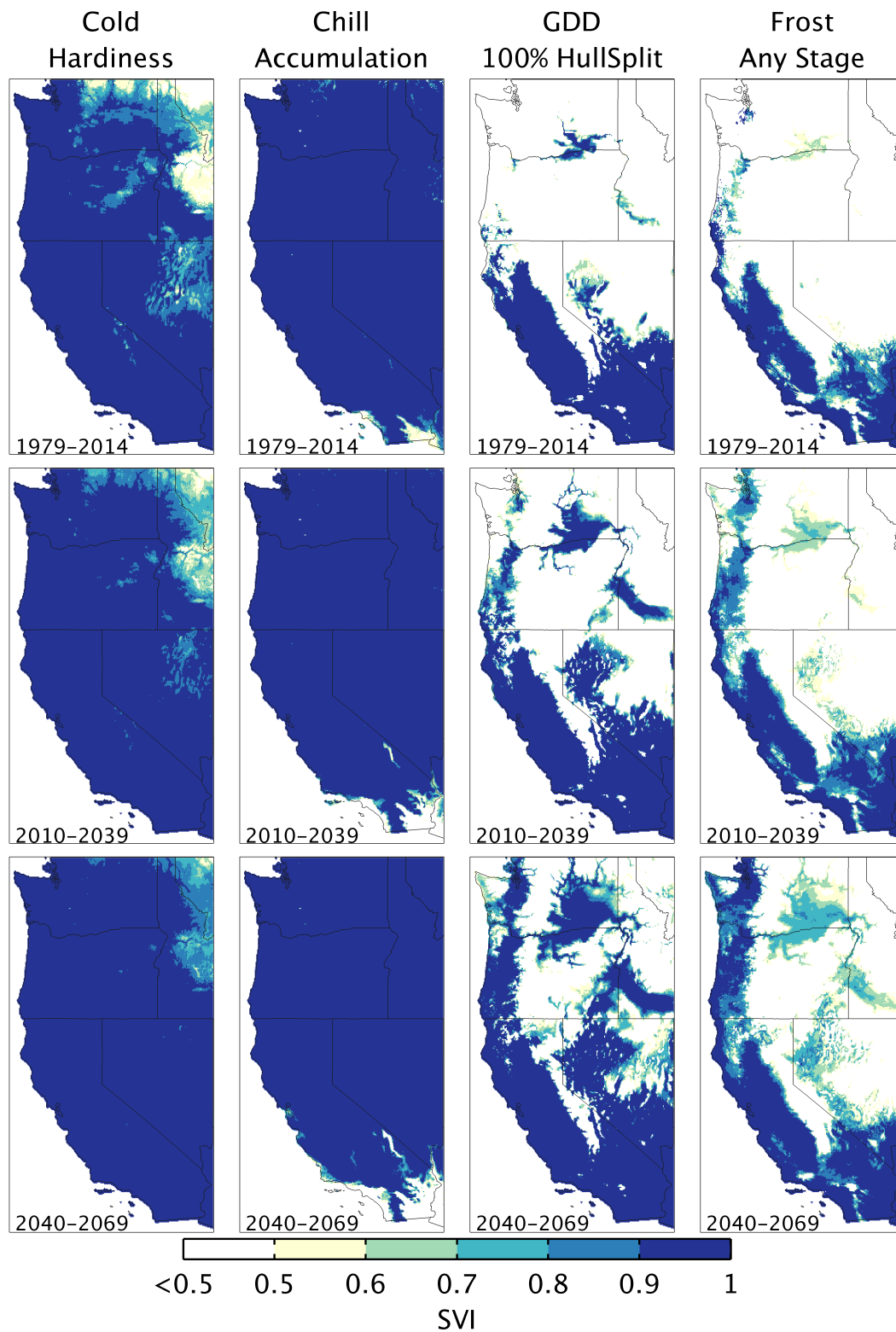


Figure 4.2 SVIs for key phenostages over the historic, early, and mid-21st century periods. Frost SVIs reflect the percent of years without frost damage at any time between ecodormancy onset and 100% hull split

