AN ASSESSMENT OF IMPACTS OF FUTURE CO_2 AND CLIMATE ON AGRICULTURE

DRAFT

A Report From:
California Climate Change Center

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DISCLAIMER

Arnold Schwarzenegger, *Governor*

WHITE PAPER

December 2005
CEC-500-2005-187-SD

Acknowledgements

We acknowledge support from the California Energy Commission and Environmental Protection Agency and the California Agricultural Extension Service. We thank the California Climate Archive for its provision of climate data, as well as the original sources like CIMIS and the Coop network. We thank Mary Tyree and Dan Cayan for supplying the climate projection scenarios and Michael Hanemann and Guido Franco for their guidance and leadership.

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 (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

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.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

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Abstract

This report evaluates how global warming and the associated rise in atmospheric carbon dioxide (CO_2) will affect agriculture in California. The pertinent literature is surveyed and distilled. It reveals a combination of positive and negative effects of warming and elevated CO_2 on crop production. Elevated CO_2 gives crops a spurt in growth, as photosynthesis responds positively to extra CO_2. But enhanced photosynthesis is not sustained as it experiences down-regulation. Elevated CO_2 also causes stomata to close. This effect has favorable implications on water saving by reducing transpiration at the leaf scale. But larger crops growing in a warmer climate will use more water. Indirect effects of elevated CO_2 and warming will include a lengthening of the growing season and more weed and insect pests. Pollination can be vulnerable if there becomes a asynchronization between flowering and the life cycle of insect pollinators.

Fruit trees need 200 to 1200 hours of winter chill to flower. Long term climate records across the fruit growing region of California were scrutinized for trends in winter chill. Global warming seems to be in motion, as all sites studied are experiencing a negative trend in winter chill accumulation. Calculations of future chill, based on CO_2 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 chill may be one way to circumvent this trend.

1.0 Introduction

California's diverse geography and microclimates enables it serve as a venue for more than 350 field and vegetable crops, fruits and nuts. 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 (Anonymous, 2003). California's ability to produce a large and diverse number of crops stems, in part, by 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, 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 derived from the snowpack on the surrounding Cascade and Sierra Nevada mountains, is stored in dams, and is distributed via a network of aqueducts and canals.

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 first ask: 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 carbon dioxide (CO_2) levels. Global mean CO_2 levels are expected to continue to rise 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 that double current CO_2 levels near 380 ppm and pre-industrial levels CO^2 levels, which were near 280 ppm (Prentice *et al.*, 2000). Because CO_2 is a radiation-absorbing greenhouse gas, its increasing burden in the atmosphere is expected to produce a warmer climate (Manabe, Wetherald, 1975). Predictions of future climate expect a 3°C to 5°C increase in the mean global temperature by 2100 (Friedlingstein *et al.*, 2003; Fung *et al.*, 2005). At the regional scale, climate simulations for California expect that a doubling of pre-industrial CO_2 levels, from 280 to 560 ppm, will produce up to a 3°C to 4°C warming, as well as 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. Proxy data, based on the analysis of the springtime advance in the blooming of lilac, provides independent evidence that supports an ongoing warming trend across the western United States (Cayan *et al.*, 2001).

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 CO_2 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, CO_2, 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 CO_2. Second, 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 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 CO_2 on crop production. Direct and indirect effects that co-vary with temperature and CO_2 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.

Table 1. Summary of positive and negative effects on California agriculture by associated elevated CO_2 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, 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	(Izaurralde *et al.*, 2003; Rosenberg *et al.*, 2003)
	Reduced probability of frost damage to crops	(Easterling, 2002; Feng, Hu, 2004)	Increase growth and accelerate life cycle of pests (weeds, insects)	(Lincoln *et al.*, 1993; Penuelas, Filella, 2001)
			Elevated ozone and associated damage	(Heagle, 1989)
			Increase VOC emissions	(Penuelas, Llusia, 2003)
			Change correspondence between flowering and insect pollinators	(De Melo-Abreu *et al.*, 2004; Penuelas, Filella, 2001)
			Increase soil and plant respiration, augments loss of soil carbon	(Rosenweig, Hillell, 1998)
			Reduce snow pack in Sierra Nevada Mountains	(Hayhoe *et al.*, 2004; Snyder *et al.*, 2002)
			Expand the range of insect pests and weeds	(Rosenweig, Hillell, 1998)

Table 1. (continued)

	Positive (+) effects	**Citations**	**Negative (-) effects**	**Citations**
CO_2				
	Increase biomass production	(Ainsworth, Long, 2005; Long *et al.*, 2004)	Greater plant respiration, which scales with increased biomass	(Gifford, 2003)
	Reduced stomatal conductance, increasing water use efficiency	(Ainsworth, 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 C3 crops	This report	Increase the absolute need for water	(Izaurralde *et al.*, 2003)
			Enhanced insect herbivory	(Lincoln *et al.*, 1993)

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. In principle, increasing temperature promotes respiration over assimilation by causing the relative solubility of CO_2 versus oxygen and the specificity factor of the enzyme Rubisco (ribulose carboxylase-oxygenase) to decrease (Farquhar *et al.*, 1980; Harley, Tenhunen 1991). High leaf temperatures (exceeding 30°C) can damage chlorophyll-proteins in the thylakoid membrane, inactivate photosystem II and promote respiration (Harley, 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. At the high extreme, most plants cease photosynthesis at temperatures exceeding 50°C (Bjorkman, 1980). At the low temperature end, temperatures between 0°C and 10°C tend to be key points for the cessation of photosynthetic activity.

Predicting how photosynthesis will vary 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 in the spring to near 40°C 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 to 3°C for each 5°C change in growth temperature (Long, 1985).

