

AN ASSESSMENT OF THE IMPACTS OF FUTURE CO₂ AND CLIMATE ON CALIFORNIAN AGRICULTURE

A Report From:
California Climate Change Center

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Arnold Schwarzenegger, *Governor*

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

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Abstract

This report evaluates how global warming and the associated rise in atmospheric CO₂ will affect several facets of agriculture in California—crop production, water use, and crop phenology. Our analysis is based on a survey of peer-reviewed literature, an analysis of trends in crop-related climate variables, and simulations with a biophysical model, CANVEG.

Our survey of the pertinent literature reveals a combination of positive and negative effects of warming and elevated CO₂ on crop production. Elevated CO₂ gives crops a spurt in growth, as photosynthesis responds positively to extra CO₂. But enhanced photosynthesis is not sustained, as photosynthesis eventually experiences down-regulation. Elevated CO₂ also causes stomata to close. This effect has favorable implications on water saving by reducing transpiration at the leaf scale. In contrast, larger crops growing in a warmer climate will use more water, at the field scale. Indirect effects of elevated CO₂ and warming on agriculture will include a lengthening of the growing and transpiration seasons, stimulation of weeds and more insect pests. Pollination will be negatively impacted if warming causes asynchronization between flowering and the life cycle of insect pollinators.

An assessment of water use for a walnut orchard for future conditions that are 3°C (5.4°F) warmer and experience 500 parts per million (ppm) of CO₂ was produced using the biophysical model CANWALNUT. Computations indicate that the orchard will use an additional 145 millimeters (5.7 inches) of water in the future. Partial stomatal closure in a high-CO₂ world increases leaf temperature of sunlit leaves and strengthens the vapor pressure gradient between leaves and the atmosphere.

Fruit trees need 200 to 1200 hours of winter chill to flower. Long-term climate records, measured across the fruit growing region of California, were scrutinized for trends in winter chilling degree-hours and chill hours. Global warming seems to be in motion, as all sites studied are experiencing a negative trend in winter chill accumulation. Calculations of trends in future chill, based on CO₂ emission scenarios and use of a global change model, indicate that by 2100, the occurrence of adequate winter chill may be lost for many fruit species. The development of cultivars requiring less winter chill may be one way to circumvent this trend.

1.0 Introduction

California's diverse geography and microclimates enables it to serve as a venue for more than 350 field and vegetable, fruit, and nut crops. From the perspective of the United States, California is nearly the sole producer of a large number of desirable fruits and crops. For example, California produces over 95% of the United State's apricots, almonds, artichokes, figs, kiwis, raisin grapes, olives, cling peaches, dried plums, persimmons, pistachios, olives, and walnuts (California Agricultural Statistics Service, 2003). California's ability to produce a large and diverse number of crops stems, in part, from the Mediterranean climate that is experienced in many of its interior valleys. There, typical climate conditions include a long growing season with ample sunshine and rainy, cool winters. Moreover, many of the interior valleys experience extended periods of fog during the winter (Suckling and Mitchell, 1988; Underwood et al., 2004). This meteorological occurrence is a key attribute for sustaining a sufficient dormant period for fruit trees (Aron, 1983). Additional factors for producing many unique crops, fruits, and nuts include an ample supply of irrigation water to fertile and arable soils.

California's cornucopia is predicated on its current climate and its supply and distribution of irrigation water; the latter is mainly derived from the snowpack on the surrounding Cascade and Sierra Nevada mountains, and is stored in dams and distributed via a network of aqueducts and canals. Unfortunately, current climate conditions in California are expected to change over the next 50 to 100 years (Hayhoe et al., 2004). So before we can assess how agriculture may vary in the future we must ask and answer: what will the climate and the supply and demand for irrigation water be in the future? Future climate projections depend upon future patterns of fossil fuel combustion, deforestation, population growth, technological innovations, and future CO₂ levels. Global mean CO₂ levels are expected to continue rising, and range between 600 and 1000 parts per million (ppm) by 2100 (Friedlingstein et al., 2003; Fung et al., 2005). For perspective, these future values will more than double current CO₂ levels (which are near 380 ppm) and pre-industrial levels CO₂ levels, which were near 280 ppm (Prentice et al., 2000). Because CO₂ is a radiation-absorbing greenhouse gas, its increasing burden in the atmosphere is expected to produce a warmer climate (Manabe and Wetherald, 1975). Climate models that simulate a coupling between the climate and carbon cycle predict a 3°C to 5°C (5.4°F to 9.0°F) increase in the mean global temperature by 2100 (Friedlingstein et al., 2003; Fung et al., 2005). At the regional scale, climate simulations for California predict that a doubling of pre-industrial CO₂ levels, from 280 to 560 ppm, will produce up to a 3°C to 4°C (5.4°F to 7.2°F) warming. They also predict a decrease in the extent and amount of winter snowpack on the mountains of California (Hayhoe et al., 2004; Izaurralde et al., 2003; Snyder et al., 2002).

Regional analyzes of climate trends over agricultural regions of California suggest that climate change is already in motion. Feng and Hu (2004) document trends in lengthening of the growing season by about a day per decade over California. They also report that thermal time, heat units that are summed and used to predict phenology and crop growth, are increasing by 30 to 70 growing degree days per decade over California. Nemani et al. (2001) analyzed long term climate records along the coastal region of northern California. They report a warming trend in annual average temperature of over

1°C (1.8°F) over 47 years. This warming was associated with a 20 day (d) reduction in the last day of frost occurrence and a 65 d increase in the frost-free growing period. Proxy data, based on the analysis of the springtime advance in the blooming of lilac, provides additional and independent evidence that a warming trend is occurring across the western United States (Cayan et al., 2001). These results indicate that plants are sensing an advance in spring.

This report evaluates the potential consequences of global warming on Californian agriculture. In making this assessment we first distill and synthesize relevant literature on the impacts of climate change on various facets of Californian agriculture. This involves an evaluation on how elevated CO₂ and warmer temperatures will affect crop growth, yield, and its associated physiological processes (photosynthesis, respiration, and transpiration). Next we evaluate long-term climate records in the crop growing regions of California to detect any emerging trends on climate indices that relate to crop production. Specifically, we examine trends in accumulated winter chill across the fruit-growing region of California.

2.0 Literature Synthesis

Crops need sunlight, heat, water, carbon dioxide, and nutrients to grow. Changing any of these factors, individually or in combination, with global warming can yield a blend of positive and negative effects on crop production and the physiological processes associated with crop production. These effects are summarized in Table 1 and discussed in greater detail below.

Predicting how crop production, and associated physiological processes, will respond to environmental perturbation is complex. First, many physiological processes (photosynthesis, respiration, transpiration) are non-linear functions of temperature and CO₂. Secondly, there are situations when the crop production and physiological processes are dependent upon antecedent conditions, causing them to experience acclimation and down-regulation. In our assessment of how California agriculture could respond to future climate and environmental conditions, we first consider the direct (respiration, photosynthesis, evaporation) and indirect (growing season length, water use) effects of increasing temperature. This analysis is followed by an evaluation of the effects of elevated CO₂ on crop production. Direct and indirect effects that co-vary with temperature and CO₂ are also discussed. For example, stresses like summertime ozone levels and growth rates of weeds, insect pests, and pathogens will increase with temperature. In addition, threshold effects like flowering and pollination may be threatened if lengthening of the growing season introduces asynchrony between the timing of flowering and the life cycle of important insect pollinators or shortens the length of the dormant period.

2.1. Temperature

Crop production is predicated on the condition that photosynthesis outpaces respiration. The enzyme reactions that promote photosynthesis and respiration vary, relative to one another, in their sensitivity to temperature, as defined by the Arrhenius equation (Amthor, 1994). In principle, increasing temperature promotes respiration over assimilation by causing the relative solubility of CO₂ versus oxygen and the specificity factor of the enzyme Rubisco (ribulose carboxylase-oxygenase) to decrease (Farquhar et al., 1980; Harley and Tenhunen 1991). High leaf temperatures (exceeding 30°C (86°F) can damage chlorophyll-proteins in the thylakoid membrane, inactivate photosystem II and promote respiration (Harley and Tenhunen 1991).

In general, net carbon assimilation of a leaf will increase with temperature until an optimum is reached—then higher temperatures limit photosynthesis (Bjorkman, 1980; Long, 1985). Furthermore, photosynthesis ceases at extremely high and low temperatures. Most plants cease photosynthesis at temperatures exceeding 50°C (122°F) (Bjorkman, 1980) and temperatures between 0°C and 10°C (32°F to 50°F) tend to be key points for the cessation of photosynthetic activity.