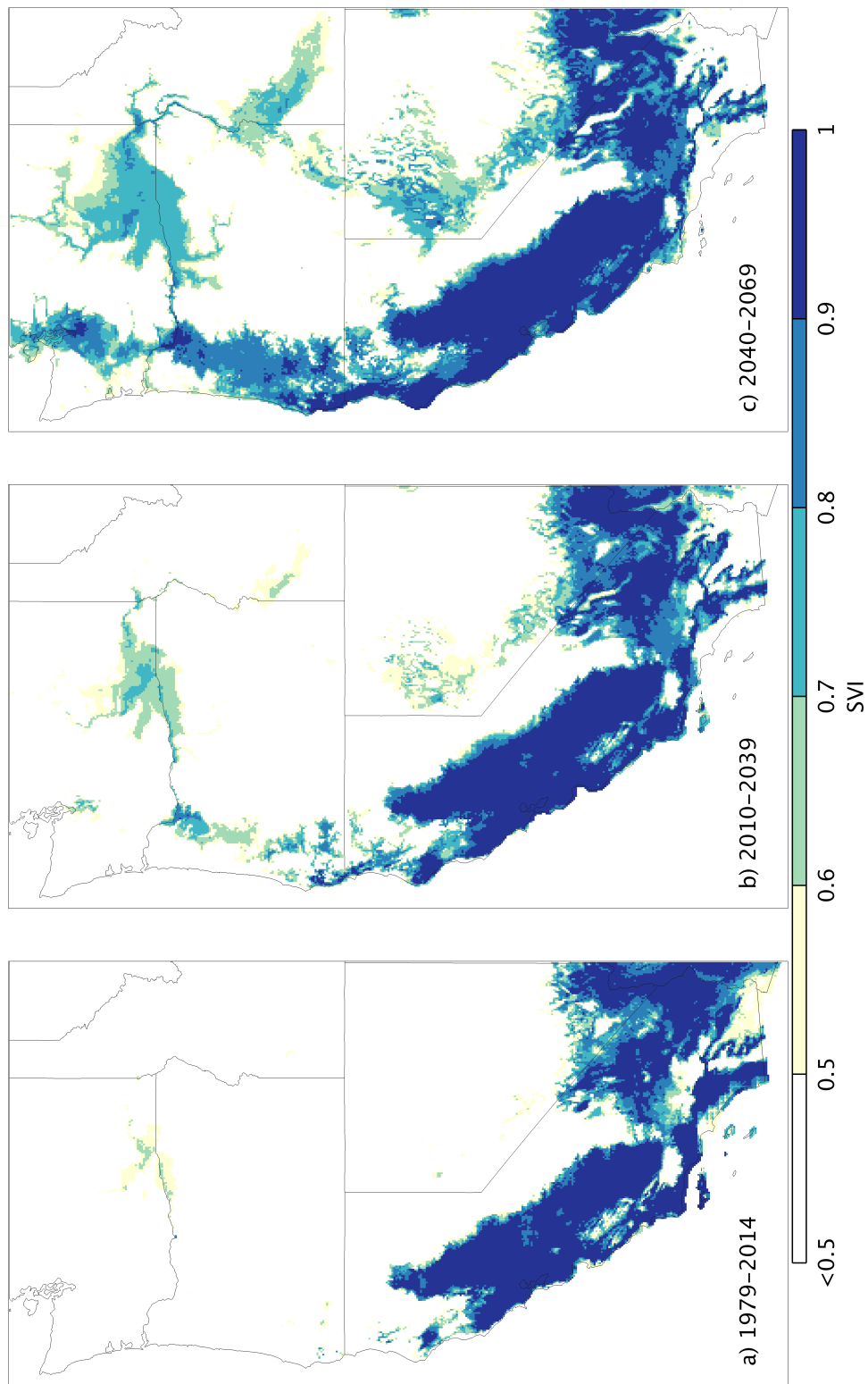


Figure 4.3 SVI over the (a) historical, (b) early 21st century, and (c) mid 21st century periods.

