agronomy

Review

Climate Change Trends and Impacts on California Agriculture: A Detailed Review

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Abstract: California is a global leader in the agricultural sector and produces more than 400 types of commodities. The state produces over a third of the country's vegetables and two-thirds of its fruits and nuts. Despite being highly productive, current and future climate change poses many challenges to the agricultural sector. This paper provides a summary of the current state of knowledge on historical and future trends in climate and their impacts on California agriculture. We present a synthesis of climate change impacts on California agriculture in the context of: (1) historic trends and projected changes in temperature, precipitation, snowpack, heat waves, drought, and flood events; and (2) consequent impacts on crop yields, chill hours, pests and diseases, and agricultural vulnerability to climate risks. Finally, we highlight important findings and directions for future research and implementation. The detailed review presented in this paper provides sufficient evidence that the climate in California has changed significantly and is expected to continue changing in the future, and justifies the urgency and importance of enhancing the adaptive capacity of agriculture and reducing vulnerability to climate change. Since agriculture in California is very diverse and each crop responds to climate differently, climate adaptation research should be locally focused along with effective stakeholder engagement and systematic outreach efforts for effective adoption and implementation. The expected readership of this paper includes local stakeholders, researchers, state and national agencies, and international communities interested in learning about climate change and California's agriculture.

Keywords: climate change; agriculture; California; chill hours; drought; vulnerability

1. Introduction

California is the largest and most diverse agricultural state in the United States of America, with 77,500 farms comprising 5.7 million ha of pasture and rangeland and 3.8 million ha of irrigated cropland that generate an overall agricultural production value of $50.5 billion [1]. The state produces over a third of the country's vegetables and two-thirds of its fruits and nuts on nearly 1.2% of the nation's farmland. California grows over 400 different commodities, some of which are produced nowhere else in the nation. About 50% of the nuts and fruits consumed in the Unites States are grown in California, including almonds, pistachios, walnuts, grapes, citrus, apricots, dates, figs, kiwi fruit, nectarines, prunes, and olives [2]. In addition, California leads in the production of avocados, grapes, lemons, melons, peaches, plums, and strawberries. California's top 20 crop and livestock commodities represented more than $41.1 billion in gross revenue in 2015 [1].

Agricultural production in California is highly sensitive to climate change. Changes in temperatures and in the amounts, forms, and distribution of precipitation, increased frequency and intensity of climate extremes, and water availability are a few examples of climate-related challenges to California's agriculture sector. Irrigated agriculture produces nearly 90% of the harvested crops in California and a decrease in water availability could potentially reduce crop areas and yields [3]. Permanent crops are among the most profitable commodities in California. They are most commonly grown for more than 25 years, which makes them more vulnerable to impacts of climate change. For California, as an agricultural leader for various commodities, impacts on agricultural production due to climate change would not only translate into national food security issues but also economic impacts that could disrupt state and national commodity systems. While California farmers and ranchers have always been affected by the natural variability of weather from year to year, the increased rate and scale of climate change is beyond the realm of experience for the agricultural community [4]. Documenting the most current knowledge on climate trends and implications of climate change on the California's agricultural sector can provide invaluable guidance for researchers and policymakers on how to prepare for and adapt to changes that may occur. The primary purpose of this review paper was to summarize the current state of knowledge on historical and future trends in climate and their impacts on California agriculture. The expected audiences are not limited to the regional or state levels but also include international communities that are interested in learning about climate change and California's agriculture.

2. Method

In this paper, we have performed a detailed literature review to document the most current understanding on California´s climate change trends in terms of temperature, precipitation, snowpack, and extreme events such as heat waves, drought, and flooding, and their relative impacts on the state's highly productive and diverse agricultural sector. This detailed review was obtained from credible sources such as the most recent reports from Intergovernmental Panel on Climate Change (IPCC) [5], various state agency reports, and research articles focused on climate change and agriculture in California. Parameters reviewed in this study have direct or indirect impacts on California's agricultural sector. For instance, both average and extreme temperatures and precipitation patterns influence crop yields, pests, and the length of the growing season. On the other hand, extreme events, such as heat waves, floods, and droughts, may lead to larger production losses, earlier spring arrival, and warmer winters due to temperature increases that cause increased pressure as result of diseases and pests, and shrinking amounts of snowpack that lead to greater risks related to water availability for agriculture. A detailed review on what we know so far in terms of historical and projected trends for these important variables and how they might influence California's agriculture is described systematically in the following sections.

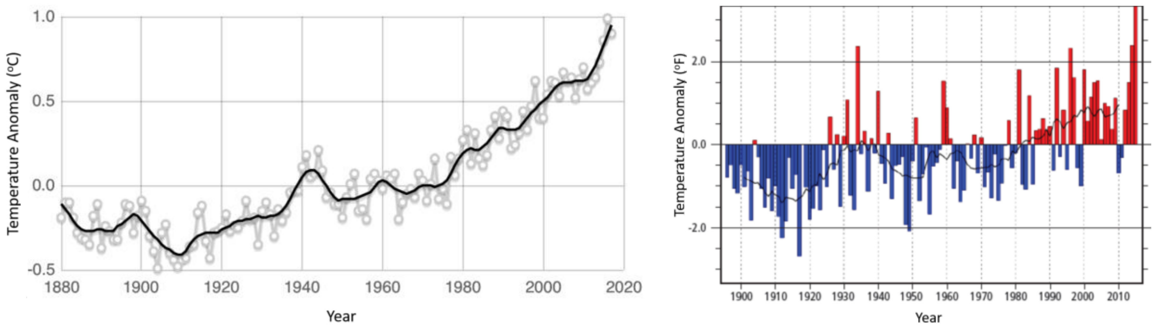
3. Climate Change Trends in California

3.1. Overview

The climate of California is highly variable, and the area contains both hot desert and subarctic environments. The proximity to the Pacific coast is the predominant force determining the climatic regions of the state. A large portion of California's ecosystem includes coastal regions, foothills, and valleys with a Mediterranean climate influenced by the cold California ocean currents and offshore winds. This allows storms to push west and limits the number of tropical storms experienced in the state. Moreover, atmospheric and oceanic signals, including the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), influence the rainfall and snow patterns within the state. This section presents a detailed review of historical and projected trends of key climatic parameters, including temperature, precipitation, snowpack, and climate extremes such as heat waves, droughts, and floods.

3.2. Temperature

Climate change is often exemplified by increased temperature. However, variability in temperature is one of the primary factors affecting agriculture, forestry, water supplies, and human and ecosystem health [6]. Figure 1a shows how the global temperature has increased by 1.4 °C since 1880 [7], whereas Figure 1b depicts the temperature variation in the state as compared to that of global temperatures. The rate of increase in minimum temperatures is greater than that of the mean or maximum temperatures [8]. Hansen et al. [9] characterized temperature increases in California from the past century, especially after 1975, using increments in mean temperature of about 1.2–2.2 °C [10]. The largest warming trends concern the summer, followed closely by spring and fall, as reported in Table 1 [11], which also reflects in-season temperatures and their variations for the period from 1895 to 2010 [12].



(a) (b)

Figure 1. (**a**) Global temperature anomalies from 1880–2016, electronically available from National Aeronautics and Space Administration, Goddard Institute for Space Studies (NASA/GISS, on 29 June 2017) [7], (**b**) California statewide mean temperature departure, October through September as reported by California Department of Water Resources in 2015 [8]. The black line denotes the 11-year running mean.

Table 1. California annual (water year) temperatures, 1895–2011, for mean, max and min linear trends in °C/100 years [11].

Linear Trends/100 Years	Annual	Winter	Spring	Summer	Fall
A. Mean temperature 1895–2011	+0.87	+0.66	+0.95	+0.94	+0.85
1949–2011	+1.45	+1.08	+1.98	+1.68	−0.56
1975–2011	+2.06	−0.58	+2.86	+3.59	+1.97
B. Maximum temperature 1895–present	+0.61	+0.51	+0.88	+0.42	+0.51
1949–2011	+0.89	+0.43	+1.67	+1.04	−0.09
1975–2011	+1.77	−2.17	+3.20	+3.31	+2.19
C. Minimum temperature 1895–present	+1.14	+0.81	+1.01	+1.46	+1.19
1949–2011	+2.01	+1.73	+2.31	+2.32	+1.22
1975–2011	+2.34	+1.01	+2.51	+3.88	+1.71

Figure 2 displays annual maximum temperature projections until the end of the century based on observations from 1950 to 2005, employing two Representative Concentration Pathways scenarios (RCP 4.5, left and RCP 8.5, right) [13]. These annual values are derived from four climate models: Hadley Centre Global Environment Model 2-Earth System, HadGEM2-ES (red), Centre National de Recherches Météorologiques, CNRM-CM5 (cyan), Canadian Earth System Model, CanESM2 (dark yellow) and Model for Interdisciplinary Research On Climate, MIROC5 (magenta). This figure includes future scenarios for Los Angeles, Sacramento, and Shasta County, from top to bottom, and reflects the spatial variability of temperature from north to south in the state. Average temperature increases will be more pronounced in the summer than in the winter and there will be more warming in inland areas than in coastal regions. As such, the tendency towards heat waves (see Section 3.5.1) encompasses heavily populated cities within the state. Figure 2 also suggests how temperatures will be persistently increasing by the end of the century.