Table 1. Summary of positive and negative effects on California agriculture by associated elevated CO₂ and regional warming

	Positive (+) effects	Citations	Negative (-) effects	Citations
Temperature				
	Longer growing season, earlier spring leaf-out and flowering, expand northern range of growth	(Cayan et al., 2001)	More summer heat stress (> 35°C), burning fruit and stressing photosynthesis	This report
	Increase rate of photosynthesis at moderate temperatures (20°C to 30°C)	(Mooney and Ehleringer, 1997)	Flowering and fruit set is less successful because a reduction in winter chill, as needed for many fruit crops, occurs	This report
	Acclimation of respiration and photosynthesis	(Atkin et al., 2005a; Gifford, 2003)	Increased evaporation and demand for irrigation water	(Izaurrealde et al., 2003; Rosenberg et al., 2003); this report
	Reduced probability of frost damage to crops	(Easterling, 2002; Feng and Hu, 2004)	Increase growth and accelerate life cycle of pests (weeds, insects)	(Lincoln et al., 1993; Penuelas and Filella, 2001)
			Elevated ozone and associated damage	(Heagle, 1989)
			Increase volatile organic compounds (VOC) emissions	(Penuelas and Llusia, 2003)
			Change correspondence between flowering and insect pollinators	(De Melo-Abreu et al., 2004; Penuelas and Filella, 2001)
			Increase soil and plant respiration, augments loss of soil carbon	(Rosenweig and Hillell, 1998)
			Reduce snowpack in Sierra Nevada mountains	(Hayhoe et al., 2004; Snyder et al., 2002)
			Expand the range of insect pests and weeds	(Rosenweig and Hillell, 1998)

Table 1. (continued)

	Positive (+) effects	Citations	Negative (-) effects	Citations
CO ₂				
	Increase biomass production	(Ainsworth and Long, 2005; Centritto et al., 1999; Long et al., 2004)	Greater plant respiration, which scales with increased biomass	(Gifford, 2003)
	Reduced stomatal conductance, increasing water use efficiency	(Ainsworth and Long, 2005; Long et al., 2004)	Increase the need for fertilizer or nitrogen	(Zavaleta et al., 2003)
	Marginal increase in the rate of evaporation for irrigated and closed canopies and C ₃ crops	This report	Increase the absolute need for water	(Izaurrealde et al., 2003)
			Enhanced insect herbivory	(Lincoln et al., 1993)
			Down-regulation of photosynthesis	(Wolfe et al., 1999)
			Weeds are benefited more than crops	(Ziska, 2003)

Predicting how photosynthesis will respond to temperature trends is complicated by the fact that the optimum temperature for photosynthesis is very plastic and varies with temperature adaptation and acclimation (Bjorkman, 1980; Long, 1985). Optimum temperatures for desert species can increase from 25°C (77°F) in the spring to near 40°C (104°F) during the summer, or shift if they are grown in cool or hot climates (Larcher, 1975). One literature survey found that the optimum temperature increases by 1°C to 3°C (1.8°F to 5.4°F) for each 5°C (9°F) change in growth temperature (Long, 1985).

Plant respiration rates will approximately double with every 10°C (18°F) increase in temperature (Amthor, 2000). However, short-term responses of respiration to temperature do not reflect long-term responses (Atkin et al., 2005b; Gifford, 2003). Basal respiration rates, at a reference temperature, are highly dependent upon whether plants are grown in hot, warm, or cool conditions (Atkin et al., 2005b; Gifford, 2003). Plants growing in cool conditions, for example, will have a larger base rate than those growing under warm conditions. Basal respiration rates also jump in value during vegetative growth periods, anthesis, and flowering (Amthor, 2000; Gifford, 2003).

On seasonal and interannual time scales, climatic warming will extend the length of the growing season. Growing season length is determined by the intervening period between the last springtime frost and the first occurrence in the autumn. A longer and warmer growing season can have potentially positive benefits for perennial vegetation like alfalfa, vineyards and fruit trees by extending their growth period. And it can lead to improved wine quality (Nemani et al., 2001). A longer growing season can have negative effects, too. It can extend the period of evaporation, thereby increasing use of a precious commodity in California, water. If the timing of flowering becomes asynchronous with insect or avian pollinators, pollination will be disrupted (Parmesan et al., 2000; Penuelas and Filella, 2001). A longer growing season will also reduce the length of the dormant period that is necessary for fruit production (Aron, 1983; De Melo-Abreu et al., 2004). Finally, pollen is very sensitive to change in temperature, so pollen viability is reduced with warming that can be associated with an earlier spring.

Additional feedbacks of warming on crop production involve atmospheric pollution, insect pests, and pollen viability. Warming during the summer growing season produces a negative forcing on crop production via the emission of volatile organic hydrocarbons (VOC) from certain crops. Volatile organic hydrocarbons, in conjunction with emissions of nitrogen oxides from fossil fuel combustion, lead to the photochemical production of ozone—a phytotoxic compound (Heagle, 1989). On the other hand, there are circumstances when the production of hydrocarbons act to protect plants from thermal shock (Penuelas, Llusia, 2003; Sharkey, Yeh, 2001), as well as to protect them from insects and pathogens. Warming causes insect pests and pathogens to develop more quickly. It will also expand the geographical distribution of insect pests (Rosenweig, Hillel, 1998).

An example of how crop yield in California may respond to warming is shown using an analysis produced by Adams et al. (2001). This assessment was based on polynomial regression models derived from climate and yield data. The analysis considered the role of increasing temperature and precipitation and changes in technology, but it assumed no change in CO₂. Nor did it consider changes in cultural practices like planting crops sooner to offset deleterious warming effects. Table 2 shows a subset of data predicting changes in crop for the San Joaquin Valley. The authors conclude that moderate climate change will not have a "serious adverse effect on the yields of most California crops." Note that the greatest reductions in yield are associated with the case that considers a 5°C (9°F) increase in temperature. Adams et al. place a caveat on their results with the condition that water supplies will need to increase to meet the additional demand for water.

Care should be applied when projecting statistical yield and water use models into the future. Such models are extrapolating beyond the bounds of the empirical data upon which they were derived. Furthermore, they do not consider complex physiological responses, e.g., the combined and non-linear response to warming, elevated CO₂, increased water demand, and accompanied stresses from ozone, pests, and weeds. Nevertheless, statistical models do provide a first and educated guess on how crop yield may respond to future conditions.

Table 2. Fractional change in yield (% change /100) relative to current production in San Joaquin Valley for eight possible changes in precipitation and temperature (Adams et al., 2001)

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Temperature change (C)	3.00	3.00	5.0	1.8	0.6	1.5	5.0	1.5
Temperature change (F)	5.40	5.40	9	3.24	1.08	2.7	9	2.7
Precipitation change (%)	0	18	0	11	4	9	30	0
Year forecasted	2100	2100	2100	2060	2020	2020	2020	2020

Crop								
Corn grain	-.0634	-.0714	-.1647	-.0283	-.0021	-.0201	-.1813	-.0167
Corn Silage	.0329	.0492	.0411	.0324	.0121	.0274	.0701	.0196
Barley	-.1386	-.1817	-.2579	-.1027	-.0363	-.0843	-.3431	-.0657
Sorghum	-.0535	-.0594	-.0774	-.0423	-.0245	-.0378	-.0865	-.0347
Cotton(pima)	-.0612	-.0830	-.1714	-.0396	-.0357	-.0346	-.2453	-0.0321
Cotton	-.1072	-.1307	-.2359	-.0764	-.0475	-.0664	-.2782	-.0554
Dry Beans	-.0914	-.1359	-.1563	-.0751	-.0266	-.0612	-.2668	-.0472
Oats	-.3346	-.3308	-.7937	-.1525	-.0427	-.1187	-.7799	-.1189
Rice	-.0756	-.1001	-.1764	-.0426	-.0003	-.0302	-.2309	-.0211
Sugar Beets	-.0753	-.0579	-.1096	-.0461	-.031	-.0429	-.0694	-.0491
Winter wheat	-.0326	-.0635	-.1009	-.0326	-.0176	-.0269	-.1507	-.0111
Durum Wheat	.029	.0467	.0293	.0256	-.0051	.0186	.0609	.0102
Valencia orange	-.1452	-.2475	-.1530	-.1837	-.1601	-.1726	-.4493	-.1498

Table 2. (continued)

Hay alfalfa	.0871	.0928	.1432	.0540	.016	.0443	.1595	.0430
Grapes (table, raisin)	-.3819	-.5247	-.7539	-.2747	-.085	-.2196	-1.0812	-.1684
Grapes (wine)	.1647	.1523	.2127	.1199	.0814	.111	.1928	.1174
Tomatoes (fresh)	-.3742	-.3566	-.7157	-.2170	-.1115	-.1877	-.6641	-.1915
Tomatoes (processed)	.0211	-.0103	.0448	-.0071	-.0111	-.0070	-.033	.0030
Almonds	.5384	.5478	.9664	.3121	.1082	.258	1.0131	.2603
English Walnuts	.076	.0407	.085	.0429	.0358	.0425	.0153	.0578
Prunes (dried)	.434	.4509	.7967	.2568	.0911	.2125	.8384	.2071
Olives	-.3995	-.3989	-.8092	-.2088	-.0547	-.1669	-.7952	-.1643
Avocados	.0099	-.1612	0.0022	-.0659	-.0151	-.0466	-.4277	.0063
Potatoes	-.149	-.1527	-.2543	-.0936	-.0388	-.0794	-.261	-.0776

2.2. Carbon Dioxide Concentration

Carbon dioxide (CO₂) is the prime substrate for photosynthesis, so from a plant perspective additional CO₂ may be viewed as a good thing. But how plants respond to elevated CO₂ is very complicated and conditional. Its assessment requires a comprehensive understanding of the biophysical, physiological, and ecological factors at play.

The majority of plants fix CO₂ via the C₃ pathway. Carbon dioxide fixation is catalyzed by the enzyme ribulose biphosphate carboxylase/oxygenase (RuBisco) in the chloroplast and forms the 3-C sugar, 3-phosphoglyceric acid (3-PGA) (Mooney and Ehleringer, 1997). Next, 3-PGA is converted to triose phosphate using adenosine triphosphate (ATP) and NADPH. Finally, some triose phosphate is used to regenerate ribulose bis-phosphate (RuBP), the substrate involved in the initial carboxylation reaction. The remainder is used to form phosphate fructose 1,6 biphosphate, the sugar that is the net product of photosynthesis (Farquhar et al., 1980).

