CLIMATE CHANGE: CHALLENGES AND SOLUTIONS FOR CALIFORNIA AGRICULTURAL LANDSCAPES

WHITE PAPER

A Report From:

California Climate Change Center

Prepared By:

Timothy Cavagnaro, Louise Jackson, and Kate Scow (Contributing authors are listed in the relevant sections.)

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.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

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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1.0 General Introduction and Scope of Report

Timothy Cavagnaro, Louise Jackson, Kate Scow

1.1. Statement of Purpose and Scope of Report

The climate of California is predicted to change significantly during the coming century. While a changing climate will impact the state as a whole, some sectors may be affected more than others. This is especially true of agriculture. Impacts may not only alter the types and locations of commodities produced, but also the factors influencing their production, such as resource availability and biotic and abiotic stresses. The nature and interrelatedness of these factors, and the response of agro-ecosystems, need to be explored to effectively mitigate and/or adapt to the effects of climate change in a sustainable manner.

To consider the challenges facing California agriculture in a changing climate, a symposium entitled "Climate Change Symposium: Challenges and Solutions for California Agricultural Landscapes" was held at the University of California (UC) Davis by the John Muir Institute for the Environment, May 12–13, 2005 (John Muir Institute 2005). Talks were presented by 29 speakers from West Coast universities and state and federal agencies, to an audience of more than 100 participants from a range of organizations and stakeholder groups. The structure of the symposium promoted open discussion among participants from multiple disciplines. The presentations and conclusions of the symposium provide the basic structure and foundation upon which this report is written.

An important outcome of the symposium was recognition not only of future impacts of climate change on California agricultural landscapes, but of the fact that actions taken now and in the near future will play critical roles in dealing with these changes. By taking a landscape perspective, the focus was not only on commodity-specific issues and agro-ecosystem changes, but also included a wider range of factors, such as water availability and transport, and interactions with urban ecosystems. As such, there is a greater need than ever to train scientists with a broad and in-depth appreciation of the complex issues of climate change. To this end, we developed a graduate-level seminar class entitled "Climate Change and the California Agricultural Landscape" (ECL/SSC 290) UC Davis (July–September, 2005). Fourteen graduate students, from both the Ecology and the Soils and Biogeochemistry Graduate Groups, participated in the class. Student workgroups, mentored by UC Davis faculty and/or a representative from a government agency, integrated material from the symposium presentations and a review of the scientific literature to identify key impacts of climate change upon California agricultural landscapes.

Adhering, for the most part, to the organizational structure of the symposium, this report consists of an integrated analysis of potential impacts of climate change upon California agriculture. It primarily focuses on identifying impacts, options for adaptation, and identification of areas where key data are currently lacking. California agriculture also has an important role to play in climate change mitigation, both in the short term and in the longer term. While not the primary focus of this report, we also identify areas and options where California agriculture may act as a net mitigator of climate change. Another outcome of this effort is a database of > 500 references relevant to assessment of climate change in California agricultural landscapes.

2.0 California Agricultural Landscapes and Climate Change

Todd Rosenstock, Sean Smukler, Timothy Cavagnaro

2.1. California Agriculture: Production and Geography

California agriculture was valued at $31.8 billion in 2004 in cash farm receipts to agricultural producers (California Department of Food and Agriculture 2006), and it currently accounts for approximately 13% of the United States agricultural cash receipts, leading the nation as it has done every year since 1948 (University of California Agricultural Issues Center 2005). With over 250 different commodities produced, California is the most diverse agricultural producer within the United States. High value horticultural commodities (fresh fruits and vegetables, and tree nuts) account for greater than 50% of the cash receipts, and dairy is the single largest commodity in terms of income in the state. The top three agricultural commodities in 2003 (in billions of dollars) were dairy (> 4), greenhouse and nursery products (3.3), and grapes (2.6). On a national scale, California produces half of the nation's total fruits and vegetables and 19% of dairy (Figure 2.1). California is vital for domestic consumption, with 80% of production bound for national markets and 20% for export.

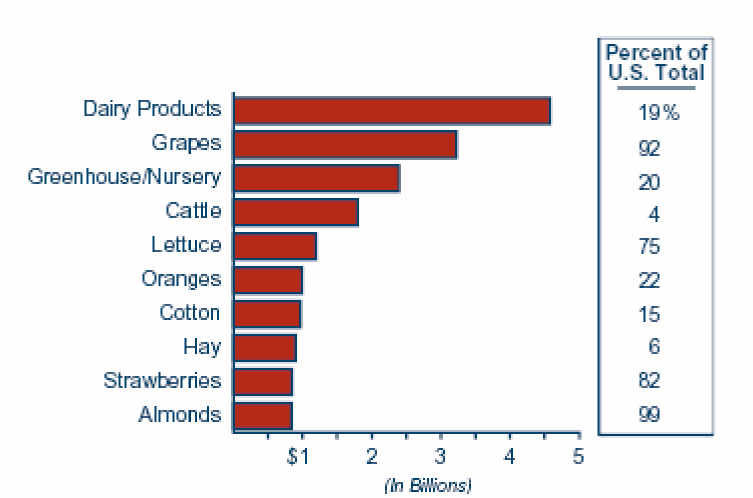

Figure 2.1. California's top agricultural commodities as a percentage of the nations total production of each commodity. Figure excerpted from Legislative Analyst's Office (2002), formal permission not obtained.

California's agricultural industry stretches well beyond the farmgate. Not only encompassing 79,631 farms, there are substantial complementary industries and rural communities in the agricultural landscape (University of California Agricultural Issues Center 2003). In California, agriculture employs approximately 1.1 million people—about 7.4% of total Californian employment. Regionally, agricultural employment is even more significant, as in the Central Valley, where it accounts for 25% of all employment. Thus, California agriculture represents a significant source of the state's income and employment, and provides a diverse range of commodities of high economic and nutritive value for the United States.

California Agriculture covers approximately 11.2 million hectares, greater than a quarter of the state's > 40 million hectares in land area (University of California Agricultural Issues Center 2005). Agriculture, including grazed grasslands, accounts for approximately one-half of the privately owned land and one-third of public lands (Figure 2.2). The diversity of topography, the latitudinal range (10 degrees), and seasonality of weather patterns, play an important role in the success of California agriculture. The California landscape is diverse, and landscape features affect climate and thus agriculture in many ways. Although a Mediterranean-type climate is present in most of California's agricultural regions, there are milder temperatures in the coastal valleys, mountain ranges which serve as rain catchments, and hotter summers and wetter winters in the Central Valley that lies between the Coast Range and the Sierra Nevada (Barbour et al. 1993). Few other states or agricultural regions exhibit climatic conditions with the confluence of availability and seasonality of water resources, along with a well-established water supply infrastructure and appropriate temperature regimes, to support a similarly diverse and productive agricultural landscape. However, the regional and climatic diversity of California also predispose the state to potentially significant impacts if large shifts in climate occur, since the commodities produced may be affected differentially. Nevertheless, with topographic diversity may come the potential for enhanced adaptive capacity in response to climate change.