Plant respiration rates will approximately double with every 10°C 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 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 growing season can have potentially positive benefits for forage crops like alfalfa by increasing their cumulative growth period. On the other hand, 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, 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. VOCs, 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 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, Hillell, 1998).

An evaluation of how crop yield in California will respond to warming was produced by Adams et al. (2001). This analysis was based on an analysis of a polynomial regression model derived from climate and yield data. This analysis assumed no change in CO_2 but did consider the role of increasing temperature and precipitation and changes in technology. A subset of data predicting changes in crop for the San Joaquin Valley are shown in Table 2. The authors conclude that climate change will not have a "serious adverse effect on the yields of most California crops." They 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 available data, and they do not consider complex physiological responses such as the combined and non-linear response to warming, elevated CO_2, increased water demand and accompanied stresses from ozone, pests, and weeds. Nevertheless, they do provide a first and educated guess on how crops may respond to future conditions.

Table 2. Change in yield (% change /100) in San Joaquin Valley (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							
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
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 is the prime substrate for photosynthesis. The majority of plants fix CO_2 via the C_3 pathway. Carbon dioxide fixation is catalyzed by the enzyme ribulose bis-phosphate carboxylase/oxygenase (RuBisco) in the chloroplast and forms the 3-C sugar, 3-phosphoglyceric acid (3-PGA) (Mooney, Ehleringer, 1997). Next, 3-PGA is converted to triose phosphate using ATP and NADPH. Finally, some triose phosphate is used to regenerate ribulose bis-phosphate (RuBP), the substrate involved in the initial carboxylation reaction. The rest is used to form phosphate fructose 1,6 bisphosphate, the sugar that is the net product of photosynthesis (Farquhar *et al.*, 1980).

At contemporary CO_2 levels the C_3 pathway is less efficient than the C_4 pathway, which is used by corn and sorghum (von Caemmerer, Furbank, 2003). Inefficiency with the C_3 cycle stems from the fact that the enzyme, Rubisco, has a dual and competing affinity to di-valent oxygen (O_2) and CO_2. The competitive reaction between O_2 and Rubisco initiates a biochemical cycle, called *photorespiration.* This auxiliary cycle causes a fraction of assimilated CO_2 to be lost. In comparison, photorespiration is absent in C_4 crops (Chollet, 1977; Farquhar *et al.*, 1980).

In principle, leaf photosynthesis of C_3 crops increases with greater levels of CO_2 because additional CO_2 increase 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 CO_2. New data show that reported responses 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 CO_2 has been accumulating over the past thirty years, as concern about the impacts of possible global warming and rising levels CO_2 has risen. The most thorough synthesis and analysis are based on literature reviews (Cure, Acock, 1986) and meta-analyzes of published data (Ainsworth, Long, 2005; Long *et al.*, 2004; Medlyn *et al.*, 1999). The interpretation of results from this rich literature has evolved as exposure methods have improved and the duration of the exposure period has expanded. Studies exist for which seedlings, plants, individual saplings and trees, crops and forests have been exposed to elevated CO_2 levels. Furthermore, a variety of techniques have been used to expose plants to elevated CO_2,. The assortment of exposure methods include controlled environments, greenhouses, open-top chambers, and *free-air* CO_2 *exposure* (FACE) systems (Cure, Acock, 1986; Long *et al.*, 2004). Growing plants at elevated CO_2 levels in pots, greenhouses, controlled environment chambers, and transparent and open top chambers in the field introduce many artifacts. Chamber-scale studies modify the environment around the plant (altering the quality of light, 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 (pots bind roots and limit growth), and they limit on the number of individuals to be studied (chambers are finite in size). FACE studies involve rings of CO_2 emitters around an area of vegetation and give the investigator a measure of the integrated response of the plant-root-soil system to elevated CO_2 (Lewin *et al.*, 1994). The CO_2 emission rate is controlled for wind direction and wind speed to maintain a target CO_2 concentration around a group of vegetation.

The assortment of studies on agricultural crops surveyed report on average an increase in photosynthesis by 52% when the subject is first exposed to double CO_2 levels. Prolonged exposure to elevated (double ambient) CO_2 results in a 29% increase in photosynthesis CO_2 (Cure, Acock, 1986), which is evidence of photosynthesis down-regulation. Overall crop yield increases with double CO_2, 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, Acock, 1986).

Contemporary reviews have used meta-analysis to examine data from FACE studies on C_3 and C_4 crops, grasses, legumes, and shrubs that have received elevated levels of CO_2 for up to 15 years (Ainsworth, Long, 2005; Long *et al.*, 2004). The FACE studies surveyed exposed the vegetation to elevated CO_2 levels between 475 and 600 ppm. On average, these studies found 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%.

Stomata 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 a down-regulation in photosynthesis. Sugars build up in a leaf because demand cannot keep up with supply. Sugars also activate genes, which in turn control the leaf's nitrogen content and modulates 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-analyzes 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 crops and their canopy photosynthesis rates increase. This will occur because plant respiration scales with photosynthesis and plant size (Gifford, 2003).

3.0 Water Use

It is difficult to manipulate evaporation in elevated CO_2 and temperature studies without introducing artifacts. We can, however, use theory and observation to deduce how evaporation may change. In principle, the stomatal closure (that is associated with elevated CO_2 levels) decreases transpiration and increases water use efficiency (Cowan, Farquhar, 1977). Feedback and feedforward effects, associated with the surface energy balance, complicate the response of transpiration to elevated CO_2 at the plant and field level (Farquhar *et al.*, 1978; Mcnaughton, 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 a function of temperature, the humidity deficit between the leaf and atmosphere will be reinforced. Consequently partial stomatal closure can promote 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 CO_2. In theory, increasing CO_2 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.

