CALIFORNIA DEPARTMENT OF FOOD & AGRICULTURE

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Climate Change Consortium for Specialty Crops: Impacts and Strategies for Resilience

Photo courtesy of Jocelyn Gretz, Rio Farms

California Department of Food and Agriculture

Contents

Executive Summary

The California Department of Food and Agriculture (CDFA) convened the Climate Change Consortium, a diverse group of individuals involved in California specialty crop agriculture, to identify specific climate change adaptation strategies for growers. Changes to the climate as a result of anthropogenic activities are well recognized and acknowledged by the scientific community. Therefore the Consortium assumed, as charged by CDFA, that climate change is now occurring and will continue to occur in the future. The realities of climate change were not debated, nor were mitigation measures identified although, some adaptation measures could also be also considered mitigation measures.

> *"As we head into another summer with less than 20 percent of normal snowpack in the Sierra-the lifeblood of Central Valley agriculture- we worry about the future"*
>
> *-Ward Burroughs, Merced County farmer; Modesto Bee opinion page June 6, 2013*

The Consortium was asked to evaluate climate change impacts and to propose potential strategies for adaptation so that California agriculture and CDFA can prepare for impacts. The Consortium discussed and documented challenges faced by growers due to climate change. The Consortium addressed climate change impacts to temperature, water resources, pests and pollination. Growers will face new challenges from changed environmental averages, trends, variability, and extremes. These challenges are summarized below. While specialty crops are the focus of this report, the Consortium's work on climate change impacts can be applied widely to California agriculture.

Challenges:

- *Increased average, minimum, and maximum temperatures in all seasons*
- *More frequent and longer-lasting heat waves in the summer*
- *Reduced number of winter chill hours and fog*
- *Uncertainty in temperature change projections and forecasts*
- *High spatial variability of climate change and impacts of climate change*
- *Reduced precipitation (drought), increased precipitation (floods), and more variable precipitation and snowpack accumulation*
- *Decreased winter snowpack, earlier timing of snowmelt and spring river runoff, and reduced spring runoff*
- *Altered reservoir storage regimes*
- *Reduced natural groundwater recharge*
- *Reduced water quality due to reduced fresh water supplies*
- *Complex and unpredictable alterations to plant, pest, and pollinator abundance and spatial distributions*
- *Altered inter-species dynamics in agricultural ecosystems*
- *Reduced effectiveness of managed pollinators*
- *Vulnerability to pest and pollinator changes*

The Consortium discussed creative solutions to be investigated and implemented at the level of individual growers; local communities, cities, and counties; and through regional and state planning processes. There was a general consensus within the Consortium that growers are managing their lands in consideration of dynamic environmental and agronomic variables and therefore, existing efforts can contribute to adapting to climate change impacts. However, for specialty crop agriculture in California to adapt and be prepared for climate change events, growers require agricultural support services, scientific answers to fundamental climate change impact questions, investment in planning and preparedness, and technological innovations. These requirements were categorized and prioritized under the categories of Outreach and Education, Planning and Resource Optimization, Research Needs, and Technology and Innovation. Listed below are some of the leading recommendations identified by the Consortium.

Leading Recommendations for CDFA:

1. *Support economic and environmental studies of the costs, benefits, and risks of adaptation strategies*
2. *Facilitate a reinvestment in grower technical assistance and trainings specific to climate change adaptation, such as for water, soil, and pest management*
3. *Advocate for inclusion of grower interests in the Integrated Regional Water Management (IRWM) process*
4. *Perform or fund a review of regulatory barriers to adaptation mechanisms, such as food safety and other regulations*
5. *Facilitate interagency coordination on the recommendations of the Climate Change Consortium*
6. *Compile a list of grower needs for weather data and forecast products*
7. *Develop research plots to study adaptation strategies and new technologies and products*
8. *Promote farmland conservation*
9. *Recognize growers who develop or adopt novel strategies to adapt to climate change*
10. *Support USDA NRCS in a review and/or creation of policies to improve growers' ability to adapt to climate change*

This report is a synthesis and summary of scientific information shared by experts in and outside of California who are working on climate change at the interface of agriculture, information from discussion that ensued in the Consortium meetings, and recommendations proposed by the Consortium. The purpose of this document is two-fold: one is to provide growers, agricultural associations, specialty crop commodity groups, the general public, state agencies, and other agricultural stakeholders with examples of climate change impacts and potential adaptation strategies, specifically as they relate to agriculture in California. Second, the document lists adaptation recommendations (beginning on page 48) that the Consortium developed, providing CDFA direction on future climate change activities.

Chapter 1: Introduction

California is the nation's leading agricultural state in gross cash receipts; $43.5 billion in 2011. A large portion of the crops grown in the state are "specialty crops." Specialty crops are defined as fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops including floriculture. In 2011, global exports of California's specialty crops reached nearly $10.9 billion. California is the United States' sole producer of several crops such as Clingstone peaches, olives, pistachios, walnuts, almonds and artichokes (California Department of Food and Agriculture 2013a). The state's unique environmental zones and Mediterranean climate allow for a diversity of crops to be produced throughout the year for local, national, and global distribution. California's specialty crop commodities are known for being a healthy, affordable, safe food source.

Impacts to agriculture from changes in weather will be felt differently in different parts of California. Temperature, rainfall, humidity, and wind are some common weather variables. Long-term patterns of weather are referred to as the "climate," and changes in weather patterns over time are defined as "climate change." Climate is essentially the *average* pattern of weather for a region, which could be a county, state, continent, or the entire world. Climate change occurs when an area's weather pattern, as indicated by weather variables, deviates significantly from the "average," or from the historically observed "normal."

Due to the many human and environmental factors influencing climate change, and due to increased variability in weather over time and across space, climate change effects are difficult to predict for a specific agricultural operation. Nevertheless, rigorous analysis of California weather data shows that climate change is already occurring in some parts of the state. Future climate trends have been predicted for California. California can expect to see increased average and more extreme temperatures; altered rainfall, snowpack accumulation, and snowmelt timing regimes; increased variability in both temperature and rainfall; and increased *and* more variable durations and frequencies of heat waves, droughts, and floods.

Temperature changes are generally used as an indicator for climate change. Below are several temperature-based examples of climate change provided to highlight the climate change effects at the global and local scales.

Climate change is well documented at the global scale. It has been demonstrated through many scientific studies and global data collection that anthropogenic activities have contributed to historically high greenhouse gas levels in the atmosphere. Consequently, there has been a global increase in average temperatures. This process of greenhouse gas induced temperature increase is known as "global warming"(Houghton & IPCC Working Group I 2001). The increase in greenhouse gases (specifically carbon dioxide) and temperatures are provided in Figure 1. Figure 1 shows increased temperatures corresponding closely with increase carbon dioxide concentrations over the last 150 years.

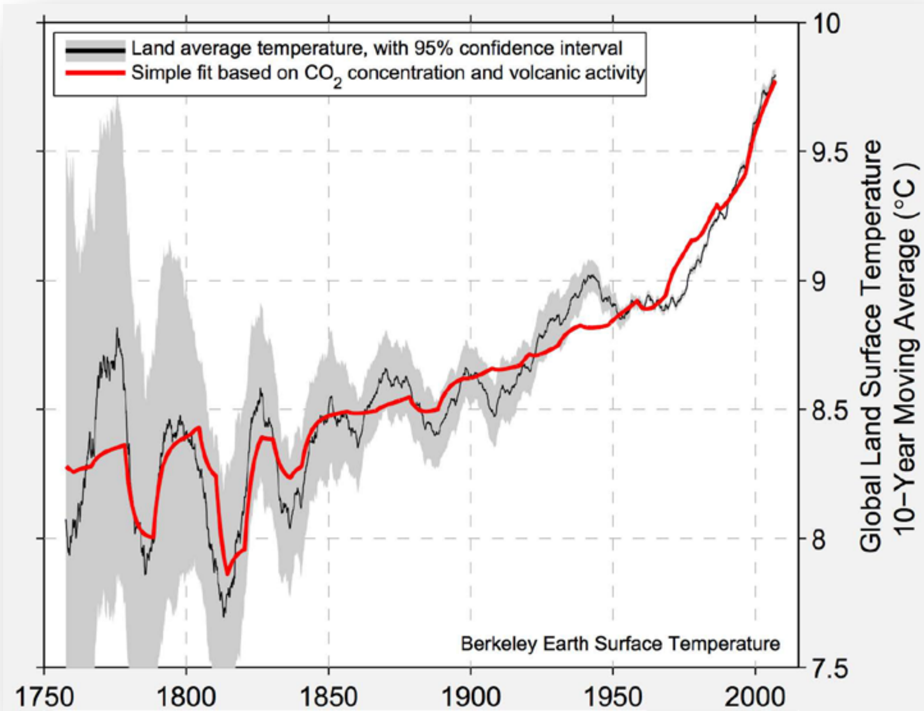

Figure 1: Ten-year moving average of global temperatures between 1750-2000 (black) and temperature predicted by CO_2 and volcanic emissions (red). The large negative extremes in the early temperature records are likely explained by volcanic activity; the upward trend in the recent record is an indication of anthropogenic change. This demonstrates the strong relationship between CO_2 concentrations and global warming. The grey area is the 95% confidence interval. From Berkeley Earth Surface Temperature.

Similarly, Figure 2 below shows that California has seen similar, more recent evidence of increased temperatures. Investigation and prediction of climate change in California is still an active area of research, but experts agree there has been, and will continue be changes in regional and statewide weather patterns stemming from climate change. Scientists anticipate an acceleration of warming across the western United States (Moser et al. 2009). California should see between a 1° F and 3° F increase in average daily temperature by 2050, and between a 2° F and 6° F increase by 2100[a] (Lobell et al. 2006; Cayan et al. 2008; Nakićenović et al. 2000). California is expected to experience increases in average temperatures in all seasons, and greater warming in the summer than in the winter (Cayan et al. 2008). Specific climate change impacts to human and environmental health (in addition to agriculture) have been documented in California (OEHHA 2013).

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[a] These estimates are generated by a model known as a coupled ocean-atmosphere general circulation model (GCM) run using climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) of low- to high-emissions trajectories (Nakićenović et al., 2000). The IPCC is a scientific intergovernmental body formed by the United Nations to provide scientific assessments of information worldwide about the risks of climate change, its potential consequences, and options for adaptation to and mitigation of consequences.

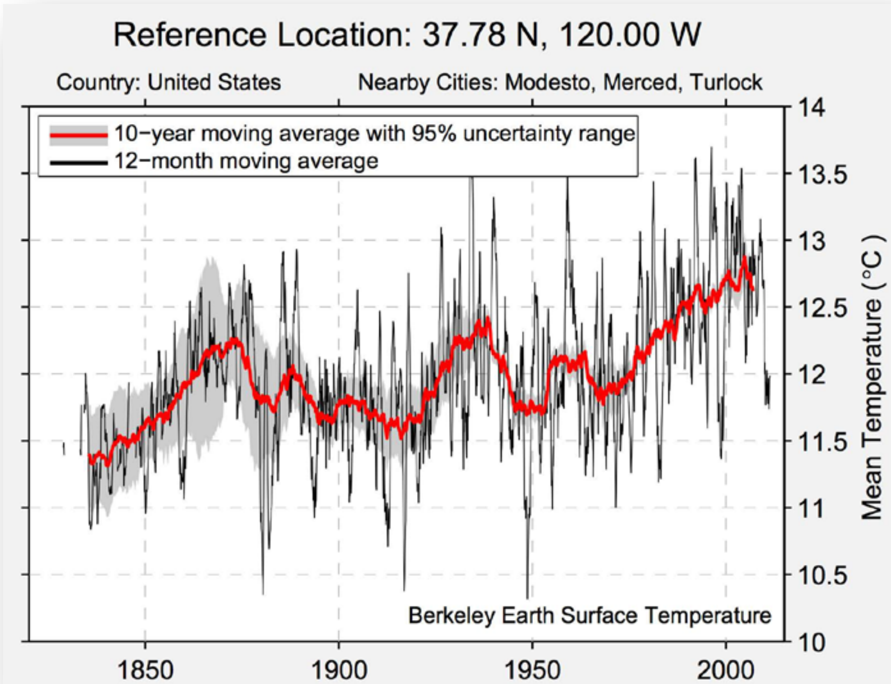

Figure 2: Ten-year moving average of temperatures in the San Joaquin Valley near Modesto, Merced, and Turlock shows temperature increases in recent years. Other areas in California's San Joaquin Valley and Southern California show similar trends. From Berkeley Earth Surface Temperature.

California's many unique microclimates allow farmers to grow a diversity of crops. The scientific consensus is that climate change will affect these microclimates, although there may be some regions that remain unaffected. Depending on the degree of change experienced in a region across several variables (e.g. temperature, rainfall, humidity, presence of plant and insect communities), there may be both negative and positive impacts to crop production. In some areas, certain crops will no longer be viable; simultaneously, there may be opportunities to grow these same crops (or new ones) in other regions of the state.

Several studies indicate that climate change will negatively impact many specialty crop yields and profits by the year 2050 and certainly by the year 2100 (Deschenes & Kolstad 2011; Medellín-Azuara et al. 2011; Lobell et al. 2006). For example, California has already observed a significant loss of winter chill hours, due to an increase in average winter temperatures (Baldocchi & Wong 2008). Winter chill hours are defined as the number of hours spent below 45° F, necessary for the flowers of fruits and nuts to bloom, and are required by certain crops to achieve high yields. Increased invasive pests, changes to plant and pest interactions, and increased plant and animal diseases in agriculture are some additional potential impacts from climate change.

An Agricultural Vulnerability Index that takes into account climate change, crop vulnerability, land vulnerability such as urbanization and soil degradation, and socioeconomic pressures has been developed for California (Jackson et al. 2012). When climate vulnerability alone is considered, the majority of the Central Valley is "vulnerable," coastal agricultural regions have "low" vulnerability, and the San Joaquin Valley and Southern California growing regions remain "moderately" vulnerable. But when climate change impacts are coupled with other vulnerability factors (such as soil degradation and urbanization), the regions where much of California's agricultural production occurs, including the Central Valley and coastal growing regions, become the most vulnerable.

Growers in California are innovative leaders in agriculture. They continually develop their own adaptations to address inter-annual variability in weather as well as other changing environmental variables. Growers employ strategies such as diversifying their water portfolios, diversifying their crops, or diversifying revenue through agro-tourism or other opportunities in order to grow strong businesses. Thinking about climate change, however, requires thinking about these strategies on a generational timeframe and on a regional scale. According to a survey of about 160 growers in Yolo County, climate change was *not* listed as a high priority concern, although over 50% of the growers agreed "the global climate is changing" (Jackson et al. 2011). Although growers may not prioritize climate change as their primary concern, they have long been concerned about issues that are likely to be exacerbated by climate change such as unpredictable water supplies, the spread of invasive pests and plant and animal diseases and reduced availability of pollinators.

