

## CHAPTER 16. CLIMATE CHANGE AND CALIFORNIA AGRICULTURE

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### ABSTRACT

Recent climate projections indicate an unambiguous warming across California and all seasons over the 21st century. Projections regarding the amount of precipitation are less clear, but it is likely that rising temperatures will reduce mountain snowpack, which provides critical natural water storage for irrigated agriculture. Changes in the timing, and potentially the quantity, of runoff will likely disrupt surface water distribution, placing agricultural operations at risk. Climate variability is also predicted to increase with more frequent occurrence of droughts.

Climate change is expected to reduce yields of major field crops, including cotton and wheat. Impacts on fruit and nut crops appear unclear, and highly dependent on the crop considered and the modeling approach used. One prominent study predicts stagnating yields for almonds and table grapes and declining yields for strawberries and cherries by mid-century. The suitability of California regions for premium wine grape production could also be negatively affected by climate change.

Animals will also be affected by rising temperatures, with milk yields likely declining due to heat stress. Workers tend to be less productive at low (under 55°F) and high (over 100°F) temperatures. Agriculture could adapt, moving dairy cows to cooler regions, but perhaps raising the cost of feed procurement. Farm workers could work at night, necessitating lighting systems and perhaps premium wages.

To combat climate change, the state has enacted a series of important legislation, starting with the 2006 Global Warming Solutions Act. While it is unclear whether California will succeed in changing the path of global climate, it is likely that constraints on greenhouse gas emissions in California will come at a cost. California farms may be affected by the state's climate policies through higher energy prices and lower processing capacity, as

food-processing plants are covered by the state's cap-and-trade program and may lose competitiveness relative to unregulated regions. The dairy and livestock sector, the main contributor to agricultural greenhouse gas emissions in California, is also expected to reduce its methane emissions greatly in the near future.

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Changing temperature and precipitation patterns may create serious challenges for irrigation water management across the state. As a result, farms will likely face an overall reduction in available surface water. During the recent drought, many almond orchards were abandoned in the Central Valley due to lack of available water.

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## INTRODUCTION

Nowhere has the field of agricultural economics transformed more over the last 15 years than in the area of climate change. In the previous edition of this book, little more than five paragraphs were devoted to the topic. Since then, California has introduced pioneering legislation to reduce greenhouse gas emissions and weathered a historic drought; the topic of climate change and agriculture regularly appears in headlines and on the news; and researchers across a number of disciplines have dedicated themselves to understanding the links between weather, climate, and agriculture. In short, the intersection of climate change and agriculture has taken center stage in discussions among farmers, policymakers, and researchers alike.

This chapter seeks to take a stock of the state of knowledge on climate change and agriculture in California, and provide an overview of climate change and how it relates to California agriculture. We begin by describing the historic and variable climate that characterizes the state, and then lean on climate change models to make projections about changes in temperature and precipitation under various warming scenarios. Next, we summarize the implications of these projected changes in temperature and precipitation for irrigated water supplies. We then ask: "what does climate change mean for agricultural outcomes?" where we focus on impact assessment for farm profitability, crop yields, animal productivity, and labor productivity. After highlighting a number of primary channels through which climate change could affect agriculture in California, we evaluate the role adaptation can play in reducing the negative effects of climate change on agriculture. Our discussion of adaptation looks at the potential of crop switching to reoptimize outcomes under a new climate regime. Given California's aggressive and trailblazing efforts to reduce greenhouse gas emissions, we also survey the efforts taken by the state to mitigate agricultural greenhouse gas emissions.

A review of the literature cited in this paper reveals a young, exciting, growing, and collaborative field, and this chapter seeks to provide a primer on the essentials of this literature for the setting of California. While this survey of

the literature is broad, it is not exhaustive. For this reason, we view this chapter as a starting point on the potential impacts of climate change on California agriculture.

Fortunately, to get a broader understanding for the fields of climate change economics, climate change and agriculture, or the methodologies underpinning this work one can seek counsel from an array of comprehensive papers on these topics (Auffhammer et al., 2013; Auffhammer and Schlenker, 2014; Blanc and Reilly, 2017; Carleton and Hsiang, 2016a; Dell et al., 2014; Tol, 2018).

While the state of knowledge has advanced substantially over the past decade, substantial uncertainty still surrounds the relationship between agriculture and climate change in California. To see this, simply look at projections about changes in the amount of precipitation across climate change models. Some project increases in precipitation; others foresee no change; and others anticipate decreases in precipitation. What emerges from these models is little consensus on the projected changes in California precipitation. These gaps in our understanding about climate change and agriculture stem in part from the complex nature of the question in the context of California. The natural and built landscape vary substantially across the state, implying that climate change may manifest itself very differently depending on the weather, topography, infrastructure, and built resilience of a region. As we discuss in the chapter, this variation makes the question of the climate change impacts on agriculture complicated, and ripe for future research.

## PAST CLIMATE TRENDS AND PREDICTED CLIMATE CHANGES IN CALIFORNIA

To set the stage for an assessment of the effect of a changing climate on California agriculture, we first look at recent trends in climatology across California regions. Then, we present future prospects of climate derived from climate models and warming scenarios for the mid-century period. The advantage of looking at past climate trends, in addition to projections of future climate, is that although historical trends may not continue into the future, their derivation largely relies on actual observations and is therefore subject to less uncertainty than climate model output. While recent trends can stem from natural weather variability, they remain important to put future projections in context.

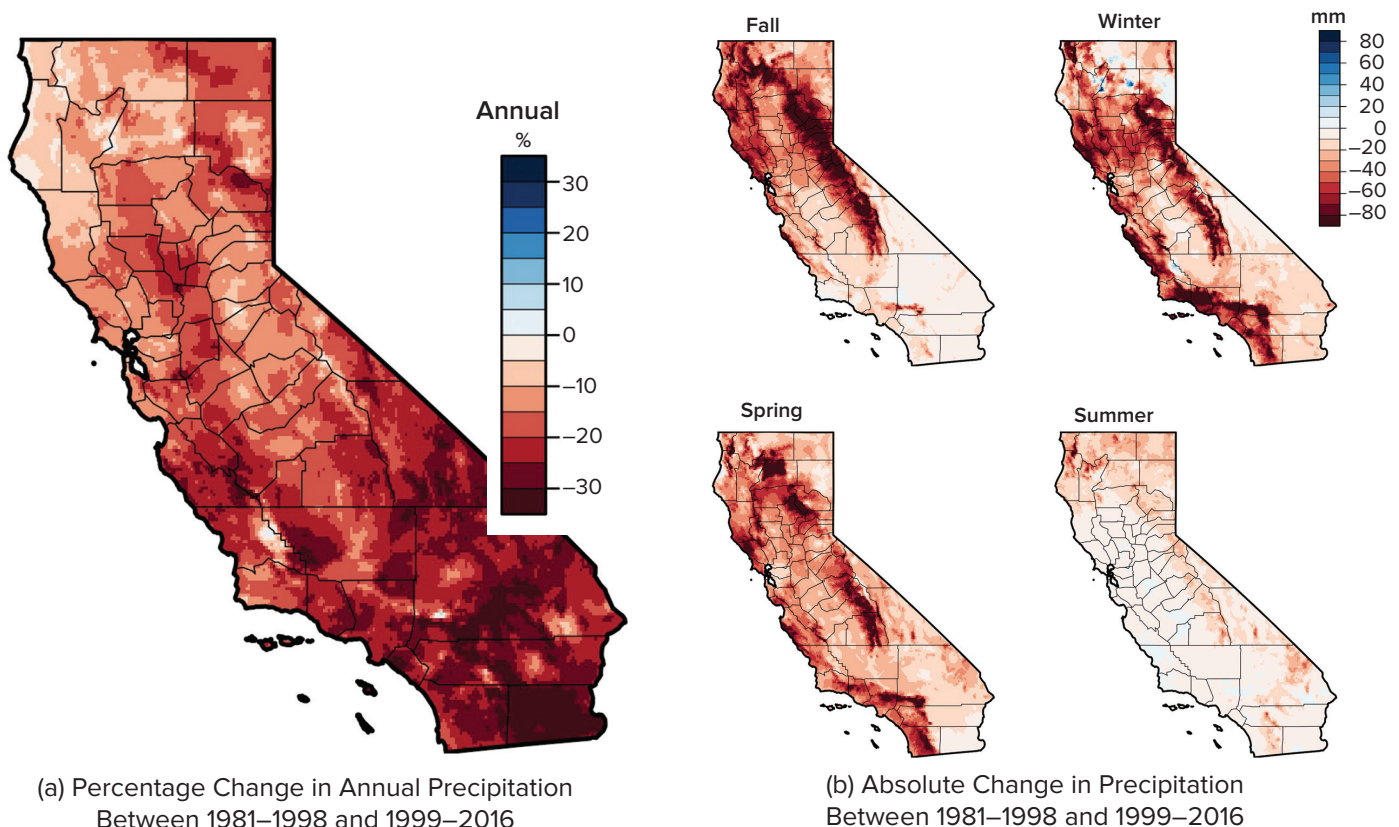
Historical trends in weather are calculated using daily gridded weather data at a 4 km resolution over the

years 1981–2016 from the PRISM database.<sup>1</sup> The PRISM Climate Group uses climate observations from a range of monitoring networks to develop spatially explicit climate databases that reveal short- and long-run climate patterns.