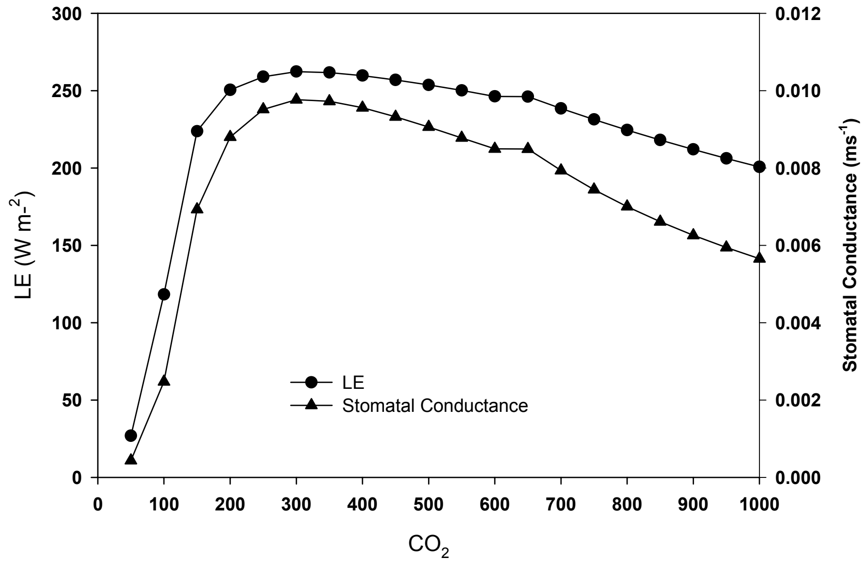

Figure 1. Theoretical variations in latent heat exchange and stomatal conductance of a C_3 leaf with varying CO_2. A coupled leaf energy balance-photosynthesis model that considers the effect of CO_2 is used to make the calculations (Baldocchi, 1994; Baldocchi et al., 1999).

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 is commonly assessed from meteorological stations and is adjusted to reflect actual evaporation. Potential evaporation, based on data from a network of California Irrigation Management Information System (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 if increase in humidity, clouds and aerosols occurs as they will decrease available sunlight. At present no trends in potential evaporation have been detected across California (Hidalgo *et al.*, 2005).

For the sake of this analysis it is more apropos 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},:

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

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, R_n is net radiation, G is soil heat flux density, and λ is 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 stresses accumulate, α falls below 1.26 and actual evaporation diminishes.

The effects of elevated CO_2 on canopy evaporation are complicated by how elevated CO_2 will increase leaf area index (this promotes evaporation in a non-linear fashion) and how it 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, Meyers, 1998; McNaughton, 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 with high CO_2 and associated stomatal closing. On the other hand, the term $s / s + \gamma$ in Equation 1 is sensitive to temperature. An increase in temperature, between 20°C and 30°C will force E / E_{eq} to increase by 15%.

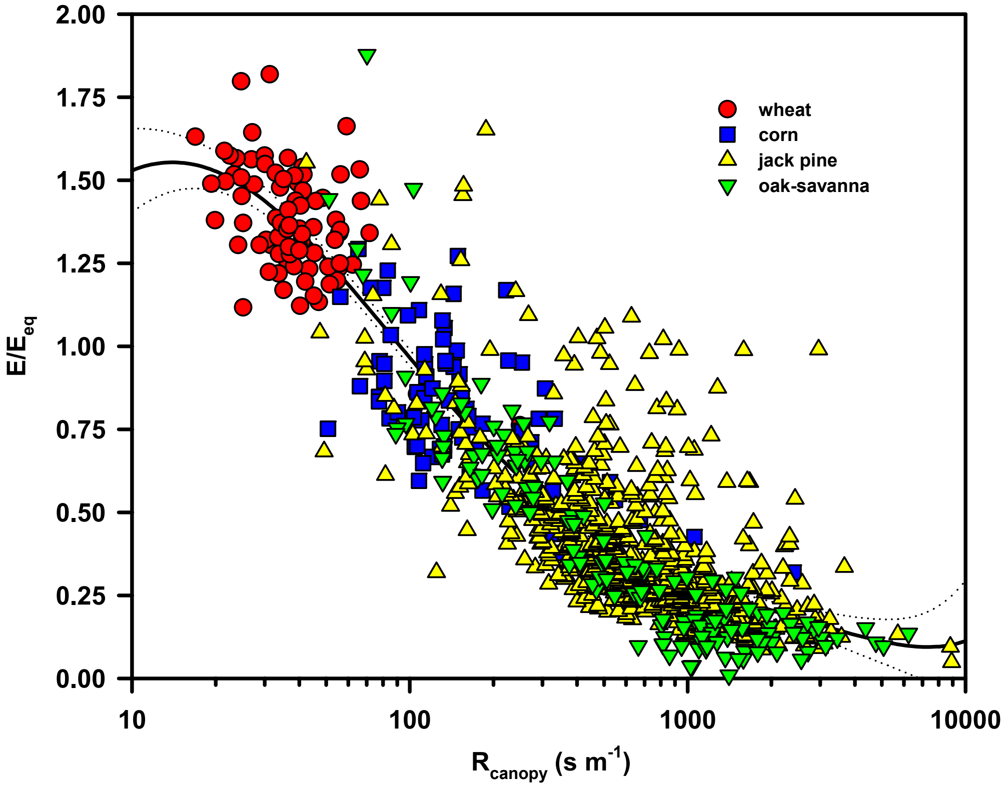

Figure 2. Relationship between normalized evaporation and canopy resistance. Data are from a variety of crops and native vegetation. (Baldocchi et al., 1997). The Figure is updated with a new set of data from a Californian oak-grass savanna.