At contemporary CO₂ levels, the C₃ pathway is less efficient than the C₄ pathway, which is used by corn and sorghum (von Caemmerer, Furbank, 2003). Inefficiency with the C₃ cycle stems from the fact that the enzyme Rubisco has a dual and competing affinity to di-valent oxygen (O₂) and CO₂. The competitive reaction between O₂ and Rubisco initiates a

biochemical cycle, called *photorespiration*. This auxiliary cycle causes a fraction of assimilated CO₂ to be lost. In comparison, photorespiration is absent in C₄ crops (Chollet, 1977; Farquhar et al., 1980).

In principle, leaf photosynthesis of C₃ crops increases with greater levels of CO₂ because additional CO₂ boosts rates of carboxylation, in a non-linear and saturating manner, and decreases oxygenation rates, thereby reducing photorespiration. Dark respiration rates, on the other hand, are insensitive to CO₂. New data show that respiratory responses to CO₂, previously reported, are an artifact of leaks in the cuvette measurement systems (Gifford, 2003; Jahnke, Krewitt, 2002).

Information on how plant growth and yield respond to elevated CO₂ has been accumulating over the past thirty years, as concern about the impacts of possible global warming and rising levels CO₂ has risen. Studies exist for which seedlings, plants, individual saplings and trees, crops, and forests have been exposed to elevated CO₂ levels. A variety of techniques have been used to expose plants to elevated CO₂. The assortment of exposure methods include controlled environments, greenhouses, open-top chambers, and free-air CO₂ exposure systems (FACE) (Cure and Acock, 1986; Long et al., 2004). Growing plants at elevated CO₂ levels in pots, greenhouses, controlled environment chambers, and transparent and open-top chambers in the field introduce many artifacts. Chamber-scale studies, for example, modify the environment around the plant (altering the quality and amount of sunlight, increasing temperature, decreasing wind, and affecting soil moisture and rainfall). Chambers also place a limit on the size of plants studied, plus they restrict growth (because pots bind roots and limit growth), and they limit the number of individuals to be studied (because chambers are finite in size). FACE studies involve rings of CO₂ emitters around an area of vegetation and give the investigator a measure of the integrated response of the plant-root-soil system to elevated CO₂ (Lewin et al., 1994). The CO₂ emission rate is controlled for wind direction and wind speed to maintain a target CO₂ concentration around a group of vegetation.

At present several thousand of papers have been published on the topic "plants and elevated CO₂," so we derive our synthesis and analysis on literature reviews (Cure and Acock, 1986) and meta-analyses of published data (Ainsworth, Long, 2005; Long et al., 2004; Medlyn et al., 1999). The assortment of studies on agricultural crops surveyed report a mean increase of 52% in photosynthesis when the subject is first exposed to double CO₂ levels. Prolonged exposure to elevated (double ambient) CO₂ results in a 29% increase in photosynthesis CO₂ (Cure, Acock, 1986), which is evidence of photosynthesis down-regulation. Overall crop yield increases with double CO₂, but the yield enhancement is highly variable for the crops studied (wheat, +35%; barley, +70%; rice, +15%; corn, +29%; soybean, +29%; cotton, +209%; potato, +83%). Sources of variability include the methodology, level of water stress, and nutrient availability (Cure and Acock, 1986).

The most recent reviews have used meta-analysis to examine data from FACE studies on C₃ and C₄ crops, grasses, legumes, and shrubs that have received elevated levels of CO₂ for up to 15 years (Ainsworth, Long, 2005; Long et al., 2004). The FACE studies surveyed exposed the vegetation to elevated CO₂ levels between 475 and 600 ppm. Studies on C₃ vegetation found, on average, that maximum photosynthetic rates increased by 31% and dry matter production and crop yield were both stimulated by about 17%. In contrast,

stomatal conductance decreased by 20%, photosynthetic capacity (V_{cmax}) decreased by 13%, and specific leaf nitrogen mass decreased by 13%. Studies conducted on C_4 vegetation found that elevated levels of CO_2 increased photosynthesis by 15% to 20% and reduced stomatal conductance by 20%. The reduction in stomatal conductance was not significantly different from what was found for C_3 vegetation.

Stomata partially close with elevated CO_2 because a plant aims to maintain a balance between CO_2 supply and demand. This is accomplished by keeping the ratio between internal and ambient CO_2 near 0.7 for C_3 plants and near 0.4 for C_4 plants (Jones, 1992). The noted reduction in leaf nitrogen and V_{cmax} occurs in association with the down-regulation in photosynthesis (Wolfe et al., 1999). Sugars build up in a leaf because the demand for CO_2 cannot keep up with supply. Sugars also activate genes, which in turn control the leaf's nitrogen content and modulate its carboxylation velocity, V_{cmax} , a measure of photosynthetic capacity.

One explanation for greater vegetative growth at high CO_2 levels is the “compound interest effect” (Centritto et al., 1999). Plants exposed to high CO_2 get a faster initial jump on growth than those grown at ambient levels. However, the relative growth rate declines with time as a plant experiences a down-regulation in photosynthesis, self-shading and additional respiratory costs (Poorter, 1993). But nevertheless, the compound interest effect applied to the initial growth spurt leads to greater cumulative growth when plants are exposed to elevated CO_2 (Centritto et al., 1999; Poorter, 1993). This is analogous to the fact that one will have more money in the bank when 4% interest is applied to an account with an initial deposit of \$1000 than to one with an initial deposit of \$500.

The meta-analyses and literature reviews surveyed do not examine the effect of elevated CO_2 on whole plant respiration. However, we can deduce that respiration, at the canopy scale, will increase as crops become larger and their canopy photosynthesis rates increase. This will occur because plant respiration scales with photosynthesis and plant size (Gifford, 2003).

Exposure to both ozone and CO_2 stimulates photosynthetic capacity relative to control conditions with normal CO_2 and high ozone (Ainsworth and Long, 2005). This response is partly attributed to the fact that partial stomatal closure, associated with high CO_2 , reduces damage to plants exposed to elevated ozone levels.

3.0 Water Use

At the regional and global scale, inferential evidence, based on measurements of continental river runoff and land surface climate models, suggests that growing levels of CO₂ are reducing transpiration (Gedney et al., 2006). Yet, it is difficult to isolate and evaluate how evaporation may respond to elevated CO₂ and temperature without introducing artifacts. We can, however, use theory and observations to deduce how evaporation from irrigated agricultural crops may change. In principle, partial stomatal closure (that is associated with elevated CO₂ levels) decreases transpiration and increases water use efficiency (Cowan and Farquhar, 1977). However, feedback and feedforward effects, associated with the surface energy balance, occur and complicate the response of transpiration to elevated CO₂ at the plant and field level (Farquhar et al., 1978; Mcnaughton and Jarvis, 1991). With no feedbacks between stomatal conductance, transpiration, and humidity, a linear decrease in stomatal conductance will produce a linear reduction in transpiration. But in nature, stomatal closure will induce an increase in leaf temperature. And because saturation vapor pressure is an exponential function of temperature, the humidity deficit between the leaf and atmosphere will be reinforced. Consequently partial stomatal closure promotes a feedback that modulates the direct effect of stomatal closure on transpiration.

Model calculations of latent heat exchange for a sunlit leaf, based on a coupled leaf energy balance-photosynthesis model, demonstrate how leaf transpiration will vary with changes in CO₂. In theory, increasing CO₂ from 350 to 700 ppm will decrease stomatal conductance by 18%, but it will reduce transpiration by only 9% (Figure 1). If a down-regulation in photosynthesis occurs, the expected reduction in stomatal conductance and transpiration will be smaller.

How can we use this information to assess how evaporation will change in the future across the agriculture region of California? First we need to assess a baseline, the current amount of potential evaporation. Potential evaporation (E_0) is defined as the evaporation rate from a well-watered, short, green surface. It is a metric that is commonly assessed from meteorological stations and is adjusted to reflect actual evaporation. Potential evaporation, based on data from a network of CIMIS stations in California, is on the order of 1344 +/- 70 mm per year over the period 1990 to 2001 (Hidalgo et al., 2005). Conceptually warming will reinforce additional potential evaporation. On the other hand, a restoring force on potential evaporation will be imposed by an increase in humidity, clouds and aerosols, factors that either decrease available sunlight (Roderick, Farquhar, 2002) or reduced the vapor pressure deficit of the atmosphere (Brutsaert, Parlange, 1998). At present no trends in potential evaporation have been detected across California (Hidalgo et al., 2005).