Figure 16.1 shows the resulting trends in precipitation, computed as the percentage change in 18-year averages between the periods 1981–1998 and 1999–2016 for annual precipitation (panel (a)), and as absolute changes in

1 There are several tradeoffs associated with reporting weather trends, including regarding geographical resolution and time coverage. The PRISM data is a high-resolution dataset that is particularly well suited to analyzing California's heterogeneous landscape. We chose to utilize the more recent PRISM data, which covers the years 1981 to present, because the longer time series stops in 2005. PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>, created 29 Jul 2016.

**Figure 16.1. Recent Trends in Precipitation**



Source: PRISM Climate Group, Oregon State University. Available at: <http://prism.oregonstate.edu>

Note: Fall: September–November; Winter: December–February; Spring: March–May; Summer: June–August.

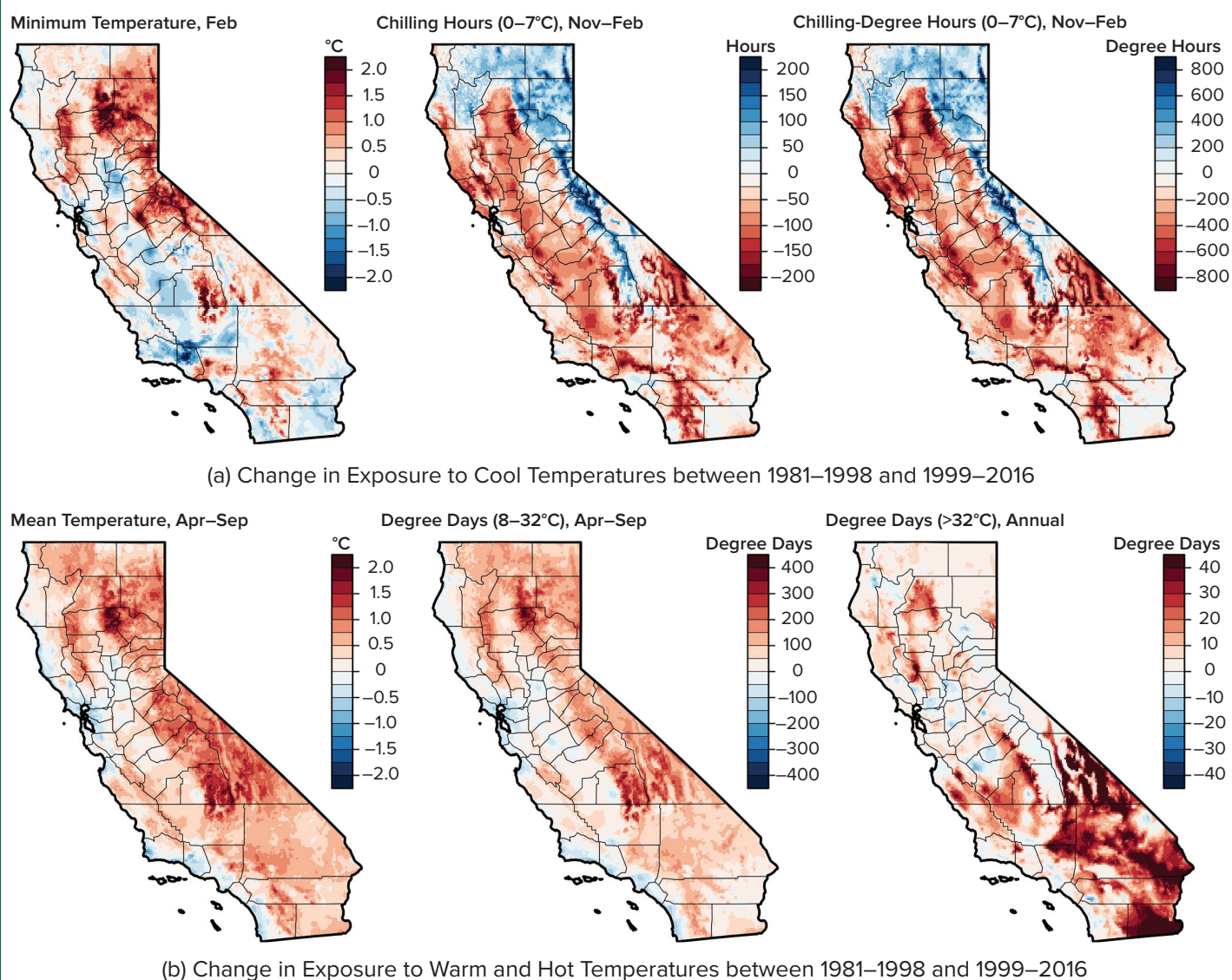


millimeters (mm) for each season (panel (b)). The figure shows decreases in precipitation of about 20 percent in the recent period, with more pronounced declines in the southern part of the state. The largest absolute reductions in rainfall have occurred in places with higher rainfall, which generally correspond to higher-altitude areas—mainly the northern part of the state (Klamath mountains), the Sierra Nevada, the Northern and Southern Coast Ranges, and the Transversal and Peninsular Ranges in the south. Because these trends are computed using 18-year averages, rather than 30-year averages as would normally be required to obtain climate normals, one should be

cautious in interpreting them. In particular, the recent multi-year drought partially drives these trends, and its impact might be attenuated when using longer time series.

Figure 16.2 describes changes in temperature over the period 1981–2016, also using 18-year averages. Panel (a) shows changes in February minimum temperature, a weather indicator that has been shown to impact almond yields (see Impacts on Key Crops, p. 360), changes in chilling hours (hours with temperature between 0 and 7°C) and changes in chilling-degree hours (a related measure that gives more weight to temperatures closer to the

**Figure 16.2. Recent Trends in Temperature**



Source: Baldocchi and Wong, 2008

bottom threshold of 0°C).<sup>2</sup> Chilling hours are a relevant climatic indicator for California agriculture because an extended period of cool temperatures is needed for many fruit trees to become and remain dormant and subsequently set fruit.<sup>3</sup> Panel (a) reveals geographically heterogeneous trends. Regions of higher altitude have experienced warming trends with higher February minimum temperature, and higher chilling hours from November to February due to a reduction of exposure to freezing temperatures. Low-altitude regions, notably the Central Valley, have experienced a cooling trend in February but an overall warming in other months. Notably, the regions of the state with fruit and nut crops have seen a decline in chilling hours which, if exacerbated by climate change, may jeopardize some key California crops (Baldocchi and Wong, 2008).

Panel (b) of Figure 16.2 describes historical trends in exposure to warm temperatures during the spring-summer growing season. The first graph shows that, except for a narrow coastal band and the Sacramento-San Joaquin River Delta, California has seen an increase in average April–September temperature of about +0.5°C across the Central Valley, with more pronounced warming in the Sierra Nevada and both the northern and southern parts of the state. When looking at degree days accumulation between 8 and 32°C, a measure of time exposure to beneficial temperatures agronomically relevant for many crops, this warming pattern persists.<sup>4</sup> One exception is the Central Valley, where some regions have experienced slightly more

degree days and others slightly less. The desert region to the southeast of the state, including the Imperial Valley, appears to have experienced an increase in degree days accumulation, as well as a large increase in exposure to heat, as captured by harmful degree days (i.e., °C exposure beyond a threshold of 32°C).

Figures 16.3 and 16.4 describe projected changes in precipitation and temperature by mid-century (2036–2065) relative to the reference period 1971–2000, based on an average of models from the ensemble of General Circulation Models (GCMs) in the Coupled Model Intercomparison Project Phase 5 (CMIP5), the latest set of climate projections of the Intergovernmental Panel on Climate Change (IPCC, 2013).<sup>5</sup> We consider projections under four Representative Concentration Pathways (RCPs). RCPs refer to greenhouse gas concentration trajectories and range from rapid emissions reductions (RCP 2.6) to continued emissions increases (RCP 8.5). We focus on the mid-century period because end-of-century projections are arguably subject to greater uncertainty. The native climate change projections in CMIP5 typically have low spatial resolution (about 100 km), so we rely on downscaled projections (1/8 deg or about 14 km) from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive. These projections are corrected for biases introduced in the statistical downscaling procedure.

The climate model ensemble projects modest increases in annual precipitation in the northern and central parts of California, in the order of 5 percent, but reductions in the southern part of the state. Most precipitation in California occurs during the winter period, and this model ensemble indicates the largest increases in absolute precipitation during winter months, particularly in higher altitude areas (up to about 30 mm). The highest increases in winter precipitation seem to happen under the most rapid warming scenario RCP 8.5. These precipitation changes remain

2 Specifically, chilling degree hours are calculated as a weighted summation over winter months of the number of hours of exposure to temperatures between 0 and 7°C, with higher weights given to cooler temperatures within this range. For instance, one hour of exposure to a temperature of 6°C would result in one chilling degree hour, whereas one hour of exposure to 4°C would result in three chilling degree hours. Temperatures below 0°C or above 7°C do not contribute chilling hours or chilling degree hours.

