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Climate change reduces frost exposure for high-value California orchard crops

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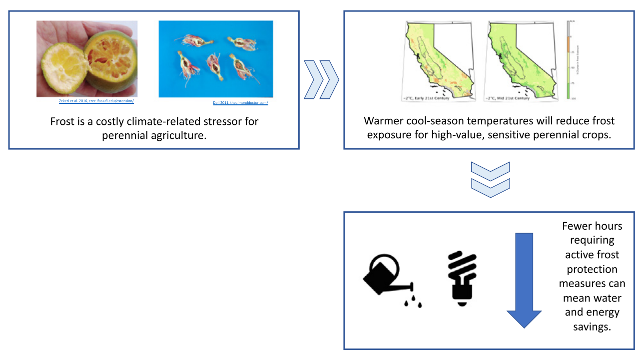
HIGHLIGHTS

- Frost damage is a key environmental concern among California perennial crop farmers.
- Climate change will reduce exposure to frost temperatures across California.
- Frost reduction varies by geography and crop-specific critical temperature.
- Less need for frost mitigation will save water, energy, money, and emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Frost exposure is a particular challenge for cultivating perennial crops, whose adaptive capacity to weather and climate impacts is limited. Irrigation is a common means of mitigating damage, but draws on limited water resources, is costly, and energy intensive. Here we examined the projected impact of climate change on the incidence of frost temperatures during the coldest winters, defined by the 98th percentile of cool season (November–April) frost hours, under both early- and mid-21st century time periods, as compared to contemporary conditions, across a range of threshold temperatures. We focused on three high-value perennial orchard crops – almonds, avocados, and oranges – to assess the effects of climate change on the incidence of temperatures below crop-specific threshold temperatures and for crop-specific critical development phases, and what these temporal changes in frost exposure may mean for the water and energy requirements for mitigating damages. Across time periods and temperature thresholds, frost exposure declines in California's agricultural regions, with an average of reduction in frost exposure of 63% by the mid-21st century. The majority of almond and orange acreage saw 50–75% reductions in frost exposure by mid-century, while avocado acreage experienced >75% fewer frost hours. This yielded attendant reductions in water use and energy costs, and growers in the highest acreage counties may save more than 50,000 acre feet of water and $4.2 million in electricity costs for water pumping per year, collectively. Although climate change is projected to increase growing season crop water demands, pest pressures, and have an overall net-negative impact on agriculture, the potential reduction in frost exposure and the accompanying water and energy costs to mitigate frost damages may allow growers to reprioritize some of their long-term decisions around farm management.

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1. Introduction

Frost exposure presents a geographical constraint to plant bioclimatic niche and can be an environmentally-limiting factor to crop production in temperate climates around the world (Maracchi et al., 2005). For agriculture, the impacts from frost exposure have important economic consequences, causing hundreds of millions of dollars in crop damages to high-value perennials in California alone (Campbell, 2008; Reyes and Elias, 2019; AgRisk Viewer, 2020; for reference, example images of crop damage due to frost in citrus (Zekeri et al., 2016) and almond (Doll, 2011) are shown in the graphical abstract). Unsurprisingly, frost is a key climate-related concern of perennial crop growers, particularly frost events that coincide with sensitive crop development periods, and future projections of frost risk have been identified as being useful for growers' long-term planning efforts (Jagannathan, 2019).

As temperatures increase in early spring, perennial crops gradually de-harden and become increasingly sensitive to cold temperatures, thereby increasing their vulnerability to frost damage. Anomalously warm late winter or early spring temperatures can also advance phenology, resulting in a false spring wherein crops break dormancy and begin their annual development earlier than normal, thereby raising the risk of damage from subsequent frost exposure. Observed changes in false springs in the contiguous US over the 20th century showed a general decline (Peterson and Abatzoglou, 2014), and research examining changes in false springs under a high emissions future climate scenario (i.e., 8.5 RCP) using a non-species-specific spring index showed a decline in hard freeze events within 7-days after leaf out across the Central Valley, but little change in false spring exposure after first bloom (Allstadt et al., 2015). However, as the risk of frost damage is both crop- and development phase-specific, and as spring onset and the occurrence of false springs can exhibit significant spatial variability (Allstadt et al., 2015), capturing changes in frost exposure over multiple temperature and time thresholds can provide an improved view of potential future frost risk.

There are two distinct types of frost events, driven by different physical processes, that can damage crops: advection frosts and radiation frosts. Although advection frosts can be associated with multiple days of sub-freezing temperatures, where temperatures drop and remain below freezing both night and day, these events are relatively uncommon in California's fruit-growing regions. Unlike advection frosts, radiation frosts are relatively common across California orchards and can occur multiple times during a typical winter. Radiation frosts result from rapid overnight cooling of the surface due to the release of radiant energy (Snyder, 2000), and are typically characterized by calm winds, temperature inversions, and daytime temperatures above freezing (Snyder and Melo-Abreu, 2005).

While protecting against advection frosts are difficult, there are a number of management activities that growers can employ to ameliorate radiation frost impacts; active frost protection measures such as wind machines, helicopters, sprinklers, and surface irrigation are common. Sprinklers and surface irrigation provide frost protection through the release of sensible or latent heat from water cooling on the ground surface, which is then moved to the orchard canopy through radiation, convection, or active mixing with a wind machine or helicopters (Snyder and Connell, 1996). For wind machine, helicopter, and irrigation pump operation, the energy and monetary cost of frost protection measures can be significant. Additionally, using water to allay frost damage can reduce water availability for later use, which may be of concern in the case of adjudicated surface water and regulated groundwater resources.

Previous work has established that climate change will have wide-ranging effects on California agriculture (e.g., Marklein et al., 2020; Pathak et al., 2018). However, there has been no research specifically examining future frost exposure across California's agricultural regions. Given the critical importance of frost damages to crop cultivation, understanding how climate change may alter the risk of frost exposure for high-value perennial crops – along with subsequent water and energy demands – provides important information relevant for orchard and risk management planning decisions. Here we address this need with a first-order approximation of the effects of climate change on frost exposure and frost damage mitigation costs for California's high-value perennial orchard crops, quantifying changes in frost exposure over a range of temperatures relevant to multiple California orchard crops. Further, we consider crop-specific critical temperatures during crop-specific critical development periods, for three exemplary high-value, frost-sensitive specialty crops (almond, avocado, and navel orange). Finally, we provide a complementary illustration of how changes in frost exposure may alter the attendant water and energy costs associated with mitigating frost damage.