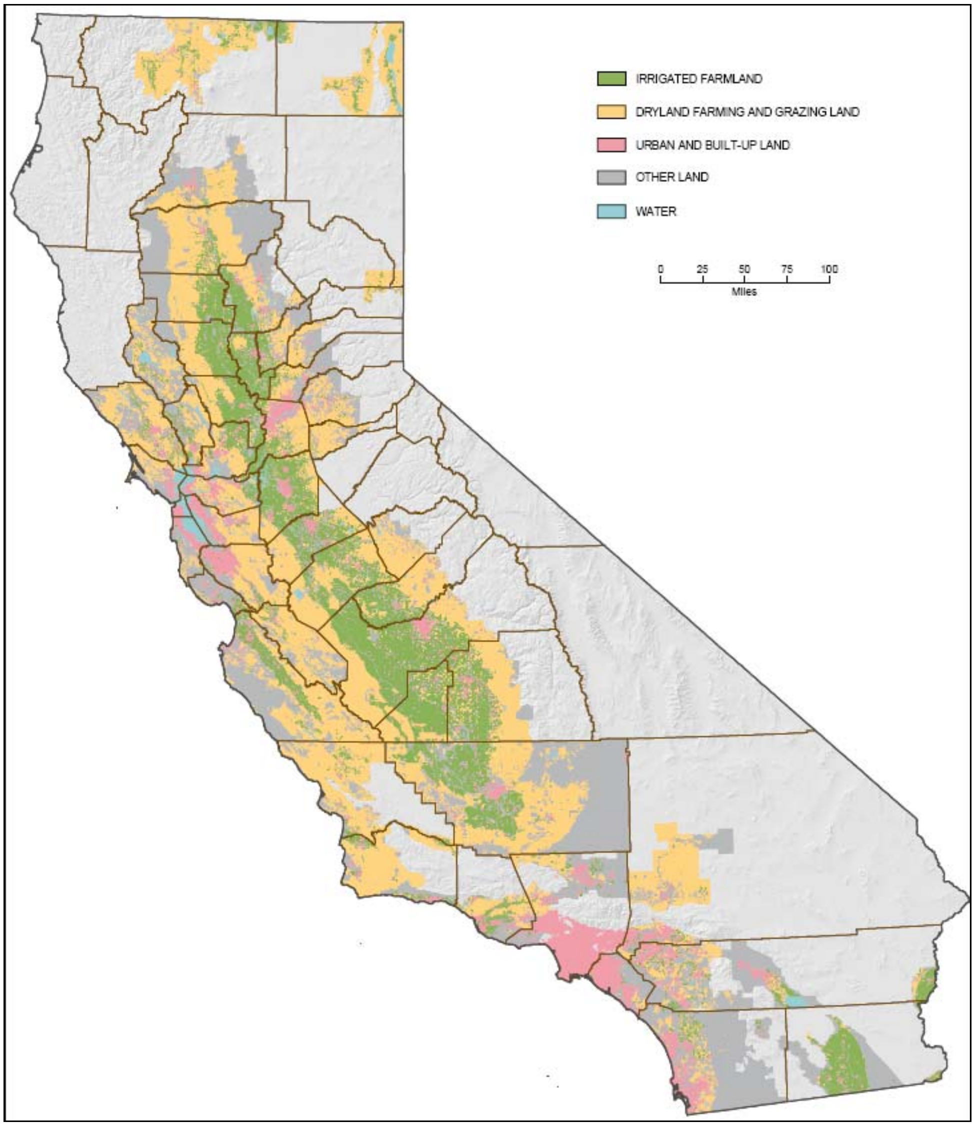

Figure 2.2. Major land uses in California in 2002. Figure excerpted from Division of Land Resources Protection (2002), formal permission not obtained.

2.2. California Agriculture and Global Climate Change

Worldwide evidence of climate change is mounting and the consensus of the scientific community is overwhelming (Oreskes 2004); over the last 50 years, anthropogenic emissions of greenhouse gases (GHGs) have caused substantial temperature and precipitation changes on a global scale (IPCC 2001). The Intergovernmental Panel on Climate Change (IPCC) reports that there has been a 31±4% increase in atmospheric carbon dioxide (CO_2) in the year 2000, relative to the time period 1000–1750, and a mean surface temperature increase of 0.6±0.2°C (1.08±0.36°F) over the twentieth century. Worldwide, glaciers are in retreat, the tundra is thawing, ice caps are melting, the sea level is beginning to rise, and weather patterns are starting to shift. These changes are predicted to continue as emissions increase over this century and the planet's mean temperature is expected to warm between 1.7° to 4.9°C (3.1°F to 8.8°F) by 2100. The effects of global climate change may be dramatic in some regions (for example, low-lying flood plains, island states, coastal regions, and glaciated landscapes), while far less severe in others, or in some situations potentially beneficial in terms of increased agricultural productivity (Easterling and Apps 2005; National Assessment Synthesis Team 2001; Parry et al. 2004). Different economic sectors will be impacted to different extents (Reilly 2001); however, it is very likely that sectors directly influenced by climate such as agriculture will be the first to be impacted by these changes and most likely to incur long-lasting effects. This report investigates how these changes are likely to impact California agriculture.

2.3. The Science of Predicting Climate Change

In recent years, considerable effort has been made to project the future global climate and the factors that drive it. Coupled atmosphere/ocean/sea-ice general circulation models (AOGCMs) provide a comprehensive numerical representation of the climate system that can be used to make credible simulations of climate—at least down to sub-continental scales and over a range of seasonal to decadal temporal scales (McAvaney et al. 2001). No single climate model is most suitable for making accurate predictions of the future climate (McAvaney et al. 2001); thus, a number of models are employed to account for uncertainties associated with each of the models themselves, and their response to a range of inputs (for example, emissions scenarios, see below). This approach of using more than one model and emissions scenario (see below) has been widely adopted (Hayhoe et al. 2004; IPCC 2001; National Assessment Synthesis Team 2001; Wilkinson 2002). For regional assessments of climate change, downscaling (both statistical downscaling and use of data from individual weather stations) of global climate models is required (Dettinger et al. 2004; Hayhoe et al. 2004; Wood et al. 2002). The nature and extent of future emissions of radiatively active substances (GHGs and sulfur emissions) play an important role in climate change modeling (Cubasch et al. 2001; Nakicenovic et al. 2000). Consequently, a number of emissions scenarios, as outlined in the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000), have been produced. The scenarios follow four main storylines, which are further subdivided and are based upon a coherent and internally consistent set of assumptions about driving forces (such as demographic, economic, and technological change factors) of emissions of radiatively active substances and their key relationships, were developed by the IPCC (Nakicenovic et al. 2000). The four emissions storylines are representative of the emissions scenarios literature and have no assigned probability of occurrence. Each assumes a distinctly different direction for future developments, such that they differ in increasingly irreversible ways (Nakicenovic et al. 2000). This leads to a range of possible emissions futures to be used in climate change modeling exercises (Figure 2.3).