The severity of the impacts of climate change on food production will be variable and crop-specific. Growers should be made aware of adaptation measures available to them. Ensuring sustainable agricultural adaptation to climate change will require a concerted collaborative effort by growers, government agencies, and agricultural service organizations. The importance of this effort is highlighted in the California State Board of Food and Agriculture report, *California Agricultural Vision: Strategies for Sustainability*. Specifically, strategy nine is titled "Assure Agricultural Adaptation to Climate Change" and has the following objective – "Assure that all sectors of California agriculture can adapt to the most likely climate-related changes in seasonal weather, water supply, pests and diseases, and other factors affecting agricultural production" (California Department of Food and Agriculture 2012).

To identify specific strategies to assure agricultural adaptation to climate change, the California Department of Food and Agriculture (CDFA) convened the Climate Change Consortium workgroup in the fall of 2012 for two purposes:

1. To determine specific adaptation strategies that can be implemented now, and on-the-ground by specialty crop growers;
2. To provide direction and action measures to CDFA that can be initiated over the next several years, based on available resources, to help California agriculture adapt to climate change.

The Consortium includes representatives from several specialty crops commodity groups in California, growers from each of the top ten specialty crops in the state, scientists from the University of California and the California State University systems, University of California Extension Specialists, a member from the California Association Resource Conservation Districts, a member from the California Agricultural Commissioners and Sealers Association, and a certified crop/pest control advisor.

Over the course of six months in 2012 and 2013, the Climate Change Consortium met four times to hear from leading scientific researchers in various fields of climate change at the interface of agriculture. The following chapters provide information presented and discussed at these meetings, and related recommendations for adaptation strategies. Understandably, a large number of adaptations highlight the need for further research. While the CDFA does not perform experimental research studies directly, the Department funds research activities and may submit proposals and refine request for proposals for research based on grower needs. The Department also provides growers with information on emerging research and research results. The development of strategic solutions with specific short- and long-term recommendations to address climate change impacts will help sustain California's diverse specialty crop food production into the future.

Chapter 2: Temperature

Introduction

This chapter covers temperature change impacts to California's specialty crops, and proposed adaptation strategies to temperature change. This chapter addresses only *direct* temperature change impacts on California crops, such as warmer air temperatures. Changes in temperature can be linked to other climatic factors. For example, higher winter temperatures may result in reduced snowpack accumulation, which reduces irrigation supplies to agriculture; reduced water availability would therefore be an *indirect* temperature change impact.

> ***Challenges:***
>
> - *Increased average, minimum, and maximum temperatures in all seasons, and increased temperature variability*
> - *More frequent and longer-lasting heat waves in the summer*
> - *Reduced number of winter chill hours and fog*
> - *Uncertainty in temperature change projections and forecasts*
> - *High spatial variability of climate change and impacts of climate change*

Crops are sensitive to the magnitude of change in temperature, extreme temperatures (minimums and maximums) and the timing of temperature changes (night vs. day, spring vs. summer). The combination of these factors constitutes "temperature change."

Across the western U.S., average annual minimum and maximum temperatures have increased since 1950; frost days[b] have declined over this same period (Bonfils et al. 2008). Since 1920, California annual daytime temperatures have increased 0.1° F per decade, and nighttime temperatures have increased 0.33 ° F per decade (Moser et al. 2009). Statewide average temperatures increased approximately 1.7° F between 1895 and 2011. Warming has been greatest in the Sierra Nevada foothill and mountain region (Moser et al. 2012). Data from weather stations located throughout the California Central Valley show increasingly warmer winters since the 1940s (Dettinger & Cayan 1995; Cordero et al. 2011). Over the entire 20th century there has been a significant rate of warming for San Joaquin Valley *minimum* temperatures in all seasons, with the greatest rate of warming in the summer and fall (Christy et al. 2006).

In general, warming is expected on an annual, seasonal, and even daily basis, with impacts differing by region. The significant, overall outcome of warming is the likely reduction in yield of some of California's most valuable specialty crops, particularly perennial crops.

[b] Frost days are a count of days (within some defined period, such as a year) that have a daily average temperature below the freezing point.

Temperature Sensitivity of Crops

Temperature sensitive crops include US staple crops such as corn, soybeans, wheat and cotton (Schlenker & Roberts 2009), as well as valuable California specialty perennial crops such as almonds, grapes, berries, citrus and stone fruits (Lobell & Field 2011; Lobell et al. 2006). Global-level data suggests there is limited historical adaptation of staple crop seed varieties or management practices to counter warmer temperatures (Schlenker & Roberts 2009). Perennial crops are semi-permanent, and therefore potentially more vulnerable to climate change impacts than are annual crops (Lobell et al. 2006). For California specialty crops, sensitivity to temperature extremes varies by crop, crop variety, and by month. For example, almond yield is strongly influenced by the temperature in the February before harvest (harvest occurs in late summer). Almond yields are higher when the nighttime temperatures in February are low (Lobell & Field 2011).

The modeled, combined impact of increasing and more variable temperatures *and* variable rainfall is to increase the probability of abnormally low yields in any given year for perennial crops such as almonds, table grapes, walnuts, and avocados (Lobell et al. 2006). While there may be some positive impacts and opportunities associated with new temperature regimes due to climate change, such as the ability to cultivate some crops in new areas, all negative impacts ultimately stand to reduce crop quality (such as decreased size and yields) (Ackerman & Stanton 2013).

Risks of temperature change to crops in general include: altered phenology (timing) of leafing, flowering, harvest and fruit production; decreased winter chill[c]; and asynchrony between flowering and pollinators (Baldocchi & Wong 2008; Baldocchi 2012). Increased spring temperatures have been shown to induce earlier spring blooms across western states (Cayan et al. 2001; Pope et al. 2013). Heat waves may cause early bolting[d] in annual crops and reduced pollination success (Cavagnaro et al. 2006). While temperature changes may not affect average statewide crop yields for some crops, uncertainty in all climate and yield model projections is great, and impacts to regional and local crop yields may occur even where impacts to statewide averages may not (Bonfils 2012; Lobell et al. 2006).

Warming and Heat Waves

Statistical model projections based on historic crop yield and temperature data suggest a 2° F warming will have differential impacts on yield across crops; yield in some crops like almonds may increase due to warming, while yield in others like wine grapes and cherries could decrease dramatically to economically unsustainable levels (Lobell & Field 2011; Jackson 2012). Warmer temperatures may contribute to greater loss of carbon in the form of carbon dioxide from agricultural and forest soils, which in turn could slightly increase total vegetative growth, although scientific understanding of this matter is limited (Cavagnaro et al. 2006; Ackerman & Stanton 2013).

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[c] Accumulation of winter chill, often measured in chill hours - the number of total hours per season between 0° F and 45° F, is necessary to convince trees that evolved in a cool winter climate that winter has passed and it is safe for their tender young flowers and leaves to emerge.

[d] Bolting is when a plant prematurely produces flowering stems before the crop is harvested, which diverts resources away from the edible parts of the plant.

Warmer spring temperatures also have negative effects on crop pollen germination, and flower and ovule size that can result in reduced fruit yields in the form of smaller, deformed (double), and fewer fruits (Pope 2012; Karapanos et al. 2010; DeCeault & Polito 2008; Beppu & Kataoka 2011). Additionally, warm springs may encourage earlier planting and early plant development. Seedlings that are out of the ground earlier are more susceptible to spring frost. If springs are warmer, but frost dates do not also change, there will be greater losses due to spring frost events.

Extremely high summer temperatures decrease photosynthesis and increase respiration, which may result in less overall plant growth and poorer quality of harvested product. Though the exact temperature thresholds for respiration and photosynthesis vary by crop, in peach, for example, leaf photosynthesis decreases from its maximum above 86° F to 50-70% between 95°-100° F (Flore 1994). Fruit growth declines above 95° F as well (Byrne 2007). Reduced photosynthesis decreases the energy supply (carbohydrates) available for plant growth, in turn reducing yield (Pope 2012; Sage & Kubien 2007). In general, high temperatures increase the rate of development of the fruit, leading to fruit that is ripe earlier and at a smaller size (Ben Mimoun & DeJong 1998).

The number of degree-days (count of days equal to or greater than a particular temperature) and frost-days (count of days during which there is frost) provide a cumulative measure of temperature extremes to which crops respond. The impacts of warming in wine grape regions include: longer frost-free periods; increasing degree-days; less winter chill and a shift to earlier bud break, bloom, and veraison (onset of ripening) – all with negative yield quantity and potential quality implications (Battany 2012).

Wine grape color and concentrations of phenolics (chemical compounds that effect the taste, color, and feel of wine) change with temperature; optimal concentrations for individual varieties are found at very specific temperatures. Therefore temperature change stands to affect wine grape color and phenolics (Poudel et al. 2009). Balance of soluble solids concentration (SSC) and titratable acidity (TA) are also important, and may be affected by temperature. Unfortunately, there is little scientific research in this area and no available temperature response information for fruit development or composition. Temperature effects on wine grape and other fruit quality are observed, but not well understood (Matthews 2012).

Singular hot spell events can also impact crop phenology. In a study of Sémillon wine grapes, vines exposed to a heat 'treatment' during ripening (onset and/or mid-stage) suffered impeded sugar flow into grape bunches – again, ultimately compromising crop quality (Greer & Weston 2010). Thus, higher temperatures in the form of hot spells may delay rather than accelerate ripening of wine grapes (and other crops where SSC is important as well). Because berries are very sensitive to direct radiation, they are susceptible to sunburn in extreme temperature events as well (Matthews 2012).

There is more research on Central Valley crop trends and responses to climate, yet coastal region agriculture, with valuable "cool season" crops such as berries and lettuce, will be affected by temperature change as well. A statistical analysis of California historical data suggests that different coastal region crops will experience different effects. Yield decreases are expected for lettuce, but yield increases for strawberries; both crops, however, may benefit (in terms of yield) from a warm, early, and dry spring, which may become more frequent with climate change (Lobell et al. 2007). More scientific research is required on climate impacts to valuable cool season coastal region crops.

Winter Chill

California's temperate tree crops (deciduous tree and vine crops, such as fruits and nuts), which evolved in climates with distinct seasons, suffer reduced yields if they do not experience adequate winter cold (Baldocchi & Wong 2008; Pope 2012). An inadequate number of chill hours can cause late or irregular blooming, which decreases fruit quality and reduces economic yield (Moser et al. 2009). There are approximately three million acres of orchards with chilling requirements in California (Jackson 2012). Throughout Central California, the number of winter chill hours has decreased since the 1950's (see Figure 3 below), and models project continued decreases by the end of the century to around half the number of chill hours seen in 2000 (Baldocchi & Wong 2008; Luedeling et al. 2009). Downward trends in winter chill are found across California's Central Valley and some coastal areas, including the growing regions of Monterey County, east Contra Costa County, the northern Sacramento Valley, Red Bluff, Davis, and Fresno (Baldocchi & Wong 2008).

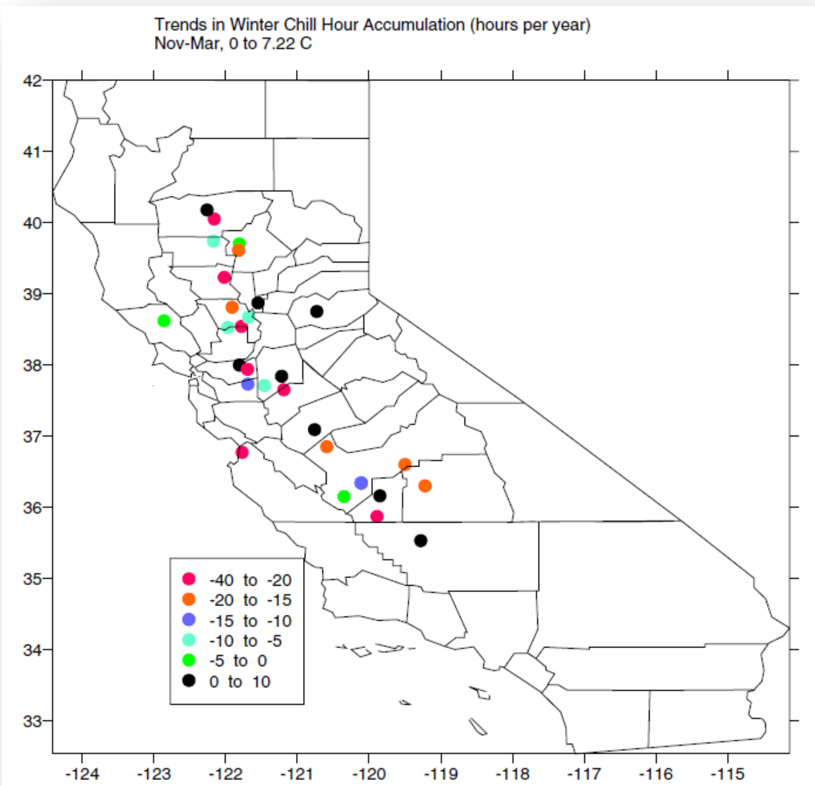


Figure 3: Map of long-term trends in the change in winter chill accumulation (hours per year) over the course of the dormant period for fruit and nut crops. The axes of the map show latitude and longitude of the data points. Each dot on the map represents a change in the accumulation of chill hours in a year. Data are derived from the California Climate Archive (Baldocchi & Wong, 2008).

Additionally, there is a reduction in chill that tree plant tissues (including buds) perceive due to a downward trend in winter fog which has been observed in the Central Valley. Winter chill accumulation, and the associated reduction is calculated based on air temperature. However, with observed and projected increases in clear warm days, buds in the sunlight will be exposed to greater warmth than they would have been if shrouded by fog. Consequently, the process amplifies the downward trend in the amount of winter chill that occurs. Although fog is potentially very important because a reduction in it corresponds to a reduction in the number of chill hours, fog is not explicitly accounted for in most climate models and its role in climate change is therefore not fully understood (Baldocchi 2012).

Adaptation Strategies

The Climate Change Consortium recognized the following strategies as potentially alleviating the direct impacts of increased temperatures to specialty crops. Each of these strategies are discussed in detail below.

Crop Breeding

The Consortium identified the need for breeding of crops resilient to heat spells and low chill winters, the predominant temperature threats to California specialty crops. A systematic search of heat tolerant crop varieties should be conducted and information disseminated to growers, ideally through an easily accessible and user-friendly online database.

On-Farm Strategies for Adaptation to Increased Temperatures

- *Switch to an established heat-tolerant or low-chill tolerant variety*
- *Consider management practices that provide cooling to sensitive crops such as shade structures, intercropping, or spray materials*
- *Alter planting and harvesting schedules*

Row crops, such as tomatoes, are susceptible to loss by heat waves during summer months. On the other hand, tree crops are already being impacted by decreased winter chill during winter months. Many high value tree crop industries in California are based on varieties with medium to high chilling requirements, in particular cherries, pistachios and walnuts. For all of these crops, there are less well-known varieties or wild relatives with lower chilling requirements. Thus, a candidate priority breeding program with a high probability of success would be winter chill requirement reduction in tree crops.