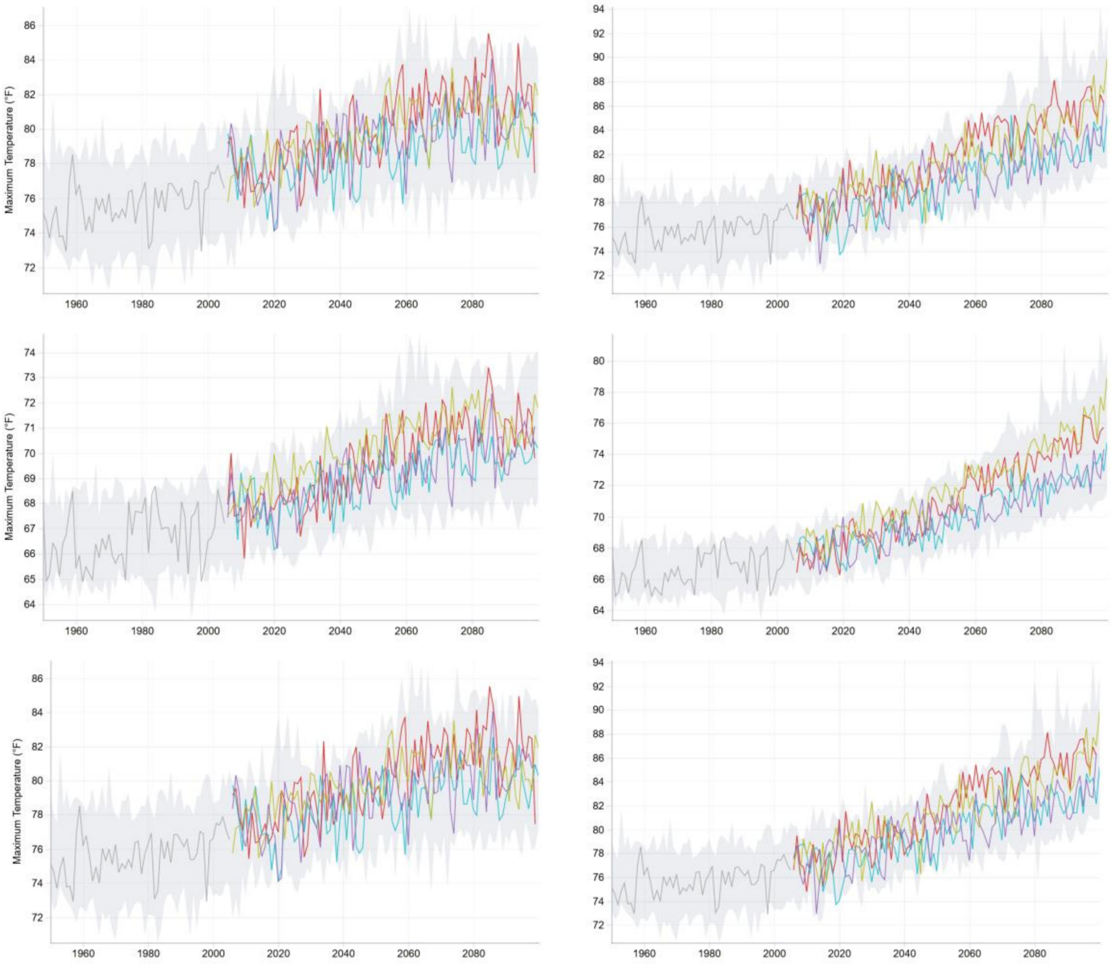


Figure 2. The historical and projected maximum temperatures (°F) in California for the period 1950–2099 for Shasta, Sacramento, and Los Angeles County (top to bottom). Left: projection based on Representative Concentration Pathways, RCP4.5 and right: RCP8.5. Extracted from Cal-Adapt interactive web portal [13].

3.3. Precipitation

Precipitation in the form of rain and snow plays a crucial role in the water supply available to California's agricultural systems. Along with the diverse geography of the state, annual precipitation records exhibit significant inter-annual variability, which makes trend analysis for water resource planning, management, and policymaking very difficult [8]. Figure 3 shows that the total annual precipitation throughout the world has increased at the rate of 2.0 mm per decade [14]. For the contiguous 48 states within the country, it has increased at an average rate of 0.17 inches per decade [15]. The variability of precipitation in California is a unique phenomenon, implying that such unpredictability is more notable in the state than other parts of the West Coast and the country as a whole [16].

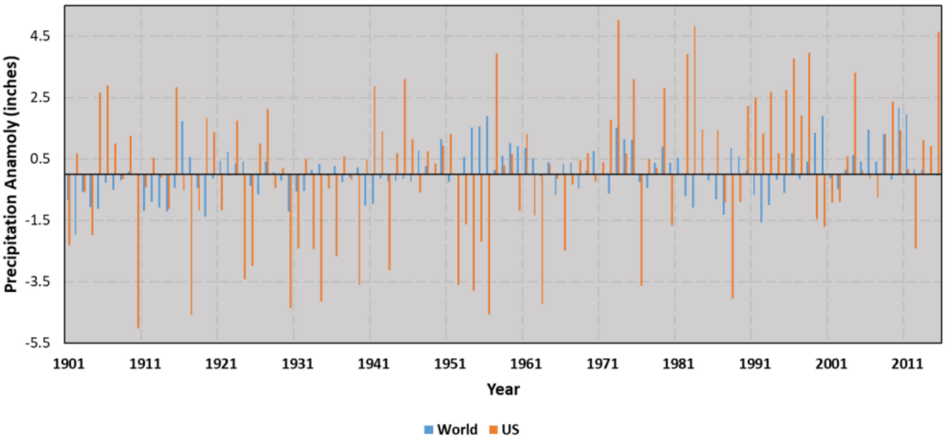


Figure 3. Precipitation anamoly from 1901 to 2015 over the land areas: worldwide and in the United States. Information presented are gathered from Climate Change Indicators: U.S. and Global Precipitation electronically published by U.S. Environmental Protection Agency (EPA) [17].

An analysis of precipitation records since 1890 as portrayed in Figure 4 implies insignificant linear trends at a 95% confidence interval. The last three wet seasons (October 2011–March 2014) represent the driest 30-month period since records began in 1895. However, the trends in Northern California exhibit the largest increases and show positive trends, while Southern California show minimum change or decreases in rainfall over the same time period [18]. Dry and wet periods within the state, especially in Northern California where winter precipitation varies every 14 to 15 years, have significant decadal variability [19]. As such, climate change indicators have increased in intensity over the 20th century, but the physical processes driving such observations are still unclear.

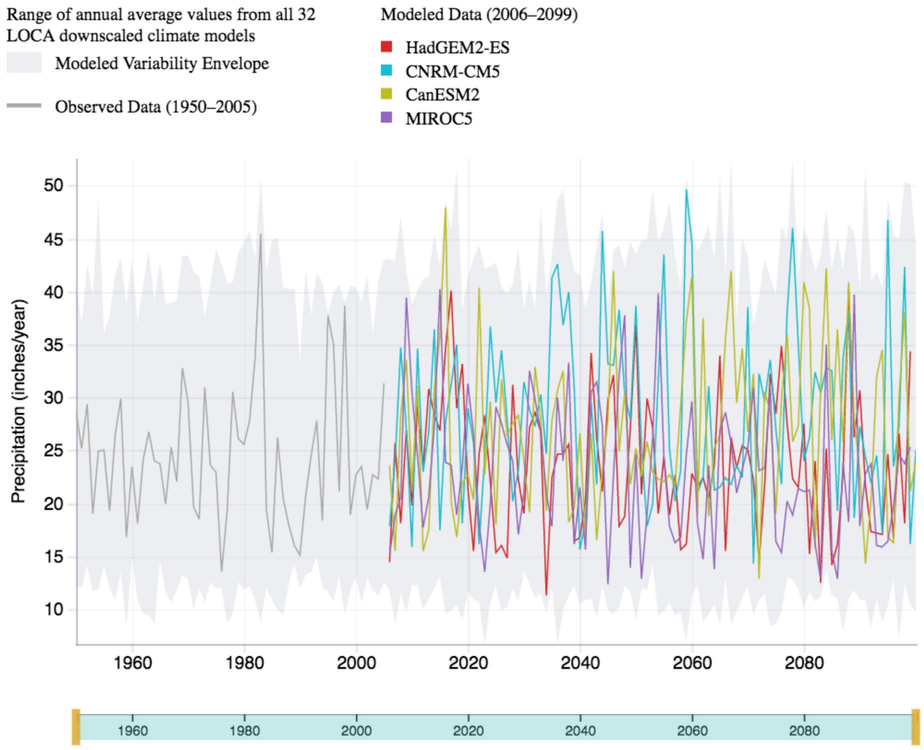


Figure 4. Historical and projected precipitation trends for the state of California. Extracted from Cal-Adapt interactive web portal [13]. Here, LOCA refers to Localized Constructed Analogs.

Globally, climate change affects precipitation in two ways: (1) by strengthening existing precipitation patterns; and (2) by moving storms away from the equator and toward the poles as atmospheric circulation changes [20]. Natural variability, however, precludes distinguishing rainfall shifts. In order to understand such variability, several climate change simulations have been performed using outputs from general circulation models, (GCMs). These simulations suggest that California will maintain its Mediterranean climate with relatively cool and wet winters and hot dry summers. Although discerning strong trends from climate projections is uncertain and difficult, a drying trend in California during the 21st century is observed through different GCM simulation scenarios developed for the Sacramento River Basin [21]. This study suggests that, while Northern California may experience higher annual rainfall amounts and potentially larger storm events, the overall state and Southern California in particular are expected to be 15 to 35% drier by 2100. Figure 4 also suggests that variability of annual precipitation will continue during the next century and that the state will be vulnerable to drought.