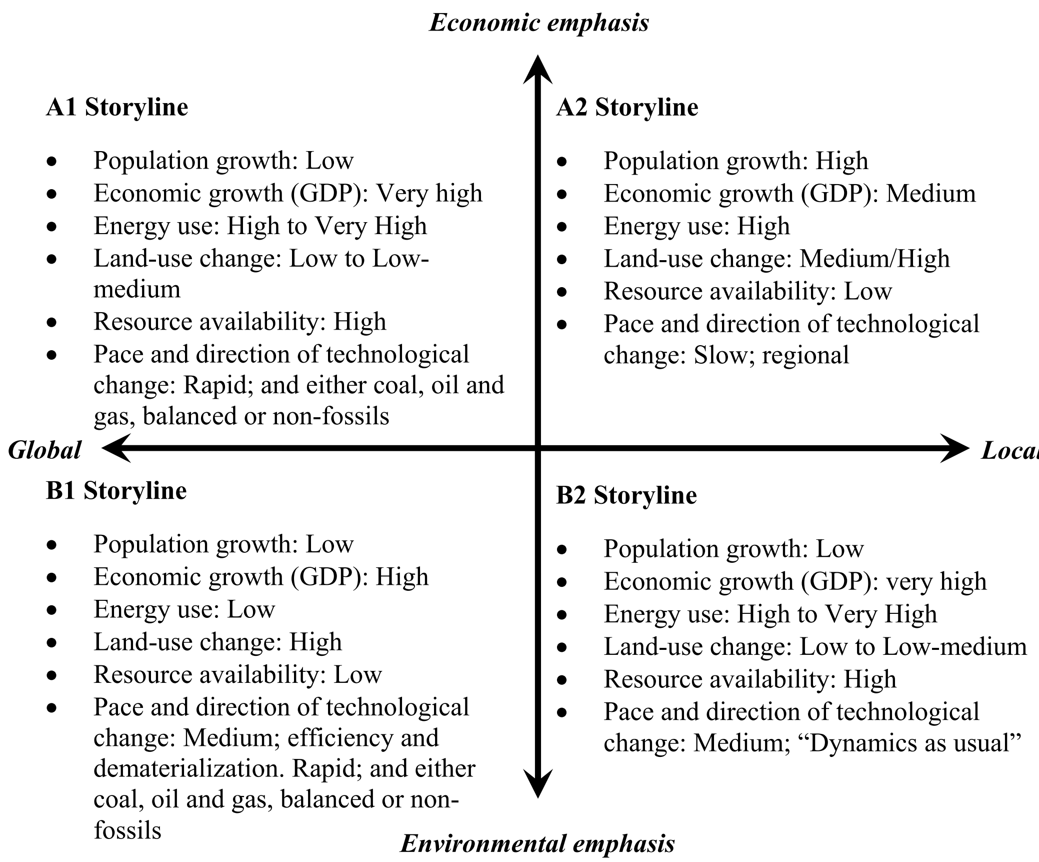

Figure 2.3. Main characteristics of emissions scenarios families outlined in the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). Emissions storylines are further subdivided based upon a coherent and internally consistent set of assumptions about driving forces of emissions of radiatively active substances and their key relationships. Emissions scenarios used for California predictions by Hayhoe et al. (2004) were A1Fi and B2 (see text). Figure based upon (Nakicenovic et al. 2000; Smith 2004).

2.4. Impacts on California Must Be Considered at Different Scales: Global, National, and Regional

2.4.1. California in the global context

Although the diversity and economic size of California's agricultural production may increase its resilience and resistance to perturbations such as urbanization, higher temperatures and increasing resource costs are projected for the next 100 years (Konyar 2001), and there is great uncertainty as to how producers will respond to a changing climate both within California and globally. Producers may face significant challenges as regional temperatures, precipitation and weather pattern variability, and national and international markets are altered by global climate change.

As commodity prices are dependent on global production and demand, any assessment of the impacts of climate change on California agriculture must be done in the context of both regional and global changes in yields. The magnitude and direction of these yields will be determined by climatic factors such as temperature, precipitation, and weather variability, and production factors such as biotic responses to elevated atmospheric CO_2 concentrations, the availability and application of nutrients, and the ability of producers to adapt to these changes. Furthermore, as global markets develop for carbon trading, opportunities may arise for California agricultural producers to mitigate GHGs (for example, through sequestration, reduction in fuel use and vehicle emissions, or biofuel production). Therefore, adjustments in global food and mitigation markets together will no doubt significantly determine California agricultural producers' response to climate change. Furthermore, because agriculture is not only of economic significance, but also secures the livelihood of most of the world's population, impacts of climate change on food and farm security are of particular importance (Zilberman et al. 2004).

Predicting yields in the coming century requires complex modeling that integrates both global and regional climate change models, crop growth models and economic models, with the expectation that climate change will likely impact different regions of the world in distinct ways (Easterling and Apps 2005; IPCC 2001; Lindner et al. 2002). Global models that have incorporated both biophysical and socioeconomic parameters have predicted that negative impacts on food production from climate change will largely be felt in the developing world, but positive impacts will be felt in the developed world (Easterling and Apps 2005; Parry et al. 2004). These studies conclude that the magnitude of this disparity will be determined by which future IPCC's emissions scenario (see below) is adopted and the degree to which crops will respond to CO_2 fertilization. Low-latitude regions of the world may not benefit from CO_2 fertilization, because the benefits are overshadowed by the predicted detrimental effects of increased temperature and/or precipitation changes (Easterling and Apps 2005). As a result, regions such as Africa or parts of Asia are predicted under the GHG intensive A1fi scenario to experience yield reductions up to 30% of 1990 levels by 2080 (Parry et al. 2004). The population at risk of hunger in Mali, for example, is predicted to increase from the current 34% to 44%, due to land degradation and then up to 72% due to the additional impacts of climate change by 2030 (Butt et al. 2005). These regions are at particular risk because their lack of infrastructure and technology impedes their producers' ability to adapt to adverse and/or altered climate conditions. In contrast, the stress caused by A1fi climatic conditions is expected to be offset for some crops such as cereals (Parry et al. 2004), by the effects of CO_2 fertilization, resulting in small increases in yield in Australia, North America, and South East South America

2.4.2. California in the U.S. context

Assessments of agricultural production in the United States (Adams et al. 1998) have used an Integrated Assessment (IA) approach, which includes complex interactions of temperature and precipitation changes with increased climate variation, changes in pesticide use, environmental effects caused by agriculture (for example, erosion, agricultural runoff into waterways), changing global markets, societal responses, and technological adaptation, to model agricultural response(s) to climate change (National Assessment Synthesis Team 2001; Reilly et al. 2003; Smith et al. 2005). Consistent among these studies are the conclusions that there will be a dramatic difference in regional impacts, but agricultural production in the United States overall will increase, commodity prices will fall, and irrigation use will go down due to increased precipitation (National Assessment Synthesis Team 2001) and potentially higher water use efficiency that results from CO_2 fertilization (Bunce 2004; Ewert et al. 2002). Climate change is therefore expected to be economically positive for U.S. consumers and negative for producers, but will entail increased pesticide use and result in increased environmental degradation (Reilly et al. 2003). Regional-level projections could be quite different in California than nation projections, because of the state's limited water resources and its focus on specialty crops.

2.5. Climate Change Model Predictions for California as a Region

2.5.1. Methods used for most recent predictions for California

In recent years, projections of the future climate under different emissions scenarios have been made for California (Hayhoe et al. 2004; Wilkinson 2002), and as part of the United States (National Assessment Synthesis Team 2001; Thomson et al. 2005) and global (IPCC 2001; Parry et al. 2004) assessments. A range of possible climate futures for California were predicted (Hayhoe et al. 2004) using the (downscaled) Global Parallel Climate Model (PCM) (Washington et al. 2000) and Hadley Centre Climate Model, version 3 (HadCM3) (Gordon et al. 2000; Pope et al. 2000), under a range of possible emissions scenarios (B1 and A1fi). The B1 and A1fi emissions scenarios bracket a large part of the range of IPCC nonintervention emissions futures (Hayhoe et al. 2004), with atmospheric concentrations of CO_2 reaching 550 parts per million (ppm) (B1) and 970 ppm (A1fi) by 2100, respectively (Nakicenovic et al. 2000). In general, the projected climate anomalies and impacts are reported as mid-century (averaged over 2020–2049 midpoint 2035) and end-of-century (averaged over 2070–2099 midpoint 2085), relative to a 1961–1990 reference period (see Hayhoe et al. (2004)). There is a degree of uncertainty (see below) associated with these climate predictions; however, they represent our current best estimate of climate change in California in the coming century, and provide the basis for the predicted impacts of climate change on the California agricultural landscape reported here.