Overall, breeding efforts should be prioritized by the crops that are most at risk. For fresh fruits, low chill cultivar options are available for apricots, peaches, plums, and cherries, for which there are low chill breeding programs in the U.S., Brazil, and South Africa. However, many of these varieties are considered less palatable or marketable than the high chill counterparts. Because pistachios, prunes and walnuts have a longer shelf-life, and because new varieties need to be agreeable to processors (shellers, dryers, etc.) as well as consumers, there are few to no low chill varieties of these crops on the market in California. Short-term adaptation strategies would be to increase breeding in these crops, and encourage cross-border cultivar trading. For crops vulnerable to summer temperature increases (this includes most temperate tree crops and cool season vegetables), breeding to increase heat tolerance is necessary (Pope 2012).

Wine grape growers could switch to longer-season varieties and harvest later, although this potentially poses an economic challenge in the form of marketplace acceptance of 'non-traditional' California varieties (Battany 2012). Nevertheless, for wine grapes, there are varieties that seek lower acid and a longer ripening season; these varieties are more amenable to warmer temperatures (Allen et al. 1990).

Crop Fertility

The scientific literature shows that high temperatures can impact crop fertility. The Consortium recommended that a literature review on the climate change impacts on crop flower fertility and an electronic clearinghouse (e.g., website) for this information, with links to literature, would be useful to specialty crop growers. Additional research in this area would be beneficial. More research is needed on germination tube formation in relationship to high temperatures.

Research Plots for Management Practices

Methods that physically manipulate a crop, such as training for a specific height or amount foliage canopy, can be used to deal with high daytime temperatures. The Consortium recommended broad research on the use of different physical plant growth training infrastructures for stone fruits and other crops to provide protection from heat stress and sunburn.

Shading and light reflection are another option for high summer temperatures. Physical structures (structures similar to hail netting) and spray materials (e.g. clay and calcium carbonate based substances) could also reduce summer heat stress. For shading, trellis and canopy structures could be used to expose or shade crops from full sun during different parts of the day, and moveable trellis structures could be used to fully expose fruits at night. For cherries, shading above 50% was shown to reduce fruit deformation (Battany 2012).

However shading in the manner similar to controlled studies may be difficult or financially infeasible on an agro-industrial scale (Beppu & Kataoka 2011; Pope 2012). Convective cooling – either through vineyard design or structures, could be used, however there is no existing information on impacts of wind in different crop canopies. Design of lower cost shading techniques is needed in order to make it practical for use in a variety of crops.

Additionally, the Consortium recommended more research on intercropping and cover-cropping, which could have a cooling effect by increasing transpiration in the field, thereby reducing heat stress. Research is needed to: 1) determine which crop combinations can be effective and practical, and 2) determine if this strategy is applicable in arid production areas where water is limited. Intercropping may also provide an additional benefit in the form of crop diversification, which may contribute to economic resilience for growers.

The Consortium recommended that funding be identified for research plots that investigate new techniques for temperature change (and other climate change) management, and provide proof-of-concept before new practices are adopted by growers. CDFA should help to coordinate the research projects with other partners such as United States Department of Agriculture (USDA) and UC Cooperative Extension (UCCE). Recommended areas of research include:

- Study the use of fans, cooling, shade netting, spray materials and other cultivation practices that can reduce heat stress;
- Study the use of photovoltaic panels as shade structures over crops;
- Study intercropping to reduce heat stress, determine which crop combinations can be effective and practical, and determine applicability of intercropping in arid regions;

- Investigate what California products and markets support the cost of climate-controlled cultivation (greenhouses);
- Study climate analogues (Ramírez-Villegas et al. 2011): locations where the present climate compares with the projected future climate of other locations, with a focus on the potential to maintain crop yield and quality in e.g. new (warmer) areas;
- Encourage the incorporation of heat stress factors (not only sunburn) in developing plant training systems, especially for those systems where training methods do not traditionally address this variable, such as many tree crops.

Transitional use of rest-breaking materials

As a transitional strategy, before the introduction of lower chill varieties, there should be options for growers to use rest-breaking chemicals that address chill deficits. The Consortium encouraged continued research in the development and use of rest-breaking chemicals, and to the extent possible, streamlining the registration process while ensuring that human health and environmental concerns are adequately addressed, as well as alternatives for organic producers investigated. For rest-breaking chemicals addressing chill deficits, more research is needed, but a short-term solution would be to have such chemicals approved for medium to high chill requirement crops.

Chapter 3: Water Resources

Introduction

Crops are sensitive to the availability of water, the quality of water, and the timing of water application. Altered climate regimes (changing precipitation patterns, temperature magnitudes, variation, and seasonal timing of extreme heat and cold) can exacerbate water availability and quality challenges. California agriculture's water supply can be split, in simplistic terms, into several regions: 1) the snowpack/runoff dependent Central Valley (region also uses some groundwater), 2) groundwater and reservoir dependent coastal areas, and 3) the Colorado River dependent Imperial, Coachella and Palo Verde Valleys. In general, and regardless of the source, water resources for agricultural irrigation are expected to decrease and become more variable with increased risks of flooding. Impacts will differ greatly by region. This chapter covers changes to water resources systems in California due to climate change and adaptation strategies proposed by the Climate Change Consortium to address water resource challenges.

Challenges:

- *Reduced precipitation (drought) or increased precipitation (floods)*
- *Decreased winter snowpack, altered (earlier) timing of snowmelt and spring river runoff, and reduced spring runoff*
- *More variable temperatures resulting in more variable precipitation and snowpack accumulation*
- *Altered reservoir storage regimes*
- *Reduced natural groundwater recharge*
- *Reduced water quality due to reduced fresh water supplies*
- *Uncertainty in predictions*

Changes in California Hydrology

Climate change will likely impact the magnitude, timing, and frequency of precipitation, river runoff, and flood events through changes to the land surface, atmosphere, and oceans. California flow regimes rely on the atmosphere, the interaction of the atmosphere with the land surface, and the state of that land surface; time of year (season) matters, as does the location (Anderson 2013; Bales 2013).

All growers, whether pumping groundwater or using surface water for irrigation, ultimately depend on an influx of winter precipitation. California precipitation is seasonal, and uniquely variable (Anderson 2013; Dettinger 2011). Fresh water supplies in the form of precipitation come mainly from seasonal and brief north-Pacific storms during October-May (Cayan 2013). About two-thirds of the precipitation that falls on the Sierra Nevada Mountains is evaporated from the ground surface and/or transpired by vegetation, and the remaining one-third moves to rivers (some of which recharges groundwater aquifers). In an average year, the Sierra Nevada Mountains receive 27% of the state's annual precipitation and provide more than 60% of the state's consumptive use of water in the form of runoff (Bales 2013).

Mountain hydrology is complex, and the amounts of water found in rivers, surface water reservoirs, and snowpack 'storage' at any given time are determined by many factors: precipitation, infiltration into soil and groundwater, snowmelt rates and the timing of melt onset, runoff, groundwater and surface water exchange, sublimation (the conversion of snow to water vapor with no intermediate melted liquid stage), and evapotranspiration (ground surface evaporation and plant transpiration). These many, interacting factors make it very difficult to predict climate induced changes to California's hydrology. Changes that do occur will impact precipitation, snowpack, runoff, and evapotranspiration (Bales 2013).

Precipitation Changes

Change in the total annual volume of fresh water in California is driven by the occurrence of sporadic, heavy rainfall events, generated from an 'atmospheric river' that flows landward from the Pacific Ocean (Cayan 2013; Dettinger 2011). It is the landfall of these atmospheric rivers that generate extreme California storm events. Climatic changes impact the nature of the atmospheric river as well as the land surface environment that contributes to storm formation (Anderson 2013; Dettinger 2011).

California has also experienced the highest national number of extreme historical episodes of rainfall events with precipitation greater than 12 inches (Anderson 2013). Simulations predict increases in the frequency and magnitude of extreme temperatures with certainty. However, predictions for precipitation extremes are less certain. Historical observations (1950-2000) of trends in precipitation, which include intensity (total precipitation per number of wet days), percentage of precipitation in very wet days, and maximum 5-day total precipitation, differ across the state, and none of the observed increased or decreased intensity trends appear statistically significant[e]. This implies that precipitation change will vary by location, but may not change dramatically (unlike temperature). The number of days with precipitation greater than 10 mm has increased across the state over this time period, but again, not significantly. Model simulations to year 2100 identify that the number of days of precipitation greater than 10 mm will decline over the entire state, but no other significant changes were projected (no increases in precipitation intensity, percentage of precipitation in very wet days or maximum 5-day total precipitation) (Mastrandrea et al. 2011).

Snowpack Changes

Much of the water supply for the semi-arid Western U.S., including California, comes from mountain snowpack (Bales 2013). An increase in temperature of as small as 2° C is known to drive significant changes in: rain versus snow storms, snowpack amounts, snowmelt timing, stream flow timing, and growing seasons. There are also concerns that snowpack changes will drive changes in flooding potential, low base flows (non-peak flows in a river or stream), groundwater recharge, and soil moisture levels in summer (Bales 2013). The influence of a 3° C increase on U.S. western states is projected to be interconnected trends of more rain and less snow, earlier snowmelt, and more winter floods (Bales 2013).

[e] Lack of statistical significance in increases or decreases in precipitation intensity simply means that none of the observed trends fall outside the range of what historical trends describe as 'normal' – the observed intensity trends are not (numerically) abnormal.

Figure 4: Snowpack in the Sierra Nevada Mountains. Photo by Noah Molotch of University of Colorado.

Direct stream runoff from storms may increase due to warmer air temperatures, which increases the portion of precipitation that falls as rain instead of snow. Consequently, snowpack (effectively winter storage) and spring snowmelt runoff could be reduced (Anderson et al. 2008).

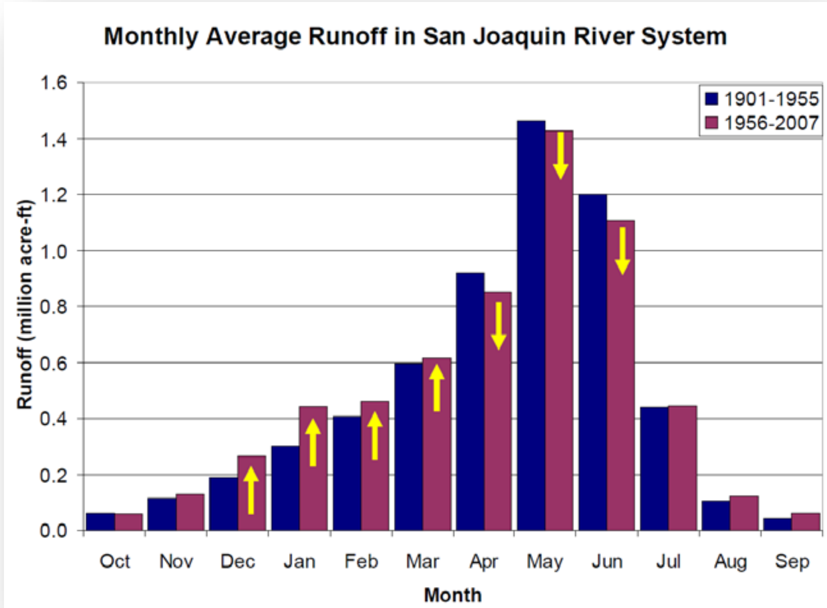
In observations of snowpack in the Sierra Nevada Mountains between 1961-1990, 100% of the winter snowpack remained on April 1st of the year; in two different climate change scenario projections for the 2070-2099 period, only 52% and 35% remained on April 1st (indicating earlier winter snow melt in a climate-changed future). General warming and drying in California is projected to result in an average decrease in Sierra Nevada April 1st snow water equivalent (the amount of water stored in winter snow present on April 1st of the year) by 2050, with the number of cases of minimal April 1st snow water equivalent becoming more frequent (Cayan 2013).

There is a large amount of uncertainty in snowpack predictions. Most California snowmelt comes from elevations above where most measurements of snowpack are currently made (Bales 2013). Snowpack and snowmelt runoff at the mountain snow-rain transition line are impacted by forest vegetation evapotranspiration and soil properties (Hunsaker et al. 2012; Bales 2013). Forest management decisions will influence snow accumulation, snowmelt timing, and water yield (the amount of runoff). The knowledge base to inform adaptive management of Sierra Nevada forests to climate change is currently insufficient (Bales 2013).

Runoff Changes

Annual river discharge from the Sierra Nevada Mountains, the source of the majority of California's freshwater, varies considerably. However, Sierra Nevada flow is associated with a larger regional pattern, and along with other major river systems like the Columbia and Colorado, flows generally alternate between high and low phases. According to historical annual flow records, repeated, or 'clustered' dry years are common in California, while wet year clusters are not. Climate change projections for runoff are uncertain, but a drier system is possible, as drier regions are projected worldwide (Cayan 2013).

Figure 5: Historical monthly river runoff in the San Joaquin River showing an increase in winter flow since 1956 and a decrease in spring flow.



Monthly average runoff in both the Sacramento River and San Joaquin River systems between 1956-2007, as compared to 1906-1955, has increased in winter months, and decreased in spring and early summer months (Figure 5) (Anderson 2013).

Over the past 100 years, April-July runoff has decreased by 23% for the Sacramento River basin and by 19% for the San Joaquin River basin. This indicates that a greater percentage of annual runoff in these two major river systems are occurring outside the traditional snowmelt season, potentially as a result of earlier onset snowpack melting. If runoff shifts to earlier in the year, runoff would occur when flood control dominates reservoir storage requirements, and the amount of runoff stored for future use (primarily for agriculture) would be reduced (Anderson et al. 2008).

Increased Water Use to Meet Increased Crop Evapotranspiration

California crop evapotranspiration (ET) accounts for an estimated 75-80% of consumptive use of state project water supplies (Anderson et al. 2008; Mukherjee 2013). Projected increases in air temperature may lead to changes in the amount of irrigation water needed due to changing rates of evapotranspiration (the combination of evaporation from the ground and transpiration from plants).

The effects of climate change on ET in California are difficult to quantify, but could potentially be significant: ET changes not only with temperature but also with CO_2 concentrations in the air, humidity and with the types of plants or crops covering a landscape. According to a Department of Water Resources (DWR) model, rates of ET in California will increase most dramatically with increases in temperature alone, and less so with simultaneous increases in both temperature and humidity (Anderson et al. 2008).