2. Data and methods

2.1. Temperature data

Two primary surface climatological datasets were used to quantify frost exposure over contemporary and future time periods. First, observed daily T_{max} and T_{min} for the period 1980–2010 were acquired from the gridded surface meteorological dataset (gridMET) of Abatzoglou (2013). GridMET is a 4-km resolution dataset developed using PRISM (Daly et al., 1997) and spatially interpolated regional reanalysis (NLDAS-2, see Xia et al., 2012) data that cover the contiguous United States at a daily time-step over the 1979 – present period. Future daily T_{max} and T_{min} were acquired from four statistically downscaled global climate models (GCMs) from the 5th phase of the Climate Model Intercomparison Project (CMIP5, see Taylor et al., 2012). These models were selected as they are the priority models identified by California's Climate Action Team and cover a range of potential future scenarios, including a “warm/dry” future (HadGEM2-ES, Collins et al., 2008), a “cool/wet” future (CNRM-CM5, Salas-Mélia et al., 2005), a multi-model “average” future (CanESM2, Arora et al., 2011), and a future scenario that is most different or “complement” to the others (MIROC5, Watanabe et al., 2010) (see Pierce et al., 2018 for more detail on model selection). Future data are downscaled to a 4-km gridded surface using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown, 2012) using gridMET as training data, ensuring compatibility in climate statistics between the downscaled GCMs and the gridded observed data.

Analysis for future frost risk exposure was constrained to simulations for the early- (2010–2039) and mid- (2040–2069) 21st century given the limited ability for developing meaningful management strategies for end-of-century projections. We focused on future experiments run under Representative Concentration Pathway 8.5 (RCP 8.5) as emissions through the early 2000s most closely followed this trajectory (Peters et al., 2013), and the RCP 8.5 scenario most closely approximates cumulative historic and anticipated future emissions through the mid-century (Schwalm et al., 2020). While projected changes in frost exposure using RCP 4.5 would likely show similar qualitative changes, the magnitude of changes may be smaller, particularly for the mid-21st century where average cool-season temperatures warm less than under RCP 8.5. However, we note that for early and mid-century time horizons, variability between CMIP5 models is greater than the variability between RCP scenarios.

2.2. Crop location data

Crop location data were obtained from the United States Department of Agriculture National Agriculture Statistics Service (USDA-NASS) Cropland Data Layer (CDL). The 30-m CDL data were aggregated to the 4-km resolution of the climate data, and were used to visualize results and make crop-specific assessments of future effects of climate change on frost exposure and resulting energy and water costs. Specifically, these data were used to identify the counties with the largest acreage of each of the three crops examined, and the counties with >1% of the statewide acreage, which are highlighted in our analysis.

2.3. Quantifying frost exposure

The frequency of frost temperatures under observed contemporary and projected future climate conditions were assessed in units of hours of exposure, quantified using daily maximum and minimum temperatures temporally disaggregated to hourly data using a modified sine curve approach (Linvill, 1990). While damage can occur with brief exposure durations <1 h, an hourly time step provides a conservative estimate of frost temperature exposure and is compatible with frost protection planning and recommendations, which are often given in units of hours (e.g., Snyder, 2000). Frost exposure hours were quantified at a monthly and seasonal time step during the cool season of November through April, and we focused on the 98th percentile of annual cool season exposure over each climatological period in order to spotlight changes in those most extreme frost years.

In assessing frost exposure that is not crop-specific, we highlight the frost exposure (in hours) for three threshold temperatures (T) – −2 °C, 0 °C, and 2 °C – that encapsulate the most frost-tender phase of development for many high-value fruit and nut trees (e.g., Gholipour, 2006; WSU, 2020). Although our temperature thresholds were selected with fruit and nut trees in mind, we conducted this generalized analysis across the entirety of the state, acknowledging that while agricultural production does not widely occur in high-elevation or forested locations, changes in frost exposure have importance for natural systems (Inouye, 2000; Inouye, 2008). In addition, we examined frost exposure for three perennial crops – almonds, avocados, and oranges – selected because of their high value, significant production, geographically variable acreage in California, and frost sensitivity (Fig. 2). California produces >99% of US-grown almonds, with an annual value of more than $6 billion. The state also produces 86% of US-grown avocados and approximately 29% of US-grown oranges at an annual value of more than $373 million and $670 million, respectively (NASS, 2019). For each crop, we identified the most vulnerable phenological stage of development and the associated threshold temperatures for analysis: −2.7 °C for almonds during bloom (Snyder and Connell, 1996), −1.4 °C for avocado during fruiting (UCCE, Ventura, 2020), and −1.1 °C for ripening oranges (Geisel and Unruh, 2003).

For the generalized and crop-specific analyses, we assess observed and modeled future 98th percentile of cool season frost exposure and quantify the change in frost exposure under climate change. Additionally, we examine 98th percentile frost exposure at a monthly time step over the observed and future periods to assess temporal variability in projected future frost occurrence. We utilized crop indemnity claims reported to USDA-Risk Management Agency available in AgRisk Viewer (2020) for each of our three example crops to identify the month with the highest historic incidence of crop frost damage due to frost and explore how future climate change may influence frost exposure during these most sensitive time periods. We note that in reporting our results for hours of frost exposure, we round to the nearest integer. Finally, we note that while we principally focused on changes in frost exposure during the coldest (98th percentile) winters for each climatological period, we used annual frost exposure to quantify trend significance. A modified Mann-Kendall test (Hamed and Rao, 1998) was used to assess the significance (a = 0.05) of over the 2010–2069 modeled period, using the 4-model mean of frost exposure during the cool season. The test of significance was performed at the aggregate county level for the top acreage counties for each crop considering only crop-containing locations within the each county.

2.4. Water and energy use estimates

The amount of water needed for active radiation frost protection is dependent on air temperatures, wind speed, and the rate and duration of irrigation, which are driven in part by the type of irrigation system in use. While simplified management approaches may exist for some crops (e.g., Doll, 2010), the duration of watering in practice depends on irrigation timing (i.e., when the sprinklers are turned on and off), which is governed by the forecast low temperature, dew point temperature, the timing of the diurnal temperature cycle, and crop critical temperature (e.g., Snyder, 2000). Further, management practices such as tree spacing, use (or absence) of cover crops, and individual grower assessments of risk also play a role in water use for frost mitigation.

Given the myriad of situation-specific conditions that can influence decisions around active frost protection, here we simplify water and energy use estimates to assume that active frost protection occurs during all hours where T < 0 °C. We also used an expert-recommended sprinkler water application rate of 30 gal per minute (gpm) per acre (Doll, 2017) to quantify irrigation needs for frost protection.

The volume of water per acre in applied for frost mitigation can be defined in acre feet (af) as

$$\llbracket Volume \rrbracket\_af = (R\,x\,60(H))/325850.943 \tag{1}$$

where R is the gpm water application rate, H is the total number of hours of water application, and 325,850.943 is the number of gallons per acre foot (af).

The volume of irrigation water needed for frost mitigation is calculated at an annual time step for each 4-km grid cell and crop acreage within that cell is accounted for using the CDL data to calculate total frost mitigation water requirements.