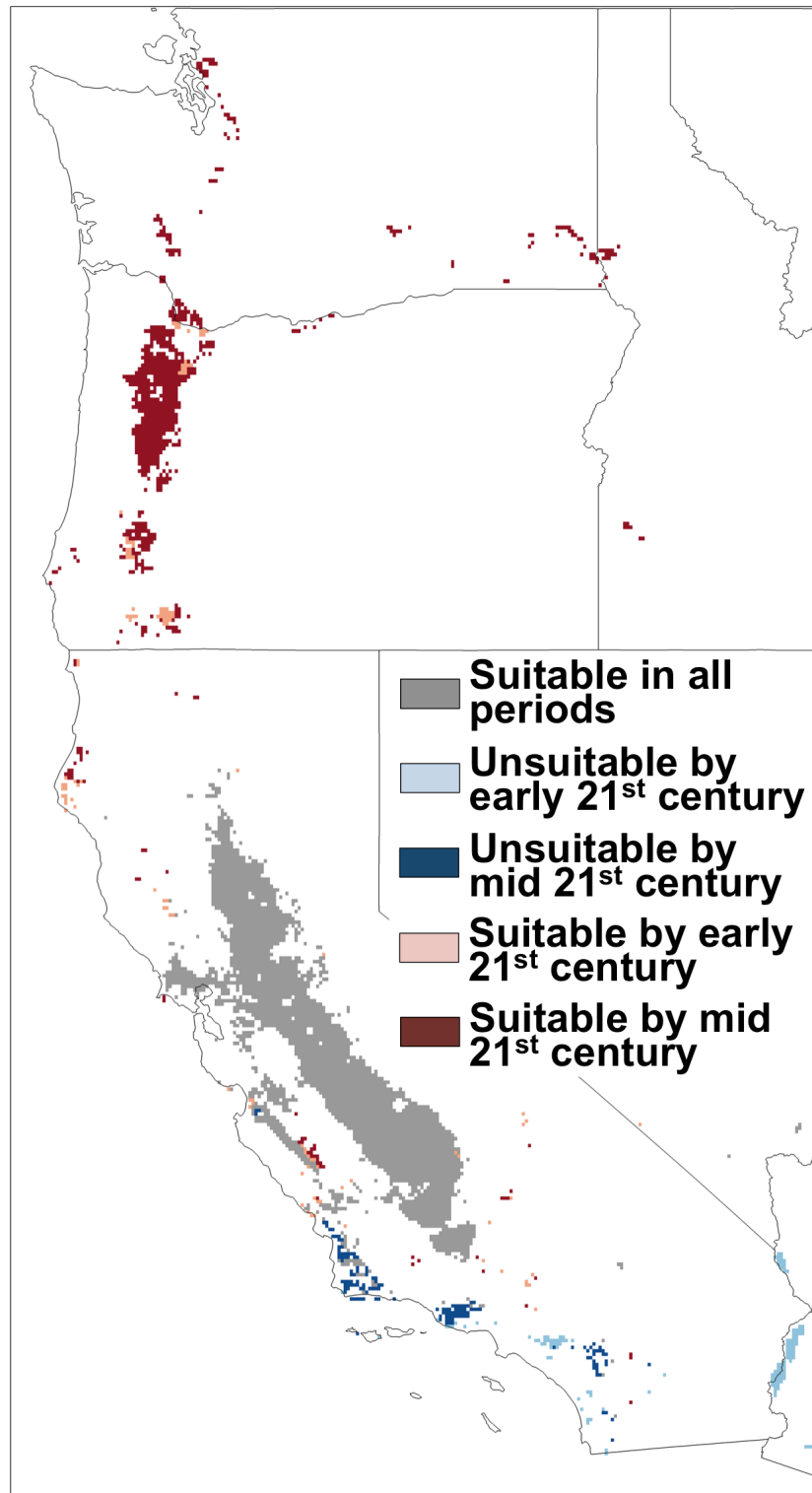


Figure 4.4 The relative expansion and contraction of the high suitability (SVI>0.8) range of almond over locations with current cropland densities >10%. Grey indicates high suitability over all periods, while blue hues indicate contraction and red hues indicate expansion. Light blue are locations with historical SVI>0.8 but a reduction below high suitability by the early century; dark blue are locations with historical and early SVI>0.8 but mid-century SVI reductions below high suitability; light red are locations that became suitable (SVI>0.8) by the early century, while dark red locations did not become suitable until the mid-21st century.