Saltwater Intrusion and Sea Level Rise

In addition to the above-mentioned rainfall, runoff, and groundwater depletion concerns, some areas face the additional problem of saltwater intrusion to surface waters (e.g., Sacramento – San Joaquin Delta) and into groundwater aquifers (e.g., Central Coast counties of Monterey and Santa Cruz).

Where land lies at or slightly above sea level, declining groundwater levels (due to overdraft) enable seawater to move inland into underground aquifers, contributing to saline groundwater, which can be unsuitable for irrigation and many other beneficial uses. California's coastal farm communities rely on groundwater rather than water delivered through California's state and federal surface water projects. Areas like the agricultural Central Coast region which rely primarily on groundwater face both limited water supplies and saltwater intrusion. Saltwater inundation is likely to be exacerbated by both reduced freshwater supplies and rising sea levels associated with climate change (Levy & Christian-Smith 2012). Since the Delta is the hub of the State Water Project (SWP) and Federal Central Valley Project (CVP) conveyance system, saltwater intrusion also stands to impact freshwater provision to the rest of the state, not just to coastal areas – this is discussed below.

Water Supply Management

Reductions in winter snowpack, and the connected changes in timing of spring runoff, are expected to alter the reliability of fresh water supplies in the state (Cayan 2013). According to climate modeling applied to the Colorado River region, runoff from the Colorado River is expected to decrease by 10-30% (Barnett & Pierce 2009). Trends for the Colorado River system are historically in concert with Sierra Nevada rivers. The Colorado River is itself a source of water to southern California (Cayan 2013). With climate change (and even under continuation of current mean annual flows), scheduled water deliveries from the Colorado River are unsustainable; drought- reduced water availability could nevertheless be mitigated through reduced average deliveries to water users (Barnett & Pierce 2009).

Farmers reliant on water deliveries through large infrastructure projects such as the State Water Project (SWP) or the Central Valley Project (CVP) are well aware that water allocations are reduced during water shortages. During the most recent drought in California, from 2007-2009, annual total (SWP and CVP) allocations ranged between 60% - 80% of average; the most junior CVP contractors received between 0-18% of their contract in each year of the drought (Christian-Smith et al. 2011).

According to model simulations using both drier and wetter climate change scenarios, median annual water deliveries from the State Water Project were projected to decrease in the long-term, alongside an increased likelihood of reduced SWP carryover storage in the drier climate case. Federal Central Valley Project south-of-Delta deliveries and carryover storage are also projected to decrease in the drier climate scenario, but increase in a wetter scenario. Northern Delta deliveries were not as sensitive to climate change (Anderson et al. 2008).

Predicted sea level rise, leading to increased saltwater intrusion from the ocean into the San Francisco Bay Delta, could necessitate increased freshwater releases from upstream reservoirs and/or reduced pumping from the Delta to southbound state and federal water projects in order to maintain compliance with Delta water quality standards. This could reduce the amount of water supplied through the state and federal projects to agriculture south of the Delta. Additionally, saltwater intrusion could impact the quality of water delivered through the state and federal projects, potentially increasing the concentration of salt by 11% from current levels (Anderson et al. 2008).

Drought

California's history is marked by extended dry spells known as droughts (Cayan 2013). In farming regions worldwide, extremes in water availability (droughts and floods) have increased in frequency and intensity over the past 50 years (Bailey-Serres et al. 2012). Semi-arid and arid regions are experiencing less precipitation, more aridity, and longer periods without precipitation (Mukherjee 2013). Simultaneously, demand for water is increasing due to population growth and environmental concerns (maintenance of stream flows for aquatic species), and water supply is becoming more variable and scarce (Mukherjee 2013).

Models indicate the U.S. Southwest is likely to become drier and experience more severe droughts in the second half of the 21st century due to reduced precipitation, reduced spring snowpack, reduced late spring and summer soil moisture levels, and reduced runoff. Drought duration, according to indicators such as soil moisture, has historically ranged from 4 to 10 years, while some droughts in the 21st century simulations persisted for 12 years or more (Cayan et al. 2010).

Climate change can impact agriculture directly via negative impacts on yield; many crops are sensitive to drought during specific developmental phases (Mendelsohn et al. 1994; Hayes 2013). In higher-temperature locations in California, irrigation systems help compensate for higher temperatures (they reduce impacts that would otherwise be felt by increased temperatures and decreased precipitation), indicating that irrigation itself will help agriculture adapt to climate change (Mendelsohn & Dinar 2003). Nevertheless, water supplies are likely to decrease alongside any increased use of irrigation for temperature management.

The predicted decrease in water availability in California is expected to have a significant negative impact on farmland values due to impacts to agricultural productivity (Schlenker et al. 2007). In the past, reduced water supplies have been shown to affect agricultural property values (Mendelsohn & Dinar 2003). An empirical study of the benefits of accounting for "water portfolios," defined as different levels of access to water supplies by farms, in California showed that different climate and water factors impact farmland sale values differently according to whether or not a farm has access to more than one source of water (such as water districts and groundwater wells) (Mukherjee 2013). For example, a farm's access to multiple sources of water reduces the impacts on a farm's value (in the form of sale price or appraised value) of salinity, high summer temperatures, and lower mean and more variable surface water supplies (CVP deliveries) (Mukherjee 2013).

Water experts often recommend improved water use efficiency on farms in order to reduce excess agricultural runoff, improve yields, and in some cases conserve water for other non-agricultural uses (Department of Water Resources 2009; California Department of Water Resources, Division of Statewide Integrated Water Management, Water Use and Efficiency Branch 2012). Irrigation efficiency is generally achieved through use of irrigation equipment such as sprinkler and drip systems, or improved management practices, such as field leveling or use of soil moisture information systems (Burt 2013; Gleick et al. 2011). However, irrigation efficiency in different locations can take different forms (e.g., drip irrigation and sprinkler systems) and have different results – depending on local geographies and management practices (Burt 2013).

Many water districts and farms in California – especially in the water-limited San Joaquin Valley and southern California, already employ many water-saving measures that fall under known best water management practices (Burt 2013). Across California, there has already been steady conversion to high-tech irrigation systems and practices; improved grower knowledge of evapotranspiration and soil moisture management; and improved distribution uniformity for efficiency (Burt 2013; Orang et al. 2008). In some regions and at some scales (such as individual field or farm scales) improved irrigation efficiency may be a valid climate change adaptation for reduced water supplies, but in other locations and scales (particularly at the basin scale), ways to reduce total water use may be to potentially fallow agricultural land or change the type of crop grown (Burt 2013).

Flooding

Flooding in terms of agricultural impacts is a collective term for 1) water logging, where soil is saturated with excess water; and 2) submergence, where unwanted standing water covers a land area. Submergence can occur as a result of flash floods, stagnant (medium-length) floods, and deep-water (long) floods. Effects of floods include low oxygen, low light, and low rates of gas exchange – all of which can damage crops although some crops are more susceptible to damage from flooding than others (Xu 2013).

Some of the most substantial historical variations in crop production in California can be traced to individual extreme weather events, such as freezes, floods, or hailstorms. Six out of ten of the most extreme historical events impacting California agriculture since 1993 were floods resulting in crop damages and losses (Lobell et al. 2009).

Research on direct flood impacts to agricultural regions in California is lacking, although floods risks will directly impact the management of water projects and the Delta system that delivers surface water supplies to Central Valley agriculture. Reservoir operations that best manage a climate-changed flood regime in the state may or may not agree with operations that best manage water supplies for agriculture. Flood damages, such as flood-induced failure of aging levee systems, may also disrupt freshwater conveyance through the Delta and throughout the Central Valley (Das et al. 2011).

In the United States, crop losses due to flooding ranked second to drought in many of the past 12 years (Bailey-Serres et al. 2012). California is highly vulnerable to flooding due to its topography and storm systems, and placement of communities and infrastructure in low-lying areas, which include agricultural regions (Das et al. 2011). However, predictions of flood likelihoods and magnitudes with climate change are very uncertain, as flood generating mechanisms include a complex and unpredictable set of climate variables (Das et al. 2011).

California has winter and spring flood events. Winter floods occur in the October-March “wet season,” and are atmospheric river events. Climate indications of winter flood likelihood are not clear enough for definitive climate change predictions. Spring floods occur in the April-July “melt season.” Temperature and solar radiation are climate factors that contribute to spring floods since spring floods stem from snowpack melt (Anderson 2013; Dettinger 2011).

Floodwaters may be fresh, stagnant, or saline and affect plants once or multiple times in a growing season. Agricultural regions can be flooded as a result of flash floods, levee failures, seasonal rises in surface water at low elevations, or tidal surges (Bailey-Serres et al. 2012). For California, the type of flood would be regional. For example, seasonal rises in surface water at low elevations with tidal surges would likely affect the Sacramento-San Joaquin Delta. Consequently this could affect statewide water conveyance. The Salinas River flood of February 1988 is an example of a coastal flood event where intense continuous winter rainfall resulted in widespread landslides and mudslides. Monterey County agriculture-related losses totaled over $7 million, involving approximately 29,000 damaged acres (Monterey County Water Resources Agency n.d.).

The most extreme historical floods in California occurred before the collection of modern data (in the 1800s). However moderately extreme Central Valley floods occurred in 1986 and 1997, both of which nearly overwhelmed flood-control systems in Sacramento (Dettinger et al. 2012). Climate change projections suggest that larger than historical storms in California might become more common with warming temperatures (Dettinger et al. 2012). Simulations of floods generated on the western slopes of the Sierra Nevada Mountains over the period between 1951-2099 yielded significantly larger magnitude 3-day floods along both the north and south of the mountain range in two out of three climate model scenarios (Das et al. 2011).

Projected climate changes may affect the state's flood regimes in several ways, including the potential to intensify or ameliorate flood magnitudes, the potential for both increased and decreased flood frequencies, and changing flood seasonality (Das et al. 2011). Major climate change concerns related to flooding include temperature changes on land that impact the land surface/watershed condition, atmospheric river characteristics and changes in a warmer atmosphere, ocean temperature and circulation patterns impacting storm formation, and year-to-year variability in climate factors contributing to flooding (Anderson 2013).

Altogether, flood impacts on California agriculture will likely be felt in the form of alterations to freshwater reservoir and conveyance systems– not only in the case of a major flood event, but also in standard annual operations that account for flood risks in the future (e.g. new timing regimes for water supply releases and potentially reduced water availability).

Adaptation Strategies

Participate in a Regional Approach to Water Management

The Consortium proposed that CDFA support a regional systems approach to water management. Integrated Regional Water Management (IRWM) is the practice of bringing all stakeholders together to manage regional water resources collaboratively, with the goal of meeting the needs of stakeholders effectively. The California Department of Water Resources supports IRWM through grants and technical assistance and currently 87% of the geographic area of the state is organized into IRWM regions (California Department of Water Resources 2012). Grower interests should be represented in IRWM activities.

There are actions that growers can take to help manage regional water sources, but these activities are specific to the conditions of watersheds and aquifers in different regions. Growers can work with partners in their area, through the IWRM process or otherwise (as appropriate) to pursue the following strategies when appropriate:

- Identify locations suitable for flood control (e.g. floodplains), groundwater recharge, and multi-benefit habitat restoration (e.g. wetlands);
- Investigate options for utilizing excess (flood) waters and rainfall for reuse, storage, or groundwater recharge;
- Exercise water conservation practices, and utilize the most efficient water delivery and irrigation systems available and appropriate (such as use of pressurized water systems and improved irrigation uniformity);
- Re-evaluate reservoir capacity and reservoir operations to manage water availability with a changing climate;
- Research appropriate regulation, management, and use of recycled/reused water;
- Improve water quality by properly managing farm water runoff, and reducing runoff where appropriate;
- Increase water holding capacity (WHC) of soil by improving soil structure and increasing soil organic matter (such as through the use of mulching, composting, permaculture, green manure).

Groundwater Recharge

As part of IRWM there should be an effort to manage groundwater on an aquifer scale. IRWMs need to define the best use for an aquifer and integrate this information into land-use planning for the region.

Figure 6: Through a public-private partnership in Pajaro Valley, stakeholders partnered to implement a managed aquifer recharge basin (the Bokariza Managed Aquifer Recharge Basin) with the goal to infiltrate 100 acre-feet of water to the underlying aquifer. Driscoll's Strawberry Associates, Reiter Affiliated Companies, Landowners, Resource Conservation District of Santa Cruz, NRCS, University of Santa Cruz, and California State University of Monterey Bay worked collaboratively to design, construct, monitor and study the recharge basin. This project is now tracked by Pajaro Valley's Community Water Dialogue, whose goal is to highlight Bokariza as a model to inspire many managed aquifer recharge basins within the watershed. Photo courtesy of Emily Paddock, Driscolls.

Research is needed to predict the decline in quality and quantity of groundwater on a local scale so that the CDFA can work with stakeholders, DWR and the SWRCB to identify ideal locations for groundwater recharge projects and facilitate permitting and planning discussions with regulatory agencies. The Consortium recommended that CDFA should advocate for an incentive, if the situation is appropriate, for growers to install groundwater recharge basins on their properties. One example of a suitable incentive could be mitigation banking so that growers receive some compensation for the use of land for environmental benefit. CDFA can also advocate for the use of flood waters to recharge groundwater: flood control plans that focus on moving water through a system quickly could instead consider strategies to retain flood waters in order to increase groundwater recharge.

Water Recycling

Limited surface water and groundwater supplies and saltwater intrusion are problems that Central Valley and Central Coast farmers have faced for many years. In saltwater inundated coastal regions, water supply problems are being in part addressed with water recycling. In some cases, such as the Pajaro Valley in Monterey County, a combination of both groundwater recharge and recycling are used to deal with limited water supplies, and represent a valid climate change adaptation strategy for regions facing future reductions in both surface and groundwater supplies (Levy & Christian-Smith 2012). In the Salinas Valley, a three-part solution based on increased local reservoir storage; conservation through improved management practices and new technologies such as soil moisture meters, flow meters and drip irrigation; and wastewater recycling have provided stable water supplies to the region alongside reduced groundwater use (Krieger 2013; Salinas Valley Water Coalition 2001).

Changes to Water Distribution Systems

The Consortium identified several changes to water distribution systems that could be advantageous for groundwater recharge and water conservation.

- Remove canal linings in some locations if there is potential to recharge groundwater;
- Research covering irrigation canals with solar panels or other methods of reducing evaporation from canals.

Forest Management to Maximize Available Water Resources

Climate change will impact evapotranspiration rates in the Sierra Nevada, possibly exacerbating water resource challenges. The Consortium recommended that CDFA support further research of sustainable forest management as a tool to improve available water resources. Specifically, methods of forest management that can maximize the water available for dry season irrigation should be studied. Additionally, the development of new tools for measuring snowpack and forecasting water availability is needed.

Water Conservation Outreach and Education

As CDFA moves forward with outreach and education about climate change adaptation, the Consortium recommended, there should be an emphasis on California's vulnerability especially to drought. This is important at the state, regional, and community planning levels. The general public also needs to be aware of the impact of drought on food supply.