The energy costs of pumping irrigation water vary depending on factors including the type of pump engine (e.g., natural gas, diesel, electric), the cost of fuel or electricity, the depth to the water table, and the number of hours the pump is in operation. For this illustration, we estimate the cost of irrigation water pumping assuming that all water is applied using electric pumps as the 2018 USDA Farm and Ranch Irrigation Survey stated that roughly 90% of the more than 94,000 irrigation pumps across the state of California are electric (FRIS, 2018). Drawing on Burt et al. (2003), the energy cost for pumping irrigation water (P_{cos}t) for frost mitigation is estimated using a kilowatt hour (kWh) per af approach

$$P\_cost = \llbracket Volume \rrbracket\_af\ x\ kWh/af\ x\ (cost())/kWh \tag{2}$$

P_{cos}t is calculated on a per-acre basis for the 98th percentile of frost exposure for each 4-km grid using the previously calculated irrigation water volumes in acre feet. As with water requirements, crop acreage from CDL data are then used to calculate total pumping costs. The kWh of energy required for irrigation pump operation can vary across operations based on factors such as pump motor. Here we use the kWh per af estimate of on-farm energy requirements for water pumping based on the California Irrigation Management Information System (CIMIS) Reference Evapotranspiration Zones (ETo zones) as calculated in Burt et al. (2003). This energy requirement value differs for well pumps versus booster pumps and groundwater pumping versus surface water pumping (Burt et al., 2003). As our purpose here is to provide a simple illustration of how changes in frost exposure may influence irrigation water and energy use, we focus solely on the energy requirements for pumping groundwater using well pumps. Finally, electricity costs for agricultural users can vary by utility company and rate plan; here we use recent state-wide average agricultural electric rate of $0.158 per kilowatt hour (kWh) (CFBF, 2019).

As with our frost quantification calculations, for each time period and GCM, we focus on the hours T < 0 °C in the 98th percentile years for our water volume and energy costs estimates. However, as this analysis is illustrative rather than comprehensive, we focus our first order estimates on only the locations of our three selected crops in the county with the greatest acreage of each crop, and compute our estimates only for each crop's critical frost damage month. For county-level reporting, the kWh per af value is the average of values across all ETo zones within the county.

3. Results

3.1. Statewide frost exposure

3.1.1. Seasonal frost exposure

The statewide median 98th percentile of annual cool season frost exposure over the 1981–2010 observed period for $T < 0$ °C ($T < -2$ °C, $T < 2$ °C) was 284-hours (139-hours, 575-hours) (Fig. 3, bottom row). To underscore the importance of considering the tail of the distribution in our analysis, we note that the median statewide climatological cool season frost exposure was significantly less than the exposure experienced during the coldest years. When considering all cool seasons over the 1981–2010 period, the median statewide exposure for the 0 °C threshold was 112 h, or less than 40% of that experienced during the coldest years; similarly, the −2 °C and 2 °C thresholds were ~24% and 54% of the hours of exposure during extreme years, at 33-hours and 310-hours, respectively. Spatial patterns of frost exposure are comparable across all three temperature thresholds, with larger magnitudes of exposure associated with warmer thresholds. Spatial patterns of frost exposure also largely follow geography, with highest exposure in climatologically cooler locations in northwestern and northeastern California and in the Sierra-Nevada Mountains. Within key agricultural regions of the state (Fig. 1), frost exposure during extreme cold years ranged from fewer than 20 h to more than 580 h, with ~200 h of average exposure across the Sacramento and San Joaquin Valleys, and ~80 and 40 h of average exposure over the Coachella and Imperial valleys, respectively.

Analyses showed reductions in frost exposure temperatures under climate change across all thresholds for both the early- and mid-century time periods (Fig. 4). Over the early-21st century period, regions with the highest contemporary frost exposure (i.e., the Sierra Nevada) generally saw greater reductions in frost hours, particularly for warmer temperature thresholds, though not all high-elevation or high-contemporary exposure locations saw equivalent reductions; higher elevations in the southern part of the state saw much smaller reductions in exposure over the early 21st century. These patterns in frost reduction largely remained into the mid-21st century period for warmer (0 °C and 2 °C) thresholds, though the differences were muted as large reductions in exposure were seen statewide. Along the coast, large mid-century frost exposure reductions are likely a function of the *lower* contemporary exposure to frost temperatures, where even modest warming would drastically reduce (if not eliminate) frost hours. Over agricultural regions of California, the Sacramento-San Joaquin Delta and the Sacramento Valley showed the largest percent reduction in 98th percentile frost exposure for $T < -2$ °C and $T < 0$ °C, with mid-century changes of −75% and −73% in hours $T < -2$ °C and −65% and −68% in hours $T < 0$ °C, respectively. Reductions in frost exposure over all of the state's agricultural regions were >50% across all three temperature thresholds, with an average of ~63% (~70%, ~54%) reduction for the 6 key agriculture regions of the state for hours $T < 0$ °C ($T < -2$ °C, $T < 2$ °C).

3.1.2. Monthly frost exposure

When considering the temporal variability in frost exposure, December showed the greatest relative change in statewide exposure to $T < 0$ °C, with an average change of approximately −66%, followed closely by the average change over November of −64% (Fig. 5). Similarly, January and February both showed reductions in statewide average exposure to temperatures <0 °C of ~61%, while changes during the spring months of March and April were nearly half of those seen over winter the months. These temporal patterns were seen across temperature thresholds (not shown). Considering changes in exposure to temperatures <0 °C over agricultural regions of the state (as shown in Fig. 5), the Sacramento and San Joaquin valleys saw their greatest regional-average relative change in frost exposure during November (~−77% and ~−66%, respectively), while the Sacramento-San Joaquin Delta's greatest change occurred during December (~−64%). The largest relative change in frost exposure in the Salinas Valley also occurred during December with approximately 61% reduction in frost hours. The typical frost season (that is, the time between the first fall freeze and the last spring freeze) in southern California's Coachella and Imperial valleys occurs during a short window from late December to early January (Hegewisch et al., 2020), months which showed an ~65–70% reduction in frost exposure over both regions. However, analyses showed that during the 98th percentile frost exposure years in these southernmost agricultural regions, frost occurs during February as well; that month had a ~−68% change in exposure over the Coachella Valley and an approximately −58% change over the Imperial Valley.