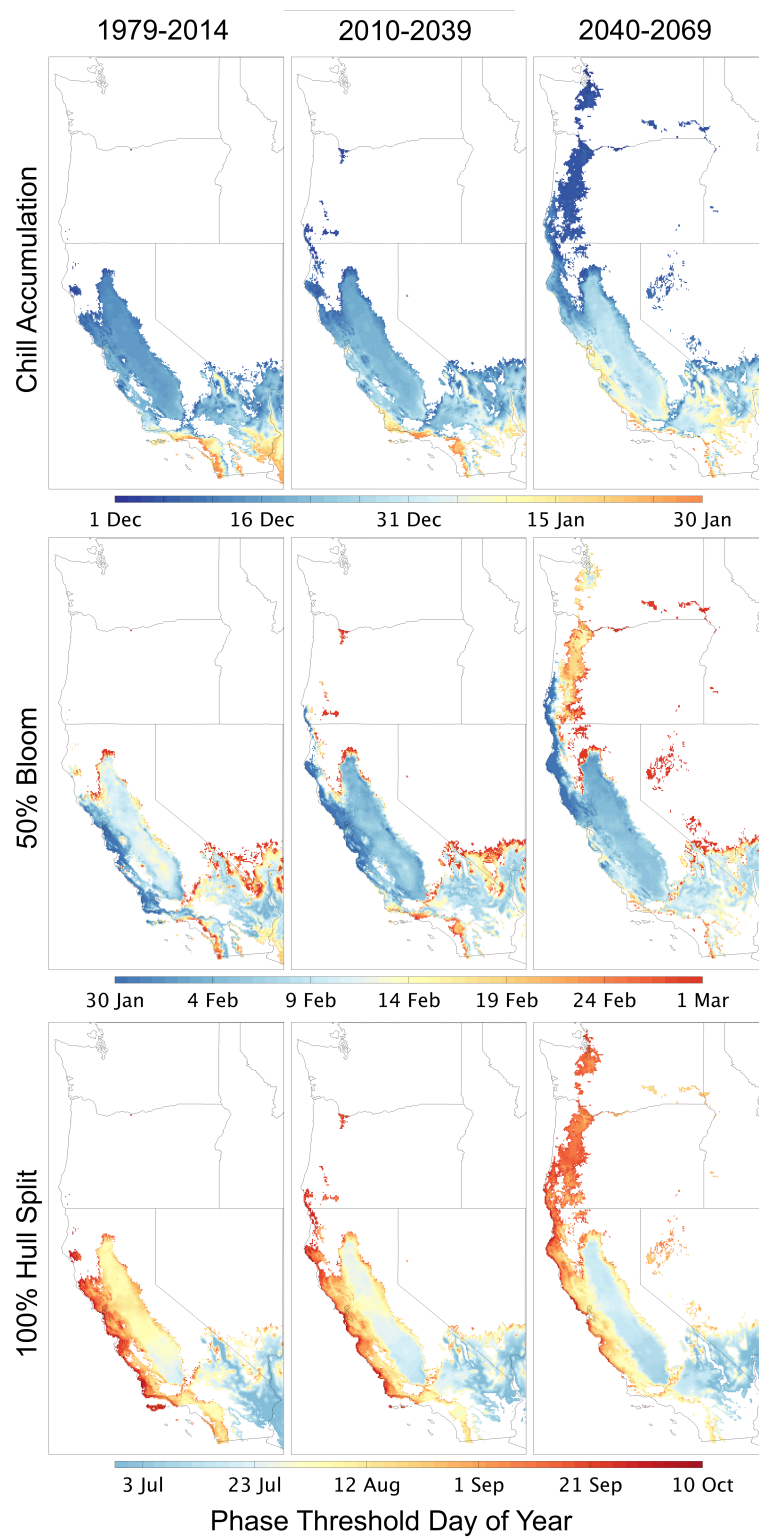


Figure 4.5 The timing of three representative phenostages – chill accumulation (top row), 50% bloom (middle row), 100% hull split (bottom row) – over the historical, early, and mid century periods.

Supplemental Tables

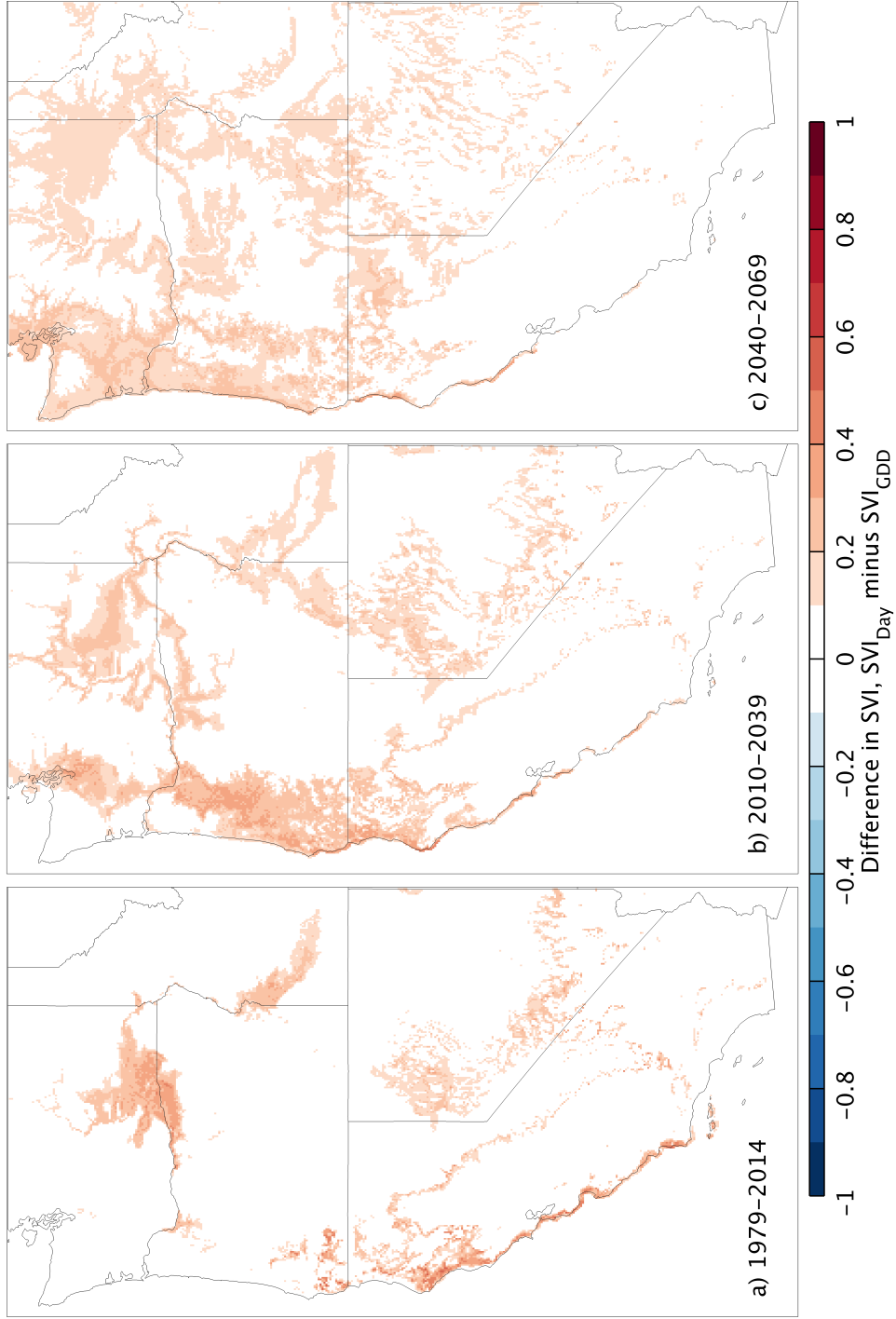
Supplemental Table 4.1. Phenological thresholds used in the SM and their sources.