In the context of IRWM processes, agricultural stakeholders can advocate for urban water conservation, improving the quality of urban run-off water, and increasing infiltration to groundwater aquifers underlying joint urban and agricultural areas. As an example, The Local Government Commission, a non-profit group that works to promote healthy and sustainable communities, has outlined elements of community planning that can protect water resources. Community design should be compact, mixed-use, walkable and transit-oriented so that automobile-generated urban runoff pollutants are minimized and the open lands that absorb water are preserved to the maximum extent feasible. Permeable surfaces should be used for hardscape. Impervious surfaces such as driveways, streets, and parking lots should be minimized so that land is available to absorb storm water, reduce polluted urban runoff, recharge groundwater and reduce flooding (see Local Government Commission Ahwahnee Water Principles for Resource-Efficient Land Use). CDFA can support and advocate for the adoption of these concepts by city and county governments.

Flood Plain Decision Making

The Consortium recommended creating an online clearinghouse for existing resources and programs that provide information on planting crops in flood plains. CDFA could facilitate the communication between growers and resource managers such as the California Department of Water Resources, counties, and the U.S. Army Corps of Engineers. For example, CDFA could notify growers on how climate change will exacerbate flooding and flood impacts. Further, the Department in collaboration with the California Department of Water Resources, could distribute informational maps that show the likely movement or growth of floodwater in flood plains during a storm or high runoff event to help growers make decisions about what crops to plant in flood plains. One potential method of distributing parcel-specific flood risk maps to growers is through the County Agricultural Commissioner's annual pesticide permitting process.

Research Needs

Pilot Projects

The Consortium suggested the development of pilot research projects on practices and products that can increase agriculture's resilience to drought:

- Research cover-cropping systems and effective crop rotation cycles for water conservation (e.g. tomato grown with drip irrigation followed by another crop type);

- Research the design, regulatory feasibility, and benefits of groundwater recharge projects;
- Develop technology and/or chemicals that can reduce evaporation from water transport systems;
- Research the impact (in terms of volume and quality) on the water system of the use of pressurized irrigation systems at field, farm, and regional scales;
- Research the feasibility and economics of using recycled water or desalinated water for agriculture.

Crop Breeding

The use of drought tolerant crops, or breeding of drought tolerant crops, may be required if climate change reduces surface water supplies (for irrigated crops) or alters rainfall conditions (for non-irrigated crops) during the growing season in order to stabilize yields (Hayes 2013). The Consortium suggested that crop breeding would play a role in climate change adaptation for drought and flooding. The Department could support continued research on crop breeding to improve drought tolerance with a prioritization of crops most susceptible to drought.

Currently, there is extensive research on the molecular biology of water stress in plants and breeding drought tolerant cereal crops (wheat, rice, barley, corn) in terms of yield benefits. There is limited research on the diverse irrigated specialty crops grown in California, but breeding for improved drought tolerance may be possible in these crops as well. For irrigated crops, use of drought tolerant varieties could help reduce the impacts of climate change in terms of water by simply reducing the volume of water used in agriculture. This could make more water available for other uses (Hayes 2013; Morison et al. 2008).

Some crops are more flood tolerant than others, and there exists more flood tolerant plants and/or genotypes, which are those that can survive a period of flooding significantly longer than others of the same species (Xu 2013). In areas where floods are expected to increase as a result of climate change, flood tolerant crops may be a viable adaptation option for some crop types. There is significant research on rice crops, which are grown in flood-prone regions worldwide, but limited research on flood tolerance for the types of specialty crops grown in California (Xu 2013; Hayes 2013).

On-Farm Strategies for Adaptation to Drought and Flooding

- *Investigate opportunities for the installation, management, and monitoring of groundwater recharge basins*
- *Do not plant in flood plains, or, choose appropriate flood tolerant crops when planting in a flood plain*
- *Reduce erosion caused by flood events by cover cropping; not planting in hilly areas; and maintaining appropriate vegetation in riparian areas that will stabilize the soil, but not hinder the movement of water.*
- *Utilize new technologies such as soil moisture sensors, tensiometers, and field level water meters to track irrigation practices.*
- *Reduce water run-off through the following management practices:*
    - *Prepare a farm water conservation or irrigation plan*
    - *Install on-farm water storage to capture rainfall*
    - *Install efficient irrigation systems*
    - *Build appropriate drainage systems such as tail water ponds and tile drains*
    - *Increase organic matter in the soil, increase worm activity and enhance soil moisture holding capacity*
- *Use crop rotation and crop diversification, allow some land to remain fallow, develop crop rotations that are compatible with drip irrigation, and, when feasible, incorporate annual crops into perennial crop systems*
- *Switch to less water-intensive crops*
- *Choose alternatives to water for frost protection such as wind machines, site planning, cover management, or other management techniques*

Chapter 4: Increased Pests and Impacts on Pollination

Introduction

Crop production (yield and quality) is sensitive to weed and insect populations. Crop production and pests are both sensitive to changes in climate. With climate change, pest and pollinator populations are expected to move higher in elevation and northwards in latitude depending on the species and location. Climate change will not have simple, linear effects, on pests and pollinators (e.g. warming resulting in the decrease of a single weed or bee species), but will impact ecosystem dynamics, which are multi-faceted and highly complex. Climate change impacts to pests and pollinators in California are therefore difficult to predict but some research work has been completed in this area. This chapter covers changes to weed and insect pest intensification and climate change impacts on pollinators in California, and proposed adaptation strategies to current and future pest and pollination challenges.

Changes in pest and pollinator populations in California are connected to other climate variables discussed in this report: specifically temperature, precipitation and hydrology/water resources. Temperature and CO_2 effects on plants and insects are widely studied. Studies on altered precipitation and water availability regime effecting plants and insects are virtually absent in terms of climate change. Insect activity and population responses may also be altered in response to changing wind conditions, but effects on winds due to climate change are poorly understood.

Challenges:

- *Altered temperature, CO_2, and water availability will have direct impacts on individual plant, pest, and pollinator species*
- *Climate change will alter inter-species dynamics and the larger ecosystems upon which agriculture depends*
- *Over-reliance on managed pollinators poses a potential risk to agriculture in light of climate change*
- *Conventionally grown, monoculture agriculture will likely be more vulnerable to pest and pollinator changes*
- *Climate change impacts to plant, pest, and pollinator species are complex and unpredictable*

Pest management adaptation strategies amidst climate change will not change substantially from the pest management strategies that exist today. However, growers and pest control managers will need to respond to new pest communities in consideration of more rapid changes in those communities than in the past.

Invasive Species

Invasive species are non-native species that threaten California's agricultural areas and wildlands by displacing native species, hybridizing with native species, altering biological communities, or altering ecosystem processes. Invasive species include weeds such as the familiar California giant reed (*Arundo donax*), yellow starthistle, and scotch broom; aquatic organisms such as the water hyacinth and hydrilla; diseases such as the beet curly top virus (BCTV); and insects such as pink bollworm (California Invasive Plant Council 2013; California Department of Food and Agriculture 2013b). The invasive species discussed here are invasive plants, insects, and crop diseases whose populations (and role in natural and agricultural ecosystems) are anticipated to change with climate change (Mills 2013).

On average, California acquires six new invasive species per year. Trade and travel primarily determine the route of invasion, but sources may change with climate change (Mills 2013). Climate-altered invasive species populations will have impacts on mixed anthropogenic and natural ecosystems. These impacts include not only agricultural, range, and timberland systems, but also vegetation zones in general. Climate change impacts will also influence hydrology and geomorphology (landform dynamics), fire regimes, wildlife populations, recreation areas, and infrastructure (Johnson & California Invasive Plant Council 2013).

Agricultural impacts from climate-change include altered crop weed presence, water supply impacts (such as clogging of conveyance or pumping systems from increased presence of aquatic plants), and changes to pollination (discussed in more detail below) (Johnson & California Invasive Plant Council 2013).

Increased Pest Pressures

Direct impacts of climate change on plant communities, pollination and pest control will become apparent via range shifting of plants and insects (Parmesan et al. 1999; Parmesan 2006; Chen et al. 2011; Deutsch et al. 2008), and from climate related changes to crop physiology such as plant respiration, photosynthesis and water use (Long et al. 2006; Tubiello et al. 2007; Georgescu et al. 2011). Available climate change predictions for pests are based primarily on individual studies on specific individual plant and insect populations. Increased temperatures have the potential to result in more invasive species introductions through expanded habitat range (and continued global trade and travel that regularly introduces new species), and greater potential for destructive pest outbreaks (Trumble 2013; Butler & Trumble 2012; Bale et al. 2002).

The literature on increased atmospheric CO_2 concentration effects suggests there are several effects on plant and insect species individually as well as on their interactions (Trumble 2013). Increased atmospheric CO_2 leads to *increased:* plant consumption by caterpillars, reproduction of aphids, predator growth and altered feeding preferences (e.g. lady beetle growth and aphid consumption), carbon-based plant defense, and effectiveness of foliar (leaf) applications of *Bacillus thuringiensis* (*Bt*, a bacterial pesticide) (Osbrink et al. 1987; Coviella & Trumble 1999; Bezemer et al. 1999; Coviella & Trumble 2000). Alternately, increased CO_2 leads to *decreased:* insect development rates (which can alter phenological synchrony with host plants), response to alarm pheromones by aphids, parasitism, effectiveness of transgenic *Bt*, and nitrogen based plant defenses (Osbrink et al. 1987; Awmack et al. 1997; Roth & Lindroth 1995; Coviella & Trumble 1999; Coviella & Trumble 2000).

Therefore, collectively the combined effect of temperature warming and CO_2 enrichment of the atmosphere will include (mostly complex unknown) impacts on biological control, pest damage, and crop production. Pest damage effects include increased damage from loss of biological control, movement of pests from south to north due to range changes, and increased damage by chewing insects and variable (unknown) damage by 'sap suckers' due to CO_2 increases. Overall, impacts to crop production will be varied, with production increases or decreases depending on crop tolerance to new pest regimes, reduced plant nitrogen content, and increases in plant defense mechanisms due to CO_2 increase (Mills 2013).

Weeds

Major direct effects of climate change that will impact weeds include elevated atmospheric CO_2, increasing temperatures, and changing rainfall patterns. Elevated CO_2 increases rates of photosynthesis, increases plant growth, and increases drought resistance (Osbrink et al. 1987; Trumble 2013). There will be major changes to plant resistance to pests and diseases and to nitrogen use (Trumble 2013). The major categories under which climate change will affect plant populations (and insects – discussed below) include the abundance, the geographic range, and the phenology (developmental timing) of different species.

Abundance

Weeds are "generalists," meaning they can adapt to many different types of environments and therefore have great reproductive capacity (Johnson & California Invasive Plant Council 2013; Dukes & Mooney 1999). Increases in atmospheric CO_2 will results in increased plant growth, as well as potentially increased water use by plants, increased combustibility of plants, and reduced herbicide effectiveness (Johnson & California Invasive Plant Council 2013). An example of this is provided by a study of Canada thistle, where CO_2 induced increases in root biomass, indicating that perennial weeds could be harder to control in a higher CO_2 world. In the study, thistle root and shoot biomass increased with CO_2 levels, as did resistance to a common herbicide, glyphosate (Ziska et al. 2004).Human activities make agricultural and wildlands even more vulnerable to weeds for multiple reasons. They include the disruption of soil and native plant populations for urban and/or rural development that would otherwise keep weed populations in check, emissions that increase atmospheric CO_2 concentrations/nitrogen deposition to the ground surface which supports weed growth, and roadside or power line maintenance activities leading to the spread of weeds (Johnson & California Invasive Plant Council 2013).

Range

Modeling of the southeastern U.S. weed (kudzu, privet, and cogon grass) geographic range response to climate change showed that weeds would greatly expand northward due to increased climatic suitability in those regions (Bradley et al. 2010). Similarly, in the western U.S., climate change could lead to expanded invasion from new species, such as through higher precipitation enabling the spread of non-native grasses (D'Antonio & Vitousek 1992; Smith et al. 2000; Martin-R et al. 1995). The weed, yellow starthistle, has been identified as already moving northeast up into the Sierra Nevada foothills (Johnson & California Invasive Plant Council 2013).

Phenology

It is unknown if the phenology (seasonal timing) of weed growth will change with climate change, as it has shown to change in some western U.S. plants (Trumble 2013).

Insects

Similar to weeds, the major direct effects of climate change that will impact insects include: elevated atmospheric CO_2, increasing temperatures, and changing rainfall patterns (Trumble 2013). Temperature directly affects development, survival, range and abundance of insect herbivores, which in turn impacts agricultural production as well as wildlands ecology (Bale et al. 2002). Increasing temperatures will generally benefit species that reproduce to create more than two generations per year (Bale et al. 2002). Overall, climate change scenario studies suggest that outcomes will include local insect extinctions, changes to endangered species and pest status of some insects and shifted geographic distributions for some insects along with shifts in their host plant ranges (Coviella & Trumble 1999).

Mitigating declines in agricultural production will require compensation for potentially increased insect pest feeding on plants. Increases in insect pest development rates and altered insect development timing are expected to hinder pest control by traditional natural or chemical means (Trumble 2013; Musolin & Numata 2003).

Abundance and phenology

There is a cascading effect of climate change on plant-insect interactions. Due to climate change, host plant suitability may change, leading to changing developmental rates of pests, leading to altered windows of opportunity for parasitism, and finally to altered nutritional status for parasites (Trumble 2013). Insect outbreaks are expected to increase in frequency and intensity with projected global climate change through direct effects of weather change (e.g. temperature or precipitation) on insect populations, and through disruption of community interactions and/or controls (Stireman et al. 2005). While little research exists, the impact of climate variability on species interactions is illustrated by a study of caterpillar–parasitoid interactions across multiple geographic regions. Researchers found that precipitation variability impairs the ability of the parasitoid to track its host caterpillar population (Stireman et al. 2005). Therefore, increased climate variability may increase the frequency and intensity of herbivore pest outbreaks by disrupting natural enemy–herbivore interactions.

Insect herbivores with a large geographic range will be less affected by temperature increases than those with localized habitats. The main effect of temperature in temperate regions (including California) is to influence winter survival. In northern regions higher temperatures extend the summer and this will impact the timing of insect reproduction. This can have the effect of either increasing or decreasing the abundance of a particular insect species depending on how climate change simultaneously affects plant growth. Insect herbivores are adapted to exploit plants with different growth forms and strategies, which will also be differentially affected by climate warming (Bale et al. 2002; Powell & Logan 2005).