3.2. Crop-specific frost exposure

Frost exposure for crop-specific critical temperature thresholds also showed a pattern of reduced exposure, with the relative change (i.e., percent reduction) increasing under projected warmer mid-century conditions as compared to early-21st century projections (Supporting Information, Table 1). Comparing mid-century exposure

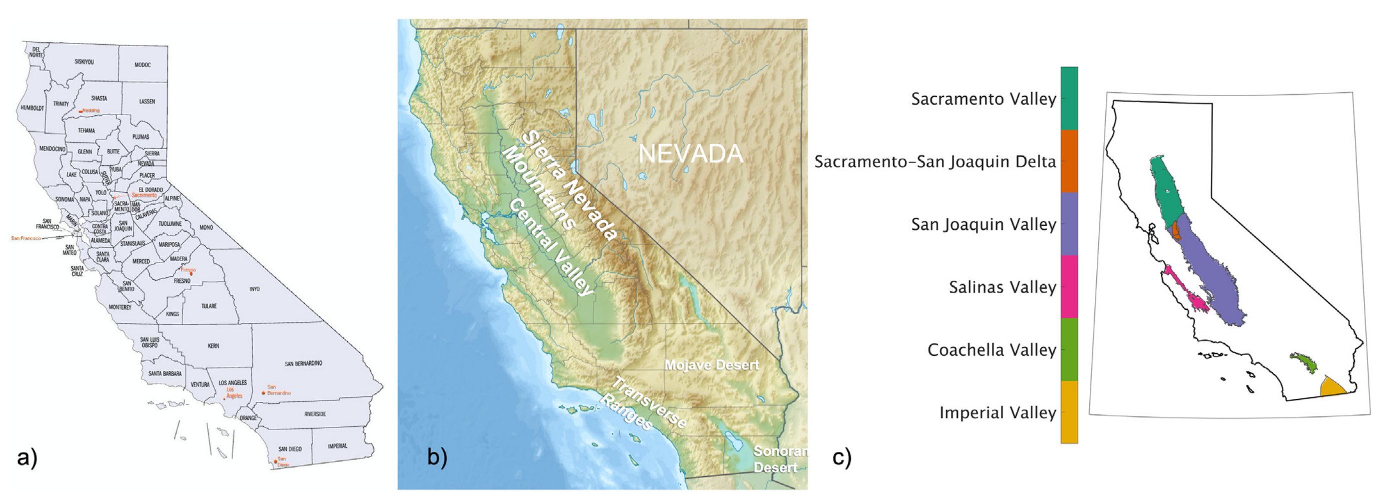

Fig. 1. To orient the reader, maps of (a) California counties*, (b) physiographic regions*, and (c) principal agricultural regions of California are provided. *Maps (a) and (b) were sourced, and map (b) adapted, from Wikimedia Commons under Creative Commons license CC BY-SA 3.0 and are referenced as (a) (California Counties Map, n.d) and (b) (Relief Map of California, n.d) below.

Fig. 2. Locations of the three frost-susceptible perennial crops examined here – (a) almonds, (b) avocados, (c) oranges – are shown in grey.

to the observed period, avocado-growing regions showed the greatest reduction in frost exposure at the county level, with five of six counties seeing reductions of 75% or more in the number of hours below the −1.1 °C critical temperature for avocado over the November – April cool season. Similarly, five of six counties saw 75% or greater reductions in frost during January (the most susceptible month for avocado frost damage), though interestingly the county showing <75% reduction in frost for the cool season was not the same county as that showing

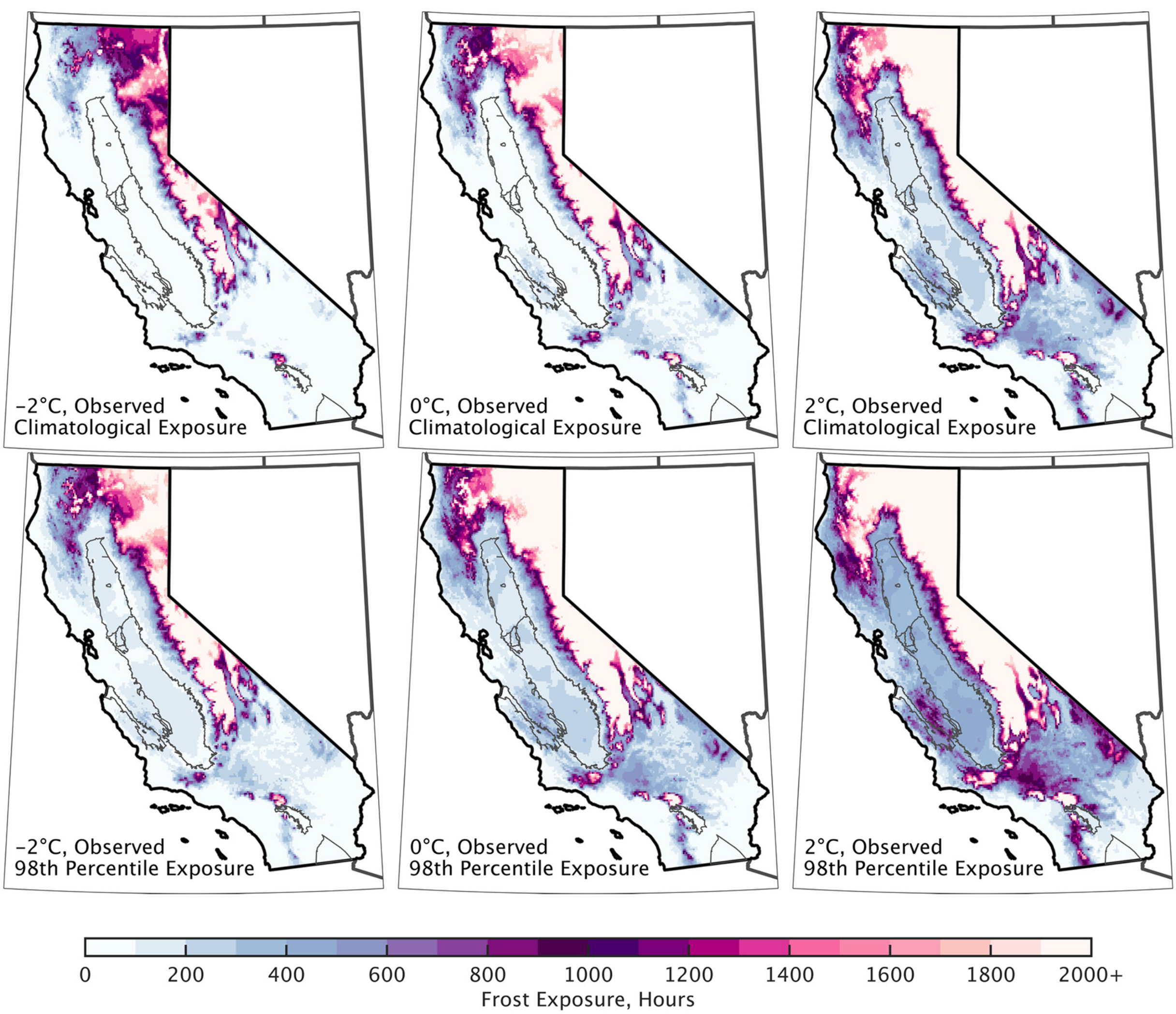

Fig. 3. The climatological (top row) and 98th percentile (bottom row) of observed frost exposure during the November–April cool season, quantified as hours below the given threshold temperature (from left to right: −2 °C, 0 °C, 2 °C). Pink shades indicate greater exposure to frost temperatures.