2.5.2. Recent predictions for California

Climate change's impact on agriculture will be the consequence of shifting impacts in both temperature and precipitation, their interactions, and the seasonality of such effects. Furthermore, the incidence of extreme weather events may also increase (IPCC 2001). The following section outlines the projections made by Hayhoe et al. (2004), with reference to other recent predictions for California, providing context and highlighting the degree of consistency and disparity between modeling efforts and approaches.

Temperature

Both the PCM and HadCM3 models coupled with high and low emission scenarios (A1fi and B1 scenarios respectively) predict an increase in average annual temperature before 2049. Higher emissions scenarios (A1fi) may result in a temperature increase that is two times higher than at lower emission scenarios by the end of the century. Seasonally, summer temperatures may increase between 2.15°C (3.87°F) and 8.3°C (14.9°F), while winter temperatures are estimated to rise between 2.15°C (3.87°F) and 4.0°C (7.2°F). Temperature changes may be less significant in the southwest coastal region with an increase in magnitude going north and northeast across the state. The relative increases of minimum temperatures may be the most dramatic, although a different modeling approach suggests that minimum temperatures may actually decline (Leung 2005).

As a comparison, the national assessment of climate change impacts on the United States (HadCM2 and Canadian Climate Center Models with the IS92 emissions scenarios, (National Assessment Synthesis Team 2001)) projects annual average temperature to increase by 2°C (3.6°F) by 2030 and 4.5°C–6°C (8.1°F–10.8°F) by 2090 in the Western United States, compared to 1.35°C (2.43°F) and 1.5°C (2.7°F) under the B1 and A1fi emissions scenarios using the PCM model, and 1.6°C (2.9°F) to 2.0°C (3.6°F) using the HadCM3 model for the period 2020–2049. For California, increases of 2.3°C (4.1°F) and 3.8°C (6.8°F) under the B1 and A1fi emissions scenarios using the PCM model, and 3.3°C (5.9°F) to 5.8°C (10.4°F) using the HadCM3 model for the period 2070–2099, respectively, are projected (Hayhoe et al. 2004).

Precipitation

Precipitation projections are more uncertain than those for temperature, because complex decadal variability is inherent in precipitation patterns. While the PCM model under the B1 emissions scenario suggests a very slight increase in precipitation, other model and emissions scenario combinations project decreases (Hayhoe et al. 2004). Other emissions scenarios iterations projected a slight decrease in precipitation, with declines of 157 mm (6.2 in)/year, 117 mm (4.6 in)/year and 91 mm (3.6 in)/year compared to current average precipitation in the HadCM3 A1fi scenario, HadCM3 B1 scenario and PCM A1f1 scenario, respectively (Hayhoe et al. 2004). Spatio-temporal patterns of precipitation can be as critical as volume (Wilkinson 2005). For example, localized precipitation may be reduced by 30% in the Central Valley and the Pacific Coast (Hayhoe et al. 2004), thus significantly impacting the major agricultural regions of the state. Further highlighting the uncertainty associated with regional precipitation projections, an increase in winter rainfall, leading to a doubling of winter runoff by 2090, has also been projected for the California region using the HadCM2 and CGCM1 models and the IS92 emissions scenarios (National Assessment Synthesis Team 2001). Temporal change is already evident as peak spring stream flows have shifted over the past 50 years, to as much as 20 days earlier in some areas (Weare 2005).

Water Supply

Water supply is central to the success of Californian agriculture. In addition to changes in precipitation, water availability will likely be influenced by rising temperatures (and hence evaporation), and consequential increases in water demand from other sectors (industrial and urban). In addition, the impacts of higher temperatures plus increases in CO_2 concentration are not clearly understood (see Section 5.3 for more detail on this topic). Increased temperatures will affect the amount of water collected and stored in the Sierra snowpack. By the end of the century, the Sierra snowpack is predicted to be 30% to 70% lower than the current winter total, due to an increase in rainfall versus snowfall, and earlier melting of the snowpack (Hayhoe et al. 2004). This change will be most prominent in the southern Sierra Nevada, and at elevations below 3,000 m (9,800 ft), where 80% of California's snowpack storage currently occurs. The changing availability of water both within California and to California agriculture, may lead to heavy reliance on groundwater resources, which are currently overdrafted in many agricultural areas (Department of Water Resources 1998). Approximately 42% of current ground and surface water is used for agricultural purposes, with the remainder split between urban and environmental uses (University of California Agricultural Issues Center 2005). However, the agricultural proportion depends on the water year type, ranging from 29% for wet (high precipitation) to 52% for dry (low precipitation) years (Department of Water Resources 2005). Demand for water resources will be further exacerbated by an increase in the population of California in the coming century, which is projected to be > 46 million people by 2030, and may reach 90 million by 2100 (U.S. Census Bureau 2005).

2.6. Responding to a Changing California Climate: Mitigation, Adaptation, and Uncertainty

As will be discussed below, gradual shifts in climate over the next hundred years will necessitate adaptations that may not necessarily require direct government intervention, and could be driven, largely by market forces, changing management practices, and technological advances (Easterling and Apps 2005). California agricultural producers have had a history of adapting to new locations, development of water resources, and changes in markets. New adaptations will be made easier and more efficient by the availability of predictive information to producers, and an appropriate policy environment. Some sectors also lend themselves to more rapid change than others. For example, perennial tree crops and vines, of which many are unique to California in the U.S. context, may be particularly vulnerable to problems. The adaptation to rapid change or extreme climatic events, such as floods, droughts, and heat waves are much more difficult to predict. Such extreme events may exceed the adaptive capacity of markets and be much more difficult for producers to cope with (IPCC 2001). Thus, development of risk and response strategies (for example, levees and increased water storage capacity) to various extreme climate change scenarios may gain more attention in the coming years.

Beyond responding to changes in climate, California producers will most likely find opportunities to mitigate the release of GHG. Agriculture will play a significant role in a portfolio of national mitigation strategies, for example, as a first step to sequestering carbon (Smith 2004). United States agriculture and forestry could remove more than 425 million metric tons of carbon equivalents (MMTCE) of combined GHGs (McCarl and Schneider 2001), based on modeling of extreme increases in carbon prices. Carbon trading could have substantial impacts for agriculture, such as increased crop value and reduction of environmental externalities.