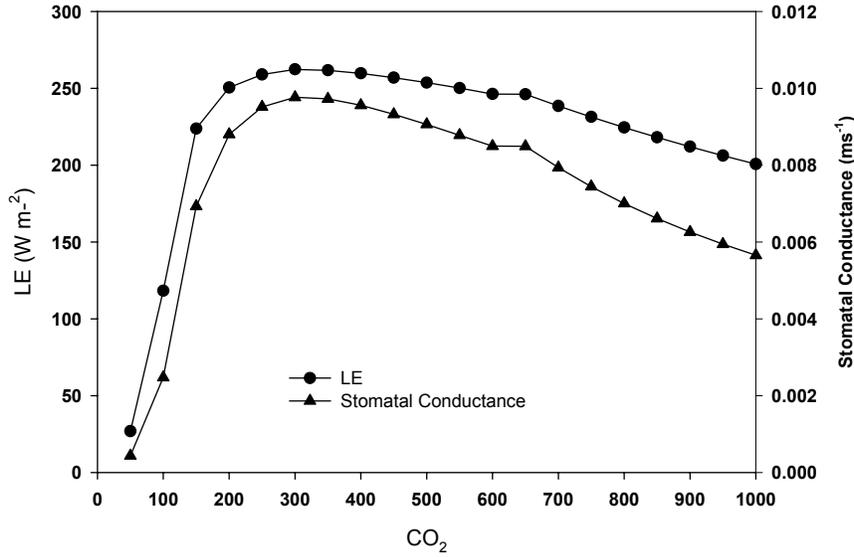


Figure 1. Theoretical variations in latent heat exchange and stomatal conductance of a C₃ leaf with varying CO₂. A coupled leaf energy balance-photosynthesis model that considers the effect of CO₂ is used to make the calculations (Baldocchi, 1994; Baldocchi et al., 1999). Computations assumed global radiation was 1000 W m⁻², air temperature was 25°C (77°F), wind speed was 1.0 m s⁻¹ and vapor pressure was 1.5 kilopascals (kPa).

For the sake of this analysis it is more appropriate to consider actual crop evaporation, rather than potential evaporation. Crop evaporation can be computed as the product of equilibrium evaporation (E_{eq}) and a canopy coefficient, α (Jarvis, McNaughton, 1986). Equilibrium evaporation, E_{eq} , is a function of available energy and temperature:

$$E_{eq} = \frac{s}{\lambda(s + \gamma)} (R_n - G) \quad (1)$$

In Equation 1, s is the slope of the saturation vapor pressure-temperature curve and is a function of temperature, γ is the psychrometric constant, available energy is described by the balance between R_n (net radiation), and G (soil heat flux density). The other symbol, λ , represents the latent heat of evaporation. The canopy coefficient varies with crop type, growth stage, soil moisture availability, and canopy coverage. For well-watered conditions, α equals 1.26, and is defined as the *Priestly-Taylor coefficient*. Under this condition, potential evaporation E_0 is approximately equal to 1.26 times equilibrium evaporation. As limits to crop growth occur and accumulate, α falls below 1.26 and actual evaporation diminishes.

At the field scale, the effects of elevated CO₂ on canopy evaporation are complicated by how elevated CO₂ will increase leaf area index (this promotes evaporation in a non-linear fashion) and how elevated CO₂ reduces the integrated canopy stomatal conductance (this inhibits evaporation). These dual and offsetting controls on evaporation produces a non-

linear response between evaporation rates (expressed in terms of latent heat exchange) and canopy surface resistance (the inverse of canopy conductance). To illustrate this effect, we examine theory and experimental data that evaluates the crop coefficient, α , as the ratio of measured actual and equilibrium evaporation. Experimental data, shown in Figure 2 (Baldocchi et al., 1997) and theoretical computations (Baldocchi and Meyers, 1998; McNaughton and Spriggs, 1986) reveal that E / E_{eq} is relatively insensitive to changes in canopy surface resistance (R_c) when R_c is less than 60 s m^{-1} . This condition is commonly met by irrigated and fertilized crops when they form a closed canopy. So water savings at the field scale are expected to be small in the future when high CO_2 forces partial stomatal closing. On the other hand, the term $s / s + \gamma$ in Equation 1 is sensitive to temperature. A 3°C (5.4°F) increase in summertime temperature (e.g., between 25°C (77°F) and 28°C (82°F), will force E_{eq} to increase by 3%.

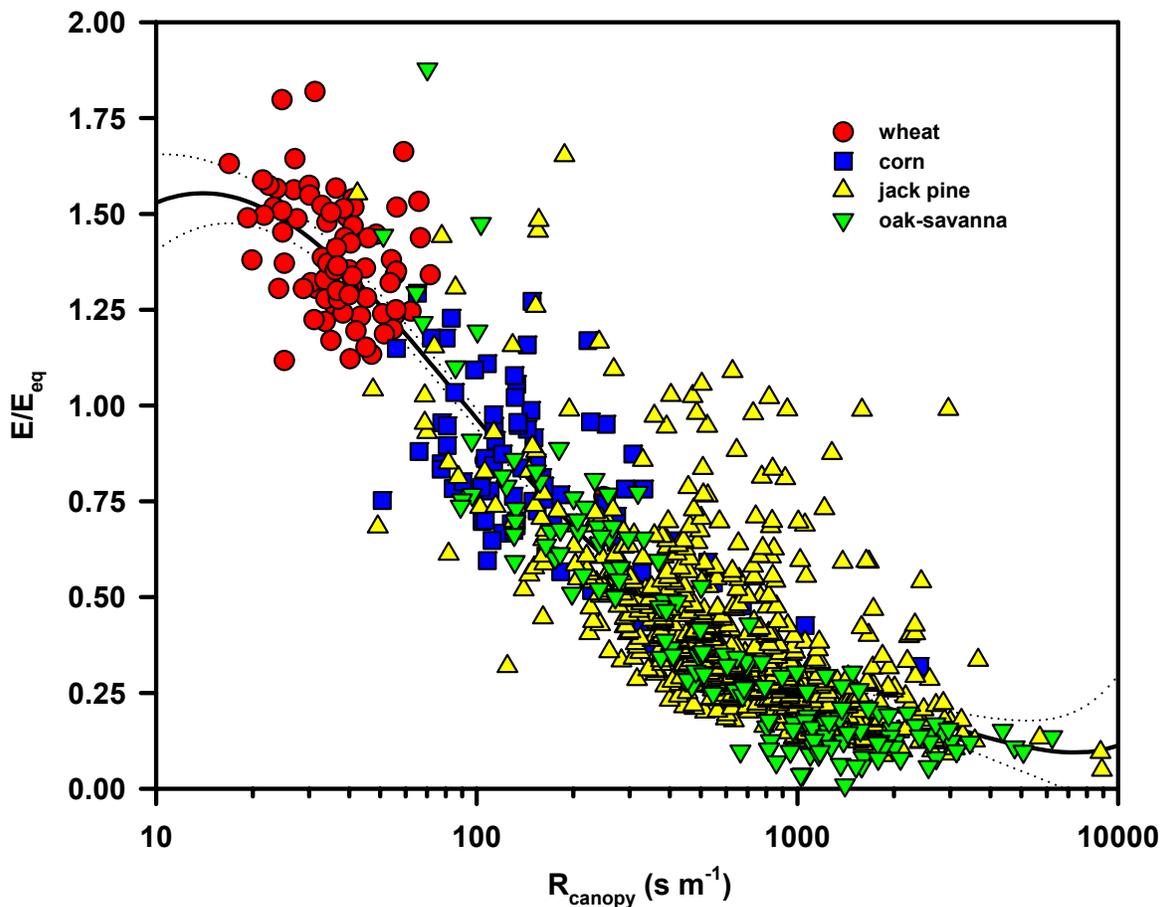


Figure 2. Relationship between normalized evaporation and canopy resistance. Data are from a variety of crops and native vegetation. (Baldocchi et al., 1997). The figure is updated with a new set of data from a Californian oak-grass savanna.

To further investigate the combined impacts of elevated CO₂ and warming on annual evapotranspiration, computer simulations were performed using the biophysical model, CANVEG (Baldocchi, Meyers, 1998). The mechanistic basis of CANVEG makes it amenable to projecting how evaporation may vary with climate and CO₂. Plus, the CANVEG model has been validated for numerous cases (Baldocchi and Meyers, 1998) so its accuracy and utility are well known (Baldocchi and Wilson, 2001). Computations were performed for a case that involves an irrigated walnut orchard growing along the eastern edge of the Central Valley. The model was forced with weather information measured near Ione, California, during 2003. Results shown in Figure 3 indicate that an orchard will use about 1054 mm (41 in) of water for contemporary Central Valley weather. This value is less the average potential evaporation for the State (1344 mm, or 53 in) and for CIMIS evaporation zone 12 (1447 mm, or 57 in; <http://www.cimis.water.ca.gov/cimis/images/etomap.jpg>). The orchard is dormant part of the year, so it is not evaporating near potential rates during the winter. However, warming the air by 3°C (5.4°F) and assuming that CO₂ is at 500 ppm forces the orchard to use, theoretically, 1199 mm (47 in) of water, an increase of 145 mm (5.7 in) or 14%. The model reveals that any potential savings in water use at elevated CO₂ conditions (attributable to partial stomatal closure) is offset by an increase the surface temperature of the sunlit leaves and its amplification of the leaf-air humidity difference. If a down-regulation of photosynthesis occurs, a different conclusion is drawn. When we ran the model and reduced photosynthetic capacity by 20%, we calculated that the orchard will evaporate 999 mm (39 in) of water—a 5% savings, in the warmer, CO₂-rich world (data not shown). We therefore conclude that minor changes in orchard water use will occur by the combined effects of higher CO₂, warmer air and a down-regulation in photosynthesis, an analysis consistent with the conclusion drawn from data shown in Figure 2.