Range

Scientific research indicates that insects will move towards the earth's poles (Parmesan 1996; Parmesan 2006; Crozier 2001; Walther et al. 2002; Root et al. 2003; Andrew & Hughes 2004; Logan & Powell 2001). Some insects may become better competitors at higher temperatures. An example is the Argentine ant (Dukes & Mooney 1999). Warming could expand the geographic range of the cold-intolerant pink bollworm in cotton into the San Joaquin Valley, a region that has been inhospitable to the pest due to heavy frost. The distribution and abundance of other cold-intolerant and/or invasive pests such as the olive fly and the Mediterranean fruit fly may also change (Gutierrez, Ponti, et al. 2008). Global warming is predicted to change the geographic distribution of the vine mealybug, an invasive pest of vineyards, and change the relative importance of its natural enemies (Gutierrez, Daane, et al. 2008). In California, climate change simulations suggest the mealybug will become less abundant and move north while enemy parasitoids become less effective (Gutierrez, Daane, et al. 2008).

Crop and pest group geographic ranges may expand or contract. For example, California olive tree and the olive fly ranges are predicted to contract in southern deserts but expand in northern and coastal regions (Gutierrez et al. 2009). Climate change will also results in changes to insect responses to pathogens, especially fungi (Stacey & Fellowes 2002).

Complexity

Responses of biological interactions are complex and cannot be predicted by single variables (e.g. increase in temperature or rainfall). Thus far, most risk assessment research on pest intensification has focused on single species performance or geographic distribution. Also, the focus has been on a single climate factor such as temperature or CO_2, with few research studies accounting for the complex interactions between multiple species and climate variables (Mills 2013; Dyer et al. 2013).

Elevated CO_2 can increase rates of photosynthesis and plant growth simultaneous to increasing pest population success. In a controlled experiment, nitrogen content of plant leaves decreased as CO_2 increased, and pest larvae consumption of plant leaves thereby increased with increased CO_2. However, CO_2 simultaneously resulted in increased plant growth – ultimately resulting in no change in the percentage of leaf area consumed by the pest (Osbrink et al. 1987; Trumble 2013).

Overall, not enough scientific data is available to accurately predict the effect of increased atmospheric CO_2 on insect plant consumption by insects, but it is expected that impacts will be species-specific (Coviella & Trumble 1999).

Impacts from changing rainfall and storm patterns, and soil moisture/water availability to plant and insect dynamics are unknown at both global and local scales. Many classes of plant pathogens are sensitive to changes in soil moisture, and initial modeling frameworks suggest crop pathogen risk responds to precipitation, soil, and plant host properties collectively (Thompson et al. 2013).

Increased temperatures will affect the interactions between pollination and seed dispersal (by animals), as well as predator-prey and parasites/pathogen-host relationships. Generally, negative impacts on ecosystem function are expected with an increased potential for species co-extinctions. Maintenance of species diversity may be the key to ensure adaptation to new and potentially more variable climate regimes (Traill et al. 2010).

Parasitoid-Host Relationships and Biological Control

Parasitoid (an organism that spends a significant portion of their life attached to or within a host organism) and host (animal, plant) relationships provide a good example of the types of complex interactions that will change with climate. The relevance to agriculture of parasitoids is that climate change may modify existing biological control programs (the rearing and release of appropriate natural enemies to invasive pests and weeds) for agriculture by reducing the effectiveness of certain parasite populations, but new untapped opportunities may exist (Hance et al. 2007).

A majority of parasitoid species is already affected by climate change, and even a mid-range warming scenario predicts a significant fraction of those may become extinct. The impact of climate change on plant and animal species is important in higher trophic (food chain) levels that depend on the capacity of the lower levels to adapt to new conditions; parasitoids are therefore organisms for which severe impacts are expected, as they are high on the trophic chain (Hance et al. 2007).

Addressing the lack of research on multiple variable impacts to biological interactions, one study examined increased CO_2 and temperature on alfalfa, armyworm caterpillars, and parasitoid wasps. The beneficial effects of parasitism disappeared at elevated temperatures due to asynchrony between pest and parasitoid development stages. The results suggest that the effectiveness of biological control and insect predators will decline with climate change (Dyer et al. 2013).

Climate change (specifically temperature and CO_2) impacts on parasitoids may reduce the effectiveness of biological control by increasing seasonal variation in natural enemy activity and geographic variation in natural enemy success (Mills 2013; Stireman et al. 2005; California Department of Food and Agriculture 2013b). For example, the future success of biological control for weeds like the yellow starthistle is difficult to predict because climate change will affect both the weed and the control species (Gutierrez, Ponti, et al. 2008). A study of chrysomelid beetles, used for biological control of St. John's wort, showed that one species of beetle is a more successful control in regions with a cold winter while another species is more suitable for regions with mild winters, due primarily to the fact that the beetles' reproductive success depends on the synchronization of their phenologies with climate (Schöps et al. 1996). Therefore, climate change adaptation efforts must take into account "multitrophic" interactions – interactions that occur at multiple levels of a food chain and between each other (Mills 2013).

Impacts on Pollination

Many crops depend on pollination by insects and other animals for food production. Globally, more and more acreage is being allocated to producing animal-pollinated crops (Rader 2013; Klein et al. 2007). Honey bees are the principal pollinator and visit 95% of the world's crops. Species of wild pollinators are known to visit at least 42% of the world's crops (Klein et al. 2012). Both honey bees and wild bees are important contributors to pollination of crops in California.

Pollinator-dependent crops consist of 40% of California's crops by value (2007) (Chaplin-Kramer et al. 2011a; Klein et al. 2007). Crop types whose production is highly dependent on animal pollination include: apples, avocados, plums, peaches, cherries, apricots, pears, raspberries, blackberries, blueberries, and almonds, among others (Klein et al. 2007). California crops that require bee pollination, but for which honey bees are poor pollinators include kiwi, blueberry, alfalfa (seed), eggplant, tomato, and pepper (Klein et al. 2007; Kremen 2013).

Climate change will impact plant pollination by altering the geographic ranges and phenologies of plants and their pollinators including the daily activity patterns of their pollinators (Parmesan et al. 1999; Parmesan 2006; Chen et al. 2011; Deutsch et al. 2008; Long et al. 2006; Tubiello et al. 2007; Georgescu et al. 2011). Mutualistic interactions (such as between insects and insect-pollinated plants) may be especially vulnerable to climate change because of the potential for phenological mismatching - if the species involved do not respond similarly to changes in climate (Kremen 2013). Thus a plant may shift its range or phenology but its pollinators may not shift their ranges or phenologies.

Crop pollinators are mostly generalists. Generalist species are expected to adapt best to climate change. Similarly, most crop plants can be pollinated by an array of species. Thus as crops and insect visitors both shift in ranges and seasonality, it is likely that new mutualisms will form. California is rich in native pollinators, with 1,500 native bee species. California's diverse native pollinator populations may confer some resilience to range and phenological shifts induced by climate change. But, even if climate change poses perhaps less risks for crop pollination than other components of agriculture, contemporary crop pollination systems are already highly vulnerable because agriculture relies almost completely on a single pollinator species - the honey bee (Kremen 2013).

While the Consortium discussed primarily animal (bee) pollination, many crops are wind pollinated. Furthermore, pollination - both from wind and bees - is sensitive to wind speed and temperature. High winds, as well as abnormally high or abnormally low temperatures, can impact pollination and fertilization of certain crops. The impacts of climate change on wind pollination are unknown, and would be a useful area for research.

Wild vs. Managed Pollinators

There are two types of pollinators – managed and wild pollinators. There are only about a dozen managed commercial pollinator species in use around the world today. The honey bee (*Apis*) comprises more than 95% of the managed pollinators. The USDA has attempted to develop new managed bees from wild bee populations but with little success. Global demand for pollination services from managed honey bees is increasing, and therefore management for pollination has become a critical input for farmers (Kremen 2013).

Meanwhile, there are serious concerns about honey bee health. There have been long-term losses in honey bee colony populations in the U.S. for over 70 years which included serious overwintering losses in the late 1980s due to Varroa mite and current annual losses of 30% since the winter of 2006 due to the little understood Colony Collapse Disorder (CCD) (Vanengelsdorp & Meixner 2010). These high levels of colony losses are not unique to the United States but now occur in most regions of the global North. There are many potential causes of CCD (and the broader phenomenon of enhanced colony losses), including disease, lack of proper nutrition, drought, pesticide exposure, poor mite control, and climate change (Potts et al. 2010; Kremen 2013).

Recently, honey bee scientists have hypothesized that the severe droughts in the Midwest in 2012 resulted in stunted sunflower plants that produced less pollen and nectar, resulting in poor honey bee nutrition. This led to greater winter die-offs of bees in the almond orchards in 2013. Another climate/drought-related hypothesis is that concentrations of pesticides in nectar (e.g. in sunflower production) under drought conditions may be higher, leading to negative impacts on bees (Kremen 2013).

The diversity and abundance of wild insect pollinators have declined in many agricultural regions worldwide. In many places, honey bee pollination replaces wild insect pollination. However, wild insects often pollinate crops more effectively. The result is enhanced fruit set compared to crops pollinated by honey bees. A synthesis of pollinator studies from around the world found that crop productivity is more strongly related to wild bee visits than to honey bee visits: all studies included in the synthesis showed a positive relationship between fruit set and native pollinator visitation but only 14% of studies showed that result for honey bees. Nevertheless, the most effective pollination is achieved through combined pollination by honey bees and wild insects (Garibaldi et al. 2013).

In California, native bees are known to enhance the effectiveness of honey bees as pollinators of almonds and sunflowers through interactions that affect how honey bees forage (Brittain, Williams, et al. 2013; Greenleaf & Kremen 2006b). Furthermore, retaining a diversity of pollinators in the system can confer resilience to environmental change (Brittain, Kremen, et al. 2013; Rader 2013).

Pollinator-dependent crops in California that are grown in large monocultures are heavily dependent on managed honey bees for their pollination. However, a recent study estimated that overall, about 35-39% of the pollination provided by insects to Californian crops comes from wild bees (e.g., from native Californian bees rather than honey bees) (Chaplin-Kramer et al. 2011b). In a study of how pollination by wild bees affects tomato production in northern California, wild bees substantially increased the production of field-grown tomatoes most likely by promoting cross pollination of the hybrid variety (Greenleaf & Kremen 2006a). The tomato crop used in the study is otherwise self-pollinating and honey bees rarely visit tomato flowers (Greenleaf & Kremen 2006a). This example demonstrates that even where it is assumed pollinators are not necessary, they may contribute to greater productivity in agriculture.

Landscape Quality and Management

The quality of the farm landscape (organic versus conventional, monoculture versus diversified) and surrounding landscape (amount and proximity of wildlands surrounding the farm) impacts pollinator populations. A global synthesis (including 39 studies, 23 crops, and 14 countries) of how surrounding landscape and farm type impacts native pollinators showed that improved landscape quality improved bee abundance. The highest bee abundances occur on fields that are organically managed, have crop diversity, and include some natural habitats (Kennedy et al. 2013; Allen 2012). In California, due to the proximity of farms to high quality habitats – chiefly rangelands, native bees supply an estimated 35-39% of the value of total pollination services (Chaplin-Kramer et al. 2011b). In California, various studies have demonstrated in almond, watermelon, tomato and strawberry fields, the important role of surrounding natural habitat, on-farm diversification, and organic management for promoting populations of wild pollinators (Morandin & Kremen 2013; Kremen et al. 2002; Klein et al. 2012; Greenleaf & Kremen 2006a; Kremen 2013). While many of the studies of the benefits of wild and managed pollinators on crop production are not climate change studies – they are relevant due to the fact that climate change stands to change agricultural environments. With little understanding of what these changes will be, diverse pollinator species presence is a safeguard against collapse of agricultural crops otherwise dependent on the managed honey bee.

Adaptation Strategies

Public Outreach Opportunities

The Consortium recommended that CDFA should continue to lead on informing the public and agricultural community about anticipated pests of concern, including plant diseases and weeds. Some possible outlets for information sharing are school agricultural days, county fairs, and the Departmental website. Education to the public should emphasize the impacts of agricultural pests on fire, the food supply and environment, and stress the public's role in protecting California's resources from pests.

CDFA currently maintains a database of pest, plant disease, and invasive weed occurrences throughout the state. This data is collected by Pest and Damage Records submitted to CDFA's laboratory. The Climate Change Consortium recommended that CDFA could expand the function of the database to make information available to growers and farm advisors via an accessible, public online system. The addition of some interactive tools, such as mapping abilities, or links to other resources could be useful to farm operators.

Pest Detection and Exclusion Activities

Early detection of invasive species coming into California is critical. CDFA's Pest Detection and Pest Exclusion programs need secure funding to track and monitor invasive species movement into and within California. A streamlined, quick response approach for eradication of those species in California must be developed and implemented.

Provide Habitat for Native Pollinators and Beneficials

Crop production will benefit most from the combined use of different pollinator species, pollinator habitat augmentation, and management practices to provide reliable and economical pollination of crops. There is ongoing research in this area, in particular with the Integrated Crop Pollination Project funded by the Specialty Crop Research Initiative of the USDA. Overall, reducing the risk of crop failures due to inadequate pollination, and improving crop yields, means diversifying pollinator sources, which include honey bees, other managed bee species, and habitat enhancements for both wild and managed pollinators (USDA Specialty Crop Research Initiative 2013; Kremen 2013).

Growers can reduce their reliance on managed honey bees and encourage native pollinators and predators by providing necessary habitat for these species on their farms, including use of polyculture, hedgerows and flower strips. CDFA can distribute documents about the costs and benefits of, managing and maintaining hedgerows and flower strip plantings to growers. UC Cooperative Extension and Resource Conservation Districts can connect with growers to promote the advantages of improving pollinator habitat. These are also appropriate organizations to educate growers on the pollination services that native species provide.

Figure 7: Flower strips (top) and hedgerows (bottom) can provide habitat and needed nutrition to pollinators and beneficial insects. Photos provided by Claire Kremen, University of California, Berkeley

Growers are not the only group that can improve habitats for native pollinators and beneficial predators. The Consortium recommended that CDFA should provide outreach to partners regarding the value of native pollinators to agricultural systems. CDFA can work with other agencies, cities, counties, Caltrans, irrigation districts, and utilities to find opportunities to create and/or restore habitat. For example, CDFA could advocate that Caltrans consider locally-appropriate options for vegetated (as opposed to sprayed and mowed) roadsides when making decisions about roadside maintenance. Some other possibilities for planned habitat areas could be canal banks, storm drainage basins, right-of ways, power pole alleyways, and agricultural buffer zones. Agencies should consider the costs and benefits of habitat restoration in these areas and compare them with the costs and benefits of the conventional management practices such as spraying or mowing. Cities and counties could begin to incorporate pollinator habitat into their climate action plans.