2.7. Conclusions

The future climate of California will clearly be different from that of the present day, raising issues of global and national importance regarding potential biophysical and economic impacts, and the role of climate change adaptation and mitigation in agriculture. The following sections of this report are devoted to predicting likely impacts of climate change on different aspects of California agriculture, presenting options (where available) for adaptation and/or mitigation, and identifying areas where further knowledge is required. The remainder of this report is divided into the following sections:

Section 3.	Climate change and greenhouse gases
Section 4.	Interactions among air quality, climate change, and California agriculture
Section 5.	Water resources and climate change: implications for California agriculture
Section 6.	Impacts of climate change on crop and animal physiology in California agriculture
Section 7.	Agricultural invaders, pests, and disease in California's changing climate
Section 8.	Land use change in California's agricultural landscapes in response to climate change
Section 9.	Synthesis, emerging trends, future directions and conclusions

3.0 Climate Change and Greenhouse Gases

Hideomi Minoshima,Victoria Albarracín, Kate Scow, Johan Six

3.1. Introduction

Greenhouse gases include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and high global-warming-potential gases such as sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and chlorofluorocarbons (CFCs). Since these gases absorb the terrestrial radiation leaving the earth's surface, changes in their atmospheric concentrations can alter the balance of energy transfer between atmosphere, land, and oceans. All atmospheric GHG concentrations are increasing each year due to anthropogenic activity which, in turn, leads to climate changes at the local, regional, and global scale (IPCC 2001; Murphy et al. 1999; Nakicenovic et al. 2000).

The present section focuses in particular on CO_2, N_2O, and CH_4 because they are the three major biogenic GHGs produced by the agricultural sector in California and across the globe. It summarizes current sources and sinks of GHGs (i.e., total amounts of emissions by each type of gas), the contribution of the agricultural sector to California GHG emissions, and considers agriculture and forests as potential GHG sinks. Potential impacts of climate change on CO_2, N_2O, and CH_4 emissions and possible mitigation strategies for GHGs produced by the agricultural and other sectors are presented.

3.2. Sources and Sinks of GHGs in California

California produced 493 million metric tons of CO_2-equivalent GHG emissions, and in 2002 was ranked as the second largest U.S. state emitter after Texas (University of California 2005b). Most emissions were CO_2 (81%) produced from the combustion of fossil fuels from industrial and transportation sources.

Overall, the contribution of the agricultural sector to GHG emissions as a whole in California is relatively small. Taken together, agriculture and forestry contributed approximately 8% of the state's total GHG emissions, including GHGs from all agriculturally related activities such as fossil fuel combustion associated with crop production, livestock production, and soil liming (University of California 2005b). Emissions arising from transportation of agricultural commodities are not included in this estimate.

CO_2 emissions from non-fossil fuels, including agricultural activities, were 2.3% of the total GHG emissions of California. Of the 2.3% of CO_2 from non-fossil fuels, agricultural activities contributed about 38%. Thus, the total contribution of CO_2 from agricultural activities to the total GHG emissions was 0.9% in 2002 (University of California 2005b). Nitrous oxide and CH_4 emissions contributed 6.8% and 6.4%, respectively, to the total GHG (on a CO_2 equivalent basis) emissions in 2002—with approximately 59% and 38%, respectively, originating from agricultural activities. An estimated 18.6 and 0.9 metric tons of CO_2-equivalent GHG came from agricultural practices and manure management, respectively, in 2002 (University of California 2005b). Thus, the agricultural contribution to the state's 2002 emissions of N_2O and CH_4 was 4% and 3%, respectively. Methane emissions from California flooded rice fields constituted a total of 0.5 metric tons of CO_2-equivalent GHG and constituted less than 2% of total CH_4 emission in California in 2002 (University of California 2005b). Methane emissions from animal production included 7.3 and 6.6 metric tons of CO_2-equivalent from enteric fermentation and manure, respectively (University of California 2005b).

3.3. How Will Changes in Climate Change Manifest in Agricultural GHG Dynamics?

Greenhouse gases are produced primarily by soil microorganisms carrying out oxidation-reduction reactions, including nitrification, denitrification, methanogenesis, and organic matter decomposition (Sylvia et al. 2004). Because changes in temperature and precipitation alter the activity of soil microorganisms, GHG emissions from agriculture would likely be affected by climate change. This section considers, in general terms, the impacts of climate change on respiration and soil organic matter (SOM) dynamics, as well as N_2O and CH_4 emissions.

3.3.1. Carbon dioxide and soil organic matter

Carbon dioxide is the end product of respiration by soil biota (microorganisms, plant roots, and soil fauna). It is produced primarily under aerobic conditions but also can be generated in the absence of oxygen (e.g., under waterlogged conditions) (Sylvia et al. 2004). A potential impact of increased temperature is loss of carbon (C) from the large reservoir of C contained in SOM in agricultural and forest soils. Although forests are currently a sink for CO_2 (20.3 metric tons of CO_2-equivalents in 2002 in California), they might become a source of CO_2, with temperature increases from global warming (Trumbore et al. 1996). This issue is critical, because SOM contains roughly two-thirds of the terrestrial C and two to three times as much C as atmospheric CO_2 (Trumbore et al. 1996).

Many researchers have investigated the effects of temperature on decomposition rates of SOM in mineral soils. Trumbore et al. (1996) reported that temperature is a major controller of turnover for a large component of SOM, as long as soil moisture is not a limiting factor. It is hypothesized that the decomposition of soil labile C is sensitive to temperature variation; whereas resistant components are less sensitive. However, Fang et al. (2005) suggested that the temperature sensitivity for resistant SOM pools does not differ significantly from that of labile pools, and that both pools of SOM will therefore respond similarly to global warming. In contrast to observations that decomposition is enhanced by increases in temperature, Giardina and Ryan (2000) reported, based on analyses of data from locations across the world, that rates of SOM decomposition in mineral soils were not controlled by temperature limitation to microbial activity and that estimates made from short term studies may overestimate temperature sensitivity. However, Knorr et al. (2005) reexamined the results of Giardina and Ryan (2000) and come to the conclusion that treating SOM as one pool is incorrect to assess the affect of temperature on SOM dynamics. When they apply a three-pool model to the data of Giardina and Ryan (2000), they found a sensitivity of SOM to increasing temperature.

Combined with other data and modeling exercises, they come to the conclusion that the slow or recalcitrant SOM pool is the most sensitive pool over longer timescales. In conclusion, there is a consensus that temperature increases SOM turnover (see also Rustad et al. (2001) for a review), but it is still debated if the labile or recalcitrant SOM pool is more sensitive to temperature increases.

Because moisture content in soils strongly affects the activities of soil microorganisms in direct, and perhaps more importantly in indirect ways (e.g., by reducing oxygen content), changes in precipitation patterns due to global warming may be one of the main impacts of climate change on SOM decomposition in mineral soils. Predictions of changes in precipitation are problematic, differing among climate models, thus making influences on SOM difficult to predict.

Other factors (soil texture, disturbance, amounts, and biochemical properties of leaf and root litter quality) influence SOM decomposition (Davidson et al. 2000), some of which may be affected by climate change, and must also be considered in projections of how SOM will behave. Temperature should not be viewed in isolation from other factors (Davidson et al. 2000). Unfortunately, the magnitude and relative importance of these factors in governing SOM dynamics have received little attention in the literature.

3.3.2. Nitrous oxide

Nitrous oxide (N_2O) is produced primarily during denitrification, an anaerobic microbial process in soils or sediments, in which nitrate is used as an electron acceptor in the absence of oxygen (Sylvia et al. 2004; Venterea and Rolston 2000a). Although nitrification (the oxidation of ammonium to nitrate) also produces some N_2O, this process is thought to be a less important source than denitrification (Venterea and Rolston 2000a). Agricultural activities—soil emissions from fertilizer use, residue burning, and animal production—are responsible for an estimated 80% of anthropogenic emissions of N_2O (Kroeze et al. 1999). Few studies have investigated N_2O emissions in agroecosystems in California. In a comparison of organic and conventional managed tomato soils in the Central Valley, N_2O emissions were found to be of short duration following the addition of organic or mineral fertilizer in the organic and conventional systems, respectively, and occurred immediately after irrigation events (Burger et al. 2005). There are, however, no published extensive and systematic studies collecting field measurements of N_2O over the growing season in different soil types of California that would permit identification of relationships between fluxes, management practices, and environmental variables. This is an important knowledge gap that needs more research.