3.4. Snowpack

The snow accumulation in the winter and spring months on the Sierra Nevada represents a primary water source for creeks, streams, and rivers, and feeds much of the water system across the state. Historically, almost 80% of the state's precipitation in an average year is provided by snow [22]. Hydro-climatic changes are attributed to the decreases in the snow-to-precipitation ratio resulting from the increasing temperature trends [23]. The Sierra Nevada snowpack is crucial to the state's water storage in surface reservoirs and available water supply for different uses. Heat spells facing parts of California at crucial times can jeopardize the state's Sierra snowpack by inducing earlier and faster than normal snow melt. With such occurrences, some parts of the state may then experience severe flooding events. Figures 5 and 6 show historical and projected snowpack scenarios in California under two potential warming conditions, suggesting that a 65% loss of the snowpack might occur by the end of the century because of a high warming scenario [21].

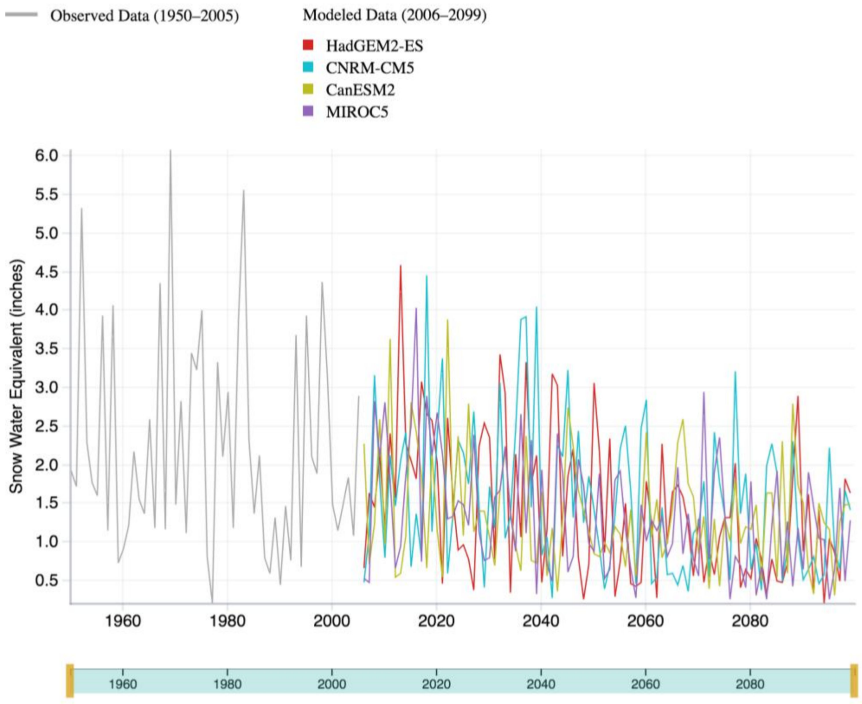


Figure 5. Snow water equivalent time series for the observed and projected time-period. Extracted from Cal-Adapt interactive web portal [13].

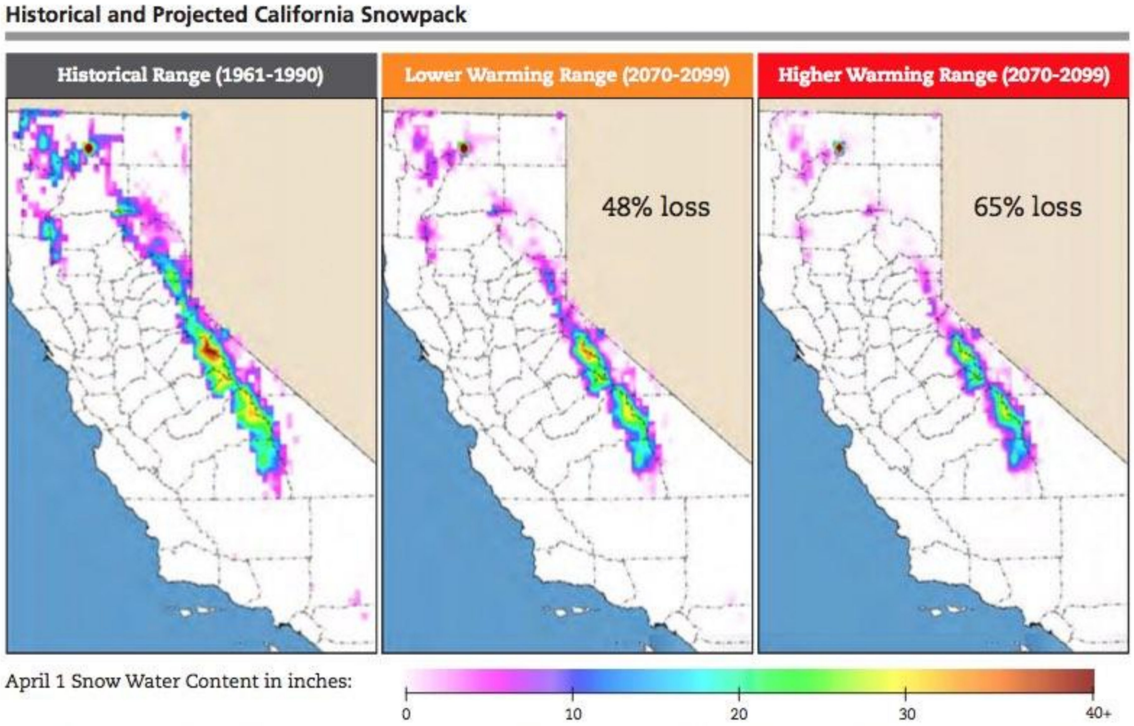


Figure 6. Historical and projected snow pack for the Sierra Nevada. Adopted from "California Climate Science and Data for Water Resources Management" published by California Department of Water Resources in 2015 [21].

3.5. Extreme Climate Events

3.5.1. Extreme Heat Events

Due to California's diverse climate, heat waves present unique challenges for the state's population. Heat waves occur when temperatures exceed the 99th percentile of its local summertime average for durations of at least 1 to 3 days. People, especially along the coast, that lack air conditioning are vulnerable during extreme heat events [24,25]. Frequent heat waves in the state impact health, economic, ecological, and social parameters, resulting in heat-related deaths and illnesses, decreased agricultural production, increased water use and thus irrigation requirements, and greater electricity demands.

Figure 7 reveals sharp increases in nighttime temperatures with the biggest impact on coastal regions [26]. Although such extreme seasonal temperatures are relevant to heat waves for all inland regions, dry daytime temperatures cause the formation of a bi-modal distribution within coastal regions. For example, daytime heat waves in the Central Valley (where agricultural irrigation may produce a cooling effect) are increasing in number [27].

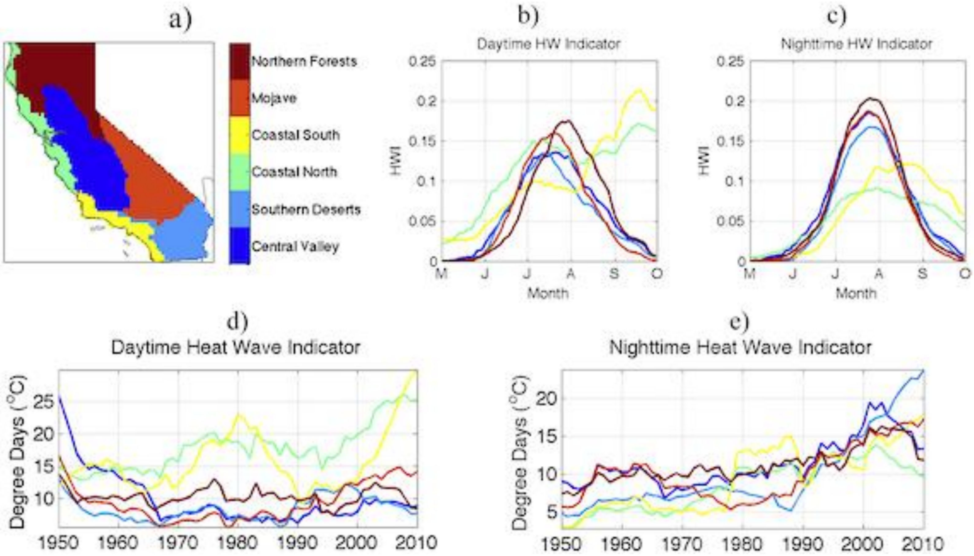


Figure 7. (**a**) California sub-regions derived from daily Heat Wave Index (HWI) variability. (**b**,**c**) The seasonality of observed daytime and nighttime heat waves for each California sub-region and (**d**,**e**) time series of the seasonal daytime and nighttime heat wave index shown smoothed with a 5-point running mean. The colors in (**b**–**e**) correspond to the sub-regions in (**a**) [26]. Copyright © 2012 John Wiley and Sons, Indianapolis, IN, USA.

3.5.2. Drought

Drought can adversely affect agricultural crop production by slowing plant growth and causing severe crop yield losses. Lower stream flow and groundwater levels as a consequence of drought can harm plants by increasing the risk of wildfires when vegetation and soil surface dry out. In order to monitor and assess the state of the Earth's climate in near real-time for decision makers at all levels, the National Oceanic and Atmospheric Administration, NOAA's National Centers for Environmental Information have been updating climate data trends and updating several drought indices [28], among which the Palmer Drought Severity Index (PDSI) is commonly used in the United States. The PDSI, presented in Figure 8, suggests that in the 2013–14 winter, the state experienced its most severe drought conditions since records began 122 years ago.