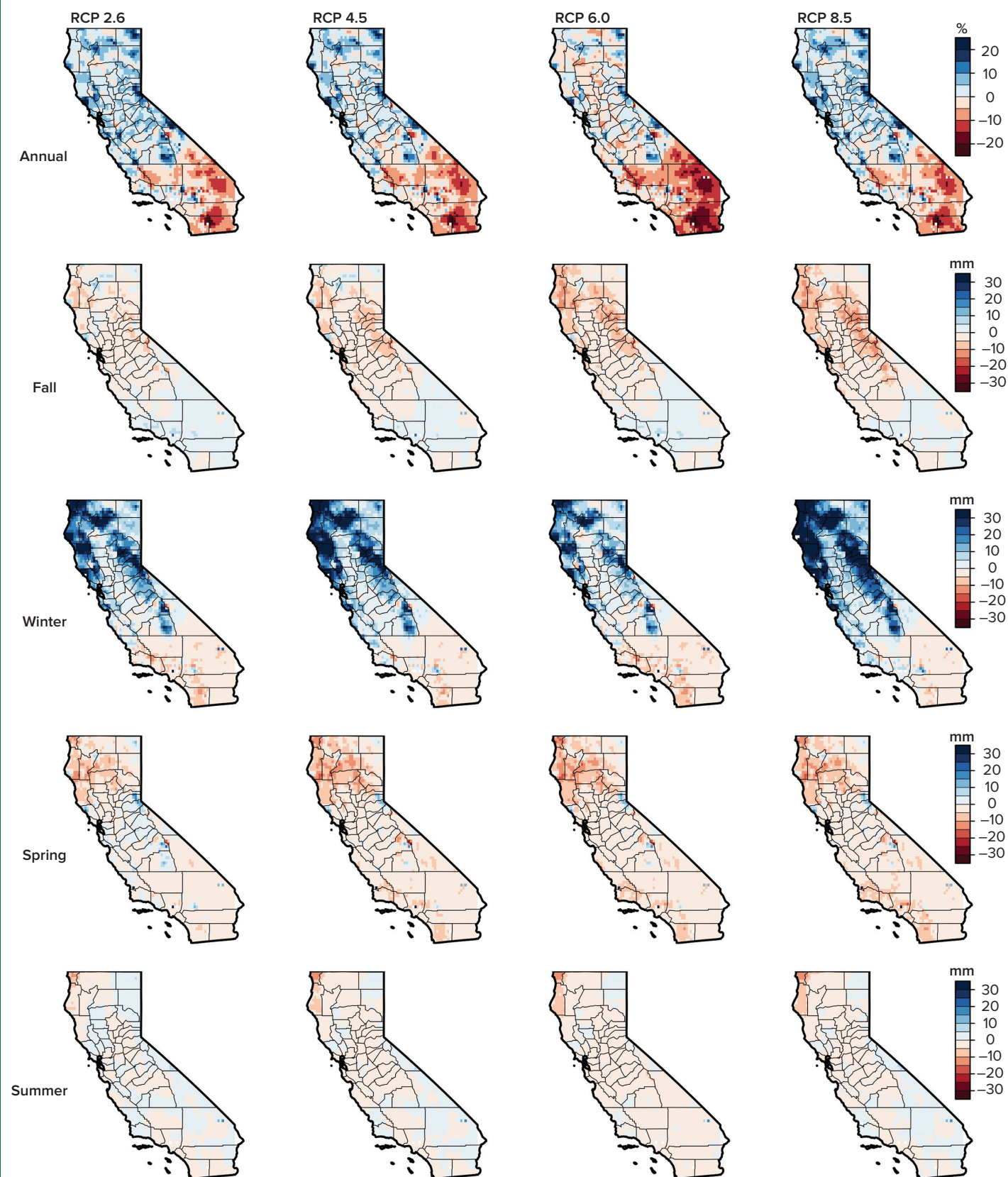
3 For instance, almonds need between 400 and 700 chilling hours. (Baldocchi and Wong, 2008).

4 Degree days between 8 and 32°C represent the total time spent at a temperature between 8 and 32°C, with warmer temperatures being counted more heavily than cooler ones—up to the 32°C threshold. For instance, one day of exposure to 9°C counts as one degree day, while one day of exposure at 10°C counts two degree days, and one day of exposure at 32°C or above counts 24 degree days. Exposure below 8°C does not contribute to degree days.

5 In Appendix Table 16.1A, we indicate, for each climatic variable and RCP scenario, the set of GCMs that were used to compute the average projection. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 16.1A of this chapter) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. [https://gdo-dcp.ucllnl.org/downscaled\\_cmip\\_projections/](https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/) (Reclamation 2013).



Figure 16.3. Projected Changes in Precipitation by Mid-Century



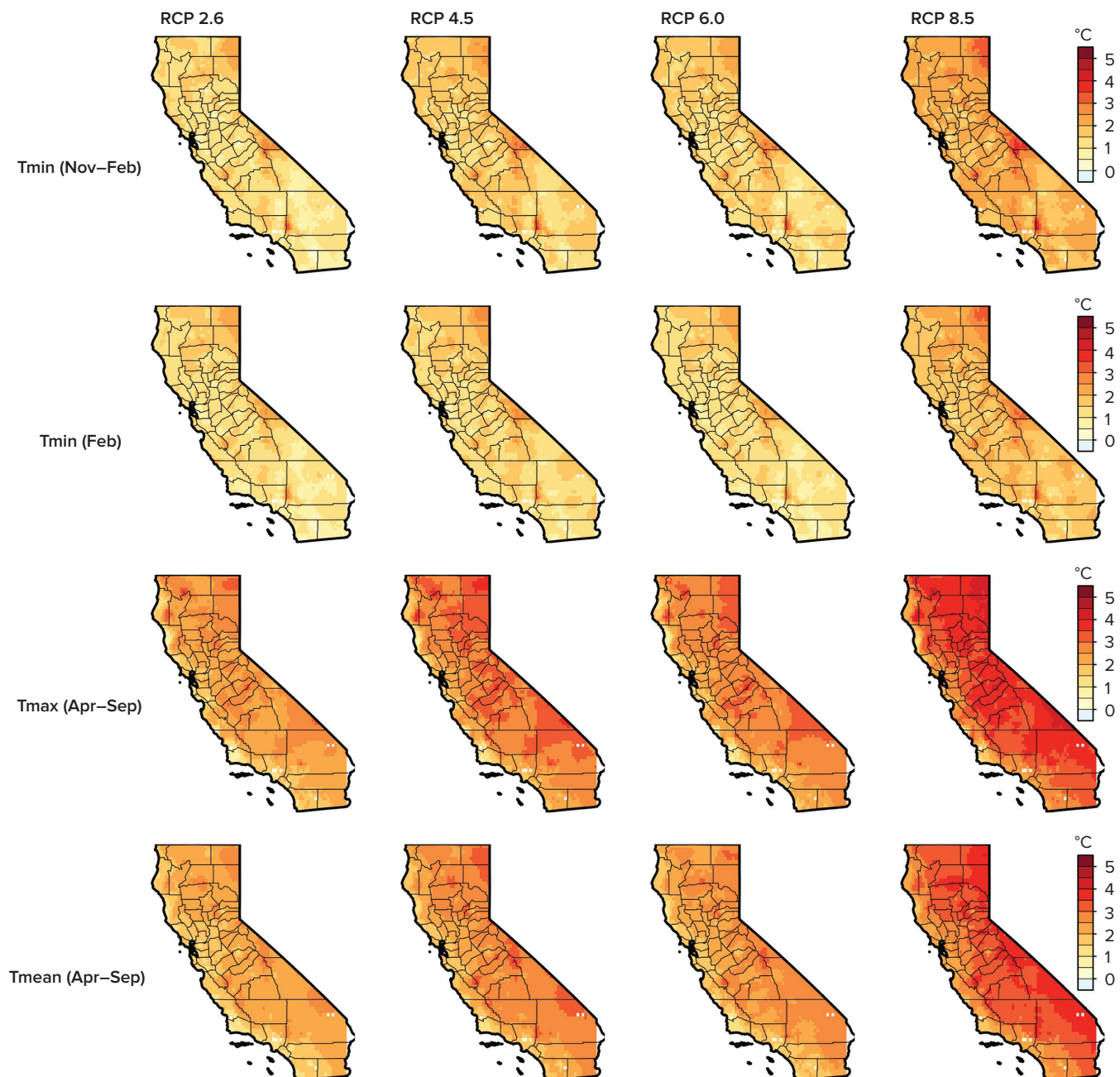
Note: Each panel represents an average of projected changes by 2036–2065 relative to the reference period 1971–2000 across several climate models (see Table 16.1A), for a given RCP scenario. Fall: September–November; Winter: December–February; Spring: March–May; Summer: June–August.

modest, highly dependent on geography, and sometimes contradict earlier predictions, e.g., Cayan et al., 2008. They should thus be interpreted with caution. Moreover, higher temperature may affect the snowpack at high altitudes, so winter precipitation has a higher chance of resulting in rainfall rather than snowfall.

Unlike precipitation patterns, temperature effects seem to be consistent across the year and geographically, and in line with earlier studies at least in term of direction (Hayhoe

et al., 2004; VanRheenen et al., 2004; Cayan et al., 2008). Our model ensemble projects unequivocal warming in virtually every part of the state and across seasons. Winter minimum temperatures are projected to rise by 1–2°C, and more under scenario RCP 8.5. Both mean and maximum temperatures are projected to increase during the months of April to September, by 2–3°C, and more under scenario RCP 8.5. Maximum temperature during those months is predicted to increase more than mean temperature.