Stage	Model Threshold	Published Range	Source
Cold Hardiness	-25°C		Janick and Moore (1996)
Chill Portions	23	23 - 30	Covert (2011)
GDD Base Temperature	4.5°C		Rattigan and Hill (1986)
1% Bloom GDD	176 (80% of 50% bloom GDD)		RAVT, University of California (1996-2006)
1% Bloom Frost	-15°C (undefined damage %)	-15 – -20°C	Janick & Moore (1996)
50% Bloom GDD	220	220 – 370	Published Range: Covert (2011)
50% Bloom Frost	-5.6°C (20% damage)	-6.5 – -3°C (up to 50% damage)	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)
100% Bloom GDD	300	300-500	Janick and Moore (1996)
100% Bloom Frost	-3.9°C (20% damage)	-5.6 - -2.2°C (up to 75% damage)	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)

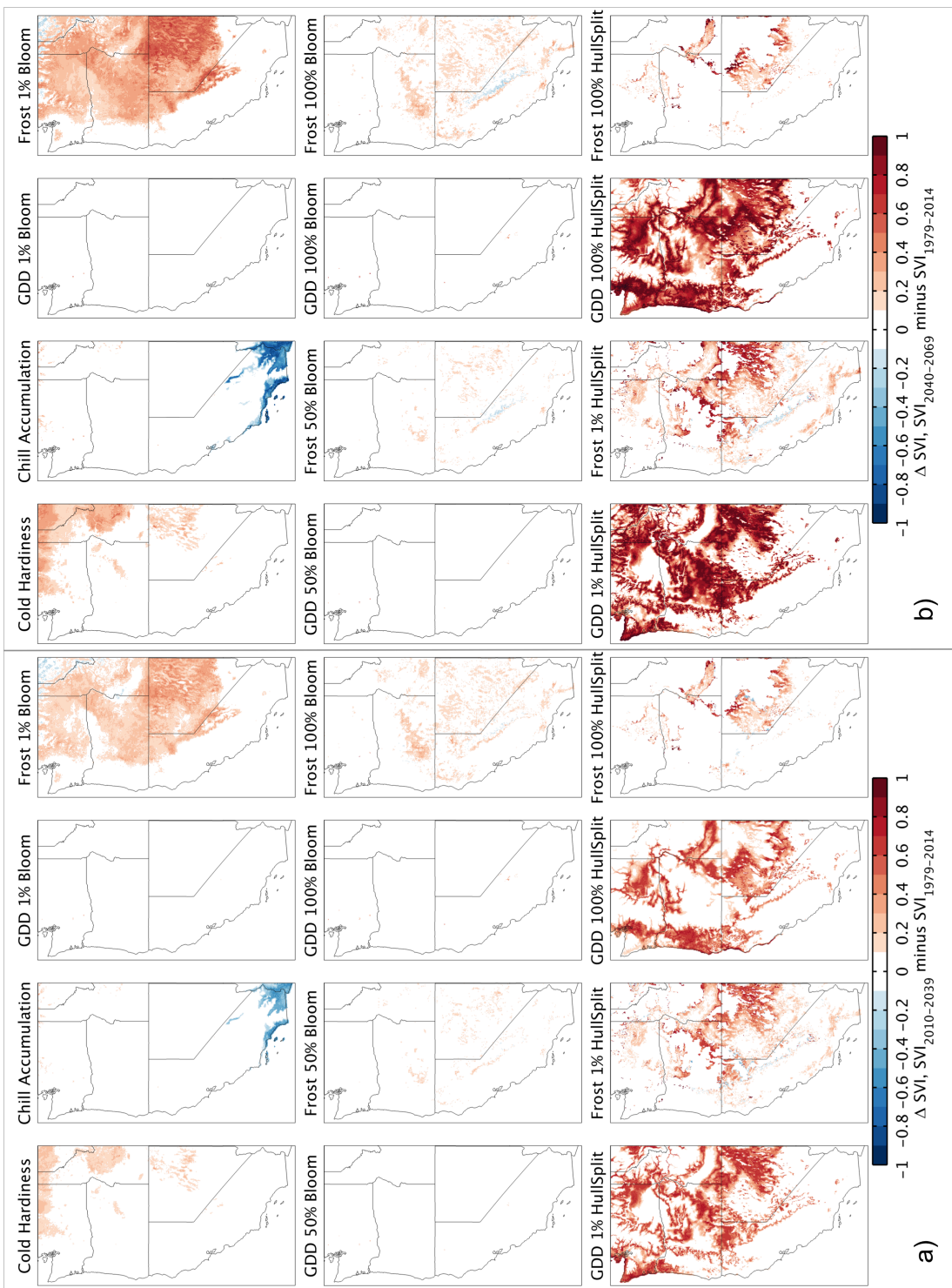
1% Hull-Split GDD	2219	~1900 - 2550	Based on Connell <i>et al.</i> (2010)
1% Hull-Split Frost	-2.8°C (19% damage)	-2.8 - -0.5°C (up to 50% damage)	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)
100% Hull-Split GDD	2750	~2390 - 3100	Based on Connell <i>et al.</i> (2010)
100% Hull-Split Frost	-2.8°C (19% damage)	-2.8 - -0.5	Model Threshold: Snyder and Melo-Abreu (2005) Published Range: Snyder and Melo-Abreu (2005), Janick and Moore (1996)
Harvest DAY	100% Hull-Split Day + 12 days	1 - 25	Based on Connell <i>et al.</i> (2010)
Harvest GDD	3032	~2760 - 3530	Based on Connell <i>et al.</i> (2010)