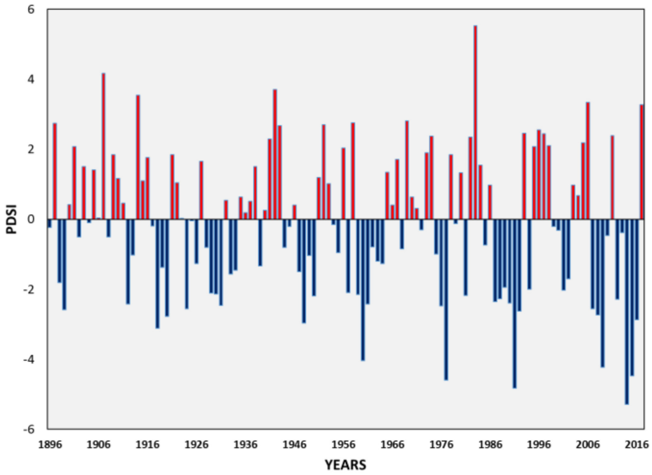


Figure 8. The Palmer Drought Severity Index (PDSI) for California for the months of December, January, and February from 1896 to 2016. Modified graph based on the information provided by NOAA [15] accessed on 3 July 2017.

The study of hydrologic indices and variables widely used in water resources planning and management at a statewide level implies that low snowpack records are a way to characterize drought [29]. According to the IPCC, the Southwestern US can expect increased frequency and intensity of drought and other extreme climate events in the future [5].

3.5.3. Streamflow and Flooding

Warmer environments can cause greater runoff caused by faster snowmelt. This, in turn, causes reservoirs to fill up earlier, increasing the odds of both winter flooding and summer water deficits [29,30]. Increasing temperatures result in more flooding events, which greatly affect plant survival through a reduction in oxygen availability, root asphyxia, and an increase in disease and nitrogen losses [31]. In terms of the factors of precipitation, temperature, and snow water content, precipitation patterns in particular greatly influence spring streamflow, followed by variations in minimum temperature.

The California Department of Water Resources (DWR) reported that the start of runoff events in California's largest watershed, the Sacramento River System, has been occurring earlier in the season [21] over the last century. The peak monthly runoff before 1955 (red line) happens to occur nearly a month earlier than after 1956 (blue line) implying that this key hydrology metric is no longer stationary (Figure 9). One conclusion of this is that peak runoff time will occur earlier in the year, reducing the ability to refill reservoirs after the flood season is over.

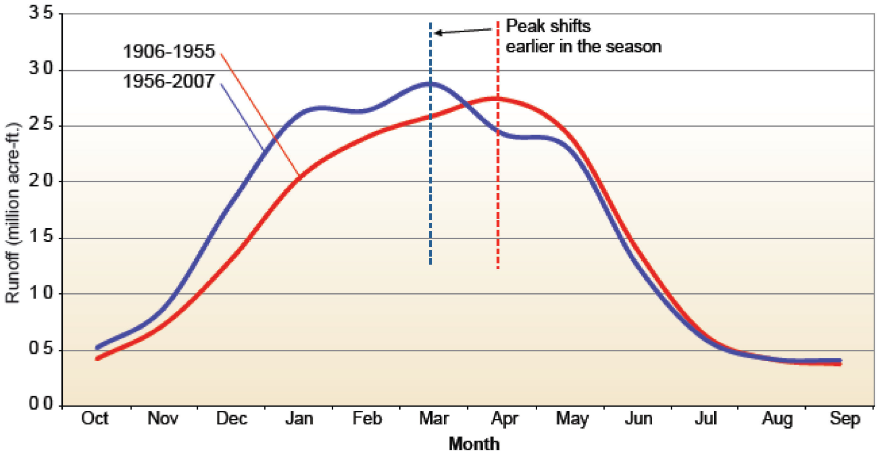


Figure 9. Monthly average runoff of the Sacramento River system. Adopted from "California Climate Science and Data for Water Resources Management" published by California Department of Water Resources in 2015 [21].

Historical analysis in the Sacramento area shows that the change in rainfall intensity is mostly centered in Northern California [11]. This means California's climate is moving toward a flood–drought pattern, potentially resulting in increased flood risks. Even though flood mitigation infrastructures such as levees, dams, and floodgates have been constructed and maintained over the last decades, the lack of proper analyses of flood-related information has made it difficult to address flood risks in California.

4. Climate Change Impact on California Agriculture

4.1. Crop Climate Relationship and Yield Impacts

Global crop production needs to double by 2050 to meet the projected demand for food from rising population, diet shifts, and increasing biofuel consumption [32]. In the agriculture sector, climate change will lead to a major spatial shift and extension of croplands, which precludes a favorable environment for crop growth across different regions [33]. Most of the permanent crops in California require several years to reach maturity and profitable production. Their market value may also depend upon several quality-related factors such as size, color, chemical composition, firmness, and aesthetic features. Most of these attributes are sensitive to even relatively small temperature changes during critical development stages and/or close to harvest. An evaluation of climate change impacts on 8 out of the 20 major permanent crops grown in California showed that temperature variations of 2 °C were most closely related to yield reductions in almonds, wine grapes, strawberries, hay, walnuts, table grapes, freestone peaches, and cherries [34].

Individual crops have specific optimum temperature ranges (temperature thresholds) at which vegetative and reproductive growth thrive and exposure to extremely high temperatures during these growth stages can affect growth and yield. Acute exposure to extreme temperature may be most detrimental during the crop reproductive stages. Table 2 outlines important temperature thresholds for some vegetable crops grown in California. This table also implies that crop species differ in their cardinal temperatures, which are unique in different stages of development [35]. Research by [36] portrays the relationship of yield versus two weather variables deemed most important for each crop. Tomatoes show favorable yields during the warmer April and June months. Pistachios require temperatures of between 0 and 7 °C for about 700 h each winter, but for the past four years there have been less than 500 chill hours [37]. It is noted that influence of climate change on vine phenology and grape composition affects metabolite accumulations under extremely hot temperatures and may affect wine aroma and color [38]. A temperature sensitivity study [39] shows that the yields for wine grapes, strawberries, and walnuts are expected to be reduced due to warm winters, while warm summers improve yields. Warmer January and February weather reduces almond yield, while warm summer temperatures are detrimental to peach yields. Cherries and table grapes do not benefit at any time of the year from a warmer climate; cherries are especially harmed by warm November to February weather due to chilling hour requirements [39].

Table 2. Temperature thresholds for selected vegetable crops [35].

Climatic Classification	Crop	Acceptable Temperature for Germination (°C)	Optimal Temperature for Yield (°C)	Acceptable Temperature Growth Range (°C)
Hot	Watermelon	21–35	25–27	18–35
	Melon	21–32		
	Sweet potato	21–32		
Warm	Cucumber	16–35	20–25	12–30 (35)
	Pepper	16–35		
	Sweet corn	16–35		
	Snap beans	16–30		
	Tomato	16–30		
Cool-Warm	Onion	10–30	20–25	7–30
	Garlic	7–25		
	Turnip	10–35	18–25	5–25
	Pea	10–30		
Cool	Potato	7–26	16–25	5–25 (30)
	Lettuce	5–26		
	Cabbage	10–30	16–18 (25)	5–25
	Broccoli	10–30		
	Spinach	4–16		

The impacts of climate change on annual crop yields are typically analyzed with a process-based model, in which analyses of many perennial crops typically involve statistical models [34]. The relationship between crop yield and climatic variables such as minimum temperature, maximum temperature, and precipitation for twelve major California crops (wine grapes, lettuce, almonds, strawberries, table grapes, hay, oranges, cotton, tomatoes, walnuts, avocados, and pistachios) was derived from historical records from 1980–2003 using regression models [36]. These climatic trends have mixed effects on crop yields for orange, walnut, and avocado, as compared to other crops. Figure 10 shows how climate change is expected to impact yields of almonds, walnuts, avocados, oranges, and grapes by 2050. Median projections for wine grape yields exhibited very small changes over the next century due to climate change, while the other five crops exhibited moderate to substantial yield declines. The impact of climate uncertainty on projections was substantial but not overwhelming. While uncertainties were slightly negative, the differences in climate uncertainty between crops reflect the fact that each crop responds in different ways to climate uncertainties.