**Figure 16.4. Projected Changes in Temperature by Mid-Century**



Note: Each panel represents an average of projected changes by 2036–2065 relative to the reference period 1971–2000 across several climate models (see Table 16.1A), for a given RCP scenario.



## CLIMATE CHANGE IMPACTS ON IRRIGATION WATER AVAILABILITY

Climate change may substantially alter irrigation supplies in California, though there is limited consensus on exact trends in precipitation patterns across climate models. Given the irrigated nature of California agriculture, and the potential of irrigation to mitigate some of the effects of increasing temperature on plants and animals alike, it is expected that changes in surface water supplies and groundwater availability will strongly influence the costs of climate change. This section provides a brief overview of the natural, built, and legal architecture that defines the state's water supply, and discusses how irrigated water availability may evolve with climate change.

Contrary to common belief, California is a relatively water abundant state with more than 200 million acre-feet of precipitation occurring in an average year. Local surface water, imported surface water, and groundwater serve as the primary water supplies. Snow and rain occurring mostly between November and April and mainly in the mountainous north supply sufficient moisture for plants during these months. Reservoirs, aquifers, and snowpack are critical for shifting water, allowing winter precipitation to be accessed during the dry months of May to October, when demand for water is greatest. Groundwater provides a stored source of water that becomes increasingly important and relied upon during periods of drought.

California's extensive water conveyance and storage systems have helped to align supply and demand geographically. To meet growing agricultural and urban demands, large city, state, and federal water projects were built in the early and mid-1900s. Led by the city of Los Angeles' diversions from Owens Valley in 1906, and San Francisco's damming of the Hetch Hetchy in Yosemite National Park in 1928, regional, federal, and state governments soon followed with larger water projects that connected major water users with streams throughout California's Central Valley, the Trinity River, and the Colorado River. Each of these projects has a colorful history. The complex network of dams, reservoirs, and canals, funded and supported by numerous agencies, helps explain how agriculture and cities can thrive in water-scarce regions of the state (e.g., Los Angeles).

An important foundation for determining the distribution and consumption of water is the legal framework that guides the assignment of water rights. California has a peculiar mix of old English and western "first-in-time, first-in-right" priority water rights. An extensive system of water contracts that govern the distribution and operation of water from water projects supplements this water rights system. During drought, lower-priority rights holders face curtailments or are denied water, regardless of the value they attach to water. Many respond by pumping additional groundwater, which has led to long-term over-pumping of less regulated groundwater in some areas.

Climate change models project changes to the variability, timing, and form of precipitation in the state. This arises from changes in precipitation patterns and warming temperatures. The warming temperatures projected under almost all climate change scenarios imply that less precipitation will fall as snow, the snowpack will melt earlier, and increased evaporation will reduce soil moisture and surface water availability. This will impact the state's ability to store irrigated water, and to manage when irrigation occurs.

Projected temperature increases will shift precipitation from snow to rain and will reduce the state's capacity to store water in the Sierra Nevada and southern Cascades snowpack. In a given year, California's snowpack stores over 15 million acre-feet and supplies approximately one-third of the water used by agriculture and cities. With climate change, the snowpack may be reduced by between 29 to 89 percent by the end of the century (Maurer, 2007; VanRheenen et al., 2004; Vicuna et al., 2007).

Warming temperatures will impact when the existing snowpack melts, and as a result when irrigated water can be accessed. In California, a mismatch exists between the timing of precipitation and demand for irrigation: precipitation occurs mainly between November and April while demand peaks between May to October. The melting of the snowpack into river basins that supply water to the State Water Project and Central Valley Project provides a natural process to align supply with demand. Warming temperatures are associated with declines in fractional

spring stream flow and an increase in the amount of total annual runoff occurring in the winter (as opposed to the spring and summer) (Vicuna and Dracup, 2007; Maurer, 2007). A change in the timing of when surface water supplies are available may have implications for the storage and delivery of irrigated water (Vicuna et al., 2007).

It may appear that the average annual precipitation in California may not change. At a state level, there is little consensus on changes in annual average state rainfall, with some predicting increases, others predicting decreases, and still others projecting minimal changes (Cayan et al., 2008; VanRheenen et al., 2004; Maurer and Duffy, 2005; Vicuna et al., 2007). These discrepancies in annual projections about the quantity of annual rainfall mask some consistent and important findings that emerge from the literature. Variability in interdecadal precipitation is expected to increase, with both droughts and floods becoming more frequent and more severe. So while average annual rainfall may change little, the variability from year to year is likely to increase (Hayhoe et al., 2004).

Climate change models project that the length, frequency, and severity of extreme droughts will increase, with the proportion of years categorized as dry or critical increasing from 32 percent to 50–64 percent by the end of the century (Hayhoe et al., 2004), and the co-occurrence of dry and extremely warm weather conditions increasing as well (Difffenbaugh et al., 2015). In addition to an increase in dry periods, winter flooding may also increase. The increased risk of winter flooding is attributable to earlier melting of the snowpack. An increase in both droughts and floods sets up a new water dilemma in the state: water managers must decide whether to increase reserve capacity in reservoirs to protect against winter flooding or increase the quantity of water stored in reservoirs to insure against droughts and/or reduced springtime runoff.

If agriculture responds to reductions in surface water supplies through increased reliance on groundwater resources, groundwater overdraft may be an indirect effect of climate change. While one cannot directly point the arrow from climate change to groundwater overdraft, droughts in California are strongly correlated with increased groundwater extraction. Recent work highlights that groundwater depletion in the Central Valley increases during droughts (Scanlon et al., 2012; Famiglietti et al.,

2011). The relationship between droughts and groundwater extraction was on display during the recent drought in California. Surface water deliveries to agriculture from the Central Valley Project and State Water Project decreased by a third, and farmers offset approximately 70 percent this reduction through an increase in groundwater use (Howitt et al., 2015). While groundwater serves as a critical source of water, particularly during droughts, management has not been optimal and there are concerns that this resource may not be available to cope with future droughts. In the last year of this drought (2014), the state passed the Sustainable Groundwater Management Act, which requires local groundwater plans to achieve sustainability. More active groundwater storage management could substantially reduce the costs of future drought to agriculture.

Changing temperature and precipitation patterns will create serious challenges for irrigation water management across the state. With less rainfall stored as snowpack and a limited capacity to hold water in existing storage systems, total water storage is likely to decrease. As a result, farms will likely face an overall reduction in available surface water, potentially exacerbated by increasing demands from urban and environmental sectors. While groundwater pumping may, as in recent times of drought, partially compensate for reductions in water deliveries, this response is not a sustainable solution to long-run surface water reductions. Increasing groundwater recharge during the wet period through controlled flooding may represent one of the most promising adaptation avenues.

## CLIMATE CHANGE IMPACTS ON AGRICULTURE

California is the leading U.S. state in terms of agricultural cash receipts, largely due to its ability to grow high-value specialty crops thanks to fertile soils, favorable climate, and large investments in both public and private irrigation infrastructure. Climate change may affect California agriculture through two main channels: the direct effect of weather on crops and animals, (e.g., through increased exposure to extreme heat), and the ability of California's natural and man-made water reserves to deliver water to crops at the time when they need it. While the impacts of a warming climate in terms of heat exposure are well documented in other parts of the U.S., evaluating the impact of climate change on California agriculture presents unique challenges due to the diversity and specificity of its main crops and its reliance on irrigation as the main source of water supply, as opposed to rainfall. In this section, we aim to take a careful look at the available evidence on the impact of climate on farm profitability, crop yields, and animal productivity.

### METHODOLOGICAL APPROACHES

Much of the uncertainty surrounding the impacts of foreseeable climate change on California agriculture largely stems from its very specificity in the U.S. agricultural landscape, which has constrained the set of methods that can be leveraged to assess climate impacts. There are three main ways to assess the possible impacts of climate change on agriculture: (i) direct experimental evidence, (ii) biophysical models, and (iii) statistical methods that directly rely on historical agricultural outcomes data.

Method (i) would consist of experimentally changing one or more aspects of weather, e.g., temperature in a controlled environment, to track how plants or animals would fare under a different climate. This method can be costly to implement, and because it is impossible to submit comprehensive natural and human systems such as a farm to experimentally designed environmental signals, it will generally fall short of delivering the net impact of climate change on agricultural outcomes.

Method (ii) is a partial answer to these challenges.

Biophysical models are stylized representations of the relationships between soils, weather, biophysical processes, and, where relevant, human actions that are calibrated using observational or experimental data. They can be used to predict outcomes (e.g., yields or crop quality) under conditions outside of those used for calibration, negating the need for additional experimental data collection. For important food crops such as wheat, agronomic models are still the method of choice to predict climate change impacts (e.g., Asseng et al., 2015). However, because these models usually require extensive experimental or observational data as a basis for calibration, and because they are more easily developed for annual than perennial crops, a large set of California specialty crops has so far escaped the attention of crop modelers. Another drawback of process-based crop models is that they usually cannot account for pests and diseases, which is particularly problematic for fruit and nut crops (Lobell et al., 2007).