To investigate the combined impacts of elevated CO_2 and warming on annual evapotranspiration computer simulations were performed for an irrigated walnut orchard in the Central Valley using the biophysical model, CANVEG (Baldocchi, Meyers, 1998). The CANVEG model has been validated for numerous cases (Baldocchi, Meyers, 1998). Plus its mechanistic basis makes it amenable to projecting how evaporation may vary with climate and CO_2. Results shown in Figure 3 indicate that an orchard will use about 1071 mm of water for contemporary Central Valley weather. This value is less that potential evaporation for the state and its region[1] because the orchard is dormant part of the year. Warming the air by 3°C and assuming CO_2 is at 500 ppm forces the orchard to use, theoretically, 1220 mm of water—an increase of 14%, or an additional 149 mm of water.

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[1] See wwwcimis.water.ca.gov/cimis/images/etomap.jpg.

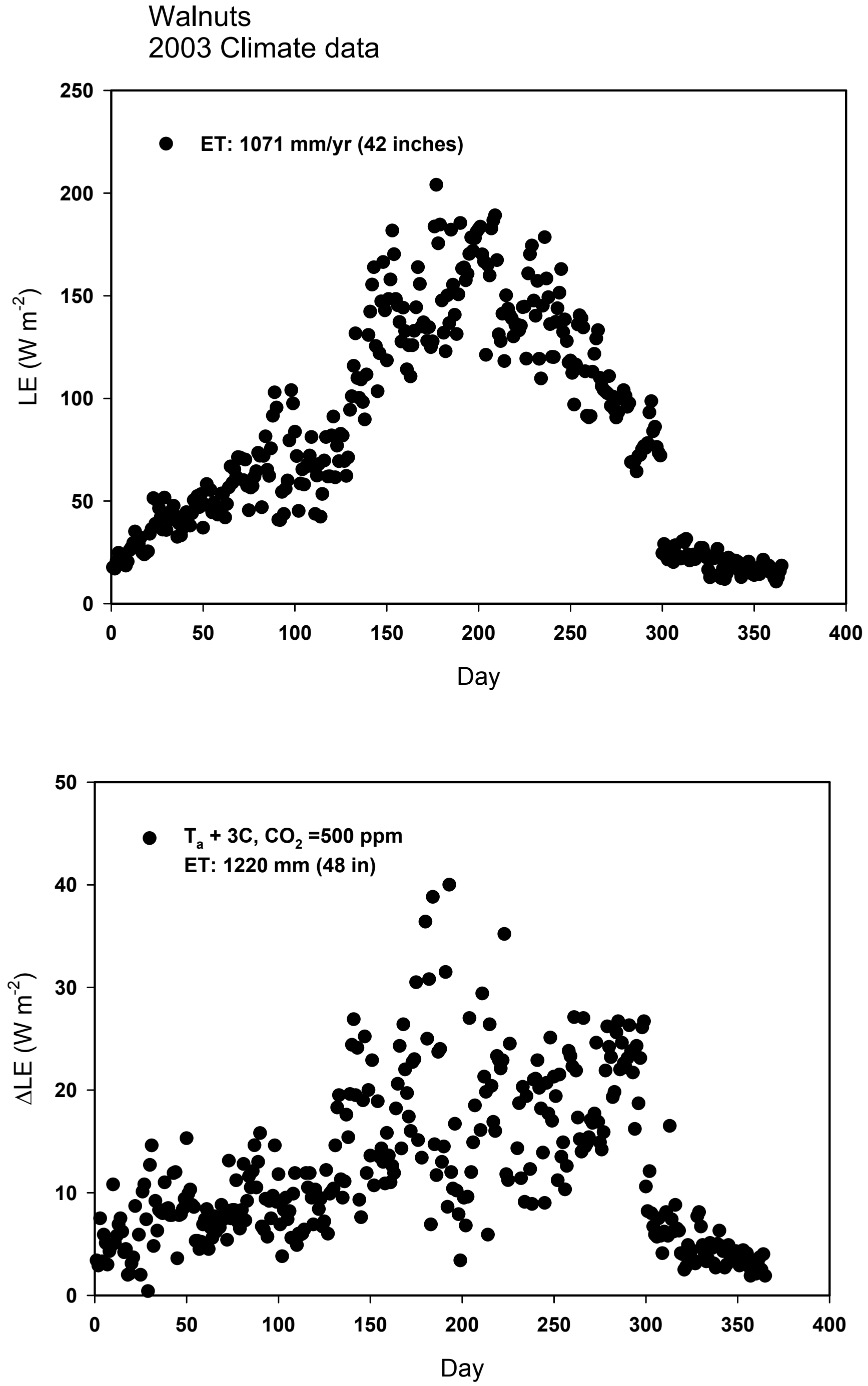

Figure 3. Computation of evaporation from a California walnut orchard. Simulations are based on the CANVEG model. The top panel shows the seasonal course of daily average latent heat exchange for 2003 weather conditions. The bottom panel shows the difference in evaporation on the assumption that air temperature increases 3°C and CO_2 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 CO_2, to 560 ppm (Izaurralde *et al.*, 2003) (Table 3). Combining warming scenarios and elevated CO_2, on the other hand, produces an increase in regional evapotranspiration. Depending upon the degree of warming, evaporation can increase by 75 to 124 mm per year. This difference is compatible with the computations based on the biophysical CANVEG model, despite the coarse-scale, the wetter climate scenario and parameterized nature of the Hadley Centre 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. This section examines long-term climate data to examine changes in other meaningful temperature statistics. Many fruit trees need between 200 and 1500 hours of winter chill (Table 4) to produce flowers and fruit (Egea *et al.*, 2003; Rattigan, Hill, 1986; Samish, 1954).