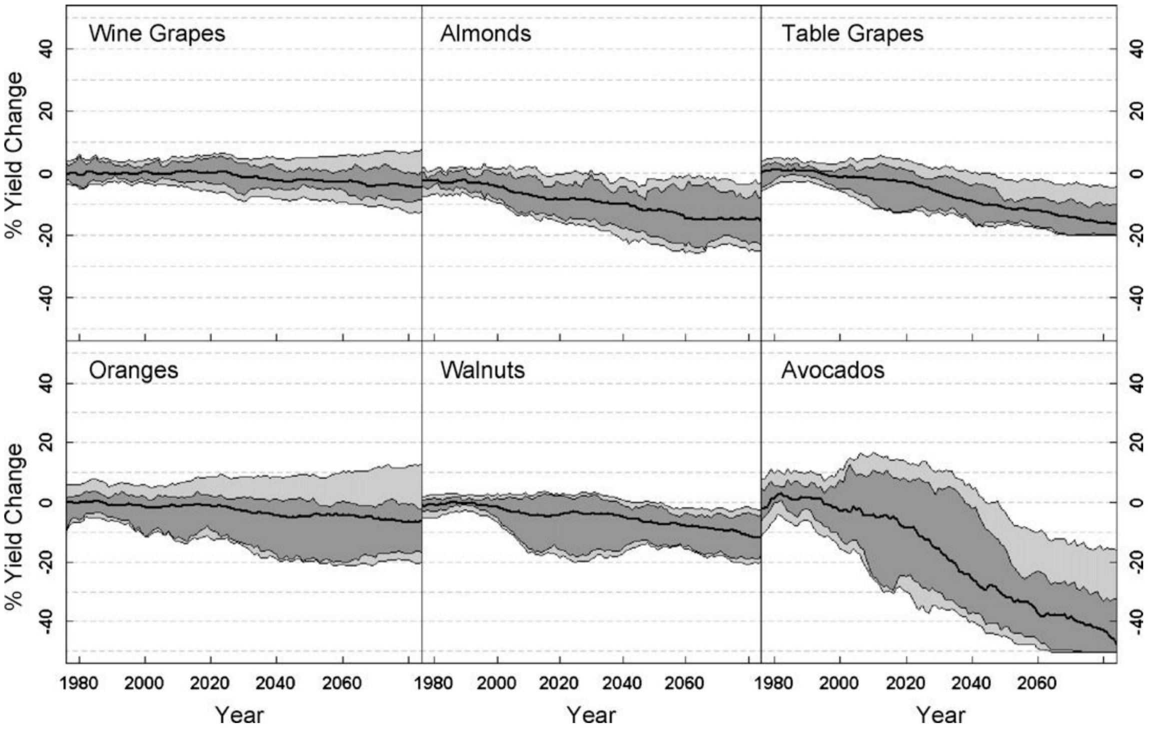


Figure 10. Crop yield changes associated with future climate scenarios, with yield anomalies from 2000–2003 average yields, in percent, constrained to historical extremes. The black line shows median projections, the dark shaded area shows 90% confidence interval after accounting for climate uncertainty, and the light shaded area shows a 90% confidence interval after accounting for both climate and crop uncertainty [34].

The impacts of climate change on crop yields for different field crops such as alfalfa, cotton, maize, wither wheat, tomato, rice, and sunflower in Yolo County and throughout the Central Valley as seen in Figure 11 [40,41] were modeled using a process-based crop model named Daycent. The model provided best estimates of yields for the period from 2000 through 2050 under high- and low-emission scenarios. While alfalfa yields were predicted to increase under climate change, yields from tomato and rice remain unaffected. The effect on wine grape yield is not expected to be high; temperature increases might adversely influence fruit quality. Heat waves in May predicted yield losses of 1–10% for maize, rice, sunflower, and tomato, whereas heat waves in June affected maize and sunflower yields [41]. Overall, a 4 °C increase in temperature may reduce yields from most fruits by more than 5%, and this figure may reach up to 40% in some important regions [42].

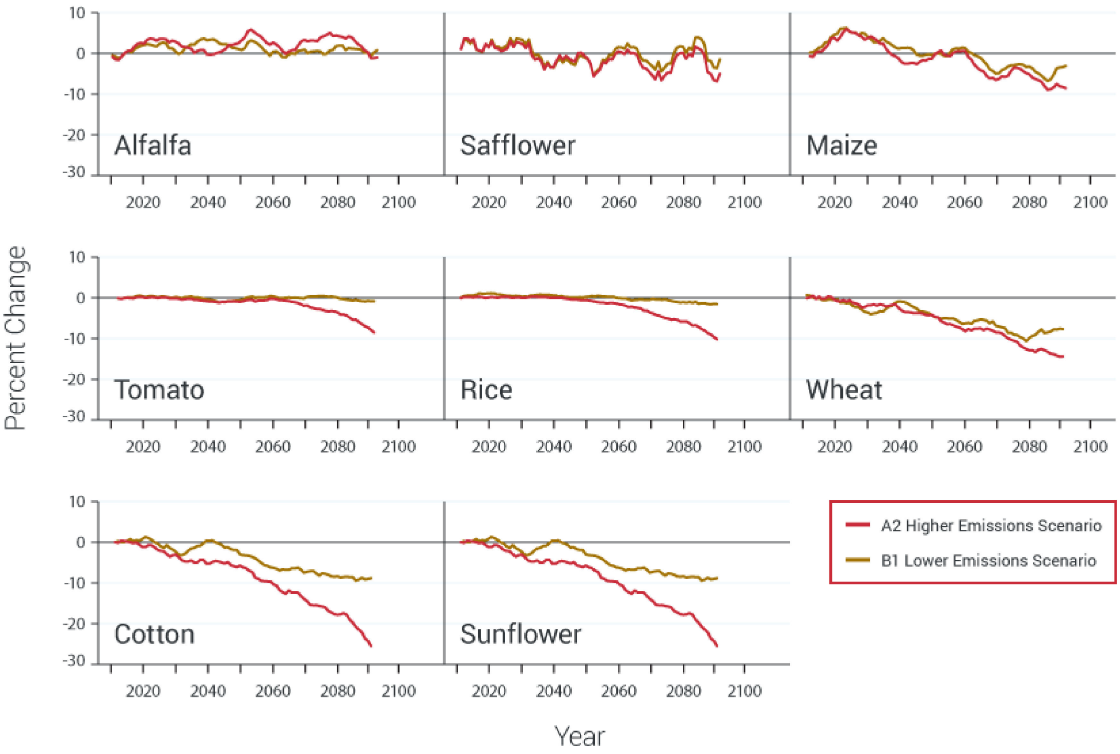


Figure 11. Crop yield response to warming in California's Central Valley based on higher emission scenario (A2) and lower emission scenario (B1) [40,41]. Copyright © 2006 Elsevier, Amsterdam, Netherlands.

4.2. Impacts on Chill Hours

Many fruit and nut crops require cold temperatures in winter to break dormancy. This requirement defines a location's suitability for the production of many tree crops [43,44]. These fruit and nut species adapt to temperate or cool subtropical climates where chilling each winter is needed to achieve homogeneous and simultaneous flowering and steady crop yields. Quantifying chilling requirements is crucial for the successful cultivation of such crops, and temperature records are converted into a metric of coldness. The lack of adequate chilling hours can delay pollination and foliation, reducing fruit yield and quality [45]. The effects of insufficient winter chill can vary among species. Walnuts and pistachios depend on synchronization between male and female flowering that is regulated by the number of chilling hours. For various stone fruits, a lack of winter chill results in delayed foliation, reduced fruit set, and poor fruit quality. In many cases, insufficient winter chilling hours result in reduced tree crop performance.

Figure 12 portrays historic and projected future changes in winter chill in California according to two different chilling models: chilling hours and dynamic models [44]. This research aimed at determining time-line management measures, such as the spraying of dormancy-breaking chemicals, as a predictor of crop yield potential for the season. The study reported that climatic conditions by the end of the 21st century would no longer support some of the main tree crops currently grown in California. As seen in Figure 12, winter chill hours in 1950 and those projected to occur between 2080 and 2099 will vary spatially between the Sacramento and San Joaquin valleys.