As a result, method (iii), estimation of statistical relationships, has so far been the method of choice in the literature to decipher climate change impacts for many California crops. This stands in sharp contrast to the large body of experimental and model-based evidence for major field crops such as wheat or corn. One of the traditional challenges associated with the statistical approach is the selection of relevant weather covariates to explain observed outcomes such as yield. Nowhere is this issue more salient than for California perennial cropping systems, which may respond to a large suite of weather signals spanning more than a calendar year.

### PROFITABILITY OF FARM OPERATIONS

Within statistical methods, two main approaches have been introduced to infer climate impacts on agriculture. The cross-sectional or Ricardian (a.k.a. "hedonic") approach, introduced by Mendelsohn et al. (1994) in their study of U.S. agriculture, compares agricultural outcomes such as farmland values across places with differing climates, controlling for an array of potentially confounding factors



such as soils, proximity to urban centers, or population. Other things being held constant, comparing land values in a "warm" vs. "cool" location will reflect the impact of warming, net of any of the adjustments made by humans to adapt to climatic conditions. The appeal for this method lies in the fact that the recovered impact implicitly includes adjustments made in response to warmer climate, such as changes in input intensity, planting dates, crop varieties, cropping patterns, etc. The main drawbacks are that these adjustments remain implicit (i.e., one does not learn how agents have adapted to climate) and that the Ricardian estimates are vulnerable to omitted variables bias; that is, the possibility that differences in outcomes across differing climates may be due to factors other than climate but correlated with it, such as unobserved soil quality attributes.

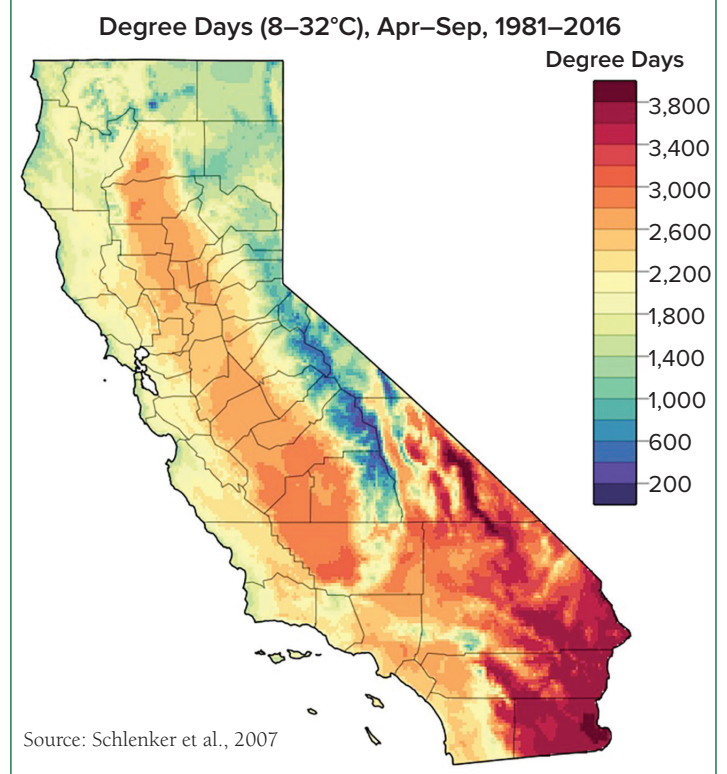
The second approach, known as the panel approach, addresses this last criticism by using panel (as opposed to cross-sectional) data and non-parametrically controlling for time-invariant confounding factors through the inclusion of locational fixed effects. The linear panel approach uses year-to-year fluctuations in weather, rather than cross-sectional climate differences, to identify the effect of climate on agricultural outcomes such as profits, revenues, or yields. As a result, panel estimates have been criticized for failing to include long-run adaptations to climate (Mendelsohn and Massetti, 2017). As indicated by Hsiang (2016), these issues reveal a tradeoff between the causality of the statistical estimate of the climate-outcome relationship and its relevance as an indicator of net climate change impacts. Thankfully, both Ricardian and panel approaches have been implemented for California, so that one may compare results from the two approaches.

Schlenker et al. (2007) is a reference study that implements the Ricardian approach on a sample of farms spanning agricultural regions of California. The authors regress geo-referenced farmland values obtained from the June Agricultural Survey of the U.S. Department of Agriculture on a set of climatic and soil variables, as well as a measure of average surface water deliveries per acre at the level of the water district. Access to groundwater is proxied using depth to groundwater, itself interpolated from well-level data. One of the innovations in the study by Schlenker et al. (2007) relative to prior work is that the effect of temperature on farmland values is modeled

through growing degree days rather than average monthly temperature over selected months of the growing season. Growing degree days are a measure of the time exposure (over the growing season) to temperatures deemed to be beneficial for plant growth; that is, neither too cool nor too hot. Depending on the initial distribution of temperature exposure, warming may result in more or less growing degree days. Heat degree days, in contrast, represent time exposure to detrimental hot temperatures. For instance, assuming that heat degree days are measured starting at a temperature threshold of 34°C, one day at 35°C would translate into one heat degree day, while one day at 36°C would translate into two heat degree days. Uniform warming would unambiguously result in more heat degree days as more time is spent at temperatures above the threshold.

The analysis by Schlenker et al. (2007) reveals that farmland values respond nonlinearly to growing degree days (calculated over the six-month period between April and September between the thresholds of 8°C and 32°C, see footnote 4), in the sense that there is a degree day "optimum," at about 2,500 degree days. This means that

**Figure 16.5. Growing Degree Days Under the Current Climate**



farmland values decrease if growing degree days are either too small (not enough useful heat accumulation) or too large (perhaps a proxy for extreme heat, which negatively affects crop growth and thus farmland values). Figure 16.5 shows growing degree days across California, computed as an average across the years 1981–2016 using the PRISM dataset referenced previously.

The map shows that most of California's Central Valley is already at or near the optimum growing degree days, and the southern part of the San Joaquin Valley is above it. In contrast, the Imperial Valley is far beyond the optimum. Further warming would thus hurt agriculture in these regions, particularly in the southern part of the state. Schlenker et al. (2007) also show that water deliveries strongly capitalize into farmland values, as expected given the irrigated nature of California agriculture. Specifically, depending on the controls included in the hedonic regression, the capitalized value of 1 acre-foot of surface water delivery, net of any charges levied by water districts, ranges from \$ 568/acre to \$ 852/acre, for an average farmland value of \$4,177 in the sample. Reductions in water deliveries caused by climate change thus have the potential to affect farmland values significantly and therefore the profitability of agriculture in California.<sup>6</sup>

Deschenes and Kolstad (2011) implement a panel approach by combining county-level profit outcomes from the Census of Agriculture for the years 1987, 1992, 1997, and 2002 with detailed daily weather station data. They regress farm profits on three main weather indicators: annual growing degree days, annual precipitation, and annual heat degree days. One drawback when implementing the panel approach on farm profits, as indicated by Fisher et al. (2012) and acknowledged by the authors of the California study, is that yearly profits may only partially reflect the impact of yearly weather on agricultural productivity, since farmers may store products across years to smooth income. In the limit, if the smoothing were perfect, yearly profits would be completely disconnected from yearly weather realizations.

<sup>6</sup> One caveat to this last point is in order. To the extent that the opportunity costs of agricultural water deliveries are not fully reflected in the retail costs paid by farmers (i.e., subsidized water), then the capitalized value of water above would overstate the actual social value of water, and the ensuing social damages from reduced water availability due to climate change.

Perhaps surprisingly, the estimates in Deschenes and Kolstad (2011) suggest that farm profits are decreasing in growing degree days, increasing in heat degree days, and decreasing in precipitation. Only the precipitation effect is statistically significant, and implies that an additional 100 mm of rainfall decreases yearly profits by about \$28 per acre. The authors then use their coefficient estimates to infer the impact of changing temperature and precipitation, as predicted by the CCSM model (version 3) from the National Center for Atmospheric Research under two warming scenarios, on farm profits. They look at two warming scenarios, a "business as usual scenario" (IPCC scenario A2) and a more moderate warming scenario (IPCC scenario B1), and two prediction horizons, 2010–2039 and 2070–2099. Their results indicate that California farm profits would increase in the medium term (+4.2 percent under scenario A2 and +6.1 percent under scenario B1) while the effect is ambiguous in the long term (0.6 percent and –2.8 percent). These effects are imprecisely estimated, however.<sup>7</sup>

To provide some context to the above damage estimates, it might be useful to compare them to estimates of the economic impact of recent droughts on California agriculture. Howitt et al. (2015) estimate the total economic impact of the 2015 drought to be \$2.7 billion, of which \$1.8 billion represent direct costs to agricultural farms. Assuming that climate change affects agriculture principally through reduced water availability, say by 2 acre-feet per acre as extrapolated by Schlenker et al. (2007), the Ricardian model implies an impact on farmland values ranging from \$1,136 to \$1,704 per irrigated acre. Using an estimate of 10 million acres of irrigated farmland, this impact translates into an economic loss of \$11.4–17.0 billion. Assuming a discount rate of 5 percent, the drought impact estimated by Howitt et al. (2015) would translate into a net present value of \$36 billion. Although it is

<sup>7</sup> The authors also estimate a model wherein the five-year moving averages of past weather variables are included as separate regressors. The regression implies much larger and negative effects of predicted climate change on farm profits, –42.7 percent and –28.1 percent under scenarios A2 and B1, respectively. While this specification is more flexible, it is not clear to us how to interpret the coefficients on the moving average, conditional on the realized yearly weather. It is the (negative) coefficient on the moving average of annual degree days that drives the large negative impacts found by the authors.

difficult to compare the two studies as their geographical scope and the set of included farming activities differ, one could speculate that the lower damage estimate implied by the Ricardian estimate reflects adaptation channels not captured in the impact study of Howitt et al. (2015). Note, however, that none of these impact estimates account for the fact that long-term climate change may reduce the amount of groundwater available to compensate for reduced surface water availability. As such, the net impact of climate change may be much larger than suggested by these estimates.