Other studies outside of California have indicated that emissions of N_2O are primarily controlled by soil moisture content, in particular the water-filled pore space (WFPS) (Davidson 1991), temperature (Keeney et al. 1979), organic carbon availability (Wagner et al. 1996), and concentration of mineral nitrogen (NH_4^+ and NO_3^-) (Ryden and Lund 1980). The latter factor is often optimal in agricultural soils for N_2O fluxes because the addition of synthetic N fertilizers and organic manures lead to elevated mineral N concentrations (Granli and Bockman 1994), at least temporarily. In addition, California agricultural systems are frequently irrigated, leading to ideal moisture conditions for denitrification and potentially N_2O fluxes (Rolston et al. 1982). Adoption of reduced tillage management systems often leads to an increased carbon content and increased percentage of WFPS in soils, which in turn may support higher rates and a longer duration of denitrification and/or N_2O fluxes (Robertson et al. 2000; Six et al. 2004). In a meta-analyses, Six et al. (2004) found that recently converted no-tillage systems have greater N_2O fluxes, compared to conventional tillage systems, but older (> 20 years) no-tillage systems have lower annual N_2O fluxes. Also, different types of nitrogen fertilizers produce different amounts of N_2O under the same reduced tillage management systems, so fertilizer-tillage interactions must also be considered (Venterea et al. 2005).

With respect to effects of water content, Dobbie and Smith (2001) found that N_2O emissions from arable soils increased about 30-fold when the WFPS was increased from about 60% to 80%. Smith (1997) suggested that, contrary to expected decreases in N_2O emissions with decreased precipitation, increased temperature might stimulate respiration and lead to oxygen depletion. This would, in turn, increase the anaerobic volume in soil pore spaces and consequently favor denitrification and N_2O emissions. Based on these estimates, N_2O emissions from both arable lands and natural ecosystems in California may be increased by rising temperature, even though it is difficult to predict the exact amount of N_2O emission increases.

Although studies indicate a positive relationship between temperature, precipitation and denitrification, the actual predictions of how N_2O emissions will respond to global warming are complicated and vary among models. For example, in the Denitrification-Decomposition (DNDC) model (Li et al. 1992) and Land Use Emissions submodels (Kreileman and Bouwman 1994), the underlying assumption is that there is a positive relationship between temperature and precipitation. However, the Carnegie-Ames-Stanford (CASA) model assumes a negative feedback on N_2O emissions as a result of climate change.

Since denitrification in soils is regulated by many factors, as described above, and given the paucity of data on N_2O emissions, it is difficult to predict the effect of climate change on N_2O emissions. A small change of N_2O concentration can lead to a large difference in global warming potential (GWP), since the GWP of N_2O is 300 times higher than that of CO_2. Thus, studying the effect of changes in temperature and precipitation on N_2O emissions is a high priority for the state (Bemis and Allen 2005). To support these efforts, more precise methods of measuring N_2O emissions in the field are needed.

3.3.3. Methane

Globally, methane is generated from natural sources (42% of the annual flux), such as wetlands, and from human activities (58% of annual flux), such as rice growing, landfill use, and animal production (Robertson 2004). Methane is produced by the process of methanogenesis, under strictly anaerobic conditions, by microorganisms that either use hydrogen gas as an energy source with CO_2 as an electron acceptor or that ferment acetate (Sylvia et al. 2004). The process occurs in the digestive system of ruminant herbivores, in anaerobic holding ponds where manure is stored, as well as in soils that are saturated with water (e.g., rice paddies and wetlands) and therefore depleted in oxygen. Practices associated with animal production are major agricultural sources of methane, both nationally and globally (EPA 2004; Robertson 2004) and, in California, likely far exceed rice production in their magnitude of methane emissions (University of California 2005b).

The relative importance of California wetlands as sources of methane to the state is unknown and warrants further study. Soil with high amounts of organic matter (Histosols), found in California wetlands and the Delta area, are a particular class of soil with high potential for methane production (Ogle et al. 2003). The current estimate of wetland acreage in California, areas where Histosols are the common soil type, is approximately 450,000 acres; some of these soils are under agricultural production (California Resources Agency 2005). Even though these soils represent 0.4% of the state's area, the global warming impact of the GHG emissions from these soils could surpass those of the mineral soils, due to emission rates and the high global warming potential of CH_4 and N_2O.

Temperature, irrigation, fertilization, available carbon, and seasonal variations are among the factors that influence production of methane in soil (Allen et al. 2003; Lindau et al. 1990; Yagi and Minami 1990). This section focuses on methane formation in soils. There has been little consideration of the effects of temperature and CO_2 on CH_4 emissions in flooded rice fields and wetlands in California. Studies from other parts of the world provide insights regarding how methane emissions may respond to climate change. Elevated CO_2 levels have been demonstrated to increase CH_4 emissions in marsh ecosystems (Darcey et al. 1994). Watanabe et al. (2005) reported that temperature is a major factor causing seasonal variation in CH_4 emission rates during continuous flooding and that higher cumulative temperature leads to higher total CH_4 emissions. Allen et al. (2003) suggested that elevated CO_2 and higher temperatures increase CH_4 emissions in flooded rice soils due to greater root exudation or root sloughing mediated by increased seasonal total photosynthetic CO_2 uptake. Other studies, however, have not observed positive correlations between temperature and methane emissions (Schrope et al. 1999). Clearly, more extensive studies of gas fluxes from flooded ecosystems are needed to predict potential effects of elevated temperature and CO_2 on CH_4 emissions in California's flooded rice fields and wetlands.

3.4. GHG Mitigation and Adaptation

The potential effects of climate change on GHG emissions are quite diverse and controlled by numerous factors (Allen et al. 2003; Davidson et al. 2000; Dobbie and Smith 2001; Giardina and Ryan 2000; Trumbore et al. 1996). However, due to the long-term legacy of today's GHG emissions, it is sensible to formulate alternatives to adapt to climate change. At present, formulating adaptation strategies for California agriculture to increasing GHG concentrations in the atmosphere is based on theory and extrapolations from global scale assessments (Cole et al. 1997). Our aim should be to decrease negative impacts, promote any potential positive impacts that may result from these adaptive strategies, and reduce environmental and social pressures that increase vulnerability to climate variability (Hulme 2005). Wilkinson (2002) has identified a series of "no regret" adaptation strategies: increased water use efficiency; limiting the footprint of development on the landscape, particularly in vulnerable habitats such as wetlands and areas subject to fires, floods, and landslides; creating nature reserves designed to accommodate future climate changes and necessary range shifts and migrations of plants and animals; reducing urban heat island impacts; and using permeable pavements so that storm water runoff can be used to recharge groundwater systems (see Section 5 also).

Agricultural, as well as forest and rangeland, soils have the potential to mitigate climate change by serving as sinks for GHGs, due to their ability to store C in the form of organic matter (Lal 2003; Robertson 2004). This section will now focus on agricultural management practices that can enhance the utilization of agroecosystems as GHG sinks. It will also consider how interactions among different GHG must be considered in developing management strategies (Robertson 2004).