Table 4 Australasian Tree Crops Source Book

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
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

Table 4. (continued)

Fruit or Nut	Chill hours needed#
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

Source: www.aoi.com.au/atcros/LM.htm

#Chill hours means accumulated cold-season hours below 7°C.
*Low-chill varieties exist which 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 hours in the fruit growing region of California. If true, this effect could have major economic and social consequences on fruit production in California. In principle, a reduction in chill hours will result in a reduction in crop yield. But if a critical threshold is reached with further warming, it could affect whether or not high-value fruit crops like almonds, cherries, apricots, and others will continue to be produced in California; some of these crops that account for over 90% of U.S. production.

We based our analysis on a combination of CIMIS and co-op climate data, available through the California Climate Archive.[2] 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, starting in the 1980s. The co-op database, on the other hand, allows us to

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[2] See www.calclim.dri.edu/.

investigate longer climate trends because many sites go back to the 1930s. But this database only produces information on daily maximum and minimum temperature. To harmonize the databases we first use the CIMIS dataset to develop and test an analytical equation for computing accumulated chill hours from maximum and minimum temperature measurements. Then we use the long co-op data record to examine if there are trends in chill hours and to extend the spatial extent of our study.

Winter chill hours 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.

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

Using hourly data from the CIMIS project we computed trends in accumulated chill hours at selected sites in the Central Valley and fruit growing coast range and foothills. An example is shown in Figure 4 for Brentwood, in Contra Costa County, a region where apricots, peaches, almonds, walnuts, apples, and cherries are grown. A strong and significant reduction in accumulated chill hours is observed over the period 1986 to 2005. The trend shown in Figure 4 is alarming, because the regression is rapidly approaching this threshold. Under future conditions orchards near Brentwood may not achieve any winter chill. For instance, if we add 5°F to the minimum temperature, to represent future climate conditions, we find that an additional 3690 hours of winter chill are lost.

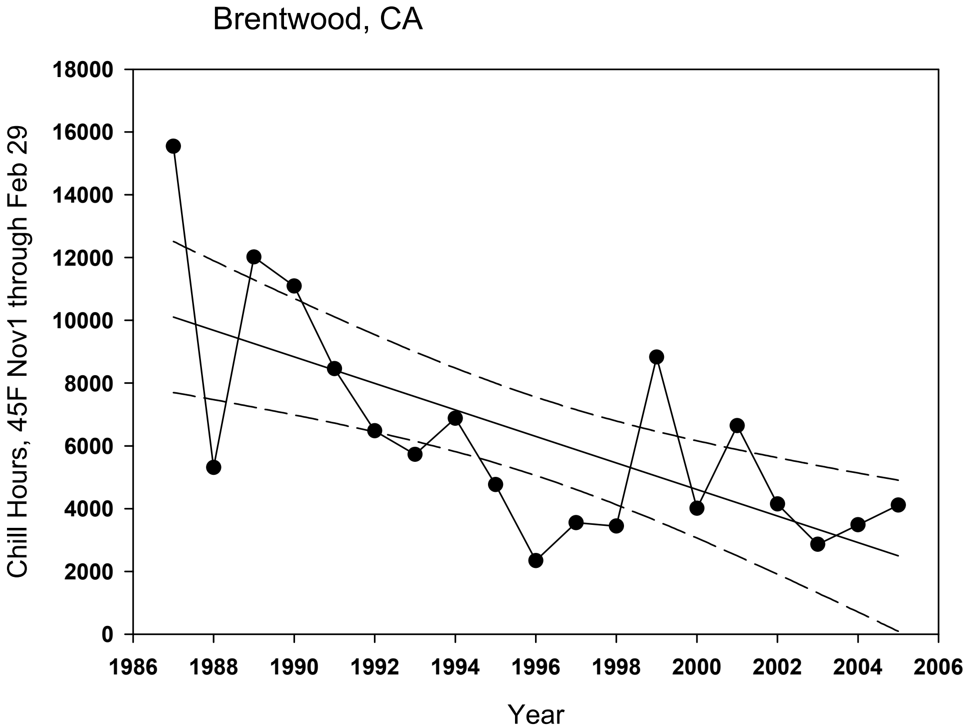

Figure 4. Trend in accumulated chill hours at Brentwood, California, between 1986 and 2005. The slope indicates a reduction of 422 chill hours per year. The coefficient of variation indicates that 48% of the variance in chill hours is explained by time.

Brentwood is near the a strong temperature gradient that occurs between the western edge of the Great Central Valley and the moderating climates of San Francisco Bay. To investigate if this trend represents the whole of California, we map out winter chill for California below. To extend the duration and spatial extent of the data record, we use climate data from the network of co-op stations, which measure maximum and minimum temperature. To compute cumulative chill hours from such data we applied trigonometric concepts to the 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).

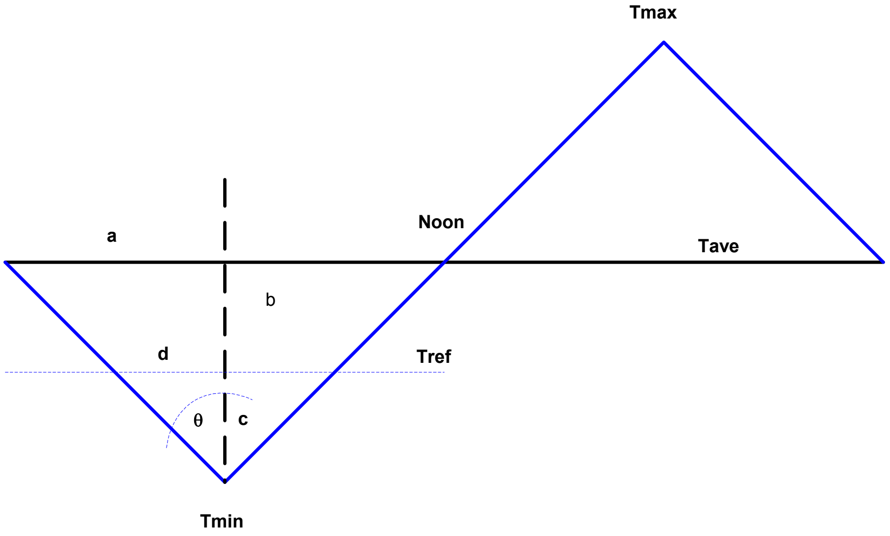

Figure 5. Schematic of the mean diurnal temperature course

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.