### IMPACTS ON KEY CROPS

Although perhaps less prominently considered in the literature, field crops play an important part in California agriculture. For example, alfalfa (used for hay) occupied 21 percent of crop acreage in 2006, while cotton and corn (grain and silage) each occupied 8 percent (Lee et al., 2011). The large California dairy industry uses several of these field crops as a production input. Milk and cream are the top agricultural commodity in terms of value (CDFA, 2016).

Lee et al. (2011) use a biogeochemical crop model calibrated to California conditions (the DAYCENT model, Del Grosso et al., 2008; De Gryze et al., 2010) to study the impacts of climate change on key California field crops under current management practices, with irrigation water assumed to be non-limiting. While their yield predictions differ significantly across the climate models and downscaling methods used to predict future climatic variables, they find that the yields of most field crops will decline under climate change. Specifically, their model predicts null to moderate yield declines by 2050 compared to 2009, followed by substantial declines by 2094 under warming scenario A2 (medium-high emissions): -25 percent for cotton, -24 percent for sunflower, -14 percent for wheat, -10 percent for rice, and -9 percent for tomato and maize. The only field crop found to be unaffected by climate change is alfalfa. These yield declines are mostly attributed to increases in temperature, and do not account for the potentially mitigating effects of CO<sub>2</sub> fertilization on yields and water demand.

Because most crop growth models are not calibrated for specialty crops, particularly perennial crops for which biophysical relationships are difficult to establish due to slow growth, most of the available evidence on the effects of climate change on California crops comes from statistical studies. The panel study by Deschenes and Kolstad (2011) discussed above includes estimates of the effect of weather variables on key California crops such as tree nuts, vegetables, grapes, cotton, and citrus, based on county-level data for the period 1980–2005. The authors include annual growing degree days and annual precipitation as regressors, and investigate impacts on both crop revenues (holding acreage constant) and physical yields. Most coefficients are imprecisely estimated and not significantly different from zero. Exceptions for the crop revenue relationships include table grapes and wine grapes, which respond positively and negatively to degree days, respectively. Pistachios and walnuts also respond negatively to degree days. (The regression does not control for heat degree days, which may correlate positively with growing degree days.) Perhaps surprisingly, lettuce and strawberry revenues respond negatively to annual precipitation. To a large extent, these effects carry out to physical yields. The study also provides estimates of climate change impacts based on predictions from the CCSM model under IPCC scenario A2 (business as usual), for the period 2070–2099.

Most predicted crop revenue impacts are not precisely estimated, except for avocados (-69 percent), cotton (+50 percent), table grapes (+205 percent), and strawberries (-51 percent). Yield effects are not always consistent with these revenue impacts. The authors conclude that the impacts of climate change on California crops will be heterogenous.

Lobell et al. (2007) use yield data aggregated at the state level over the period 1980–2003 for 12 major California crops to determine the weather characteristics that have the most explanatory power for yield anomalies. They construct yield anomalies by netting out linear trends (to capture the effect of smooth technological change) as well as past yield realizations (to capture the effect of alternate bearing for perennials). In contrast to the study by Deschenes and Kolstad (2011), the authors allow for the effects of weather to vary by month of the year. They also consider minimum (nighttime) and maximum (daytime)



temperature as opposed to degree days, and allow weather over a 24-month period covering the calendar harvest year and the year prior to harvest to affect crop yields.<sup>8</sup>

Their results for the three highest-revenue crops over the period are as follows. Wine grape yields increase in April nighttime temperature (due to lower risk of frost during the post-budbreak period) and in June precipitation (which may be detrimental to grape quality, however). Lettuce yields increase in April daytime temperature (up to about 23°C) and in the daytime temperature of the month of October of the prior year. The authors speculate that temperatures during these particular months are affecting lettuce crop yields in different parts of the state. Finally, almond yields decrease markedly in February nighttime temperature (likely due to a shortened dormancy period) and January rainfall (perhaps due to lower pollination and increased disease risk).

Lobell et al. (2006) use the regression models estimated on historical data by Lobell et al. (2007) to predict the impact of climate change on the yields of six major perennial crops, accounting for uncertainty in climate predictions and in the statistical estimation of the climate-yield relationship. They assess uncertainty in climate predictions by utilizing six climate models and three emissions scenarios. The authors address uncertainty related to the fact that the projected climate may exceed the extremes of the historical climate ("projection" uncertainty) by allowing a variant of their predictions to constrain projected yields within the bounds observed in the historical record. This method implicitly assumes that the new climate will not result in yield realizations that lie outside of past extreme realizations.

Under this conservative assumption, the authors find that wine grape yields will not be affected much by climate change over the 21st century, but that the yields of other perennials, namely almonds, table grapes, oranges, walnuts, and avocados, will likely decline, particularly for avocados (about -40 percent by the end of the century).

8 To avoid model overfitting due to the large number of potentially relevant covariates, they select up to three weather indicators, each allowed to affect yield in a quadratic fashion, based on measures of in-sample fit (R-squared). For example, a weather indicator may be average maximum temperature during the month of May of the harvest year.

For these five crops, when accounting for climate model and estimation uncertainty, these negative effects remain statistically significant. Allowing projected yields to exceed historical realizations has two main effects on predictions. First, uncertainty surrounding estimates increases markedly, and more so for predictions for later years. Second, except for oranges, yield predictions appear more negative. For instance, yield effects for table grapes reach about -35 percent by the end of the century, versus -20 percent with constrained yields.

Lobell and Field (2011) extend the previous study by considering 20 California perennials in California counties over the period 1980–2005 and greatly refining the model specification and the model selection method used in Lobell et al. (2007). As such, they offer the most reliable study to date on the likely impacts of climate change on California perennials. In order to determine whether the historical record is conducive to reliable statistical inference, the authors use different statistical models and compare results across models, keeping only crops for which model results are consistent and pass a simple out-of-sample validation test. In particular, they exploit the panel structure of their data to evaluate the robustness of their predictions to the inclusion of county fixed effects, which control for time-invariant factors that may be correlated with local climate, such as soils. Out of 20 perennials crops, only four crops exhibit statistical climate-yield relationships that appear robust enough as a basis for climate change predictions: almonds, strawberries, table grapes, and cherries.

To assess the overall response of these crops to warming, the authors first investigate the impacts of uniform increases in temperature by +2°C, holding precipitation constant. Almond yields appear to be hurt by higher nighttime temperatures in February and April, but benefit from higher nighttime temperatures in May and July. This is in contrast to the results of Lobell et al. (2006) that only consider the effects of warmer nighttime temperature in February. Strawberry yields are declining in nighttime temperatures during the months of March through May, and increasing in nighttime temperatures during the months of June through August (but they are hurt by higher daytime temperatures during these summer months). In contrast, cherries appear to suffer from higher temperatures throughout the months of November to

February, particularly at night, consistent with the view that reduced chilling is driving the yield impacts of warming. Finally, table grapes appear relatively insensitive to warming except for a sensitivity to higher daytime temperatures during the month of June.

The authors then use the predictions of six climate models and two warming scenarios (A2 and B1), downscaled to California counties' agricultural areas, to predict the yields of these four crops by 2050. Predicted almond yields exhibit a slightly positive trend with a projected increase of less than 5 percent by 2050 relative to the 1995–2005 climate. Predictions for table grape yields indicate no large effect of climate change on yield, with relatively high precision. In contrast, the yields of strawberries and cherries are predicted to decline significantly by 2050 (particularly for cherries, about –15 percent by 2050), although the uncertainty surrounding the actual declines remains large.

Gatto et al. (2009) also implement a statistical panel approach for premium wine grapes. Their study covers four counties in Northern California (Napa, Sonoma, Lake, and Mendocino) and focuses on temperature and precipitation effects on yield and price (a proxy for quality). Unlike Lobell and Field (2011), they only consider three weather indicators: April minimum temperature, July–August maximum temperature, and dormant season precipitation, selected exogenously. They estimate quadratic relationships in each weather indicator, separately for cool and warm weather varieties. They then use the climate projections in Cayan et al. (2008) to infer impacts on revenue per acre by 2034. Their study suggests increases in crop revenue in Sonoma, Lake, and Mendocino but decreases for Napa driven by price reductions.

White et al. (2006) analyze how climate change by the end of the 21st century may affect the suitability of U.S. land for premium wine grape production. An area is deemed suitable in their study if its climate meets a certain growing degree day requirement (1,111–2,499 GDD between April and October), an average growing season temperature requirement (13–20°C), as well as a series of requirements related to exposure to both very hot and very cold temperatures during key stages of the production cycle. Although the study does not discriminate areas according to factors such as soils or altitude, it indicates a reduction

in the suitability of current California regions, likely due to increased average growing season temperature and increased exposure to extreme heat (>35°C).