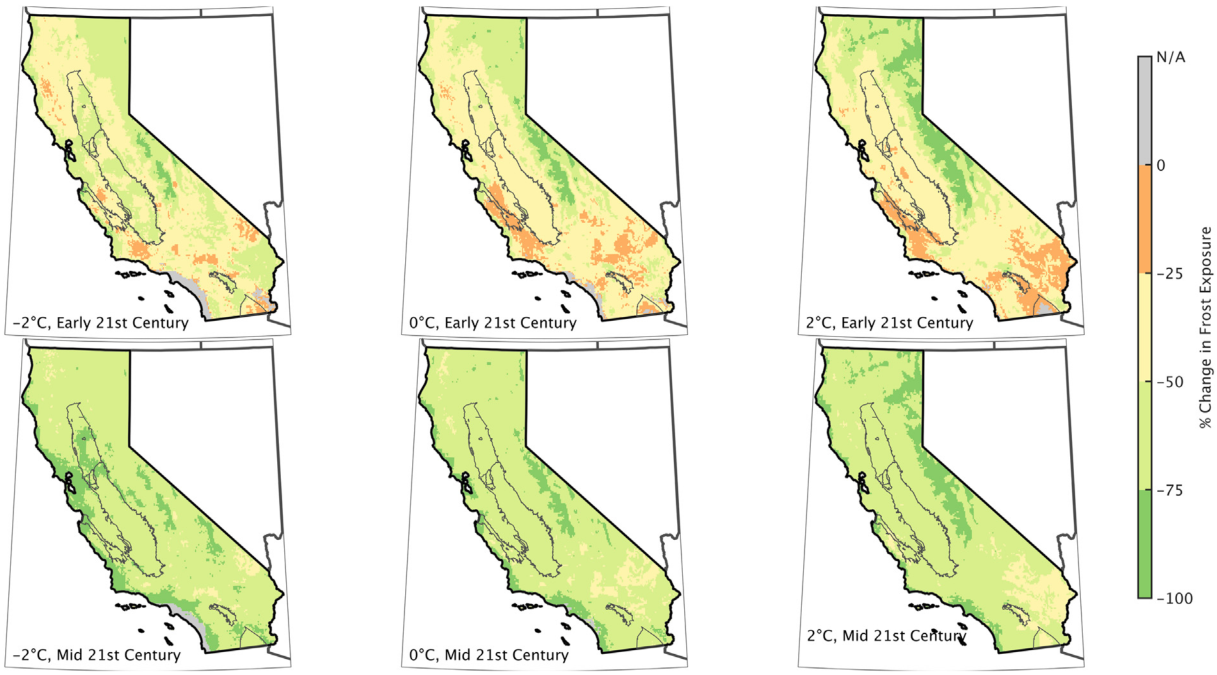

Fig. 4. The relative change in 98th percentile frost exposure, in units of hours below the given threshold temperature, between the observed period and the early- (top row) and mid- (bottom row) 21st century periods. Shown is the 4-model mean percent change in exposure for each threshold and time period comparison. Green shades indicate a greater than 50% reduction in exposure, while yellows and oranges indicate less reduction in exposure. Areas in grey are those locations where contemporary 98th percentile of frost exposure over the cool season was <8 h.

<75% reduction during January. Across orange- and almond-growing regions, the majority of locations showed 50–75% reductions in exposure to crop-specific critical temperatures during the cool season when aggregated to the county level. However, almond locations in Yolo County and orange locations in Ventura and San Diego counties showed reductions in frost exposure >75% by mid-century. Likewise, with only two exceptions, all almond and orange counties showed 50–75% reductions in hours below the respective crop-specific critical temperatures during February and December, the months with highest frost damage susceptibility for almonds and oranges, respectively. Almond growing locations in Madera County showed a 46% reduction in February hours $T < -2.7$ °C by mid-century, a smaller change than other almond counties, while orange growing areas in Ventura County showed a larger change than other orange-growing counties with a 100% reduction in December hours $T < -1.4$ °C. When acreage is considered, ~28,000 acres of almonds showed a 75–100% reduction in 98th percentile cool season frost exposure by the mid-21st century relative to contemporary conditions, and approximately 1.2 million acres of almonds showed a 50–75% reduction. Similarly, ~54,000 acres of avocados and nearly 10,000 acres of oranges had 75–100% less cool season frost exposure during the coldest years by the mid-century, and 696 acres of avocados and ~157,000 acres of oranges showed a 50–75% reduction in exposure.

3.3. Implications for water and energy demands

Finally, we illustrated how changes in frost exposure may drive reductions in attendant water and energy demands for mitigation for each of our selected crops during their respective critical months and in their respective counties of greatest acreage. Within-county kilowatt hour per acre-feet (kWh/af) pumped varied by 250.5 kWh across the ETo zones for Fresno County (almonds), by 148 kWh for Ventura County (avocados), and by 250.5 kWh for Tulare County (oranges) (Table 1, compiled from Burt et al. (2003), and with reference to ETo Zones delineated by Jones (1999)).

Concomitant with declines in frost exposure under climate change, the projected water demand for mitigating frost damages and the attendant energy costs were lower across each of our selected crops within their respective highest-acreage counties (Fig. 6). The average water demand for frost protection of almonds in Fresno County declined from 0.21af per acre per year ($\frac{af}{ac}/yr$) over the contemporary period to $0.19\frac{af}{ac}/yr$ by the early-21st century and $0.11\frac{af}{ac}/yr$ by the mid-21st century. Similarly, the average water demand for avocados (oranges) in Ventura (Tulare) County declined from $0.11\frac{af}{ac}/yr$ ($0.88\frac{af}{ac}/yr$) to $0.03\frac{af}{ac}/yr$ ($0.43\frac{af}{ac}/yr$) by the mid-21st century. The mean difference between contemporary and early-21st century water demands for avocado was $<0.01\frac{af}{ac}/yr$ and the declines from the early-21st century period to the mid-21st century period for oranges were similarly modest. Our first-order approach to estimating changes in the energy and monetary costs of groundwater pumping for frost mitigation showed complementary declines in groundwater pumping costs over time, with an average annual savings of \$7.63 and \$5.62 per acre by the mid-century for almonds and avocados in Fresno and Ventura counties, respectively. The average mid-century savings for Tulare County oranges was a whopping \$32.75 per acre per year. With >227,000 acres of almonds, these mean water and energy savings equate to >10,000-af and >\$1.73 million in countywide water and cost reductions for Fresno County almond producers collectively, while Ventura County may save >1000af and ~\$110,700 annually on countywide avocado frost mitigation. Owing to the significant savings in county average pumping costs, Tulare County orange producers may collectively save >\$2.9 million in energy costs – along with >40,000-af of water – by mid-century.