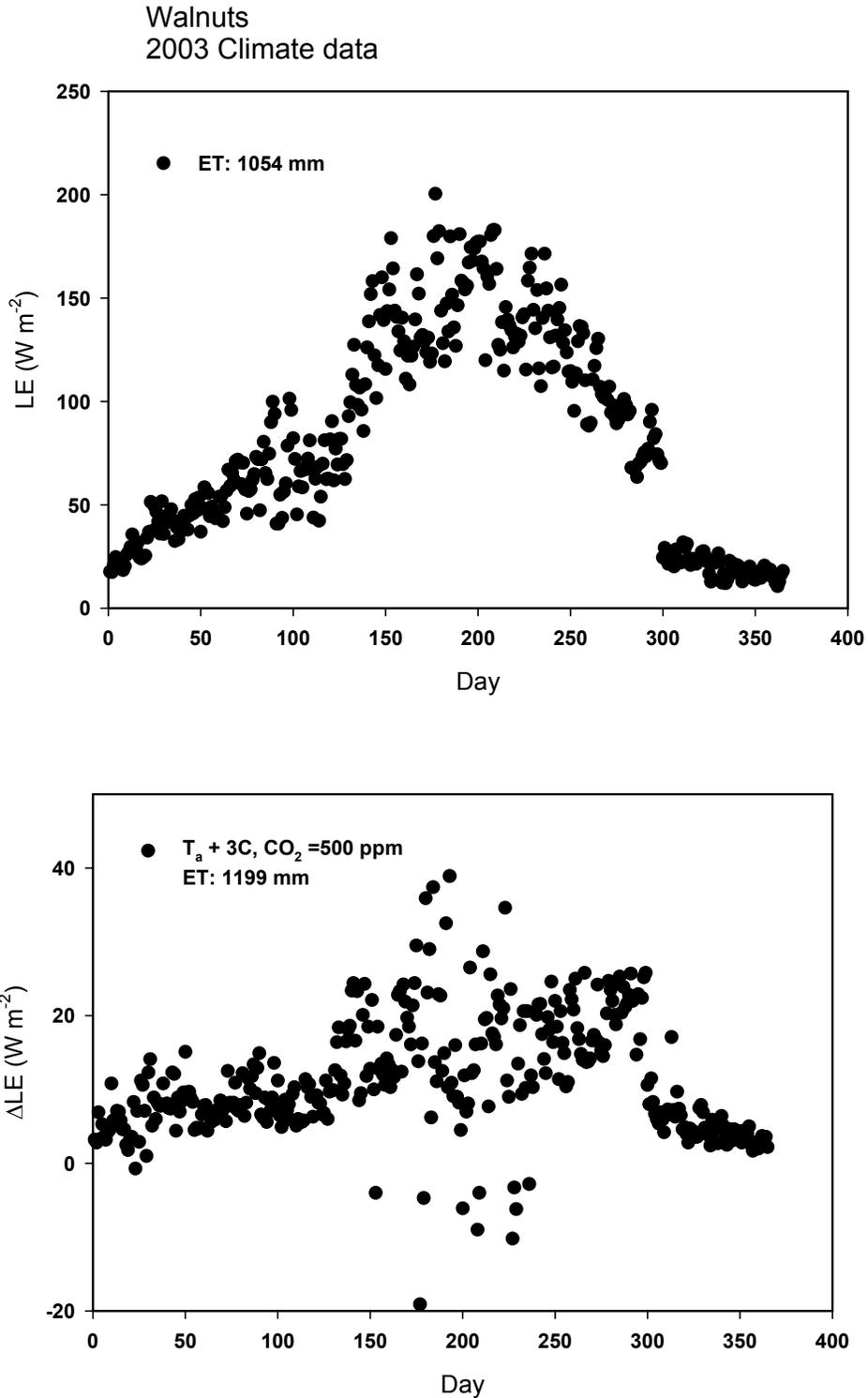


Figure 3. Computation of evaporation from a California walnut orchard. Simulations are based on the CANVEG model. The top panel shows the seasonal course of daily average latent heat exchange for 2003 weather conditions. The bottom panel shows the difference in evaporation on the assumption that air temperature increases 3°C and CO₂ is at 500 ppm.

Simulations of regional water use produced by the general circulation climate model developed at the Hadley Centre in the United Kingdom indicates a small deduction (-7%) in evapotranspiration across the Pacific region, with an increase in CO₂, to 560 ppm (Izaurralde et al., 2003) (Table 3). Combining warming scenarios and elevated CO₂, on the other hand, produces an increase in regional evapotranspiration. Depending upon the degree of warming, evaporation can increase by 75 to 124 mm (3 to 5 in) per year. This response is consistent with computations based on the biophysical CANVEG model, despite the coarse-scale, the wetter climate scenario, and parameterized nature of the Hadley Centre evaporation sub-model (Hayhoe et al., 2004).

Table 3. Estimates of regional evaporation for the western Pacific region of the United States. Scenarios based on the Canadian Climate and Hadley Centre climate models are used. (Izaurralde et al., 2003)

	Evaporation (mm)
Base: 365 ppm, 799 mm of precipitation, 12.2°C average air temperature	318
	Change in evaporation
Base @ 560 ppm	-7
H1 @ 560 ppm, + 44 mm of ppt, + 1°C in maximum temperature	75
H2 @ 560 ppm, +164 mm of precipitation, + 2.9°C maximum temperature	124

4.0 Contemporary Temperature Trends

The previous agricultural-climate analysis by Hayhoe et al. (2004) focused primarily on trends in mean temperature. Here we examine other temperature statistics that are meaningful to agriculture and are buried within long-term climate data. Examples include summation of chilling temperature and probability statistics associated with exceeding critical temperatures.

Many fruit trees need a critical amount of winter chill to produce flowers and fruit. Table 4) shows that many fruit tree species need to experience between 200 and 1500 hours below a base of 7°C or 45°F during the winter (Egea et al., 2003; Rattigan, Hill, 1986; Samish, 1954). Winter chill can be computed as the number of hours below a critical temperature (chill hours) or as the summation of hours times the number of degrees temperature is below a critical value (chilling degree hours) (Aron, 1975; Richardson et al., 1974.).

Table 4. Number of hours below a threshold temperature, e.g., 7°C for dormancy. Australasian Tree Crops Source Book <http://www.aoi.com.au/atcros/LM.htm>.

Fruit or Nut	Chill hours needed#
Almond	400–700
Apple*	400–1,800
Apricot*	350–1,000
Asian Pear (Chinese)	400–600
Asian Pear (Japanese)	300–750
Avocado	0
Blackberry	200–700
Blueberry (Florida)	0–200
Blueberry (northern)	700–1,200
Chestnut	400–750
Citrus	0
Crabapple	300–500
Currant	800–1,500
European pear	600–1,500

Table 4. (continued)

European plum	700–1,800
Fig	100–500
Filbert	800–1,600
Gooseberry	800–1,500
Grape	100–500
Japanese plum*	500–1,600
Kiwi*	400–800
Kiwi 'Twei' (female)	0–200
Kiwi 'Vincent' (female)	0–200
Mulberry	400
Nectarine*	200–1,200
Peach*	200–1,200
Pecan	300–1,600
Persimmon	100–500
Pistachio	800–1,000
Plum-cot	400
Pomegranate	100–200
Quince	100–500
Raspberry*	100–1,800
Sour cherry	700–1,300
Strawberry	200–300
Sweet cherry (most)	600–1,400
Walnut*	400–1,500

Note : Chill hours means accumulated cold-season hours below 7°C (45°F).

*Low-chill varieties that need less chilling.

Under current climate conditions this dormancy is met because prolonged periods of fog in the Valley enable the trees to experience a sufficient period below a certain temperature threshold (e.g., 45°F, 7°C). In the event of climate warming we hypothesize that regional and global warming will reduce accumulated number of chill degree hours or chill hours in the fruit-growing region of California. In principle, a reduction in chill degree hours will result in a reduction in crop yield and quality. If true, this effect could have major economic and social consequences on fruit product in California. And if critical thresholds are reached with further warming (see Table 4), sustained production of high-value fruit crops like almonds, cherries, apricots, and others will be in jeopardy.

We based our analysis on a combination of CIMIS and National Weather Service (NWS) Coop climate data, available through the California Climate Archive.¹ The CIMIS data is hourly, so it is ideal for computing accumulated winter chill hours, but unfortunately the data record is for a short duration to detect climate trends with confidence as it started in the 1980s. The NWS coop database, on the other hand, allows us to investigate longer climate trends, because many sites go back to the 1930s. However, this database only produces information on daily maximum and minimum temperature. To harmonize the databases, we first used the CIMIS dataset to develop and test an analytical equation for computing accumulated chill hours from maximum and minimum temperature measurements. Then we used the long coop data record to examine if there were trends in chill hours and to extend the spatial extent of the study.

Winter chill-degree hours (*CDH*) were summed between November 1 and Feb 28. On a daily basis the number of chill hours is computed relative to a reference temperature, in this case 45 °F.

$$CHD = \sum_0^{24} T_{ref} - T(t) \quad (2)$$

Using hourly data from the CIMIS project we computed trends in accumulated chill degree hours at selected sites in the Central Valley and fruit-growing coast range and foothills. An example of current trends in chill degree hours is shown in Figure 4 for Brentwood, in Contra Costa County—a region where apricots, peaches, almonds, walnuts, apples, and cherries are grown. A significant trend indicating a reduction in accumulated chill degree hours is observed over the period 1986 to 2005. The trend in Figure 4 is alarming because the regression can be extrapolated to approaching zero in the near future, suggesting that orchards near Brentwood may not achieve any winter chill.

Brentwood is near a strong temperature gradient that occurs between the western edge of the Great Central Valley and the moderating climates of San Francisco Bay, so this case may not represent all of the Central Valley.