Hayhoe et al. (2004) use an even more parsimonious model based on the average monthly temperature at the time of ripening to infer the suitability of future climate for wine production in current California wine regions. They find that grape ripening will happen two months earlier and at higher temperatures, leading to a degradation in wine quality by the end of the century (2070–2099) in all wine regions except the cool coastal region.

## IMPACTS ON ANIMAL AGRICULTURE

Animal agriculture is an essential part of California agriculture. Dairy is the top commodity in the state in terms of value before almonds and grapes (CDFA 2016). It generated more than \$6 billion in revenue in 2015. Cattle and calves rank fourth. Broiler and egg production are also important, ranking in the top 20 commodities by value.

Unfortunately, while the literature on the effects of climate change on California crops has grown significantly in the recent past, there are still relatively few studies looking at the impact of climate on animal agriculture. A quick search, in fact, reveals that the most commonly debated aspects of climate change and animal production in California are proposed measures by the state to reduce greenhouse gas emissions due to livestock, the major contributor to greenhouse gas emissions from California agriculture (e.g., Alexander, 2016).<sup>9</sup> As such, the California animal sector may face more challenges from climate regulation than from climate change itself.

That is not to say that animal production is insensitive to climate change. Indeed, in July 2006, and again in June 2017, thousands of cows died from heat waves in the San Joaquin Valley. The heat also affected the poultry sector (CNBC, 2017). More generally, heat stress has been documented to have a negative impact on dairy

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9 Agriculture contributed about 8 percent of California greenhouse gas emissions in 2015. Out of these, enteric fermentation and manure management from livestock were the main contributors, with about two-thirds of emissions. Dairies themselves accounted for 60 percent of total agricultural emissions (California Air Resources Board, 2017b).

productivity. A Cooperative Extension report from the University of California, Davis indicates that temperatures exceeding 38°C can cause significant stress on cattle and other livestock, exacerbated by high humidity. In cattle, heat stress may result in decreased milk production, poor reproductive performance, an increase in the frequency and severity of infections, and death (Moeller, 2016). Lower dietary intake under heat stress partially drives the decrease in milk yield. Heat stress also affects the quality of milk through lower fat, solids-not-fat, and protein content. (Aggarwal and Upadhyay, 2013). Hayhoe et al. (2004) compute statewide losses for the dairy sector by the end of the century (2070–2099) ranging from 0 to 22 percent depending on the emissions scenario considered, the climate model used, and the assumed sensitivity of milk production to heat.

### **IMPACTS ON FARM LABOR PRODUCTIVITY**

Like animals, humans are generally less productive under environmental stress, notably high temperatures. California's specialty crop agriculture can be labor-intensive, particularly for crops requiring manual harvests such as lettuce, berries, premium wine grapes, or peppers. These industries are particularly sensitive to labor market conditions such as seasonal labor shortages. A climate-change-induced reduction in labor productivity could have serious consequences for them.

Several studies document the effects of heat exposure on labor supply and labor productivity, including Graff Zivin and Neidell (2014) and Carleton and Hsiang (2016b). Studies specific to agriculture and to California are much more rare. Stevens (2017) uses worker-level information in the California blueberry industry to estimate the relationship between ambient temperature and labor productivity, as measured by the weight of berries picked by unit of time, controlling for an array of potentially confounding factors. He finds that worker productivity is negatively affected by both very low (between 50–55°F) and very high (above 100°F) temperatures, but that farms have partially adapted to heat by scheduling picking prior to the hottest part of the day.



## ADAPTATION

Human societies have two main avenues to respond to the potential threat of climate change: adaptation and mitigation. Adaptation consists of a suite of behavioral changes that allow achievement of a new economic optimum under the new climate and thus improve on outcomes obtained under the old behavior (Antle and Capalbo, 2010). Mitigation consists of taking measures to reduce greenhouse gas emissions and concentrations to curb changes in climate.

The issue of adaptation has become prominent in the climate change literature (Moore and Lobell, 2014; Burke and Emerick, 2016). Because many studies project detrimental impacts on economic biophysical or economic outcomes, the extent to which such impacts already account for adaptation, and the extent to which further adaptation measures could lessen these impacts, have become central questions for climate policy. Climate research can provide answers to both questions. As indicated above, Ricardian damage estimates are usually interpreted as net of any adaptations taken in the past. While they cannot account for new adaptation that may occur as a result of new technologies, they are generally considered to be a better predictor of net impacts than estimates based on year-to-year weather fluctuations or output from biophysical process models. Identifying the behavioral changes that could lessen climate change-induced damages has also been the focus of many climate studies related to agriculture (Rosenzweig and Parry, 1994; Ortiz-Bobea and Just, 2013).

In the context of California agriculture, a few studies have attempted to delineate possible adaptation measures. Scientific research on adaptation is particularly relevant and important for perennial plants. These plants are distinct because they are commonly grown for several decades (e.g., 25 years for grapes, or more for premium wine grapes (Diffenbaugh et al., 2011)), leaving little opportunity for individual farmers to experiment in the face of a changing climate. It also means that publicly funded or incentivized adaptation measures may be justified from a social perspective to speed up and facilitate coordinated adaptation (Gatto et al., 2009).

Lobell et al. (2006) provide county maps of projected perennial crop yields under either +2°C or +4°C warming as a percentage of current statewide average yields in order to provide insights into possible adaptation through crop reallocation across regions. Under +2°C warming, walnut yields would be lower than the current state average in every single county, meaning that adaptation through geographical relocation could likely not buffer against yield effects. For almonds, table grapes, and avocados, current yields could be maintained only at the cost of relocating to areas mostly disjoint from current production regions. Predictions are even bleaker under the +4°C scenarios, except perhaps for wine grapes, although maintaining current yields would still require significant relocation for this crop.

In a less normative exercise, Lee and Sumner (2015) investigate the link between historical acreage allocation and climatic indicators such as precipitation, growing degree days, and chilling hours in Yolo County, California, controlling for price expectations. They project that warmer winters, particularly from 2035 to 2050, will cause lower wheat acreage and more alfalfa and processing tomato acreage. Only marginal changes in acreage are projected for tree and vine crops, in part because chilling hours would remain above critical values. Their study also indicates that price expectations have played a much larger role in the historical acreage allocation among their set of crops than climatic factors.

Lobell and Field (2011) investigate whether specific almond varieties are less sensitive to higher minimum temperatures in the critical month of February (see *Impacts on Key Crops*, p. 360) using statewide almond production data by almond variety. Unfortunately, they fail to find significant differences in the sensitivity of output to weather, indicating that selecting among currently available varieties offers little promise to cancel climate change impacts on yield.

Regarding the California dairy industry, which might be susceptible to more frequent and/or severe heat waves, a possible adaptation measure, beyond shade provision and

the use of sprinklers, would be the relocation of production to cooler areas. The location of dairies is partially linked to the production of animal feed such as silage corn and alfalfa. This means an increase in the procurement cost of feed if these activities cannot be moved simultaneously due to soil or climatic limitations or competing land uses.<sup>10</sup>

Diffenbaugh et al. (2011) investigate the impacts of warming on the suitability of current wine regions for premium wine production in the Western U.S., including the North and Central Coast regions of California. Their suitability requirements combine a growing degree day window (850–2,700 GDD between April and October) with average growing season temperature (<20°C) and exposure to extreme heat (less than 15 days with maximum temperature exceeding 35°C). While the GDD window itself does not appear to affect much the suitability of the North and Central Coast regions under climate warming by 2030–2039, suitability (as measured in loss of suitable area) is substantially affected once the extreme heat and average growing season temperature are considered, as exemplified by Napa County (about –50 percent in suitable area) and Santa Barbara County (–30 percent in suitable area).

Relaxing the extreme heat requirement from less than 15 to less than 30 days would greatly diminish these predicted losses, suggesting that one pathway of adaptation would be to increase plant's ability to withstand extreme heat. The study also suggests a decline in the quality of wine produced in these regions driven by the increase in growing degree days. The authors suggest that available adaptation measures include shifts in vineyard location, shifts in varieties, changes in vineyard management (e.g., adapting trellising systems), and changes in winery processing (e.g., acidification or alcohol removal). Nicholas and Durham (2012) further mention the increased use of irrigation (which may be a limited option under decreased water supplies), application of a kaolin clay that acts as a sunscreen, or installation of an evaporative cooling system.

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<sup>10</sup> For example, in 2015 the top five counties for milk and cream were Tulare, Merced, Kings, Stanislaus, and Kern. The top five counties for silage production were Tulare, Merced, Stanislaus, San Joaquin, and Kings.

## CLIMATE MITIGATION EFFORTS BY THE STATE

California's Global Warming Solutions Act of 2006, also known as Assembly Bill 32 (AB 32), established a greenhouse gas (GHG) emissions target for statewide emissions by 2020 equal to 1990 emission levels. In 2016, Senate Bill 32 (SB 32) codified a reduction target of 40 percent below 1990 emission levels by 2030. One of the many instruments to achieve these emissions reductions is California's GHG cap-and-trade program, overseen by the California Air Resources Board (ARB). Firms that are under the cap must cover their emissions with an emission permit (allowance).