Research Needs

Some questions require further study in regards to habitat restoration on farms:

- What are the actual food safety risks of habitat restoration on farms? The Consortium recommended that documenting the food safety concerns of habitat restoration and risks to consumers would be beneficial.
- Research is needed to quantify the damage done by vertebrates such as ground squirrels, gophers, and voles and how to counter the impact.
- Research is needed on application of habitat restoration in large conventional agriculture settings. For example, at many locations in the San Joaquin Valley monocultures are grown over large areas. How can components of pollinator habitat be integrated into this type of land management?

On-Farm Strategies for Adaptation to Increased Pest and Pollination Pressures

- *Diversify crops*
- *Stay informed on emerging pests of concern through CDFA's website*
- *Practice Integrated Crop Pollination: the use of managed honey bees combined with native pollinators*
- *Attract native pollinators and other beneficials with hedgerows, flower strips, and polyculture*
- *Provide nesting sites for native pollinators*

Quantify the Economic Benefits of Providing Habitat to Beneficials

The Consortium recommended that the Department can partner with growers who have implemented habitat restoration on their properties and use historical records to quantify the costs and benefits of cover crops, hedges, and poly mixtures. One possibility would be to compare pesticide use records in areas where restoration was implemented to areas where the practices have not been implemented.

Honey Bee Health

Production of many of California's specialty crops such as almonds and melons relies heavily on managed honey bees and honey bee health has been in decline, and is therefore a cause of concern. Research on honey bee health is ongoing, and the Consortium recommended additional support for research on the following:

- Identify and register new and safe products or biocontrol methods to deal with Varroa mite;
- Study bee species for breeding, especially with regard to species' resistance to Varroa mite;
- Study pesticide impacts on honey bee health;
- Study nutritional needs of honey bees and methods of supplying this nutrition (e.g. hedgerows, flower strips).

Crop Breeding

Breeding is needed for self-fertile varieties, starting with breeding for species completely reliant on pollination, such as almonds.

Pest Forecasting and Biocontrol

CDFA should adopt pest forecasting tools and/or models that incorporate climate change and pest-specific observational data on pest distribution. CDFA could generate a list of pests that will likely be a threat to specific agricultural regions in California under future climate conditions. The Consortium recommended the Department should support research for biocontrol for expected pests and ensure that the process for importing a specific biocontrol agent remains in place.

California has generalist beneficial species that may provide control of many new invasive pests. There is a need to study the interactions of these species with the anticipated pests to see if the generalist species can provide effective control.

Chapter 5: Additional Recommendations

The Climate Change Consortium identified several over-arching themes that can lead to better communication and the streamlining of resources with the goal of increasing specialty crop agriculture's resilience to climate change.

Involve Growers in the Climate Change Adaptation Discussion

There is a need to improve growers' understanding about climate change impacts and focus on adaptation strategies that are practical and with purpose. The Consortium noted that it was important to encourage growers to recognize and integrate adaptation measures into operational decisions. Also, it was important to encourage growers to share their adaptation experiences for better monitoring and to inform future research and funding needs.

The California Energy Commission sponsored a study on climate change adaptation in Yolo County, *Adaptation Strategies for Agricultural Sustainability in Yolo County, California* (Jackson et al 2012). In this study, growers were surveyed about their perspectives of climate change impacts and how these impacts influence their decision-making about farming practices. It would be helpful to continue to survey grower perspectives and attitudes about climate change on a statewide level. What have growers experienced about climate change? What adaptation strategies have growers already taken? Why or why not are growers interested in doing certain actions? Growers are likely to have insights into adaptation strategies that are regional and crop-specific.

Grower Technical Assistance and Incentives

Climate change impacts increase grower needs for technical assistance. Resource Conservation Districts, UC Cooperative Extension, and USDA Natural Resource Conservation Service are appropriate programs or agencies for this type of technical assistance. These agencies can provide one-on-one training and expertise to growers about climate change impacts and adaptation strategies. These resources need to be locally available to growers at any scale of operation. CDFA can support these efforts through advocacy to public agencies and private stakeholder groups for reinvestment into technical assistance agencies.

The Consortium recommended that it is important to encourage industry to provide leadership in finding solutions to offset climate change impacts by providing incentives to growers. CDFA can support USDA Natural Resource Conservation Service in a review and creation of policies to improve grower's ability to adapt to climate change. It would be necessary to consider new technologies for water, soil, and pest management and suggest ways to scale best management practices (BMPs) to farms of all sizes. BMPs would be incentivized through cost-sharing or low interest loans and would include (among other BMPs):

- implementation of water conservation plans;
- use of water efficient technology and improved irrigation uniformity (see Figure 8);
- soil moisture and groundwater monitoring;
- water budgeting (such as metering, where appropriate) (see Figure 9);
- on-farm water storage;

- groundwater recharge projects;
- building water holding capacity of the soil;
- habitat restoration projects;
- managing hedgerows or flower strips.

Figure 8 (top): An on-farm water meter used as part of conservation efforts. Photo courtesy of Jocelyn Gretz, Rio Farms.

Figure 9 (bottom): Irrigation uniformity testing in a sprinkler irrigated field. Photo courtesy of Jocelyn Gretz, Rio Farms.

The Consortium also encouraged growers to incorporate climate change into their normal and long-term business planning, and thereby leverage existing grower capabilities that may otherwise go unrecognized.

Educational Events

CDFA can partner with other governmental agencies, NGOs, industry groups, and academics to inform growers of the benefits of building climate change resiliency into their farming practices. The Consortium recommended that CDFA should tailor some climate change outreach programs to target pest control advisors and plant nutrient managers since these agricultural support service personnel works closely with growers and often initiate decision-making on-farm in regards to water use, pest control, and other management strategies. This information distribution pathway will help facilitate the transfer of technical scientific information to growers.

The Consortium suggested it would be beneficial to host an annual or bi-annual winter conference on climate change adaptation for the agricultural community. Multiple state agencies, researchers, and growers could participate in order to share recent research and discuss adaptation activities.

Interagency Cooperation

Interagency coordination with key partners, such as California's Strategic Growth Council, on the recommendations of the Climate Change Consortium, to ensure cross-agency efforts are critical to support the adaptation needs identified by the Consortium.

Recognition for Innovative Growers

Recognizing growers that implement climate change adaptation strategies on a CDFA website and through creation of a Climate Change Adaptation Award would be useful. The award would be designed as an incentive for growers to plan for climate change and would draw positive attention to grower brands. Outreach to the broader public through media would be integral to this effort. A food-focused media campaign might include recognizing growers at farmers markets, events with celebrity chefs, press releases, and other venues to publicize the benefits of agriculture to the community and environment.

International Information Sharing and Grower-to-Grower Exchange

The Consortium recognized that CDFA should partner with the agricultural industry to establish an international grower-to-grower information sharing program. California growers with expertise in production, who are also early innovators, can be identified by commodity groups and be connected through an exchange in order to share adaptation practices specific to their commodities. These growers could exchange information and potentially visit with other growers in California, other states, and internationally to learn about cropping patterns and cultivation practices that can be applied to promote resiliency to climate change. In particular, the program should consider climate analogues - places with climates similar to California's future climate zones.

CDFA should work with commodity groups to identify partnerships (growers here and elsewhere); help facilitate webinars or other meetings; assemble a comprehensive list of other existing programs/documents that work to offset climate change impacts in other states and countries. CDFA can coordinate the dissemination of this information to growers through a comprehensive climate change adaptation information website and promote farmer-to-farmer education.

Establish an Online Research Needs Forum

Management techniques, alternate crops, and cultivars identified as part of a California-specific adaptation portfolio will need to be studied further in California before they are recommended to growers. Research plots can substantiate and maximize the value of new techniques and cultivars before they are adopted by California growers.

The Consortium recommended the development of an online forum to match the needs of industry groups and growers to researchers. The forum would be a place for growers to express their needs, and for researchers to propose research projects based on those needs. The forum would likely appeal to researchers that often need to meet an outreach requirement for funding. Additionally, the forum could include a function to identify funding and encourage the cooperation of growers in the research process so that projects can be completed "on-farm."

Farmland Conservation and Smart Growth

Conserving irrigated farmland may reduce the impact of urban heat islands and mask the regional climate warming effects of greenhouse gases (Jackson 2012; Bonfils & Lobell 2007; Kueppers et al. 2007). A recent study shows that urban land use in Yolo County, California, had average emissions of more than 70 times that of irrigated cropland (Haden et al. 2013). CDFA should work to educate local and state governments about the climate benefits that adjacent agriculture can provide, and to encourage smart growth regulations, which include boundaries on development. The Consortium recommended that CDFA should also advocate for policies that provide financial incentives for farmland protection, prioritizing farmland near urban boundaries and identifying farmland with highly productive soils. Capacity for farmland preservation currently exists through the Williamson Act (State of California, Department of Conservation 2007).

Investigate Regulatory Barriers to Adaptation

Growers need to be able to react quickly to changing weather or year-to-year variations in weather or pests. Some regulations may not allow for short-term flexibility. Regulations should be studied to identify if there are any barriers that may limit the adaptation of agriculture to climate change. In particular, the following regulations need to be investigated to make sure that they do not hinder climate change adaptation:

- EPA and DPR registration of pesticides relative to climate change threats;
- Special local need registrations and emergency exemptions (Section 24(c) and Section 18 of the Federal Insecticide, Fungicide, Rodenticide Act);
- Water rights, and water trading rules;
- Federal crop insurance program for specialty crops to address California conditions.

Crop Breeding

The Consortium recommended crop breeding specifically for resilience to climate change impacts. Growers support crop breeding as a practical solution for environmental pressures. A poll taken by farmers in Iowa indicated that 63% feel that the seed industry should develop crop varieties that will be resistant to changes in future weather patterns (Iowa State University 2011).

CDFA can be a centralized location for organizing and advocating for breeding needs, and can provide guidance to breeders regarding potential future crop stresses. CDFA should work with the USDA, UCCE, and specialty crop industry groups to create a list of breeding priorities so that crops with more vulnerability to climate change pressures are targeted first for research. For example, due to grower demand and clear climate trends, the breeding of low-chill cherry varieties should be a priority since cherries are already being impacted by decreased winter chill hours in California.

Federal, state and industry partnerships are needed to support and fund University research programs that use modern genetic techniques to identify genes that promote climate change resilience (heat-tolerance, low-chill, drought-resistant, flood-resistant, disease or pest-resistant). Similar partnerships are needed to translate basic research discoveries into new crop varieties that will serve the California agricultural industry and consumers. CDFA also can help by supporting the development of crop breeding collections with known genetic inheritance and by facilitating field testing of new varieties in collaboration with federal agencies.

Integral to any breeding program will be the successful marketing of new varieties. The marketability of new cultivars will weigh considerably during the breeding process. Yield and quality of the product must be maintained.

As new varieties of crops are developed, the Consortium believes it is vital to continued agricultural success that the genetic materials of crops are preserved and diversity maintained. CDFA can support preservation of genetic resources by pursuing funding and working with private partners.

Identify Infrastructure and Economic Opportunities and Barriers to Relocating Crops

The Consortium recommended that CDFA should initiate a study of the infrastructure and economics of relocating crops within the state as well as to outside of the state. For example, what infrastructure (such as processing facilities) would be required to produce avocados in another region of California? This project would involve quantifying the costs of infrastructure building, comparative cost studies of moving or losing certain crops, identifying possible partnerships with existing organizations and groups in order to make relocation more feasible. Studies of climate analogues (mentioned previously) can be used in this process. For example, projections suggest that mid-range warming scenarios will result in winters in Yolo County resembling current winters in Kings County (Pope 2012). Given this projection, what opportunities might exist for expansion of certain crops into Yolo County? To complete this type of study, cooperation between multiple agencies and research institutions would be required, not only to conduct the study, but also to validate the findings.

Invest in Improved Weather Forecasting and Communication

Growers need access to the specific forecast and historical data through intuitive and accessible interfaces. The Consortium recommended identifying specific weather-related needs of growers. For example, using farming expertise, CDFA can work with growers to identify what data is important to their particular crop cycle (such as ET rates, chill hours) and see that these parameters get incorporated into agency and commercial products. CDFA should provide growers with links to services and new research/tools on their website, serving as a portal for existing programs such as the Department of Water Resources' California Irrigation Management Information System (CIMIS) and the National Integrated Drought Information System (NIDIS).

Commercial Opportunities for New Technologies and Products

- *Farm equipment suitable for multi-cropping and increasingly diversified farming operations*
- *Shade-producing structures and products*
- *Heat and drought, low-chill, and flood tolerant crop breeds*
- *User friendly weather prediction and climate monitoring tools for growers*

Improvements in Technology

Climate change may represent a business opportunity for the development of technologies and equipment to meet new demands in the marketplace. For example, the development of a practical tool to measure bud development and chill accumulation could help growers make decisions about applying rest-breaking materials.

Marketing Efforts

California's high standards in labeling and import requirements must be maintained. CDFA should be involved with marketing the benefits of California grown products because they meet truth in labeling requirements, pesticide safety requirements, and have a reduced risk of spreading invasive pests. Under future climate change conditions, growers will count on additional marketing efforts to offset economic losses and increased expenses. The Department can be involved in this effort.

Summary of Recommendations

The Climate Change Consortium recommended ways that CDFA can help growers adapt to climate change through the categories of Outreach and Education, Planning and Resource Optimization, Research Needs, and Technology and Innovation. Table 1 below lists the recommendations in these categories. Further information about each recommendation is provided in Table 2.

Table 1. Summary of categories and recommendations by title. More detail for each recommendation is provided in Table 2 below.

Recommendation	Corresponding Page Number in Table 2	Corresponding Page Number in Final Report
Outreach & Education		
Grower Technical Assistance	50	42
Interagency Cooperation	51	44
Recognition for Innovative Growers	52	44
International Information Sharing and Grower-to-Grower Exchange	52	44
Establish an Online Research Needs Forum	53	44
Pest and Beneficial Species Outreach	53	38
Flood Risk Outreach	53	27
Interagency Habitat Restoration Projects	54	39
Climate Change Adaptation Conference	54	43
Planning and Resource Optimization		
Participation of Agricultural Interests in Integrated Regional Water Management Process	55	24
Review Regulatory Barriers	56	45
Farmland Conservation	56	45
Improve Growers' Ability to Adapt to Climate Change	57	42
Secure Funding for Pest Programs	57	38
Marketing Efforts	57	47
Research Needs		
Economic and Environmental Studies of the Costs, Benefits, and Risks	58	15, 26-28, 40, 46
Research Plots for Experimental Study	59	15
Crop Breeding	59	14, 28, 40, 45
Improve Honey bee Health	59	40
Study Impacts of Saltwater Intrusion	60	25-26

Recommendation	Corresponding Page Number in Table 2	Corresponding Page Number in Final Report
Pest Forecasting	60	41
Augmentative Biocontrol	60	41
Crop Fertility	60	15
Technology and Innovation		
Weather Information	61	46
Field Level Monitoring Tools	61	47

Table 2. Further explanation of each recommendation by category.