¹ www.calclim.dri.edu/.

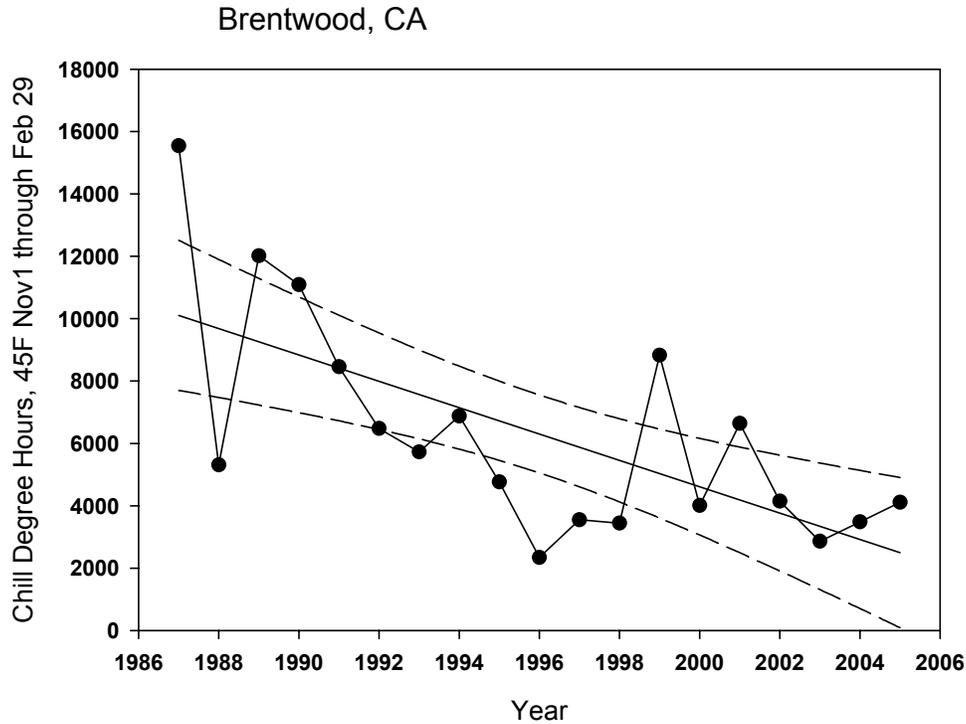


Figure 4. Trend in accumulated chill degree hours at Brentwood, California, between 1986 and 2005. The slope indicates a reduction of 422 chill degree hours per year. The coefficient of variation indicates that 48% of the variance in chill degree hours is explained by time.

To extend the duration and spatial extent of the data record this study used climate data from the network of National Weather Service Coop stations, which measure maximum and minimum temperature. To compute cumulative chill degree hours from such data we applied trigonometric concepts to an ideal diurnal temperature course. First we assumed that the diurnal temperature course can be described by two adjoined triangles—one between the daily mean and the minimum temperature and the other between the daily mean and the maximum temperature (Figure 5).

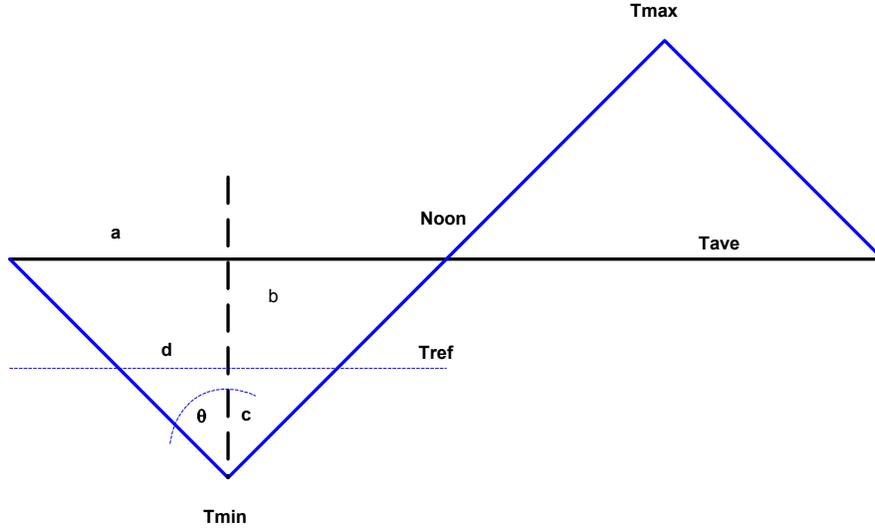


Figure 5. Schematic of the mean diurnal temperature course. Line *a* is 6 hours in length, line *b* is the distance between average and reference temperatures, line *c* is between the reference and minimum temperature, and line *d* is one-half the duration that temperature is below the reference temperature.

We know the length of segment *a* is 6 hours and the length of segment *b* is the difference between the daily average and minimum temperatures. So we can compute the tangent of the angle theta.

$$\tan \theta = \frac{a}{b} = \frac{6hr}{T_{ave} - T_{min}} \quad (3)$$

The length of segment *c* is the difference between the reference and the minimum temperatures, so we can compute the length *d*, which is one-half the time below the reference temperature.

$$d = \tan \theta \cdot (T_{ref} - T_{min}) \quad (4)$$

Chilling hours (*CH*) is then computed as 2 times *d*.

With information on *CH* at hand, we next compute the summed chill degree hours (*CDH*), based on the midpoint between T_{ref} and T_{min} .

$$\sum CDH = d \cdot 2 \cdot \left(T_{ref} - \frac{T_{ref} + T_{min}}{2} \right)$$

To evaluate how well this method works, we compared summations of chill degree hours based on hourly meteorological data and minimum and maximum temperature data for Zamora, California (Figure 6). There is a slight bias between the two measures, but overall the correspondence is quite good ($r^2 = 0.91$, regression slope is 0.91).

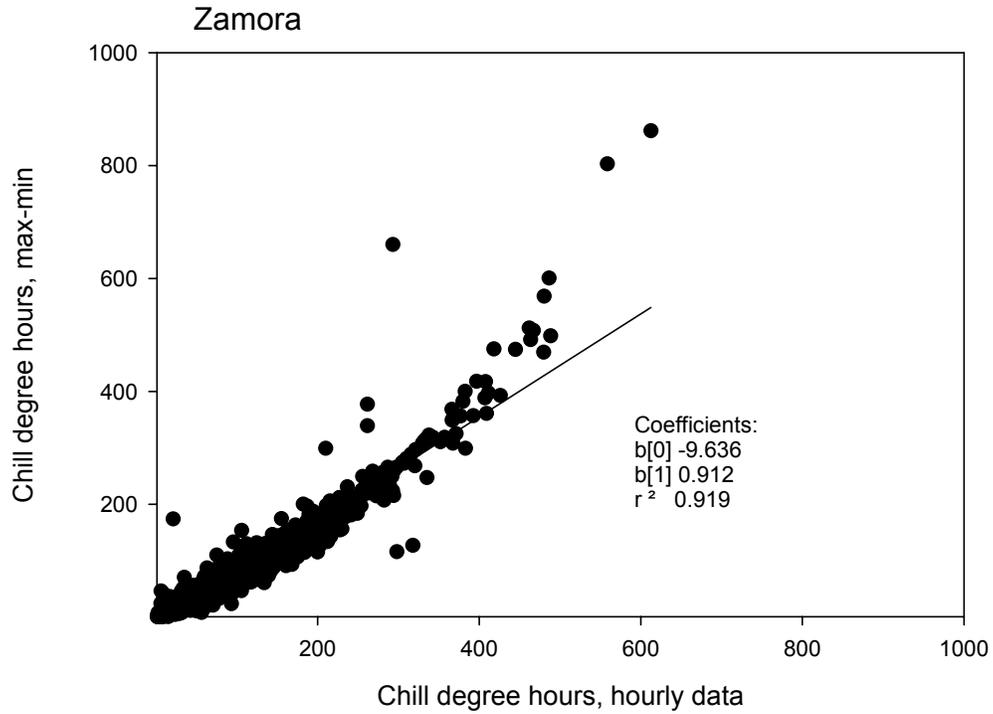


Figure 6. Comparison between accumulated chill hours using hourly and maximum and minimum temperature measurements for Zamora, California.

Next we investigated longer climate records, starting with the coop station near Angwin, just north of Santa Helena (Figure 7). At this station, the 50-year climate record indicates a weak trend in chill degree hours. However, like Brentwood, there is noted a downward trend if we only investigate data since 1980.