With the exception of Harvest DAY, this table is as it appears in Chapter 3. For full citations from Table 4.1 sources, please refer to Chapter 3 References.

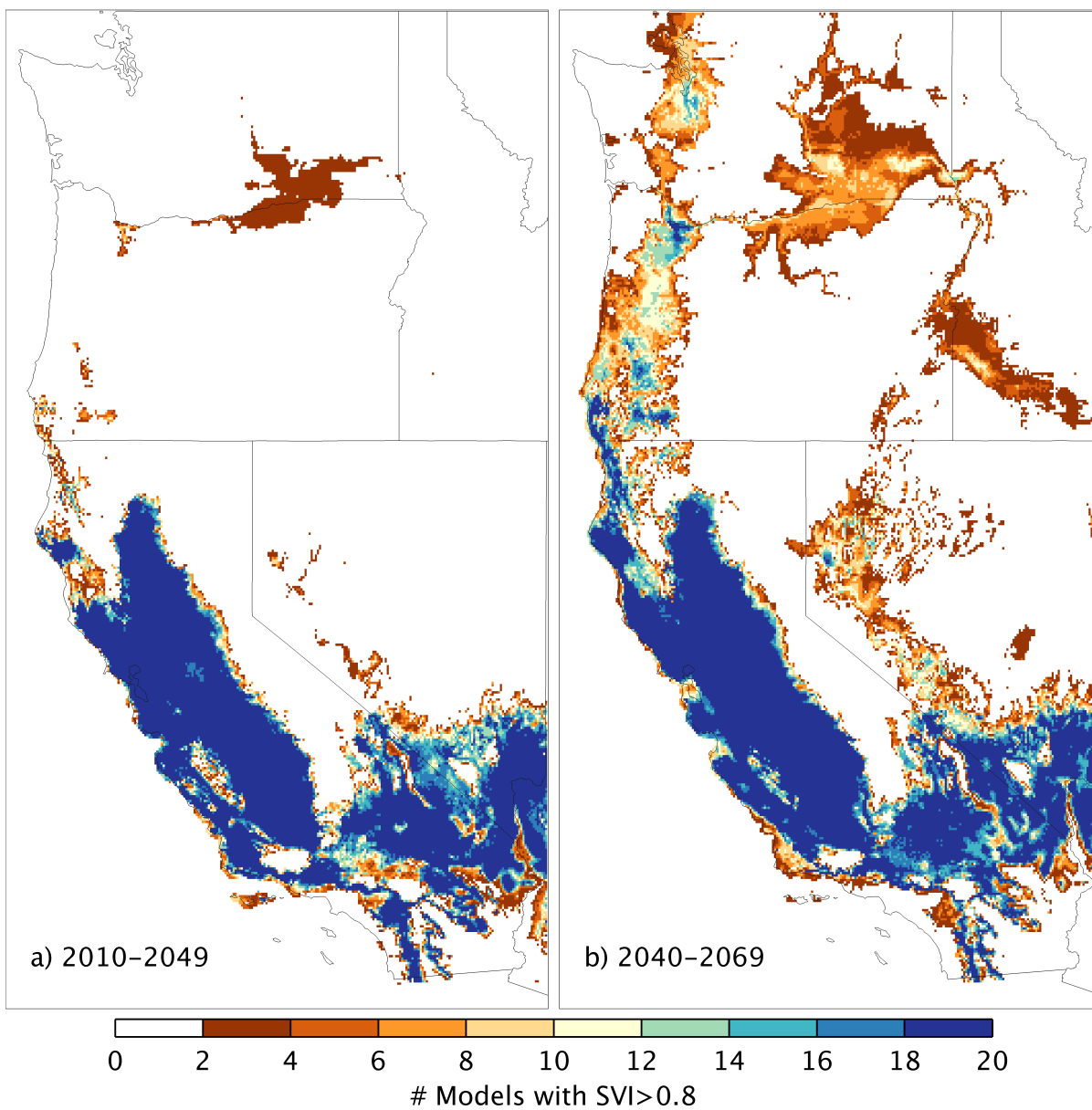
Supplemental Figures



Supplemental Figure 4.S1 Differences between SVI when using days post-100% hull split (SVI_{Day}) versus GDD (SVI_{GDD}) when calculating viability for the (a) historical, (b) early 21st century, and (c) mid 21st century periods.