3.4.1. Carbon dioxide - CO_2

Table 3.1 summarizes potential mitigation strategies for CO_2 and the magnitude of the potential impacts at a global scale. Studies performed in partnership by the California Department of Forestry (CDF) and the California Climate Change Center (CCCC) estimated the statewide baseline of C stocks in California lands and the potential to sequester C in existing forests and oak woodlands. These studies indicated that the potential to sequester C is substantial and relatively inexpensive (Franco et al. 2005). Also the CCCC, in collaboration with the California Department of Food and Agriculture (CDFA) and the University of California Kearney Foundation of Soil Science, commissioned a scoping study of the potential to sequester C in agricultural soils in California. This study provided the basis to design a new and ongoing research project that includes the enhancement and validation of agroecosystem models (Denitrification-Decomposition (DNDC) and DAYCENT) prior to their use for California studies (Franco et al. 2005).

Table 3.1. Summary of CO_2 global mitigation potential for agriculture, expressed as decreases in net C emission rates or as net C storage rates. Table excerpted from Cole et al. (1997) as revised by Sauerbeck (2001); formal permission not obtained.

Category	Annual Global Value (Pg C)*
Reducing C emissions	
Reduction in fossil energy use by agriculture in industrialized countries (assuming 10%–50% reduction in current use) [a]	0.01–0.05
Increasing C sinks	
Increasing soil C through better management of existing agricultural soils (globally) [b]	0.4–0.6
Increasing soil C through permanent set-aside of surplus agricultural land in temperate regions [c]	0.015–0.03
Restoration of soil C on degraded lands (assuming restoration of 10%–50% of global total) [d]	0.024–0.24
Fossil C offsets	
Biofuel production from dedicated crops	0.3–1.3
Biofuel production from crop residues	0.2–0.3
Total potential CO_2 mitigation	**0.9–2.5**

* picograms of carbon.
[a] Finite limit over 50 years.
[b]Assuming a recovery of one-half to two-thirds of the estimated historic loss (44 Pg) of C from currently cultivated soils (excluding wetland soils), over a 50-year period.
[c] Assuming potential C sequestration of 1–2 kg C m^{-2} over a 50-year period, on an arbitrary 10%–50% of moderate to highly degraded land (1.2 x 10^9 ha globally).
[d] Based on 25% recovery of crop residues and assumptions on energy conversion and substitution.

Mitigation of elevated atmospheric CO_2 concentrations can be achieved by reducing agricultural fuel emissions, sequestering C in soils, and by producing biofuel to replace fossil fuels (Cole et al. 1997; Paustian et al. 2000). There has been considerable interest in achieving cost-effective, short-term CO_2 mitigation through C sequestration in agricultural soils (Cole et al. 1997; Lal et al. 1999; Marland et al. 2003). Traditional farming systems usually prepare the soil by plowing the soil, ranging from a single pass with a cultivator for weed control, to multiple diskings, subsoiling, and leveling of the field. This produces the oxidation of SOM and concomitant release of CO_2 into the atmosphere. No tillage (NT) systems eliminate plowing and might thereby preserve SOM and reduce CO_2 emissions. The adoption of NT has been demonstrated to have the potential to sequester C in agroecosystems, but the magnitude of C sequestration is strongly dependent upon climate and cropping system (Six et al. 2004; Smith and Conen 2004). However, these findings are not very relevant to California, since minimum tillage (MT) rather than NT is the more feasible alternative for most of the crops in California which are furrow-irrigated and thus require some working of the soil to build beds. Research addressing the potential for C sequestration in various California agricultural soils and management systems is underway, supported by the Kearney Foundation of Soil Science (see http://kearney.ucdavis.edu/). Preliminary estimates of soil C sequestration with MT indicate, however, less potential for mitigation than with NT (Jackson, Six, Horwath, Mitchell, pers. comm.).

Another management strategy for mitigation is to increase primary productivity and C fluxes into the soil through cover cropping (Kong et al. 2005; University of California 2005b; University of California 2005c) A *cover crop* is any crop grown during a period which would otherwise be a fallow period and that provides soil cover. One goal is to prevent soil erosion by wind and water of the bare soil and to provide a source of nutrients when incorporated in the spring. Often a legume is chosen for the added benefit of nitrogen fixation. Use of cover crops is preferable to importing external sources of carbon, such as manure, that requires fossil fuel consumption for transport to the site (Schlesinger 2000). In California, the use of winter cover crops is not uncommon, but not widely practiced across the state. Cover cropping, in California soils, has shown to increase C sequestration, especially in combination with MT (Mitchell, Six, pers. comm.).

Production of biofuel from dedicated crops and crop residues could enhance mitigation of GHG by increasing primary productivity and fixing C in the standing biomass. Biofuels such as ethanol and biodiesel are of interest both in terms of reducing reliance on petroleum and other nonrenewable fuels, as well as providing new sources of in-state energy supplies. The physical resource potential of biomass wastes and residues in the state was estimated to be 51 million dry tons annually, translating into 3.5 billion gallons of ethanol production, approximately 20% of the current highway motor fuel consumption in California (Bemis and Allen 2005). The potential energy supply potential of biofuels is under extensive study by the state and considered in greater detail in other documents (California Energy Commission 1999).

3.4.2. Nitrous oxide – N_2O

Agricultural management practices to reduce N_2O emissions include changes in N management strategies through reduction or better timing of inputs and changes in irrigation management (Kroeze et al. 1999; Laegried and Aastveit 2002; University of California 2005b). The potential impact of carbon sequestration on increased N_2O emissions from soil must also be considered to develop an integrated management strategy (Li et al. 2005; Mummey et al. 1998; Six et al. 2004).

Precision farming, where fertilization targets specific zones exhibiting N deficiency in a field, minimizes N_2O production since most added N will be utilized by the crop and therefore not available to the microorganisms (Mosier et al. 1996). Utilization of nitrification inhibitors can also reduce N_2O produced from soils (Kroeze et al. 1999) and different formulations of mineral N fertilizers produce different amounts of N_2O emissions (Kroeze et al. 1999; Laegried and Aastveit 2002).

To help manage N_2O, careful irrigation management could reduce the duration of elevated N_2O emissions, even when C and inorganic N availability are high and mineral fertilizer levels could be reduced, especially when soil moisture cannot be controlled (Burger et al. 2005). In the California Central Valley, Burger and Jackson (2003) found in irrigated organic systems, which receive higher organic matter inputs, a gradual release of inorganic N during the growing season, thereby potentially limiting the availability of N for N_2O emissions. The greater input of C can also support a more active microbial community which can immobilize more N and potentially prevent the buildup of available N (Venterea and Rolston 2000a; 2000b).

Given the close interrelationships among different biogeochemical cycles (e.g., C and N), the net GHG emissions of an entire agroecosystem must be considered when designing management strategies for GHG mitigation in soil. Emphasis on only CO_2 sequestration may overlook potential interactions with emissions of N_2O and other GHGs (Robertson et al. 2000; Six et al. 2004). Little research has been conducted in California's irrigated and heavily tilled agricultural soils on potential interactions among GHG emissions that might result from different mitigation practices. As carbon sequestration is increasingly considered in the state as a mitigation strategy, impacts on N_2O must be addressed.