4. Discussion

Though climate change is projected to be a net-negative for agricultural production in California (Pathak et al., 2018), the declining occurrence of frost temperatures across California is one benefit of projected

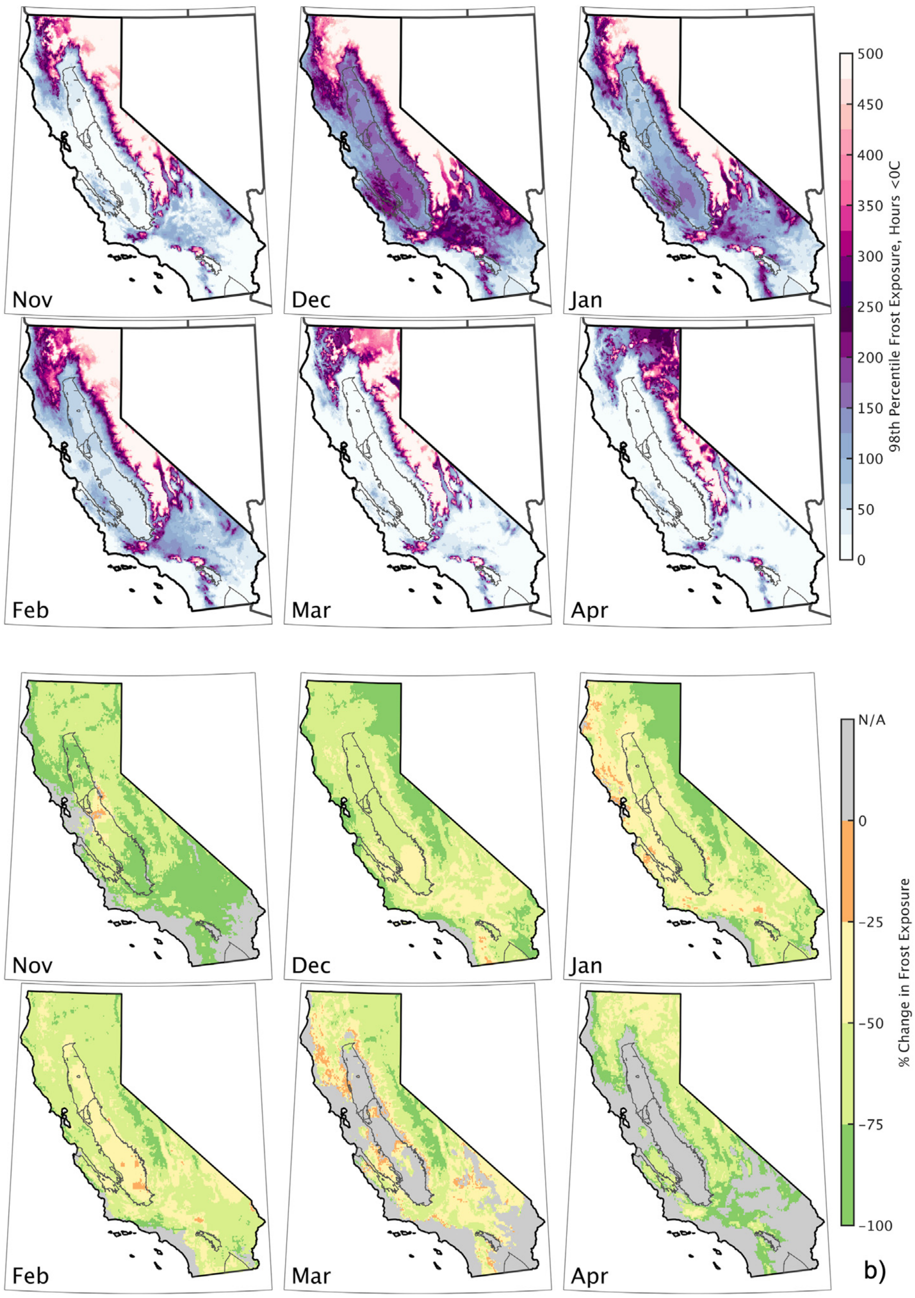

Fig. 5. (**a, top panels**) The 98th percentile of annual exposure to frost hours below 0 °C over the observed period in units of hours, for each month during the cool season. Pink shades indicate greater frost exposure. (**b, bottom panels**) The percent change in frost exposure ($T < 0$ °C) for each month during the cool season between the observed period and the mid-21st century period. Shown is the 4-model mean of percent change in exposure. Green shades indicate greater reductions in frost exposure during the given month. Areas in grey are those locations where the 98th percentile of contemporary frost exposure for the month was <1 h.

changes and is in line with studies showing warming winter (December – February) and spring (March–May) temperatures over the coming decades. Winter daytime temperatures across California are projected to increase ~2.2–3 °C degrees by mid-century under RCP 8.5, and winter nighttime temperatures will increase ~2.2–2.7 °C (Hegewisch et al., 2020). Similarly, projections under RCP 8.5 show California's coldest winter temperatures will warm by >2.5 °C across much of the state, with some locations seeing warming >3 °C by mid-century (Parker and Abatzoglou, 2016). This latter study also showed that climatically colder locations generally experience a greater degree of warming than warmer locations, supporting our results of greater reductions in frost exposure in the Sierra Nevada as compared to warmer locations like the Central Valley and the Southern California deserts. Likewise, our findings complement previous work showing an observed warming trend in spring temperatures across the extratropics of the Northern Hemisphere (Angert et al., 2005; Cordero et al., 2011), and earlier observed dates of last spring freeze across California, as well as fewer frost days (Easterling, 2002). Under a high emissions scenario (RCP 8.5), spring temperatures are projected to warm 2–2.8 °C by the mid-21st century, and the last spring freeze is projected to occur as much as 70 days earlier over the same period, and 25–45 days earlier over California's Central Valley specifically (Hegewisch et al., 2020).