Supplemental Figure 4.S2 Change in SVI for each phenostage between the historical and early periods (a, left), and the historical and mid 21st century periods (b, right). Blue hues indicate a decline in suitability for the stage, while red hues indicate an increase in suitability.



Supplemental Figure 4.S5 Robustness of projected SVI as defined by the number of models showing SVI > 0.8 over the (a) early- and (b) mid-21st century periods

CHAPTER 5: CONCLUSIONS

Concluding Thoughts and Future Research Needs

Climate change presents significant challenges to sustaining agricultural production sufficient to meet growing global food demands, and these challenges are highlighted in the cultivation of perennial orchard crops, which are subject to potentially adverse environmental conditions year-round and over their decades-long lifespans. While previous studies have shown climate change to result in reductions in crop yield in current crop cultivation locations (Lobell et al. 2006; Lobell and Field 2007; Schlenker and Roberts 2009), the ability of high-value perennials such as almonds to be cultivated beyond their current range under climate change had not been previously explored.

This dissertation addresses this knowledge gap through examining thermal metrics relevant to the geographies of agricultural production. Chapter 2 of this dissertation examined climate change impacts on winter average minimum temperatures, winter extreme minimum temperatures, and USDA cold hardiness zones (CHZs), which provide a common measure of assessing climatic suitability for crop cultivation in a given location. While future temperature projections resulted in a warming of average minimum winter temperatures by the mid-21st century, the differential warming of winter extreme minimum temperatures resulted in a northward shift of CHZs and an expansion in the suitable overwinter range for several perennial tree crops. In chapter 3, almonds were introduced as a high-value perennial crop for further study and additional thermal drivers of suitable crop range were considered in two modeling approaches for estimating the potential distribution of the species. While the empirical species distribution modeling (SDM) approach provided comparable spatial results to the more complex and computationally intensive mechanistic modeling (MM) approach, the limitations of the correlative approach of the SDM may yield results driven by climatological similarity rather than physiological function. Conversely, the MM not only provides an ability to investigate the relationships between climate, phenology, and physiology, but is also better suited to capture the impacts of interannual climate variability on crop cultivation. As chapter 3 concludes that MMs are preferable for assessing climate change impacts on perennial crop cultivation, chapter 4 utilizes the MM developed in chapter 3 to examine how climate change may influence the thermal drivers of almond distribution, and how climate change may alter almond phenology and the geography of almond cultivation. Chapter 4 concludes that warming temperatures will alter almond's phenological timing, and while reductions in winter chill may

yield a contraction of suitable area for almond cultivation in southern California, decreased frost risk and increased heat accumulation across much of the western US will largely generate a geographic expansion of almond's thermal niche. The projected area of expansion includes more than 12,000-km² of cropland and highlights the northern Willamette Valley as a potential hotspot for future almond production.

Though this research explored the thermal potential for agricultural expansion, a multitude of factors important to crop production were not considered. Specifically, water supply, water security, and irrigation infrastructure (both physical and legal) are key to orchard crop cultivation and are likely to be impacted by climate change (Averyt et al. 2013; Elliot et al. 2014; Vano et al. 2010; Xu et al. 2014). Further, biotic interactions within the orchard system can influence the success of crop cultivation and the management practices necessary to ensure high quality and high quantity yields. Climate change may result in a mismatch in crop phenology and pollinator life cycles (Polce et al. 2014), and may also prompt increased pest and disease damage barring alterations in orchard management (Cavagnaro et al. 2006). Finally, non-environmental factors such as competing land use, cultural and political influence on agricultural systems, and economic incentives were not quantified though these elements all inform the practicality of crop production (Luedeling et al. 2011). To begin to address some of these issues, future research will be conducted to determine what the additional water demands for almonds may be under future climate scenarios, and how land use and climate changes may influence water demands and availability in the Central Valley of California and across the Northwest more broadly.

While the potential for translocation of crops may exist under future thermal conditions, providing a potential boon for regional economics and opportunities for maintaining stability in food supply, the significant knowledge gaps outlined above limit our understanding of the true capacity for novelty crop cultivation. Although some components of the food production system not considered here – such as soil characteristics, precipitation, evapotranspiration, and competing land use – may be built into future model iterations and allow for an improved picture of cultivation potential, the complexities of food production will still require collaborative efforts across multiple disciplines in order to develop a more complete picture of the adaptive capacity of perennial agriculture in the face of climate change.