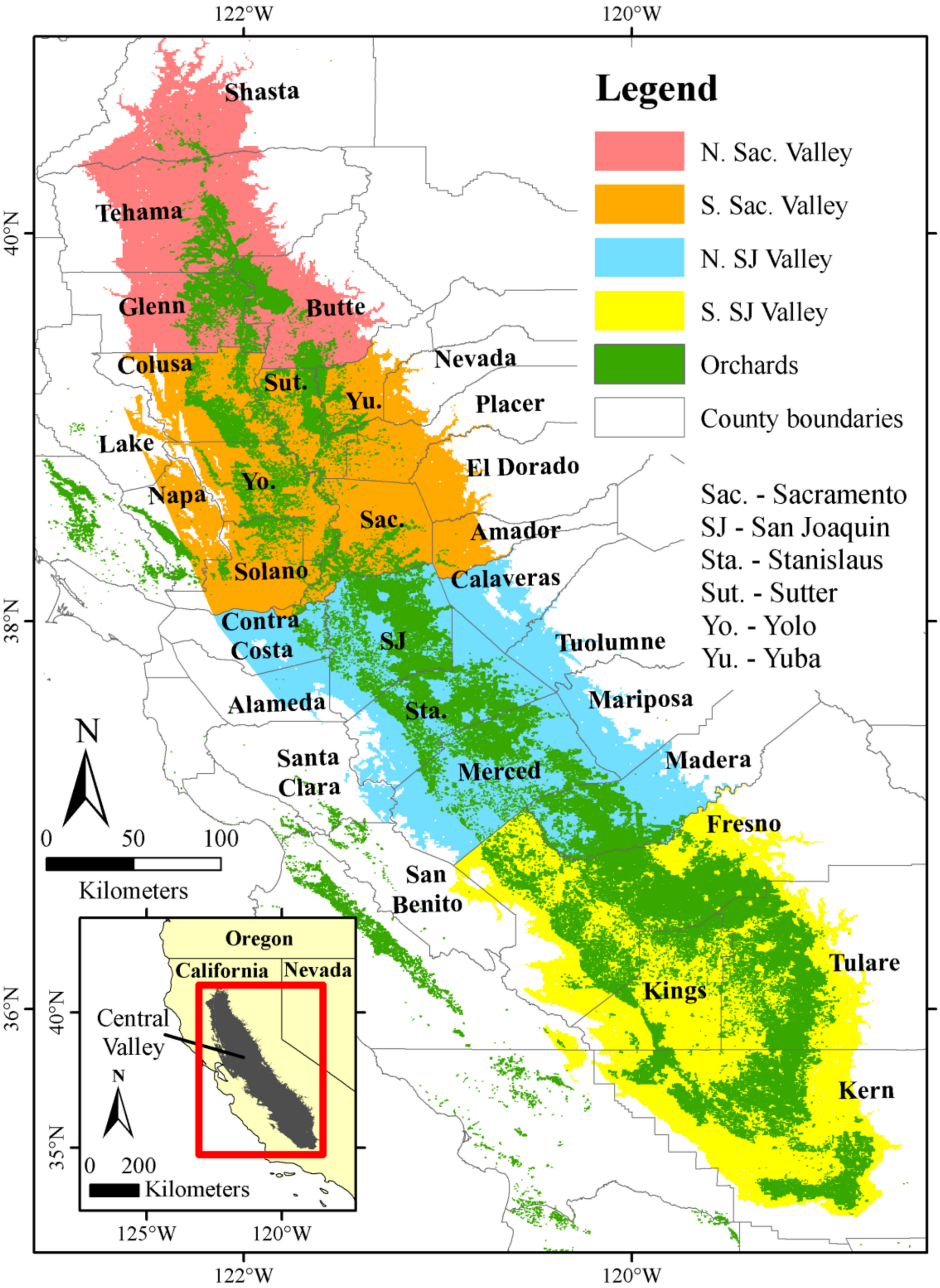


Figure 12. Overview of California's Central Valley, showing the distribution of orchards that require winter chill [44].

Figure 13 shows that around the year 1950, growers in the Central Valley could rely on having between 700 and 1200 chilling hours, depending on the location of their orchard in the valley. Information about chilling requirements is presented in Table 3 for different tree species [35]. Figure 13 suggests that winter chill conditions for cultivars requiring 200 chilling hours (almond, fig, olive, persimmon, and pomegranate) are unlikely to become critical by the end of the 21st century. For chilling requirements of 500 h (chestnut, pecan, and quince) only about 78% of the Central Valley will be suitable for production by the end of the 21st century. For cultivars that require more than 700 h (apricot, kiwifruit, peach, nectarine, plum, and walnut), only 23–46% of the valley remains suitable and only 10% will remain viable by 2080–2095. Only 4% of the area of the Central Valley was suitable in the year 2000 for species such as apples, cherries, and pears, which have chilling hour requirements of more than 1000 h. However, virtually no areas will remain suitable by 2041–2060 under any emissions scenario [44]. Among the most climate-sensitive trees and vines, walnuts require the highest number of chill hours, implying a future decline in walnut acreage within the valley [46].

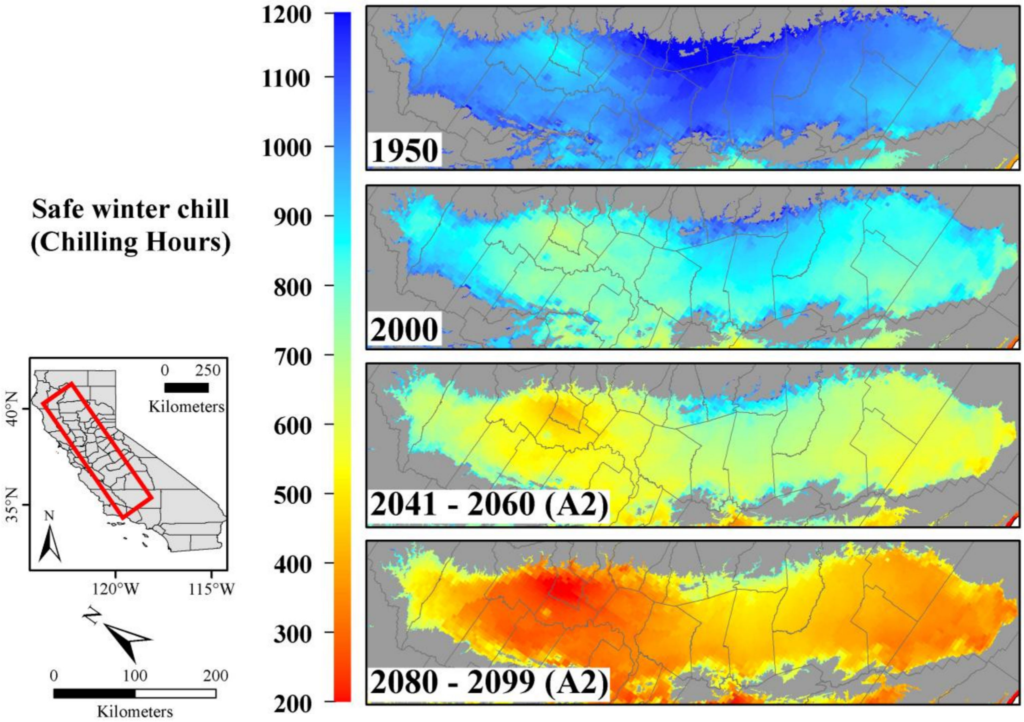


Figure 13. Safe winter chill in California's Central Valley in 1950, 2000, 2041–2060, and 2080–2095 [44].

Table 3. Chilling requirements for different fruit and nut tree species [35].

Type of Tree	Approximate Hours	Equivalent Time in Days or Weeks if Continuously Exposed to 7.2 °C/45 °F or Below
Almond	200–300	8–13 days
Apple	1200–1500	7–9 weeks
Apricot	700–1000	4–6 weeks
Cherry, sour	1200	7 weeks
Cherry, sweet	1100–1300	6–8 weeks
Chestnut	300–400	2–3 weeks
Fig	few hours	—
Filbert (Hazelnut)	1500	9 weeks
Kiwifruit	600–850	3.5–5 weeks
Olive	200–300	8–13 days
Peach/Nectarine	650–850	4–5 weeks
Pear	1200–1500	7–9 weeks
Pecan	400–500	3–4 weeks
Persimmon	<100	4 days
Pistachio	1000	6 weeks
Plum, American	3600	5 months
Plum, European	800–1100	5–6 weeks
Plum, Japanese	700–100	4–6 weeks

Table 3. *Cont.*

Type of Tree	Approximate Hours	Equivalent Time in Days or Weeks if Continuously Exposed to 7.2 °C/45 °F or Below
Pomegranate	200–300	8–13 days
Quince	300–400	2–3 weeks
Walnut, Persian (Payne)	700	4 weeks
Walnut, Persian (Franquette)	1500	9 weeks

4.3. Impacts on Plants, Pesst, and Diseases

Climate change may have impact on the incidence and severity of plant disease and influence the further co-evolution of plants and their pathogens [47]. Climate change may affect pathogen development and survival rates, modify host susceptibility, and result in a spread of diseases such as sudden oak death to the forests of Coastal California and Southwestern Oregon [48,49]. Moreover, plant diseases could be used as indicators of climate change in which the environment can move from being disease-suppressive to disease-conducive, or vice versa [50,51].

Plant diseases, insects, and invasive weeds are mostly caused by temperature-related climate factors, with the invasion of previously uninhabitable areas, for example, Yolo County [52]. For instance, while milder winters help many frost-sensitive insects to survive, and increased temperature may help promote more rapid reproduction in other insects [53]. Crop diseases including animal, fungal, bacterial, or viral pathogens are often spread through an insect vector, wind, or anthropogenic activities. In Yolo County, it was noted that soybean rust spread throughout the world due to increases in severe weather events such as hurricanes [52]. Recently, stem nematode has been reported in alfalfa in Yolo County, which can spread in various ways including through waterways and irrigation runoff, contaminated farm equipment, and other anthropogenic means. Statewide integrated pest management (IPM) involves listing common diseases and insects, and allows us to elucidate potential plant disease and manage all kinds of pests elsewhere within the state [54].

4.4. California Agricultural Vulnerability to Climate Risks

Volatility in agricultural markets and cost of energy, fertilizers, and other inputs can have a multitude of unpredictable biophysical and social consequences [41,55]. In order to reflect the aspects of exposure, sensitivity, and adaptive capacity to climate risks, agricultural vulnerability indices are often assessed by examining biophysical and social indicators over time and space. Among various indices, the Social Vulnerability Index (SVI) is used to explore vulnerability to environmental hazards [56]. To date, there is no single data point to measure crop vulnerability across the landscape. Merging coupled crop and economic models may provide a better picture of specialty crop vulnerability [55].

The Agricultural Vulnerability Index (AVI) for California integrates a broad set of biophysical and social indicators relevant to state and local efforts to adapt to changes in climate, land use, and economic forces. As such, the California AVI is meant to be a starting point for "place-based" adaptation planning throughout California. The AVI assigns each variable to one of four sub-indices: climate vulnerability, crop vulnerability, land use vulnerability, and socioeconomic vulnerability based on an a priori judgment and spatial resolution [56].

Figure 14 establishes some of the most vulnerable agricultural regions to climate change from multiple perspectives. The Salinas Valley and the San Joaquin Valley are identified as two of the most vulnerable agricultural regions [56]. While agriculture in the Imperial Valley and the corridor between Fresno and Merced are found to be very vulnerable to climate change, northern regions of the state may provide hospitable environments for fruits (wine grapes) and vegetables.