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

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.

$$d = \frac{chillhours}{2} = \tan\theta \cdot (T_{ref} - T_{\min}) \tag{4}$$

With this information at hand we can compute the summed chill hours based on the midpoint between T_{ref} and Tmin.

$$\sum chillhours = d \cdot 2 \cdot \left(T_{ref} - \frac{T_{ref} + T_{\min}}{2}\right) \tag{5}$$

To evaluate how well this method works we compared summations of chill 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).

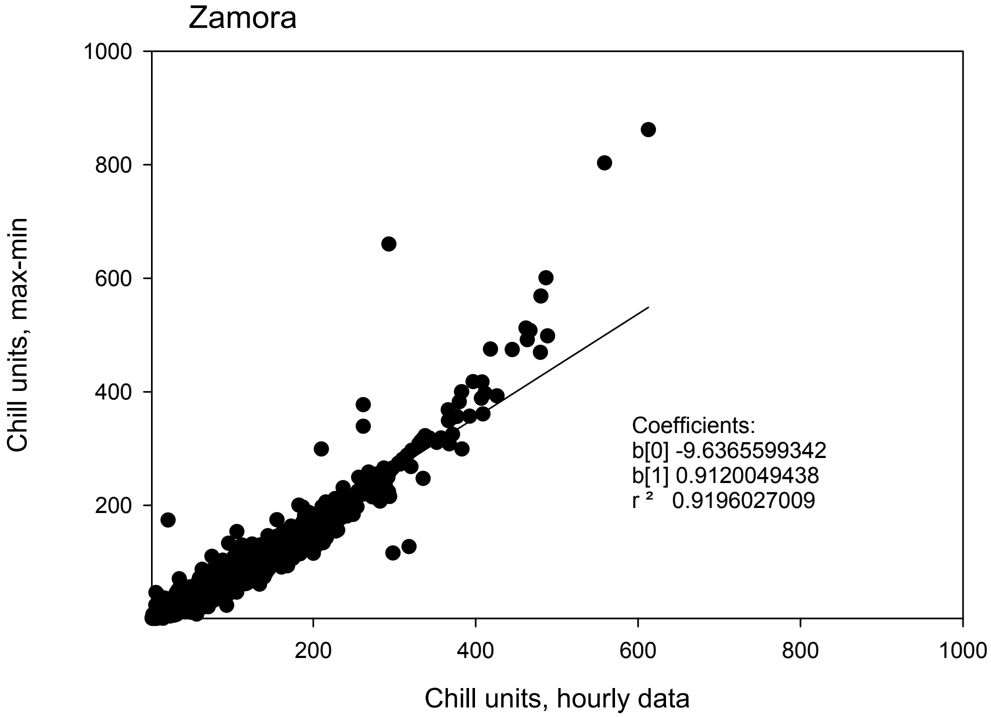

Figure 6. Comparison between accumulated chill hours using hourly and maximum and minimum temperature measurements for Zamora, California.

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 units. However, like Brentwood, there is noted a downward trend if we only investigate data since 1980.

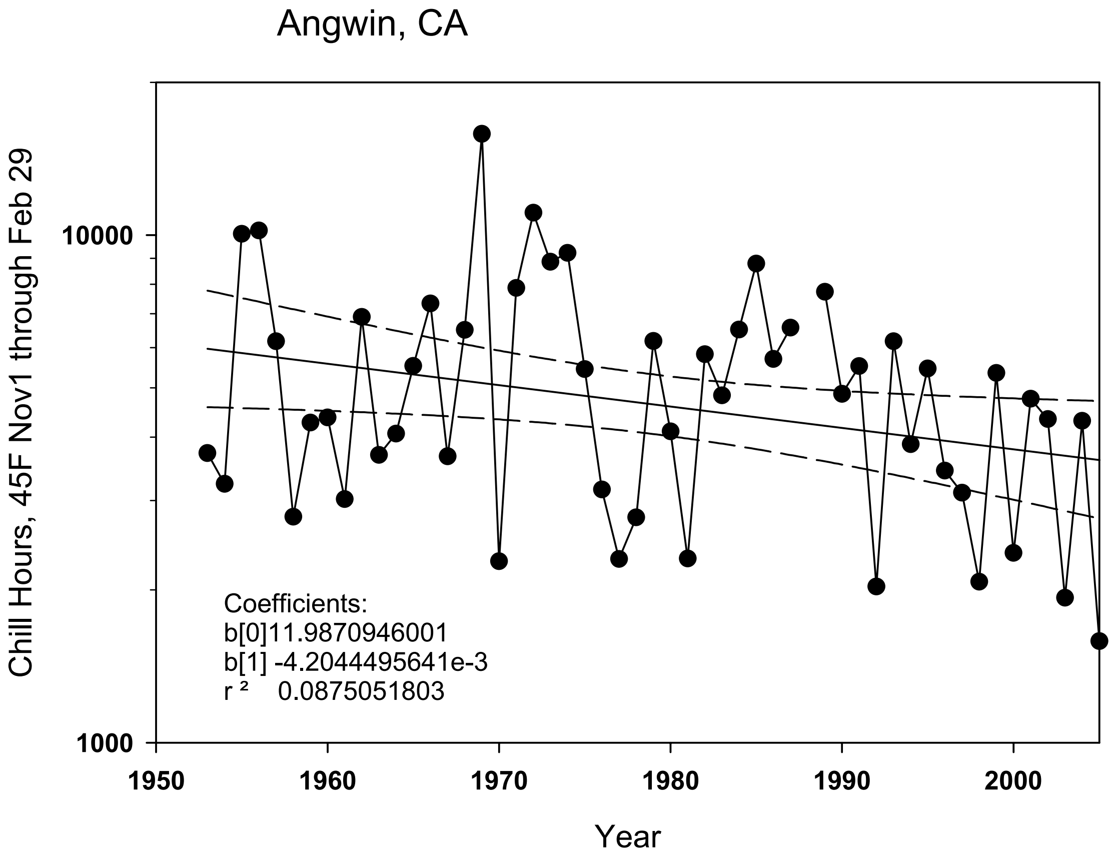

Figure 7. Long-term trend in accumulated chill hours at Angwin, California.