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APPENDIX A

A mathematical expression of the mechanistic model presented in Chapter 2

For a given location x , for each year t , the mechanistic model functions as follows

$$\begin{aligned}
 chz &= \begin{cases} TN_n \leq -25^\circ\text{C}, & 0 \\ TN_n > -25^\circ\text{C}, & 1 \end{cases} \\
 cp &= \begin{cases} CP_{cum} < 23, & 0 \\ CP_{cum} \geq 23, & 1 \end{cases} \\
 sb &= \begin{cases} GDD^\circ\text{C} < 176, & 0 \\ GDD^\circ\text{C} \geq 176, & 1 \end{cases} \\
 sbf &= \begin{cases} sb = 1 \wedge T_{min(cp:sb)} \leq -15^\circ\text{C}, & 0 \\ sb = 1 \wedge T_{min(cp:sb)} > -15^\circ\text{C}, & 1 \end{cases} \\
 hb &= \begin{cases} GDD^\circ\text{C} < 220, & 0 \\ GDD^\circ\text{C} \geq 220, & 1 \end{cases} \\
 hbf &= \begin{cases} hb = 1 \wedge T_{min(sb:hb)} \leq -5.6^\circ\text{C}, & 0 \\ hb = 1 \wedge T_{min(sb:hb)} > -5.6^\circ\text{C}, & 1 \end{cases} \\
 fb &= \begin{cases} GDD^\circ\text{C} < 300, & 0 \\ GDD^\circ\text{C} \geq 300, & 1 \end{cases} \\
 fbf &= \begin{cases} fb = 1 \wedge T_{min(hb:fb)} \leq -3.9^\circ\text{C}, & 0 \\ fb = 1 \wedge T_{min(hb:fb)} > -3.9^\circ\text{C}, & 1 \end{cases} \\
 hs &= \begin{cases} GDD^\circ\text{C} < 2219, & 0 \\ GDD^\circ\text{C} \geq 2219, & 1 \end{cases} \\
 hsf &= \begin{cases} hs = 1 \wedge T_{min(fb:hs)} \leq -2.8^\circ\text{C}, & 0 \\ hs = 1 \wedge T_{min(fb:hs)} > -2.8^\circ\text{C}, & 1 \end{cases} \\
 hf &= \begin{cases} GDD^\circ\text{C} < 2750, & 0 \\ GDD^\circ\text{C} \geq 2750, & 1 \end{cases} \\
 hff &= \begin{cases} hf = 1 \wedge T_{min(hs:hf)} \leq -2.8^\circ\text{C}, & 0 \\ hf = 1 \wedge T_{min(hs:hf)} > -2.8^\circ\text{C}, & 1 \end{cases} \\
 har &= \begin{cases} GDD^\circ\text{C} < 3032, & 0 \\ GDD^\circ\text{C} \geq 3032, & 1 \end{cases}
 \end{aligned}$$

$$MM(x, t) = \{chz * cp * sb * sbf * hb * hbf * fb * fbf * hs * hsf * hf * hff * har$$

where

- chz assesses cold hardiness suitability based on the coldest minimum temperature of the year, TN_n

- *cp* assesses chill accumulation based on cumulative chilling portions between November 1 and March 31 (CP_{cum}), as calculated using the dynamic chill model (Luedeling et al 2009b)
- *sb* assesses heat accumulation needed to reach 1% bloom, where $GDD^{\circ C}$ is the annual accumulated growing degree days between November 1 and October 31, as calculated using T_{base} of $4.5^{\circ C}$
- *sbf* assess frost risk at half bloom, as determined by daily T_{min} between the completion of chill accumulation and 1% bloom (*cp:sb*)
- *hb* assesses heat accumulation needed to reach half bloom, as in *sb*
- *hbf* assesses frost risk at half bloom, as determined by daily T_{min} between 1% bloom and half bloom (*sb:hb*)
- *fb* assesses heat accumulation needed to reach full bloom, as in *hb*
- *fbf* assesses frost risk at full bloom, as determined by daily T_{min} between half bloom and full bloom (*hb:fb*)
- *hs* assesses heat accumulation needed to reach the onset of hull split (1% hull split), as in *hb*
- *hsf* assesses frost risk at 1% hull split, as determined by daily T_{min} between full bloom and 1% hull split (*fb:hs*)
- *hf* assesses heat accumulation needed to reach the completion of hull split (100% hull split), as in *hb*
- *hff* assesses frost risk at 100% hull split, as determined by daily T_{min} between 1% hull split and 100% hull split (*hs:hf*)
- *har* assesses heat accumulation needed to dry nuts sufficiently for harvest, as in *hb*
- $MM(x,t)$ assesses the viability for almond cultivation for location x in year t as determined by the product of each individual development stage, where a value of 1 for each development stage indicates a viable year t for location x , while a value of 0 for any development stage results in an unviable year.

APPENDIX B

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Parker LE, Abatzoglou JT (2016) Projected changes in cold hardiness zones and suitable overwinter ranges of perennial crops over the United States. Environmental Research Letters 11(3):034001 doi:10.1088/1748-9326/11/3/034001

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Parker LE, Abatzoglou JT (2017) Comparing mechanistic and empirical approaches to modeling the thermal niche of almond. International Journal of Biometeorology

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