Our efforts focused on RCP 8.5 as a more likely future climate scenario; however, results from the 6th phase of the Climate Model Intercomparison Project (Eyring et al., 2016) are forthcoming. CMIP6 models are driven by 8 different future global scenarios that offer a

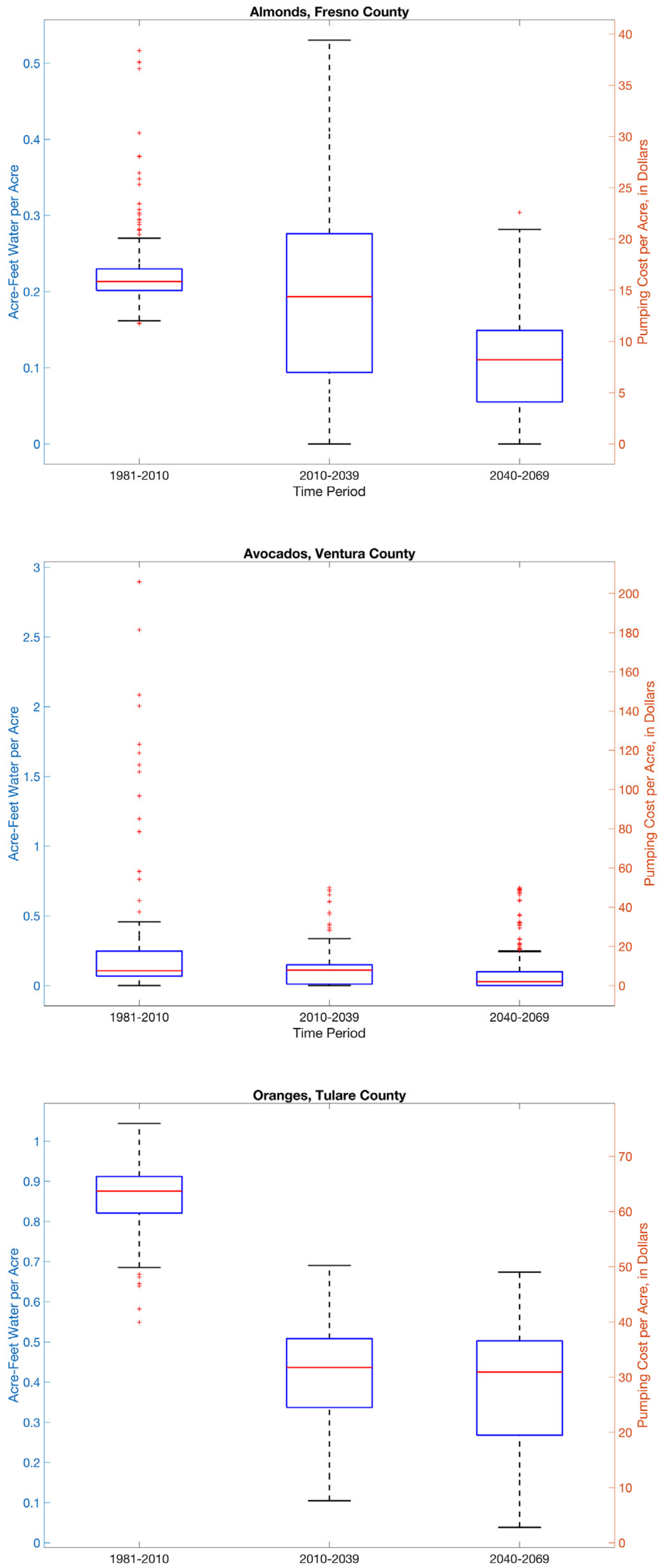

Fig. 6. Annual irrigation water use in acre-feet & energy costs in US Dollars for electric groundwater well pumps for crop-specific critical months in the given top-acreage county, assuming irrigation occurs all hours <0 °C.

wider range of potential outcomes as compared to the 4 scenarios in CMIP5. Although these overall trends of warming and lengthening of the frost-free season will undoubtedly carry over to CMIP6 experiments (e.g., see Cook et al., 2020), and we would anticipate the overall trend of declining frost exposure for California orchard crops would also carry over, we acknowledge that the degree of warming or the number of hours of frost exposure reduction will be quantitatively different. Were this analysis to be repeated using the highest emissions scenario from CMIP6, we anticipate that the degree of warming and attendant reduction in frost exposure would be greater, though we note that, as with CMIP5, inter-model variability exceeds inter-scenario variability at our mid-21st century time horizons; additionally, other scenarios in the CMIP6 suite may prove to better capture a more likely future and that under lower emissions scenarios total hours of frost reduction may be lower than what is projected here.

While we did not use a phenology-based approach for assessing crop-specific frost risk, our findings of reduced frost exposure across time, space, and crop type are supported by phenology-based studies across different crops and climatic regimes that also show reductions in frost exposure under climate change, despite earlier onset of bloom (e.g., Hoffmann and Rath, 2013; Molitor et al., 2014). More specifically, the phenology-based thermal suitability model of Parker and Abatzoglou (2018) shows minimal frost risk for California almonds under future climate conditions despite budburst occurring an average of 6 days earlier by mid-century; this approach also shows declines in frost exposure for other perennials, even with advanced phonological events such as earlier bloom in climatically cooler and more northerly locations (Hegewisch et al., 2020b). However, we acknowledge that other studies have shown mixed or opposing results with respect to climate change effects on frost exposure, and that choice of crop, location, phenology model, time period, and emissions scenario can all influence frost exposure trends (Darbyshire et al., 2016; Ma et al., 2019; Mosedale et al., 2015). Still, our results showing reduced frost exposure over seasonal and monthly time spans are complementary to the aforementioned works and we offer that in the absence of crop-specific phenology models, which are limited in their existence and costly in terms of time and computational expense, analysis at the monthly time step provides an improved picture of potential frost risk for many crops.

Even with the use of crop-specific phenology models, researchers have acknowledged the limitations in capturing local-scale impacts such as future frost risk given the spatial resolution of GCM data, even when downscaled (e.g., Allstadt et al., 2015; Parker and Abatzoglou, 2018). Further, the nature of climate data – from its inherent uncertainties (e.g., Knutti and Sedlácek, 2013), to its spatial and temporal scale, and uncertainties specific to its method of downscaling (e.g., Maraun and Widmann, 2018) – can also introduce uncertainty in future frost exposure projections, and, in the case of scale or downscaling methodology, can result in quantitatively differences even when all other methodology remains consistent. Although we utilized a dataset that provides the most temporally complete, highest spatial resolution daily data available over our study area, it is important to concede that the temperatures leading to frost damage inherently matter at the plant level. GridMET data have been validated against a suite of meteorological station data (Abatzoglou, 2013) and we acknowledge that the bias between gridded and station data may be sufficient to alter our estimates of frost exposure. However, we note that exploratory analysis (not shown) suggests that GridMET has a slight (~0.5–1.5 °C) warm bias in T_{min} compared to CIMIS stations, meaning that the trends in reduced frost exposure shown here may be conservative.