It is also useful to note how Southern California shrub lands could move to higher elevations as a response to cooler climates and greater precipitation because of rising temperatures and reduced precipitation in their current environments. As noted, non-native grasslands could be converted into shrub lands and consequently exhibit reduced range and proficiency [57]. Various model scenarios suggested that forage production for cattle grazing might decline because of decreases in annual precipitation [58]. Forest diseases such as pitch canker are vulnerable to warmer winter temperatures and affect the root and stem-base of a wide range of broad-leaved and coniferous species [59]. The grassland habitat in the Sacramento Valley may decline by 1–20% by 2070 due to warmer winter temperatures and variable precipitation [60]. The eastern edge of the Central Valley might become climatically unsuitable for grassland habitats including valley oak under drier conditions and the northern Central Valley to a large degree may become unsuitable for such habitats under wetter conditions [61]. It is estimated that 24–59% of current California foothill, valley forests, and woodlands will not be climatically suitable for oak woodlands by the end of the century.

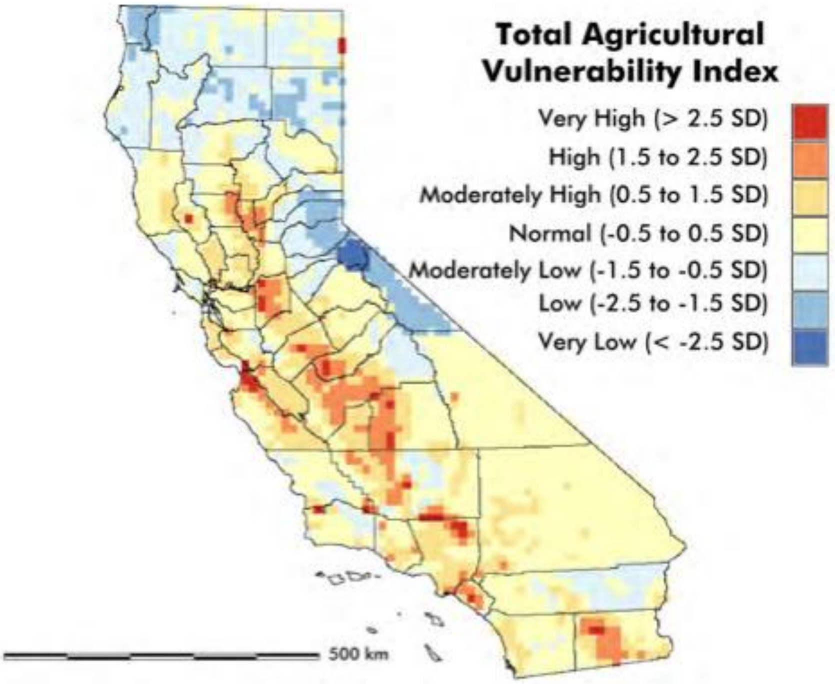


Figure 14. The Agriculture Vulnerability Index for California that integrates indices for climate, crop, land use, and socioeconomic vulnerability based on standard deviation (SD) as published in vulnerability and adaptation to climate change in California agriculture, 2012, by California Energy Commission [56].

5. Important Findings and Directions for Future Research and Implementation

The range of studies on trends and impacts of climate change on California agriculture presented in this review paper justifies the importance of enhancing the adaptive capacity of agriculture to reduce vulnerability to climate change and gain substantial benefits. This section summarizes important findings on climate change impacts for California agriculture and relevant adaptation research efforts for research and implementation. While the list is extensive and reflects information based on what is known now, it is important to note that in the long term, state and national priorities should reflect the expected impacts of climate change. Table 4 summarizes important findings from this paper and relevant adaptation strategies, followed by a section discussing future directions for research and implementation in detail.

Table 4. Summary of key findings and potential adaptation strategies for California agriculture with respect to changing climate [10,15,18,21,23,26,41,44,47,53,62–89].

Climate Change Trends (Key Findings)	Agricultural Impacts (Key Findings)	Agricultural Adaptation Strategies for Future Research and Implementation
Temperature • Average temperatures increased by 1.2–2.2 °C since last century • Daytime temperatures increased by 0.1 °C per decade, and nighttime temperatures increased by 0.33 °C per decade • Faster warming in the late winter and early spring but no trends in the fall • Projected temperature increases with low and high emission scenarios are of 1.5 °C and 4.5 °C, respectively	• Substantial decline in winter chill hours for many fruit and nut trees by the late 21st century • Reduced water availability for agriculture (irrigation) because of more crop evapotranspiration demands • Increased frequency and intensity of heat waves adversely impacting temperature sensitive vegetable crops • Altered phenology that includes leaf development, flowering, harvest, and fruit production • Reduced fruit quality (such as decreased size and yields), especially impacting high value crops like strawberries and grapes • Only about 78% of California's Central Valley is expected to be suitable for chestnut, pecan, and quince production and 23–46% of the Valley suitable for apricot, kiwifruit, peach, nectarine, plum, and walnut by the end of the 21st century • Increased nighttime temperatures may decrease crop yields due to increased rate of respiration • Decline of wine grape yields by 10% across the state of California by the end of the 21st century • Pests emerge earlier in the season and persist longer due to warmer temperatures in the spring and fall • Crops invaded by diseases, pests, and weeds associated with changing temperature, e.g., the lygus bug may migrate in the reproductive phase of the cotton crop, resulting in serious yield losses • Milder winters favorable for survival of frost-sensitive insects and increased temperature promotes their reproduction rapidly For example, the pink bollworm has negatively impacted cotton in the Imperial Valley and can be consistently found in the San Joaquin Valley [58]	• Adaptation of integral system approaches to improve water use efficiency in crops, through more efficient soil and irrigation management • Switching to low-chill varieties • Altering planting and harvesting schedules • Prioritizing crop breeding strategies to select for traits with low-chill requirement temperate fruit and nut crops • Adapting ad hoc crop rotations and associated and agricultural practices (tillage systems, soil cover management, etc.) to improve soil retention capacity • Adopting suitable management practices that provide required cooling effects • Further research on rest breaking controls for perennial crops with chill hour requirements • Identifying potential pests that will likely be a threat to specific agricultural regions in California under future climate conditions and developing strategies to control them • Adopting more pest-resilient varieties due to increased pest pressure in California under a warmer climate

Table 4. *Cont.*

Climate Change Trends (Key Findings)	Agricultural Impacts (Key Findings)	Agricultural Adaptation Strategies for Future Research and Implementation
Heat Waves • Increasing trend in regional hottest daytime temperatures for coastal regions. The Mojave and Southern Deserts have had the coolest nighttime temperatures of all regions between 1950 and 2010 • Progressively and relatively less intense desert heat waves and more intense coastal heat waves in the future • The frequency and intensity of heat waves are projected to increase in future	• Increased yield of perennial vegetation (positive effect) but reduced length of the dormant period (negative effect) • Early bolting in annual crops and reduced pollination success • Predicted yield losses for maize, rice, sunflower, and tomato from summer heat waves • Reduced photosynthesis and increased respiration lessening overall plant growth and decreasing the quality of harvested product	• Shifts in crop mix and diversification • Research on germination tube formation in relation to high temperatures • Evaluating and adopt heat-tolerant agronomic plant species • Using heat forecast information to be prepared for heat stress mitigation practices
Precipitation and snowpack • Increased number of days with precipitation greater than 10 mm across the state over 1950–2000, although this is statistically insignificant • No clear trend in precipitation projections over the entire state. Increased yearly and decadal variability in terms of drier and wetter conditions • Decreases in the snow-to-precipitation ratio • Higher annual rainfall amounts and potentially larger storm events during the next century • Potential 65% loss in snowpack expected by the end of the century	• Earlier snowmelt, and more winter floods • Stunting of plant growth due to nutrient leaching • Increased risk of waterlogging and oxygen depletion in the soil • Delayed crop plantings • Precipitation fluctuations likely to decrease water availability and crop production in the future [78] • Increased risk of soil-borne diseases and rot diseases • Impacts on tree crops by washing away of pollen during flowering due to unpredictable heavy rain events • Crop production on irrigated lands affected because of drainage loss	• Changing crops or adjusting different harvest and planting/sowing dates • Understanding farmers' perceptions and adaptations to precipitation variability • Cultural practices to minimize risks due to uncertainties in precipitation • Reducing the length of the irrigation season, breeding crops that develop in a shorter time period than those presently under cultivation • Adapting integral system approaches to improve water use efficiency by better crop, soil, and irrigation management • Switch to crops with low evapotranspiration demands • Increasing water storage in dams and reservoirs • Improving rainwater harvest • Improving on-farm water control and application, soil fertility management, and use of improved genotypes. Deficit irrigation • Artificial groundwater recharge • On-farm water capture and storage

Table 4. *Cont.*

Climate Change Trends (Key Findings)	Agricultural Impacts (Key Findings)	Agricultural Adaptation Strategies for Future Research and Implementation
Drought • Drought duration ranged from 4 to 10 years • Some droughts in the 21st century persisted for 12 years or more • The most severe drought conditions were reported in the 2013–2014 winter with respect to the last 122 years of records • Expected 50% increase in the number of severe drought in the state by the end of this century	• Severe yield losses due to drought-related water stress • Decreased water supplies and use of irrigation due to increased water demand • Exacerbated insect and disease problems • Perennial crops increasingly susceptible to insect infestations and disease • Reduced root growth, which will impact contact with propagules of soil-borne pathogens • Surface water shortages primarily offset by increased groundwater pumping	• Introducing drought-tolerant plants and changing cropping systems • Using conservation practices such as organic mulch between rows, cover crops for better infiltration, and no or minimum till practices, to improve soil health • Increasing the utilization of pressurized irrigation systems such as sprinkler and drip irrigation • Improving management practices, such as field leveling or use of soil moisture information systems for irrigation management • Increasing the use of pressurized irrigation systems at the farm, local, and regional scales (to be researched) • Reducing evaporation from water conveyance systems via conversion from traditional open supply channels to closed systems or suitable chemicals • Increasing the utilization of recycled water • Increasing the utilization of soil management practices, crop establishment, and foliar application of growth regulators that optimize stomatal performance