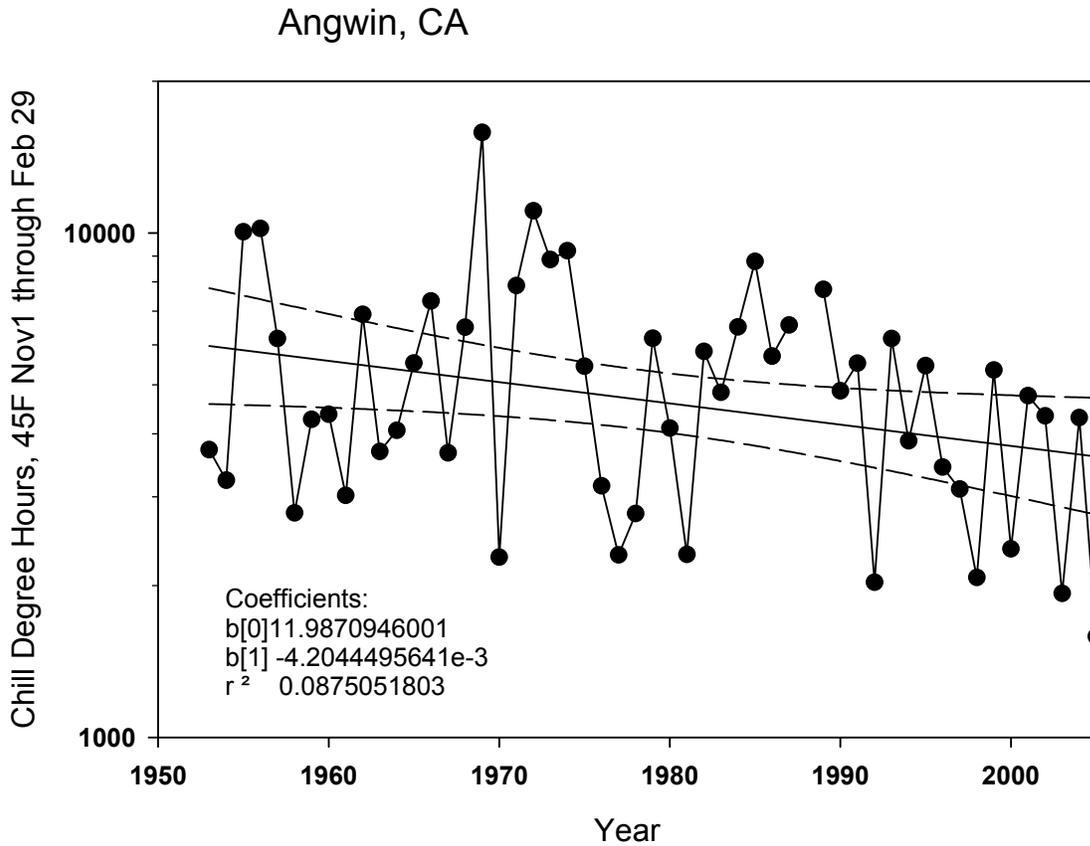


Figure 7. Long-term trend in accumulated chill degree hours at Angwin, California.

Applying this analysis for 27 climate stations across the fruit-growing valleys of California, we were able to produce a map of trends in chill degree hours (Figure 8). All sites are experiencing a significant downward trend in winter chill hours; the loss in winter chill hours ranges between 50 and 500 chill degree hours per year. The greatest rates of change are occurring in the Bay Delta region and the mid-Sacramento Valley.

Trends in Winter Chill Hour Accumulation (degree hours per year)
Nov-Mar, 32 to 45 F

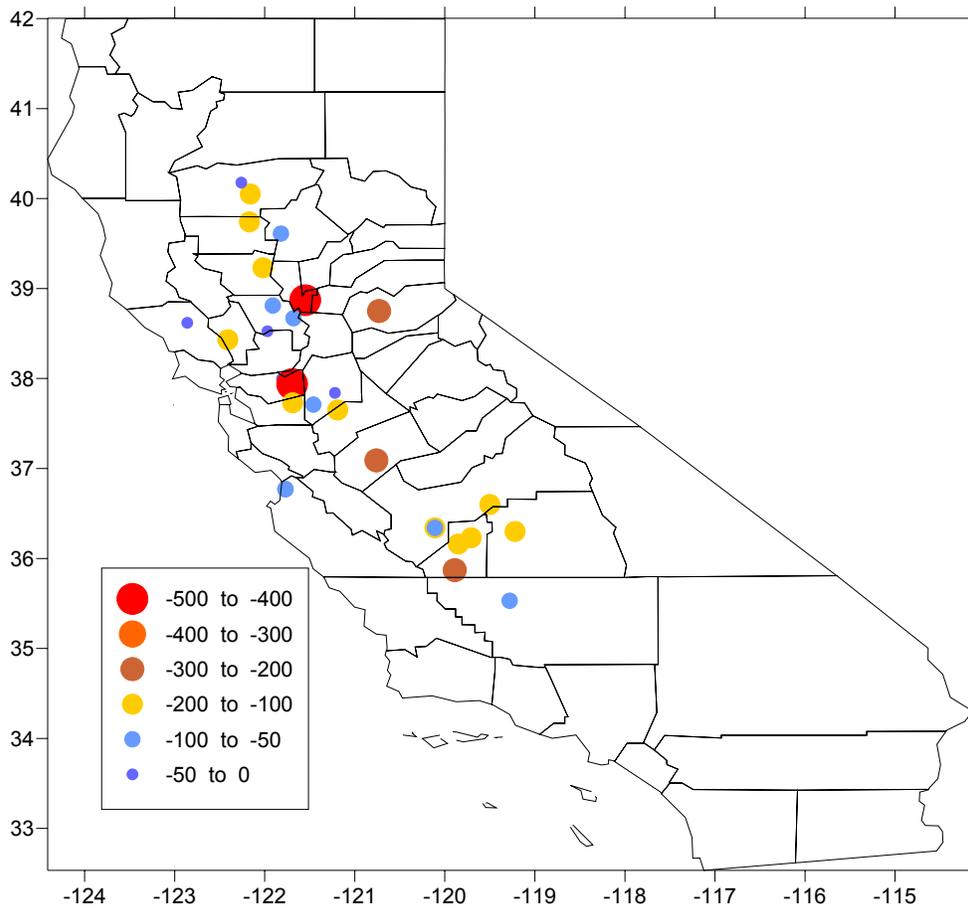


Figure 8. Map of long-term trends in the change in winter chill accumulation (degree hours) over the course of the dormant period. Data are derived from the California Climate Archive.

How current trends in accumulated winter chill-degree hours can be extrapolated into the future were analyzed based on datasets developed from climate projection. One case involves the B1 scenario, which expects CO₂ to reach 500 ppm by 2100, and the NOAA GFDL climate model. The other case is the A2 scenario, where CO₂ is expected to reach 900 ppm by 2100. Grid-scale climates were disaggregated and corrected to three locations up and down the Central Valley (Red Bluff, Davis, and Fresno) with a technique originally developed for adjusting GCM output for long-range streamflow forecasting (Wood et al., 2002) and later adapted for use in studies examining the hydrologic impacts of climate change (Maurer and Duffy, 2005; VanRheenan et al., 2004).

We observe that regions ranging from the southern to northern end of the Central Valley will experience less than 2000 chill degree hours by 2100 with both climate change scenarios. But fewer winter chill degree hours are accumulated with the warmer A2 scenario.

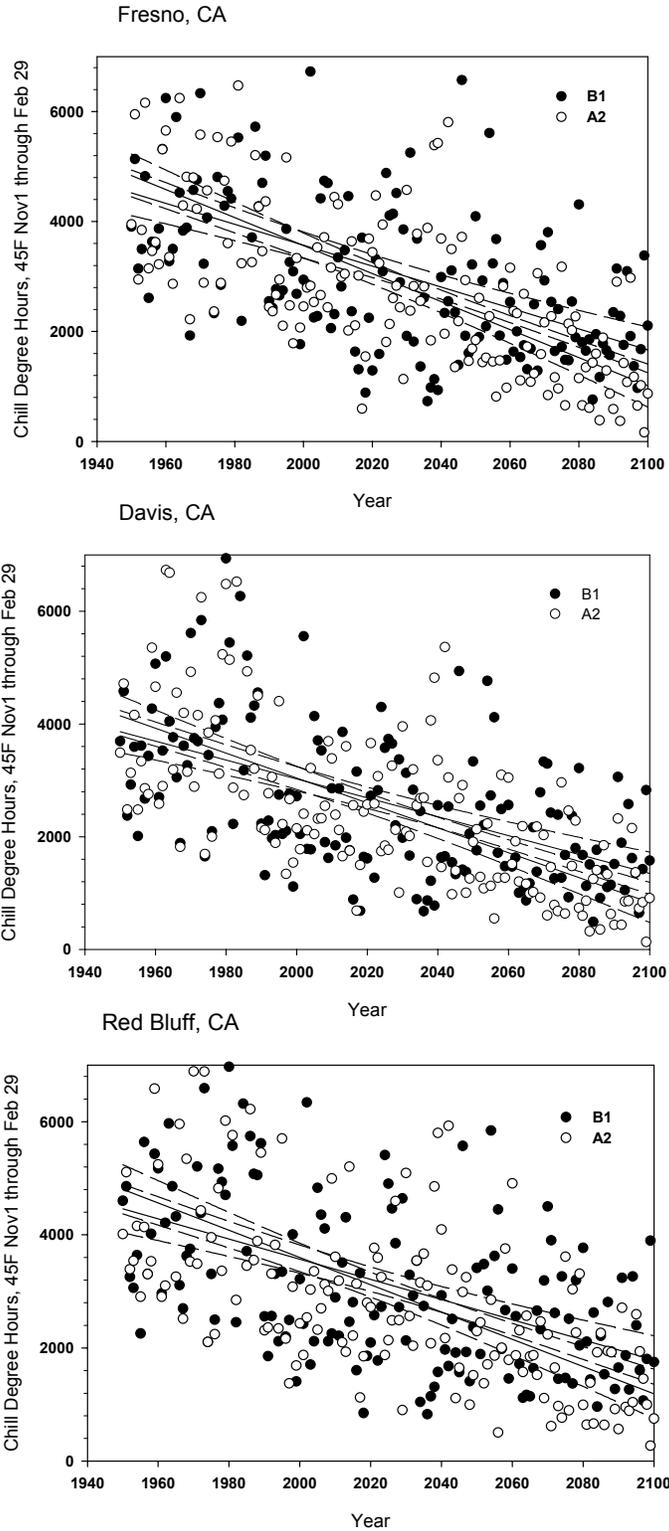


Figure 9. Current and future projections of chill degree hour accumulation for three sites up and down the Central Valley (Red Bluff, Davis, and Fresno). Climate projections were computed to 2100 for scenarios B1 and A2.