At the orchard level, as much as 1.5 °C variability in temperature has been observed within even small, uniformly managed almond orchards (Snyder and Connell, 1993), and the spatial resolution of downscaled GCMs is insufficient to capture localized landscape variations (e.g., aspect, cool air sinks, etc.) and other characteristics that drive microclimate variability within the orchard. Further, GCMs may not fully capture mesoscale processes that may influence frost events, particularly advective events. Dynamically downscaled regional climate models (RCMs) may be better suited to capturing these phenomena, though RCM output was not available for all of our four selected GCMs. Still, previous work has shown RCMs to have strong spatial

Table 1
The ETo zones within each of the highest-acreage counties for each crop, and the energy for on-farm groundwater pumping in kWh per acre foot for those zones. The county average kWh/af was used to calculate costs of groundwater pumping based on the acre-feet requirements for each 4-km grid cell.

ETo zone	Energy for on-farm groundwater pumping kWh/af
Fresno county (almonds)	
10	510
12	360.5
14	392
15	611
16	478
County average	470.3
Ventura county (avocados)	
3	493
4	493
9	362
10	510
14	392
County average	450
Tulare county (oranges)	
12	360.5
14	392
15	611
16	478
County average	460.4

correlation to dynamically downscaled products, and while some RCMs (e.g., RCM4) show greater projected winter warming over California, others (e.g., RCA) provide comparable results (Parker and Abatzoglou, 2016). Finally, with respect to the water and energy use for mitigating frost damages, we acknowledge that real-world orchard management decisions are far more situationally specific than simply applying irrigation water at all hours <0 °C, and that factors such as wind speed, dewpoint temperature, duration of frost temperatures, cover crop status, crop development phase, within-orchard microclimatic characteristics, alternative means of treatment (e.g., helicopters, heat lamps), and individual risk all influence irrigation timing and duration (e.g., Doll, 2010; Snyder and Connell, 1996; Snyder and Melo-Abreu, 2005).

While reduced frost risk is a benefit of warming temperatures, warmer winters and the overall reduction in frost exposure statewide have implications for agricultural pest management (Pathak et al., 2018). With fewer freeze events and generally warmer winter and spring seasons, insect diapause is expected to shorten, allowing for greater reproductive capacity. In a modeling study, Luedeling et al. (2011) concluded that the generation numbers of major walnut pests – codling moth, navel orangeworm, web-spinning spider mites, and European red mites – are likely to increase under future climate change and may create more future pest management challenges for growers. Likewise, with respect to annual crops, less frost exposure would provide an opportunity for growers to plant their crops earlier than normal. However, these earlier plantings may provide opportunity for insects to feed on these crops earlier, allowing insect populations to begin their life cycles earlier and potentially add additional generations during a typical growing season (Trumble and Butler, 2009), including for navel orangeworm, one of the most challenging pests for California tree nut producers (Pathak et al., 2020). Further, the potential increase in pest pressure is not limited to agricultural pests; warming winter temperatures are conducive to the bark beetle life cycle, which has had profound effects on California's forests (Bedsworth et al., 2018; Fettig et al., 2019; Larvie et al., 2019).

The same warming phenomena yielding reduced frost risk are also projected to decrease chill accumulation (Luedeling et al., 2009), which is needed for proper flower and fruit development in many perennial crops. Additionally, warmer winters are expected to result in reduced mountain snowpack, while warmer springs may induce rapid snowmelt and flooding beyond reservoir capacity, potentially reducing water availability for growers who rely on surface water for irrigation (Pathak et al., 2018). Further, warmer winters, particularly if met with reductions in snow cover, can lead to reductions in soil moisture which may lead to an earlier wildland fire season in the decades to come (Stephens et al., 2018).

Actions exist for the California agricultural community to respond to both the positive and negative effects of warming temperatures and reduced frost exposure. For example, crop breeding programs are working to develop new crop varieties with lower chilling requirements, as well as varieties with greater defenses against certain pests. Additionally, some growers may elect to plant new crops, taking advantage of warmer temperatures to cultivate frost-intolerant crops in areas that were previously climatically unsuitable. For example, growers are now planting lemons and avocadoes in parts of Ventura County that 50 years ago would have been considered frost-prone (e.g., Stolz, 2018). Research efforts are also being made to improve irrigation efficiency and crop water-use efficiency (e.g., see Parker et al., 2020), which may help curb any reductions in water availability resulting from greater regulatory controls, reduced snowpack, and/or un-stored runoff.

Reductions in water use and energy costs for frost protection, as we estimate here, may provide opportunities for growers to reassess their annual water budgets and reinvest their energy savings into their operations. We also note that reduced kWh requirements for irrigation pumps could reduce greenhouse gas emissions across our selected crops and counties by a collective ~11,400 metric tons of CO_2 per year, given current US energy production standards with an average of 0.429 kg CO_2 emissions per kWh (carbonfund.org). It is important to note however that any water and energy savings – and subsequent emissions reductions – achieved as a function of reduced frost exposure will likely be outpaced by the increase in water and energy demands for irrigation during the warm season, as irrigation is the primary means for responding to heat events, which are projected to increase in frequency, intensity, and duration (Parker et al., 2020). However, we do not have the ability to account for changes in water future management, and note that California has already seen an increase in water use efficiencies in recent decades (Tindula et al., 2013), which may lower future water and energy irrespective of reduced frost exposure or increased heat exposure. Still, our results show that even without any improved energy or water efficiencies, growers will see savings during the cool season as a function of reduced need for frost mitigation. Finally, while we performed these analyses over select, high-value perennials in California, the approach is easily transferable to other crops and regions, and can be replicated with future updated climate scenarios.

5. Conclusion

Climate change projections show a decline in frost exposure across California. While reductions in frost risk vary by location, timing, and crop, future cool season frost risk will be reduced by ~50 to 100% for some of California's most frost-sensitive, high-value perennial crops. Additionally, we show that projected changes in frost exposure may result in tens of thousands of acre feet of water and millions of dollars in energy costs saved, and potentially tens of thousands of metric tons of CO2 emission reduced, across California orchards. Through examining these changes to exposure during extreme frost years, and through detailing the implications of frost exposure changes for three illustrative high-value orchard crops, we highlight one potential benefit for agricultural production from climate change. However, the interactions of this benefit with the potential tradeoffs such as reduced chill, increased pest pressure, and greater potential for heat damages remains to be fully explored, in addition to the complex interactions among these benefits and tradeoffs and plant physiology and phenology. These important lingering questions highlight the need for more comprehensive study to provide growers with clear, actionable knowledge for improved, wholistic, and climate-informed decision making. Still, quantifying changes in cool-season exposure to frost temperatures does provide useful projections of climate change impacts to a critical agroclimatic metric, and this information may prove helpful for growers and farm managers in their decision making, and provide insight for long-term orchard management planning. Ultimately, such improvements in planning can support the adaptive capacity of agricultural operations and consequently bolster food security at regional, national, and – given the outsized reach of California agriculture – international scales.

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Author credit statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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