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 units (Figure 8). All sites are experiencing a significant downward trend in winter chill, the loss in winter chill hours ranging between 50 and 500 hours per year. The greatest rates of change are occurring in the Bay Delta region and the mid Sacramento Valley.

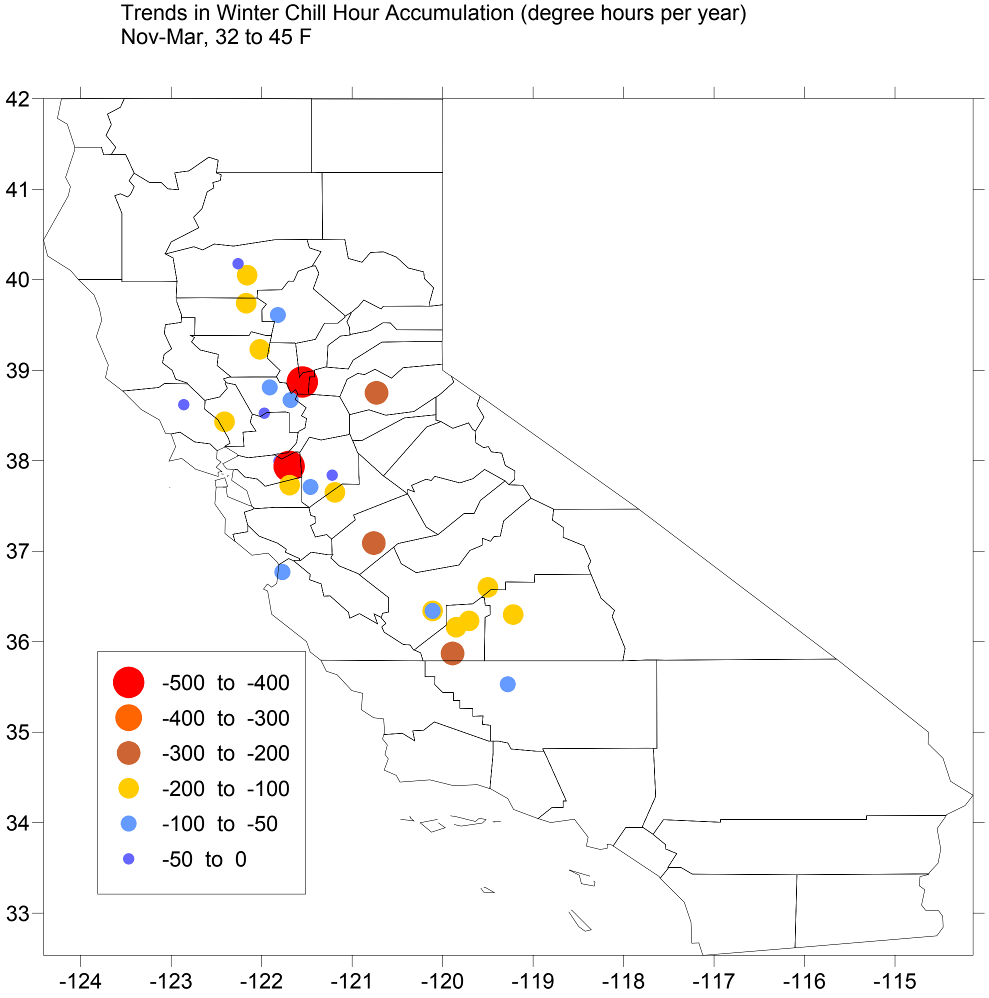

Figure 8. Map of long term trends in the change in winter chill accumulation over the course of the dormant period. Data are derived from the California Climate Archive.

How current trends can be extrapolated into the future were analyzed based on datasets developed from climate projection. One case involves the B1 scenario, which will expect CO_2 to reach 500 ppm by 2100, and the NOAA GFDL climate model. The other case is the A2 scenario, where CO_2 is expected to reach 900 ppm by 2100. We observe that regions ranging from the southern to northern end of the Central Valley will experience less than 2000 hours of sufficient winter chill by 2100 with both scenarios. But fewer winter chill hours are accumulated with the warmer A2 scenario. Both climate scenarios cause the local winter climate to approach the critical thresholds for many fruit trees species. In the future, one may be a substitute fruit species that need less chill hours (e.g., peaches for almonds) or with selective breeding current fruit trees may be substituted with varieties requiring less winter chill.