Allowances are allocated to firms or auctioned off and can be subsequently exchanged in the allowance market. By controlling the aggregate quantity of allowances, ARB can reduce aggregate emissions in covered sectors over time. Emitters in uncovered sectors do not need permits to cover their emissions. However, they may be able to participate in emission reductions by generating offsets, that is, voluntary emission reductions that are then purchased by emitters to cover emissions in lieu of an allowance. The incentive for the offsetting firm to engage in costly emission reductions is that the unit price of the offset may be higher than the cost of reducing emissions for that firm.

Agriculture has so far been kept out of the sectors covered by California's cap-and-trade program, perhaps because agricultural emissions represent a modest, though non-negligible share of statewide emissions (8 percent), but also because of the difficulty of accurately and reliably measuring greenhouse gas emissions from animals and working lands (Garnache et al., 2017). Despite these difficulties, there is some evidence that the agricultural sector may be able to supply GHG emission reductions at a competitive price, suggesting that it could play a larger role in future GHG reduction targets, if not as part of the capped sector, at least through the possibility of generating offsets (Pautsch et al., 2001; De Gryze et al., 2009, 2011; Garnache et al., 2017). In its 2017 Scoping Plan, which lays down a strategy to achieve California's 2030 greenhouse gas target, ARB indicates that "the agricultural sector can reduce emissions from production, sequester carbon, and build soil carbon stocks [...]" suggesting an increased

contribution of agriculture to GHG reduction efforts in the future.

### METHANE EMISSIONS FROM THE DAIRY AND LIVESTOCK SECTORS

As the No. 1 source of agricultural GHG in the state (60 percent), methane emissions from the dairy and livestock sectors are likely to become one of the primary levers to reduce the carbon footprint of California agriculture. In 2016, Senate Bill 1383 (SB 1383) set a target for statewide reductions of methane emissions to 40 percent below 2013 levels by 2030. Manure management and enteric fermentation in the dairy and livestock sectors represent a large share of the state's methane emissions, 65 percent in 2013 according to ARB (CARB, 2017d, Appendix C). Livestock and dairy manure management is singled out (along with organic waste management) in SB 1383 and the ensuing Short-Lived Climate Pollutant Reduction Strategy developed by ARB (CARB, 2017d) as an essential lever to reach the statewide methane reduction target.

One of the main avenues to reduce emissions of methane from manure is the installation of anaerobic digesters that capture methane and either use it on site to generate electricity or funnel it into a methane pipeline. Barriers to the widespread adoption of digesters are the very high infrastructure and maintenance costs involved (Ashton, 2016),<sup>11</sup> the need for procurement contracts for the surplus energy generated on-farm, and the disposal of by-products. As a result of these hurdles, voluntary adoption of digesters in the dairy and livestock sector has been slow, despite existing incentives from various state agencies.

Besides direct subsidies to the installation of infrastructure on the farm, which have been channeled through CDFA's Dairy Digester Research and Development Program, existing incentives include the possibility to claim the greenhouse gas reductions attributed to the capture of

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11 The California Department of Food and Agriculture reports that 18 dairy digester projects were funded in 2017 across California. The average total project cost was in excess of \$6 million per project (CDFA, 2017).



methane in a digester either as an offset under the state's cap-and-trade program or, when using captured methane as a transportation fuel, as a credit pursuant to the state's low-carbon fuel standard (CARB, 2017c). Beyond current incentive programs, SB 1383 directs ARB to begin regulating methane emissions from dairy and livestock manure management operations no sooner than 2024, and provided the proposed regulations are technically and economically feasible, with a goal to achieve a 40 percent reduction below the sector's 2013 levels by 2030.

In 2015, ARB adopted an offset protocol for rice cultivation in order to incentivize practices that reduce methane emissions from flooded rice fields (CARB, 2015). As of December 2017, no offsets had been claimed pursuant to this protocol, either in or outside of the state (CARB, 2017a).

## CARBON SEQUESTRATION

Sequestration of carbon in agricultural soils has the potential to contribute to net reductions in agricultural GHG emissions. Cultivation practices that have been shown to promote carbon sequestration in soils in California include reduced tillage, manure application, and winter cover cropping (De Gryze et al., 2011). The California Department of Food and Agriculture (CDFA) currently encourages adoption of such practices through its Healthy Soils Program. In 2017, the program awarded \$3.75 million for projects ranging from the establishment of hedgerows to the use of cover crops or compost application in fields.<sup>12</sup>

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<sup>12</sup> CDFA also incentivizes GHG emission reductions through its State Water Efficiency and Enhancement Program, which aims to promote the adoption of water- and energy-saving irrigation systems throughout the state.

## EFFECTS OF CALIFORNIA'S CLIMATE POLICY ON ENERGY PRICES AND THE LOCAL FOOD PROCESSING INDUSTRY

California's new ambitious target to achieve GHG emissions 40 percent below 1990 levels by 2030 likely means that California businesses, including farms, will see a rise in energy prices relative to a world without constraints on emissions. Energy costs represent a non-negligible share of operating costs for many farming activities (use of mechanical power for field work, groundwater pumping, indoor climate control and lighting, powering of processing equipment).

Downstream processors like tomato or milk processing plants are also affected by rising energy prices, which may reduce their demand for farm output as the profitability of their operations declines. Food processors in California directly emit GHG through the burning of natural gas, and as such are covered by the cap under the cap-and-trade program. A gradual tightening of the emissions cap over time means that these processors will face higher total costs of energy procurement, which may dramatically affect their competitiveness and lead to a reallocation of food-processing plants towards unregulated regions outside California (Hamilton et al., 2016).

Since many farm products cannot be economically transported over long distances for processing, relocation of plants outside California implies that supplying farms will either need to shut down or convert to production of other, less-affected commodities. For instance, Hamilton et al. (2016) predict that a carbon price of \$20 per metric ton, without allowances handed in to California processors, would lead to a more than 7 percent decline in the California supply of processing tomatoes. The authors find more modest effects in the cheese, wet corn, and sugar sectors. While it is difficult to predict the extent to which these effects will impact the agricultural sector as a whole, absent compensating mechanisms, farmers should anticipate reduced profitability from policies that directly raise energy prices for farms and the food-processing sector.

## CONCLUSION

In this chapter, we review the scientific, agronomic, and economic literature to provide a broad survey on the topic of climate change and agriculture in California. This area of study is distinct in its topical and methodological breadth. Economists, hydrologists, climate scientists, engineers, and agronomists have brought their disciplines to bear on questions about the effects of climate change on temperature and precipitation patterns, irrigated water supplies, and agricultural outcomes, and the role adaptation can play in mitigating the costs of climate change. Despite the remarkable development of climate-related research, many key questions remain unanswered.

The available scientific evidence, even when gathered across a relatively large array of disciplines, does not paint a clear picture of the impact of climate change on California agriculture over the next century. We expect that in the next iteration of this book series, a new generation of research on this still nascent topic will provide further clarity on the complex relationship between agriculture and climate change in California.

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## APPENDIX

Appendix Table 16.1A. Set of GCMs Used to Derive Average Projections by 2036–2065, for Each Climatic Variable and RCP

GCM	Precipitation						Temp. mean						Temp. max						Temp. min					
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5	2.6	4.5	6.0	8.5
access1-0		X		X		X		X		X		X		X		X		X		X		X		X
access1-3		X		X		X		X		X		X		X		X		X		X		X		X
bcc-csm1-1		X		X		X		X		X		X		X		X		X		X		X		X
bcc-csm1-1m		X		X		X		X		X		X		X		X		X		X		X		X
canesm2		X		X		X		X		X		X		X		X		X		X		X		X
ccsm4	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
cesm1-bgc		X		X		X		X		X		X		X		X		X		X		X		X
cesm1-cam5	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
cmcc-cm		X		X		X		X		X		X		X		X		X		X		X		X
cnrm-cm5		X		X		X		X		X		X		X		X		X		X		X		X
csiro-mk3-6-0	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
ec-earth	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
fgoals-g2	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
fgoals-s2		X		X		X		X		X		X		X		X		X		X		X		X
fio-esm	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
gfdl-cm3	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
gfdl-esm2g	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
gfdl-esm2m	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
giss-e2-h-cc		X		X		X		X		X		X		X		X		X		X		X		X
giss-e2-r	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
giss-e2-r-cc		X		X		X		X		X		X		X		X		X		X		X		X
hadgem2-ao	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
hadgem2-cc		X		X		X		X		X		X		X		X		X		X		X		X
hadgem2-es	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
inmcm4		X		X		X		X		X		X		X		X		X		X		X		X
ipsl-cm5a-lr	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
ipsl-cm5a-mr	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
ipsl-cm5b-lr		X		X		X		X		X		X		X		X		X		X		X		X
miroc-esm	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
miroc-esm-chem	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
miroc5	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
mpi-esm-lr	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
mpi-esm-mr	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
mri-cgcm3	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
noresm1-m	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
noresm1-me	X	X		X	X	X		X	X	X		X	X	X		X	X	X	X	X		X	X	X
Total	24	36	18	33	24	36	18	33	23	33	17	30	23	33	17	30	23	33	17	30	23	33	17	30