Table 4. *Cont.*

Climate Change Trends (Key Findings)	Agricultural Impacts (Key Findings)	Agricultural Adaptation Strategies for Future Research and Implementation
Flood		
• Six out of ten of the most extreme historical flood events in California occurred within past 25 years • Expected 50% increase in the number of severe flooding events in the state by the end of this century • Earlier runoff events • Peak monthly runoff occurring nearly a month earlier after 1956 than before 1956 • Increase in the magnitude of three-day flooding events as revealed by the Variable Infiltration Capacity (VIC) hydrologic model driven by general circulation models (GCMs) • Risk of larger magnitude three-day floods along both the northern and southern mountain ranges over the period 1951–2099 as depicted by simulations of two climate models	• Water logging, where soil is saturated with excess water • Increased submergence, where unwanted standing water covers a land area • Low oxygen, low light, and low rates of gas exchange that damage some crops • Alterations to freshwater reservoir and conveyance systems • Extreme flooding events delay late harvesting of strawberries along the central and southern California coasts as well as citrus harvest	• Adapting reservoir operations that best manage climate-change induced flooding events • Flood plain mapping and management • Plant breeding strategies for improved salt tolerance • Switching from traditional salt-sensitive crops like strawberries to salt-tolerant crops along the coastal areas of California • Avoid planting on flood plain areas • Introducing real-time controls that provide early warnings alert to local decision makers of extreme weather events

5.1. Climate Change Is Intensifying Challenges for the Agriculture Sector in California

The detailed literature study on climate change in California clearly reveals that temperatures are increasing at significant rates. Both daytime and nighttime heat waves are expected to become more frequent and intense. Precipitation is becoming highly variable, which increases the risks of frequent and intense droughts and floods in the state. Snowpack has reduced considerably and is projected to shrink further in the future climate. These changes in climate are placing increasing pressure on agricultural production systems in California. Reduced numbers of chill hours, increased pest pressure, increased water demand and water-induced stress, as well as variable and unreliable water supply, are examples of factors that are projected to adversely impact the yield and quality of various crops grown in California. Given that California is a world leader in the production of many important specialty crops, without timely and effective actions, negative climate change impacts may further intensify the challenges to meet local and global food demands. Climate change is also contributing to resource variability and constraints beyond food security, such as periodic water shortages alternating with intense precipitation and flood events, water and soil degradation, and increasing pressure from existing and new pest species. As resource limitations and food security challenges emerge, the urgency of addressing these issues has become critically important.

5.2. Need for Localized Agricultural Adaptation Research to Minimize the Risks Due to Increased Temperatures and Extreme Heat Waves

Temperature increases and extreme heat waves have direct impacts on agricultural production. There are several possible adaptation options available, which mostly concern variations of existing climate-risk management practices. For crops that are sensitive to extreme heat, research to breed and test new plant varieties that are heat-tolerant or better adapt to water stress is of high priority. Several California fruit and nut crops are losing yield and decreasing in acreage due to reduced chill hour accumulations as a direct consequence of increased winter and nighttime temperatures. Along with breeding programs to produce low chill requiring varieties, management practices that can extend crops' winter dormancy periods should be investigated and documented for implementation. Since different crops react to temperature changes differently, research efforts on climate adaptation should be crop-specific and related to local environmental conditions for successful adoption.

Due to increased temperatures, the impact of pests, diseases, and weeds is increasing substantially, with their altered growth cycles possibly becoming concentrated and impacting crop harvests. In this regard, research efforts should focus on documenting crop-specific potential threats due to existing and new pests and diseases. Research should also target the development and validation of new models to simulate pest growth cycles and formulate effective counter-measures, such as earlier harvesting windows or timely pest control treatments. Adaptation should not only be based on climatic stimuli alone, but also consider non-climatic forces such as economic conditions, politics, environment, society, and technology, which have significant implications for agricultural policy- and decision-making.

5.3. Increased Research Efforts on Expanding Adaptation to Water Shortages in Agriculture

As explained in this paper, increased variability in precipitation patterns, reduced snowpack, and groundwater depletion due to recurring and prolonged droughts have added further pressure to the existing strain of the state's agricultural water supply. Weather-related variability and changes have indirect effects on agricultural production through uncertain agricultural water supply and demand that will all make farmers increasingly vulnerable to vagaries and uncertainties in the near future. There is a broad range of options to cope with water shortages in agriculture, which could help in buffering agricultural production risks. Generally speaking, they can be divided between supply enhancement and demand management options, and can be deployed at different levels along the agricultural water supply continuum, from the water source to farmers and beyond, to the consumers of agricultural goods.

Supply enhancement refers to increasing access to conventional water resources and as such can be done at different scales. At the river basin scale, efforts include enhancement of water storage in dams and reservoirs, rainwater harvest, and inter-basin water transfers. At this scale, further research efforts should target improved accuracy in predicting significant rain events and linking these predictions to dynamic operation of dams and reservoirs to optimize water storage and flood protection. Artificial groundwater recharge and re-use of municipal wastewater are both priority options at irrigation scheme level. In this regard, additional research is needed to better characterize the benefits and risks of artificial groundwater recharge with storm water through agricultural fields during crop dormancy. At the farm and field scales, the adoption of agricultural practices that capture rainwater and reduce runoff, such as establishing winter cover crops, no tillage and minimum tillage, and incorporation of crop residues can strongly contribute to increase infiltration and soil water storage. In this context, applied research should better determine the economic and ecologic trade-offs of such practices to address growers' concerns and inform decisions. At the same time, research efforts are needed to evaluate the cost-effectiveness and potential of safe on-farm drainage water recycling.

Demand management entails a set of measures that can be deployed at different levels of the agricultural water use chain, to control water demand either by raising the overall economic efficiency of its use or by re-allocating water resources. At the river basin and irrigation scheme levels, a major goal is to improve the efficiency of water use by reducing water losses in the process of agricultural production. This can be achieved by decreasing the non-beneficial use of water through reduction of leakages and evaporative losses in water conveyance and distribution systems. Canal lining, conversion from gravity-fed to pipe conveyance, and enhanced irrigation delivery services through pressurized distribution networks are improvement measures towards better controlled, more flexible, and reliable water delivery that could also support a transformation from low-return to high-return agriculture. Precise water application through micro-irrigation systems, improved irrigation scheduling, and soil moisture monitoring are viable options for reducing water losses at the farm and field scales. At the farm and field levels, increasing agricultural water productivity is probably the most valuable avenue for managing water demand in agriculture. In general, obtaining higher crop yields and reducing the volume of applied water while maintaining acceptable production levels are the most important factors in crop-water productivity increase. Reductions of applied water could be pursued through deficit irrigation, which allows farmers to apply less water than the full crop water requirements, thus aiming at an economic optimum between crop water use and crop yields under water shortage conditions. In this regard, research efforts should target a better knowledge of the crop response to water deficits in the different growth stages to schedule irrigation in a way that maximizes water savings while minimizing yield losses. Crop simulation models could also be properly parameterized for local conditions with data resulting from field experiments, and then be utilized to formulate viable and effective strategies for optimizing crop performances under limited water supply.

5.4. Stakeholder Engagement and Extending Knowledge

Climate information and adaptation research offer much potential to enhance agricultural resilience to climate risks through improved agricultural decision making, such as through preparing for expected adverse conditions or taking advantage of expected favorable conditions. To help growers manage risks, it is important to develop locally relevant, need-based decision support tools that are viable and aligned with growers' economic objectives. Coordinated efforts are needed to engage agricultural stakeholders in climate adaptation discussions, understanding their needs and barriers to climate change adaptations. Since each crop responds to changes differently, dialogue with stakeholders about adaptation may also vary. Research only has value if it leads to informed decision-making at the local scale. Climate change has been traditionally viewed as a global issue and translating its implications at local, farm, and field scales with adverse impacts facing farmers has been often challenging. Cooperative extension can play a major role in developing educational programs on agriculture and climate change at local and regional scales, to help stakeholders translate the science into actionable strategies. Increased dialogue is needed for agricultural professionals to address communication challenges related to climate change and agriculture.

6. Conclusions

This detailed review provides sufficient evidence that climate in California has changed significantly, and this change can be expected to continue in the future. Increased minimum and maximum temperatures, highly variable and shifting precipitation patterns, reduced amount of snowpack in the Sierras, and increased frequency and intensity of weather extremes such as heat waves and drought are examples of climate change indicators for the state. These trends are negatively influencing California's highly productive agricultural industry. Impacts on agriculture include low chill hour accumulations, crop yield declines, increased pest and disease pressure, increased crop water demands, altered phenology of annual and perennial cropping systems, and uncertain future sustainability of some highly vulnerable crops. The detailed reviews on trends and impacts of climate change on California agriculture justify the importance and urgency for a stronger focus on enhancing the adaptive capabilities of agriculture to reduce vulnerability to climate change and gain substantial benefits. California agriculture is very diverse and since each crop responds to climate differently, climate adaptation research should be locally focused along with effective stakeholder engagement and systematic outreach efforts for more effective adoption and implementation.

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