These Consortium recommendations were made for CDFA as the principal agency, but given the overlap of agriculture with other sectors (e.g., water), the importance of collaborating with other state, federal, and research agencies are noted. The following ranges have been adopted for "Timeframes": short = 0-6 months, medium = 6-18 months, long = > 18 months. The following expense distributions have been approximated for "Potential Cost": Low = $ 0-1,000, Medium = $ 1,001-10,000, High => $10,000. UC ANR is the University of California Agricultural and Natural Resources which includes agricultural Extension Services (e.g., farm advisors).

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Outreach & Education				
Grower Technical Assistance CDFA should facilitate an increase in grower technical assistance and trainings specific to climate change adaptation, such as for water, soil, and pest management, by doing the following: 1. Advocate for *public* (e.g. CA Public Utilities Commission, California Energy Commission, etc.) and *private* (e.g. commodity groups) re-investment in grower technical assistance such Resource Conservation Districts and UC Cooperative Extension; 2. Increase grower awareness of existing technical assistance and training programs; 3. Act as a clearinghouse for climate change adaptation-specific best management practices (BMPs) and coordinate with other groups to disseminate this information to growers; 4. Coordinate with agencies and education institutions to develop new trainings, (optional) certification programs, and continued education units (CEUs), for pest, soil, and water management practices that help growers adapt to climate change. CDFA should: • Coordinate trainings through existing training funding programs carried out by agencies and groups like DWR and Irrigation districts; • Tailor climate change outreach programs to pest control advisors and nutrient managers.	• Resource Conservation Districts • UC ANR Cooperative Extension • California State Universities • Regional Water Boards • Ag Associations & Commodity Groups • Agricultural Commissioners • Growers • Department of Water Resources (DWR) • Irrigation Districts • Natural Resource Conservation Service • California Certified Crop Advisors • California Association of Pest Control Advisors • Association of Applied IPM Ecologists • Xerces Society • Audubon California	Primary	Medium	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Interagency Cooperation CDFA should ensure that staff are present and advocating for growers during agency and cross-agency discussions (e.g., Strategic Growth Council, California Energy Commission, Public Utilities Commission) regarding energy and water use efficiency and other matters relevant to climate change adaptation. CDFA should ensure cross-agency efforts support the adaptation needs identified by the Consortium.	• California Strategic Growth Council • Governor's Office and Planning and Research • State Board of Food and Agriculture • Climate Action Team • Local Agency Formation Commissions (LAFCOs) • California Public Utilities Commission (PUC) • California Energy Commission (CEC) • California Department of Water Resources (DWR) • Regional Water Boards	Primary	Short	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Recognition for Innovative Growers CDFA should recognize growers who adopt climate change adaptation and resilience practices. The CDFA should acknowledge growers in a publically accessible, *food-focused* context, using: • Grower case studies posted to the CDFA website; • A food-focused media campaign that includes farmers markets, events with celebrity chefs, California grower "branding"; • A CDFA "Climate Change Adaptation" award.	• CDFA Environmental Farming Act Science Advisory Panel • UC ANR • Resources Conservation Districts • Ag Associations & Commodity Groups • Agricultural Commissioners • Non-governmental organizations • Media outlets • California Farm Bureau Federation	Secondary	Medium	Low
International Information Sharing and Grower-to-Grower Exchange CDFA should fund and coordinate the development of an international grower-to grower information-sharing exchange that will help California growers: • Identify low chill and heat tolerant varieties used in locations outside California (nationally and internationally); • Identify alternative crops that may be grown successfully in the various regions of California under future conditions; • Investigate management practices that can counter the weather impacts of climate change such as heat stress, drought, and flooding; • Identify management practices for pests that may be helpful with increased pest pressures, and that support beneficial pests and pollinators.	• International Embassies • International Consulate General offices • International Universities • California Farm Bureau Federation • University of California System • Ag Associations & Commodity Groups • Growers • Agricultural Coalitions • Agricultural Commissioners • UC ANR	Tertiary	Short	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Establish an Online Research Needs Forum CDFA should fund and establish on online research needs forum to match grower adaptation needs with researchers in the field.	• Growers • Agricultural Coalitions • Ag Associations & Commodity Groups • UC ANR and Other Universities • Agricultural Commissioners	Tertiary	Short	Low
Pest and Beneficial Species Outreach CDFA should inform the public about pest and plant disease threats as well as beneficial plants, insects, and pollinators, relevant to climate change adaptation. Outreach could be conducted through: • Events such as school Ag Days, fairs and media outlets; • A newly created database of pest and damage records available to growers and farm advisors; • Distribute educational materials to growers about the benefits, costs, management and maintenance of hedgerows and flower strips.	• CDFA Plant Health Division • CDFA Environmental Farming Act Science Advisory Panel • California Department of Pesticide Regulations • California State Association of Counties • Agricultural Commissioners • UC ANR • California Invasive Species Council	Tertiary	Short/Medium	Low/Medium
Flood Risk Outreach CDFA should inform growers of the increased flooding risk due to climate change and: • Compile an online list of existing resources and programs that deal with flooding; • Distribute parcel-specific maps that predict movement or growth of flood plains to help growers make decisions about planting in those areas.	• California Department of Water Resources (DWR) • Resource Conservation Districts • Agricultural Commissioners • Municipal Water Districts • Ag Associations & Commodity Groups • Agricultural Coalitions	Tertiary	Medium	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Interagency Habitat Restoration Projects The CDFA should work with Key Partners to identify opportunities to create habitat for beneficial native pollinators. CDFA should provide outreach to Key Partners regarding the value of native pollinators to agricultural systems.	• Caltrans • Local (City, County) Governments • Utility companies and California Public Utilities Commission (PUC) • Irrigation districts • Resource Conservation Districts • CDFA Environmental Farming Act Science Advisory Panel	Tertiary	Long	Low/Medium
Climate Change Adaptation Conference The CDFA should host a winter (annual or bi-annual) statewide conference on climate change adaptation for all agricultural stakeholders: agencies, growers, agricultural groups, and researchers. Information about the conference would be shared on a website including research abstracts.	• Multiple State Agencies • Growers • Ag Associations & Commodity Groups • Agricultural Commissioners • UC ANR and other Universities	Tertiary	Medium	Medium

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Planning and Resource Optimization				
Participation of Agricultural Interests in Integrated Regional Water Management Process CDFA should advocate for inclusion of grower interests in the Integrated Regional Water Management (IRWM) process (beyond Irrigation district representation) and any future *regional* water planning processes coordinated by the Department of Water Resources (DWR). Grower needs to be addressed in these efforts including: • Identifying locations for flood control (e.g. floodplain), groundwater recharge, and multi-benefit habitat restoration (e.g. wetlands); • Options for utilizing excess (flood) waters for reuse, storage, or groundwater recharge; • Utilizing pressurized water systems where appropriate; • Re-evaluating reservoir capacity and reservoir operations to manage water availability with a changing climate; • Appropriate regulation, management, and use of recycled/reused water; • Existing or emerging conflicts between urban and agricultural water use (expected to increase with climate change); • Water quality (expected to decrease with climate change); • Promotion of water conservation and efficiency at field, district, and regional scales; • Low impact development to improve urban-impacted infiltration to groundwater aquifers.	• Department of Water Resources (DWR) • Regional Water Boards • Irrigation Districts • Growers • Ag Associations & Commodity Groups • Agricultural Commissioners • Caltrans • Department of Fish and Wildlife • Resource Conservation Districts • California Farm Bureau Federation • Other local stakeholders	Primary	Long	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Review Regulatory Barriers The CDFA should perform or fund a review of regulatory barriers to climate change adaptation including food safety. Safe and sustainable revisions of the following should be considered: • EPA and DPR registration of pesticides relative to climate change threats; • Section 18 and Section 24(c) of FIFRA • Water rights, and water trading rules; • Federal crop insurance program for specialty crops to address California conditions. • Food safety regulations	• California Department of Pesticide Regulations • Pesticide/Chemical Manufacturers • California Department of Public Health • Ag Associations & Commodity Groups • Agricultural Commissioners • Food and Drug Administration • Leafy Green Products Handler Marketing Agreement (LGMA) • State Water Resources Control Board • California Department of Water Resources (DWR)	Primary	Medium/Long	Low
Farmland Conservation The CDFA should promote farmland conservation through Key Partners to increase agriculture's economic resilience to decreased revenue and increased costs associated with climate change. Also ensure adequate time for agricultural land transition to alternative crops in the long-term instead of to urban development in the short-term.	• California Department of Conservation • Local (City, County) governments • Land trusts • Local Agency Formation Commission • USDA Natural Resource Conservation Service (NRCS)	Secondary	Medium/Long	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Improve Growers' Ability to Adapt to Climate Change CDFA should support USDA Natural Resources Conservation Service in a review and/or creation of policies to improve growers' ability to adapt to climate change. These policies should: • Promote new technologies for climate change relevant to water, soil, and pest management; • Incentivize grower adoption of technologies and practices for improved water management, which includes use of: water meters, soil moisture sensors, on-farm water storage, and groundwater recharge where possible; • Suggest ways to scale best management practices (BMPs) to all sizes of farms.	• USDA Natural Resources Conservation Service (NRCS) • Ag Associations & Commodity Groups • Growers • Resource Conservation Districts • UC ANR Cooperative Extension • Irrigation districts • California Department of Water Resources (DWR)	Secondary	Medium	Low
Secure Funding for Pest Programs CDFA should maintain and secure additional funding for pest exclusion and detection programs.	• Legislature • Ag Associations & Commodity Groups • State Board of Food and Agriculture • Agricultural Commissioners • USDA Animal and Plant Health Inspection Service (APHIS) • California Department of Fish and Wildlife	Tertiary	Ongoing	Medium
Marketing Efforts CDFA should coordinate with USDA to promote and market California brands to offset expected economic losses and/or increased expenses due to climate change.	• USDA • Grower Associations • Commodity groups	Tertiary	Medium/Long	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Research Needs				

Economic and Environmental Studies of the Costs, Benefits, and Risks of:
• Crop relocation, including infrastructure considerations, and climate analogues; define where crops will be best suited under future climate conditions considering soil type, topography, water availability, and potential hazards;
• Crop-specific sustainability of hothouse/greenhouse production and the development of BMP's for individual crops;
• Water Management, in terms of:
  - Increasing above and below ground water storage capacity;
  - Groundwater recharge;
  - Use of recycled/reused or desalinated water;
  - Efficient irrigation technology implementation;
  - Reduction of evaporation from irrigation canals using solar panels or chemicals;
  - Sustainable forest management practices to enhance water resource availability for agricultural systems downstream.
• Maintaining wild or restored habitat areas in agricultural, urban and non-urban areas (including road sides and utilities' right-of-ways), while ensuring food safety components of agricultural operations.
	• University of California
	• Ag Associations & Commodity Groups
	• California Department of Water Resources (DWR)
	• Xerces Society
	• Audubon California
	• Resource Conservation Districts
	• US Bureau of Reclamation
	• Regional Water Boards
	• Irrigation Districts
	• California Department of Public Health
	• Food and Drug Administration
	• Produce Marketing Association
	• United Fresh
	• Local Governments
	• Caltrans
	• Utilities (PG&E)
	• California Public Utilities Commission
		Primary	Long	High

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Research Plots for Experimental Study: Locate research plot space for the study of: • Structural, mechanical, or biological methods to reduce crop heat stress; • Crop training systems for perennial crops to protect them from heat stress and sunburn; • Climate-controlled cultivation of certain crops; • Cover cropping and crop rotations that can efficiently utilize irrigation systems and prevent runoff; • Water conservation and/or efficiency outcomes of grower use of soil moisture monitoring, on-farm water storage, and improved irrigation uniformity; • Benefits of habitat restoration in large-scale agricultural systems. • Methods or inputs to increase winter chill quantity and quality.	• University of California • Ag Associations & Commodity Groups • UC ANR • USDA Natural Resource Conservation Service (NRCS) • Xerces Society • Audubon California • Resource Conservation Districts	Secondary	Long	High
***Crop Breeding*:** Coordinate with key partners to promote research on: • Crop heat and cold tolerance; • Low chill varieties; • Self-fertile varieties of almonds and other pollinator-dependent crops; • Maintain public crop breeding programs (e.g., secure funding for maintenance of germplasm information).	• University of California • Plant Breeding Companies • Growers • USDA	Tertiary	Long	High
Improve Honey Bee Health Identify new methods and products to improve honey bee health, in terms of: • Disease • Breeding • Pesticides • Nutrition	• University of California and California State University • Ag Associations & Commodity Groups • UC ANR Cooperative Extension • USDA	Tertiary	Long	High

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Study Impacts of Saltwater Intrusion Study saltwater intrusion on agricultural lands, asking the following questions: • Where are the greatest threats? • Will sea level rise add to the problem - in coastal areas or elsewhere? • What are the adaptation solutions available to growers?	• Coastal Conservancy • Army Corps of Engineers • Resource Conservation Districts • California Department of Water Resources (DWR) • University of California and California State University Researchers	Tertiary		
Pest Forecasting CDFA and other agencies should develop and adopt pest forecasting tools that account for the effects of climate change	• USDA Animal and Plant Health Inspection Service (APHIS) • University of California • National Aeronautics and Space Administration (NASA)	Tertiary	Medium/Long	Medium/High
Augmentative Biological control Study opportunities in augmentative biological control, the release of large numbers of native natural enemies, for emerging pest threats (e.g., assess the ability of California's beneficial generalist species to provide control for new invasives).	• University of California • Other Universities	Tertiary	Long	High
Crop Fertility Research to describe and determine the effects of climate change on fertilization and pollination of California crops.	• University of California • Other Universities	Tertiary	Medium	Low

Recommendation	Key Partners	Level of Priority	Timeframe	Potential Cost to CDFA
Technology and Innovation				
Weather Information CDFA should compile a list for NOAA of grower needs for weather data and forecast products for up to 21 day forecasts including improved: • Accuracy and spatial resolution; • Grower-specific data products such as heat- or chill-hours, fog presence, soil moisture, evapotranspiration (ET), drought and flood prediction indicators; • Access to data (the historical record) through accessible data interfaces and/or list of providers of relevant data products; • Warning systems.	• National Aeronautics and Space Administration (NASA) • National Oceanic and Atmospheric Administration (NOAA) • National Weather Service • Ag Associations &Commodity Groups • Agriculture Coalitions • California State University • University of California • Cal Emergency Management Agency	Secondary	Long	High
Field Level Monitoring Tools CDFA should develop a list specific to grower needs for vegetation and pest information from new/emerging technologies (e.g., remote sensing, mobile sensors) for field level monitoring of environmental variables and farm management.	• National Aeronautics and Space Administration (NASA) • Private Companies • California State University • University of California • Ag Associations &Commodity Groups • Agriculture Coalitions	Tertiary	Medium/Long	Medium/High

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