Figure 10 illustrates accumulated chill hours using climate simulations at three sites distributed along the longitudinal axis of the Central Valley. In general, winter chill hours will decrease from a baseline of 1000 hours, as observed in 1950, to about 500 hours by 2100. Both climate scenarios indicate that the local winter climate will approach the critical thresholds for many fruit trees species (Table 4). In the future, one may need to substitute fruit species that need less chill hours (e.g., peaches for almonds) or produce cultivars that require less winter chill.

Climate change can also affect the probability of exceeding critical temperatures, such as those that will cease photosynthesis or damage fruit by causing it to burn. We investigated the probability distribution of sunlit leaf temperatures for a walnut orchard with the CANVEG model, as an example. Figure 11 shows there is a low probability (0.073%) of leaf temperature exceeding 40°C (104°F) with contemporary climate. Evaporative cooling helps leaves control and modulate their surface temperature. The probability of exceeding a 40°C (104°F) threshold increases to 2.73% with mean air temperature increasing by 3°C (5.4°F) and CO₂ increasing to 500 ppm (scenario B2) because stomatal closure at high CO₂ weakens the leaf's ability to use evaporative cooling as a means of controlling its temperature. The greater occurrence of extreme temperatures will negatively impact fruit quality during the summer.

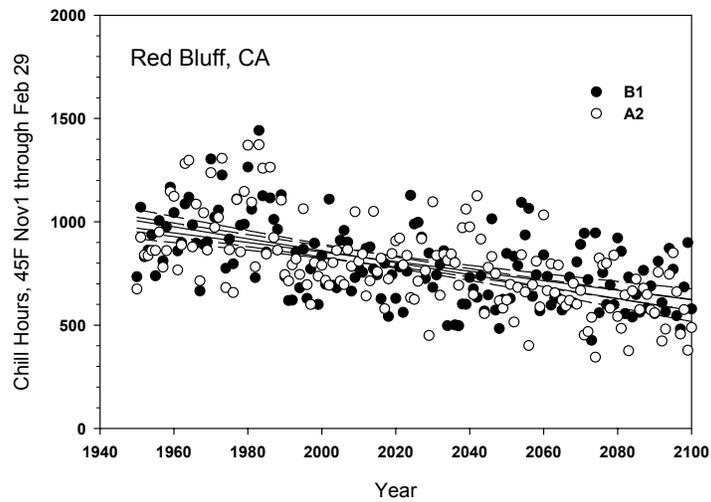
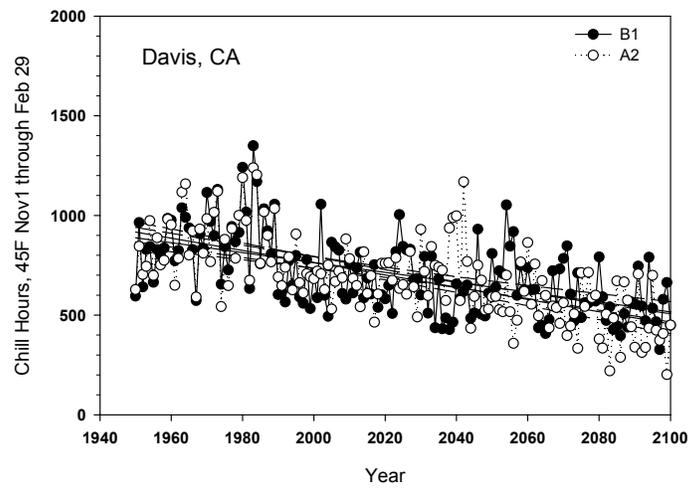
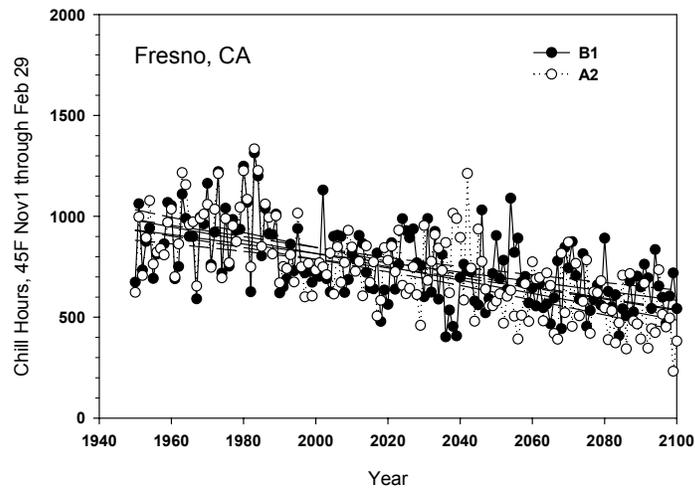


Figure 10. Current and future projections of chill hour accumulation for three sites up and down the Central Valley (Red Bluff, Davis, and Fresno). Climate projections were computed to 2100 for scenarios B1 and A2.

Walnuts
Sunlit leaves

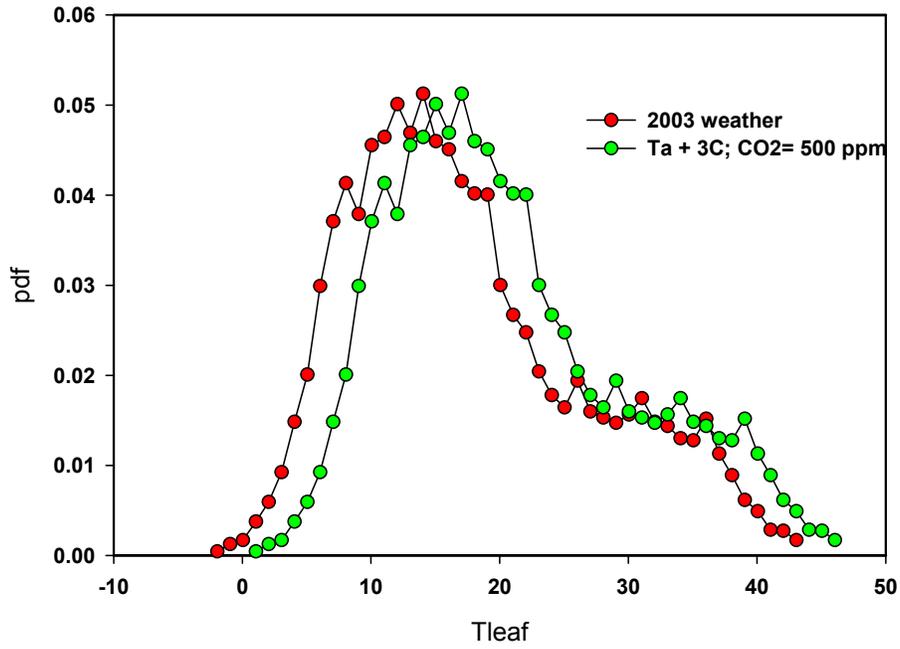


Figure 11. Probability distribution of sunlit leaf temperature for contemporary and future climate conditions

5.0 Conclusions

This report has evaluated the effects of a warmer climate and high CO₂ on aspects of California agriculture. Analysis was based on a survey of the scientific literature, application of biophysical models and an assessment of trends in current and future climate conditions.

This survey of the pertinent literature reveals a combination of positive and negative effects of warming and elevated CO₂ on crop production. Elevated CO₂ gives crops a spurt in growth, as photosynthesis responds positively to extra CO₂. But enhanced photosynthesis is not sustained, as photosynthesis eventually experiences down-regulation. Indirect effects of elevated CO₂ and warming on agriculture will include a lengthening of the growing and transpiration seasons, stimulation of weeds, and more insect pests. Pollination will be negatively impacted if warming causes asynchronization between flowering and the life cycle of insect pollinators.

Elevated CO₂ causes stomata to close and have the potential to save water by reducing transpiration. But feedbacks between stomatal conductance, the temperature and humidity deficits of a leaf, and the air dampened the reduction in water savings. And indirect factors may increase water use because larger crops growing in a warmer climate will use more water, at the field scale. An assessment of water use for a walnut orchard for future conditions (temperature is 3°C (5.4°F) warmer and CO₂ is 500 ppm) was conducted with a biophysical models. A typical orchard will use an additional 145 mm (5.7 in) of water in the future. Partial stomatal closure in a high-CO₂ world increases leaf temperature of sunlit leaves and strengthens the vapor pressure gradient between leaves and the atmosphere.

Global warming may also affect fruit production in a negative manner. Fruit trees need 200 to 1200 hours of winter chill to flower. Long-term climate records, measured across the fruit-growing region of California, were scrutinized for trends in winter chilling degree-hours and chill hours. Global warming seems to be in motion, as all sites studied are experiencing a negative trend in winter chill accumulation. Calculations of trends in future chill, based on CO₂ emission scenarios and use of a global change model, indicate that by 2100, the occurrence of adequate winter chill may be lost for many fruit species. The development of cultivars requiring less winter chill may be one way to circumvent this trend.

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