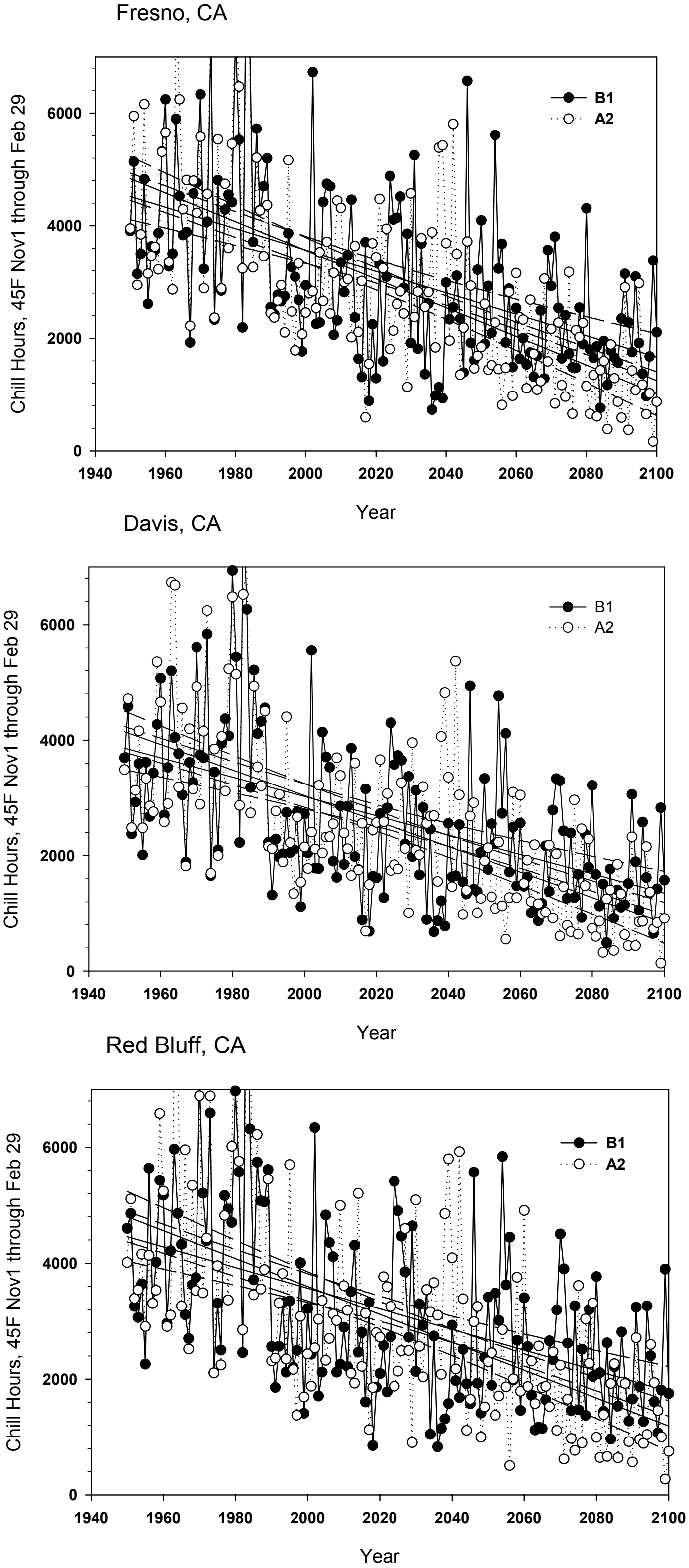

Figure 9. Current and future projections of chill hour accumulation for three sites up and down the Central Valley (Red Bluff, Davis, and Fresno). Climate projections were computed to 2100 for scenarios B1 and A2.

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 10 shows there is a low probability (0.073%) of leaf temperature exceeding 40 C with contemporary climate. Evaporative cooling helps leaves control and modulate their surface temperature. The probability of exceeding this threshold increases to 2.73% with mean air temperature increasing by 3 C and CO_2 increasing to 500 ppm (scenario B2) because stomatal closure at high CO_2 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.

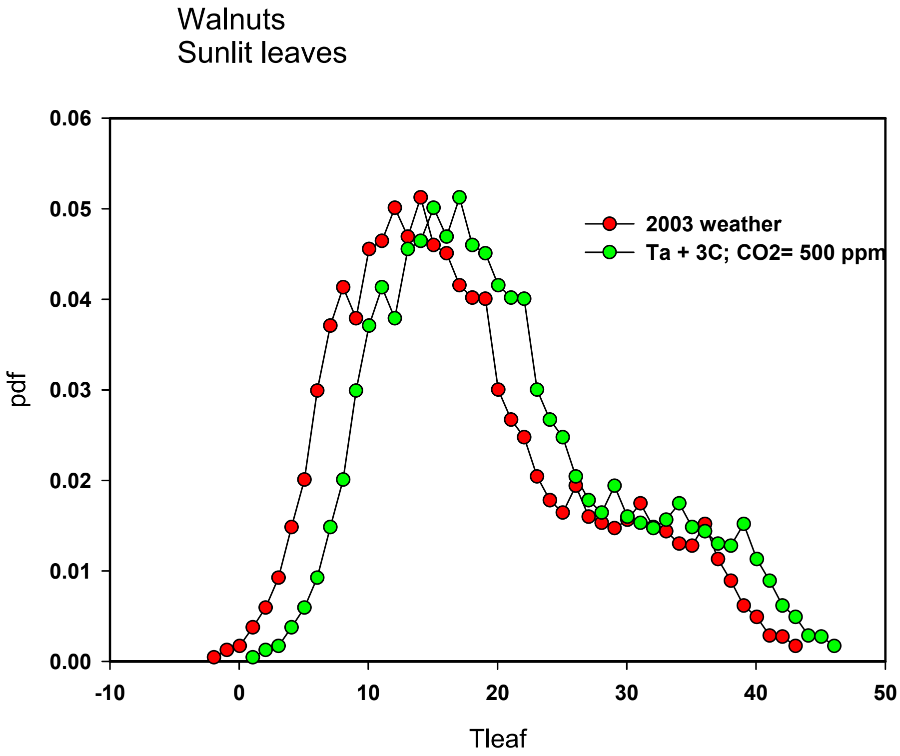

Figure 10. Probability distribution of sunlit leaf temperature for contemporary and future climate conditions.

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