3.4.3. Methane – CH_4

Agricultural methane emissions in California are derived mostly from practices associated with livestock production or from rice cultivation. Enteric fermentation (microbial process in digestive system of ruminant animals) comprised 52.7% and manure management 43.1%, representing a total of 95.8%, of the total agricultural CH_4 emissions in California (Bemis and Allen 2005). The current knowledge on effective nutritional ways to suppress CH_4 indicates the use of lipids as a promising natural option (Moss et al. 2000; Van Nevel and Demeyer 1996). Medium-chain fatty acids (Dohme et al. 2001) and fats (Dohme et al. 2000; Machmuller and Kreuzer 1999) are particularly efficient against ruminal CH_4 synthesis. However, it is not clear whether CH_4 mitigation strategies to reduce emissions from enteric fermentation may be counterbalanced by higher CH_4 releases from manure that may contain higher concentrations of residual fermentable organic matter (Bemis and Allen 2005). Diet changes can reduce CH_4 production from manure. For example, additions of crude protein to animal feed can slow down the rate of CH_4 synthesis (Hashimoto et al. 1981; Kulling et al. 2001).

The greatest reductions of CH_4 emissions from manure can be achieved through proper management of manure in anaerobic lagoons and in small digesters (Cole et al. 1997).

Manure wastes are disposed of directly onto land, e.g., in pasture lots (common for beef cattle), stored as slurries in anaerobic lagoons before land application (common for dairy cattle), or decomposed in digesters (Choate et al. 2005; EPA 2004). Virtually no CH_4 is produced from manure applied to land, so there is little opportunity for mitigation there (University of California 2005b). In contrast, there is a great potential to reduce not only CH_4, but also N_2O, by implementing improved manure treatment systems. Currently, the majority of the sludge originating from diary cows is stored in anaerobic lagoons; whereas a small fraction is treated in digesters. Properly designed, covered anaerobic lagoons and plug flow digesters can be especially effective in reducing and offsetting CH_4 emissions from manure by both capturing emissions and utilizing them to produce heat or electricity. Another alternative to reduce emissions is composting the manure. Although this practice is not as effective in reducing CH_4 emissions as covered anaerobic lagoons and digesters, and does not produce electricity, it is much simpler and inexpensive to implement. The applicability of these manure management practices, and therefore the potential for CH_4 emission reductions, is determined by technical constraints, production scale, and market penetrability (Choate et al. 2005). Managing animal production to maintain high productivity, with an optimized diet and anaerobic digestion of manure, is likely the most efficient way to reduce GHG emissions from livestock production (Clemens and Ahlgrimm 2001).

Rice production is a major source of agricultural CH_4 emissions, but irrigation management could significantly reduce CH_4 fluxes. For example, Yan et al. (2005) found a reduction of 60% and 52% by incorporating single and multiple drainage cycles into rice management, respectively, compared to that from continuously flooded rice fields. Nutrient management and utilization of new rice cultivars**,** more efficient in taking up N from soil, would result in a larger amount of C and N fixed in the biomass, decreasing emissions of both CH_4 and N_2O into the atmosphere.

3.5. Gaps and Future Research Questions

At present there is limited quantification of the mitigating effect of various agricultural practices in California. This quantification is an essential step that has to be taken towards planning, policy making and further implementation of GHG mitigation practices.

A major source of uncertainty regarding GHGs in California is associated with our incomplete understanding of the sources and mitigation potential of CH_4 and N_2O—both of which are GHGs with high global warming potential. Our estimates of N_2O fluxes from California agricultural soils are particularly poor and difficult to model, derived from the fact that so little data have been collected in California and that the environmental drivers of this process are not well understood. In addition, there is a need for specific research on GHG emissions from Histosols (Ogle et al. 2003), not only on current emission rates, but also on the potential that wetland restoration could have in reversing these negative impacts.

The consequences of changes in management practices to achieve mitigation of GHGs need to be better characterized in California soils; Table 3.2 summarizes some potential issues. This information is essential for evaluating the trade-offs of different mitigation strategies both with respect to GHGs and, beyond that, with the system as a whole. This information is urgently needed to develop effective and efficacious management plans and policies. Research on some of these issues is ongoing as part of the research program of the Kearney Foundation of Soil Science.

Table 3.2. Summary of potential side effects of carbon mitigation options in terms of other aspects of agroecosystem ecology (adapted from Smith et al. (2001)).

Land-management practice	Other potential negative impacts on agroecosystem ecology	Other positive impacts on agroecosystem ecology
No-till farming	Possibly poorer rates of seed germination, more diseases	Greater soil biodiversity, water conservation, improved soil fertility
Animal manure	Acidification, phosphorus and nitrate leaching	Better soil structure and fertility
Sewage sludge	Possible hazard for heavy metals and organics pollutants	Improved soil fertility
Cereal straw	Crop pathogen accumulation, toxin production, immobilization of nutrients, unpredictable N release	Greater soil biodiversity
Agriculture de-intensification	Surplus arable land not available for woodland or bioenergy	Improved soils structure and fertility; improved livestock welfare
		Greater biodiversity
Natural woodland regeneration	—	Greater biodiversity; increased aesthetic and amenity value
Bioenergy crop production.	Soil mining	Greater biodiversity

3.6. Conclusions

The impact of the California agricultural sector on global warming is small, due to the relatively low GHG emissions from this sector, although contributions of CH_4 and N_2O are more substantial than of CO_2. It may be difficult to predict the impacts of global warming on CO_2 and N_2O emissions from mineral soils in California's arable lands, grassland, and forests due to the variable prediction of precipitation and insufficient knowledge regarding effects of temperature and other factors on CO_2 and N_2O emissions.

California's agricultural lands constitute a resource for mitigation of GHG emissions. Soil C sequestration has been proposed as the most efficient and natural strategy during the first half of the twenty-first century (Batelle 2000). Management practices to increase the GHG sink capacity of these lands have additional benefits, due to improvement of soils and conservation of natural resources. The benefits of soil and other types of C sequestration are limited in duration because vegetation and soils (under a given set of environmental and management conditions) have a finite capacity to sequester CO_2 (Cole et al. 1997). Reducing emissions of CH_4 and N_2O by best management practices and reduced fuel use resulting from, for example, the reduction in tillage of agricultural soils are mitigation strategies that will have a longer-lasting benefit.

4.0 Interactions Among Air Quality, Climate Change, and California Agriculture

Julia Silvis, Guy Shaver, Frank Mitloehner, Deb Niemeier

4.1. Introduction

Air quality refers to the clarity, smell, and even taste of the air surrounding us. Atmospheric trace gases are involved in many interactions which determine air quality, as they are heated by solar radiation, transported by wind, and scrubbed out of the atmosphere by rain. Air quality affects climate change in two main ways: by altering the atmospheric greenhouse effect and by reducing the amount of solar radiation reaching the earth's surface (Chameides et al. 1999; Cohan et al. 2002; Menon 2004). In addition, aerosols can also have local effects (for example, as a result of particulates, volatile organic compounds (VOCs), and ozone (O_3) production) that directly reduce crop productivity (Chameides et al. 1999; Mauzerall and Wang 2001). Air quality in California is affected by emissions and their regulation both within and outside the state. Such regulations vary between states and regions, and countries, both in terms of their stringency and the types of emissions.

Agriculture is impacted by climate change (Rotter and Van De Geijn 1999), air quality (Unsworth and Ormrod 1982), and also by the interaction between these two phenomena (Henry et al. 2005; Shaw et al. 2002). For instance, O_3 formation is positively correlated with temperature, can directly interfere with plant metabolism (Mauzerall and Wang 2001), and can indirectly compromise symbiotic relationships within plant communities by reducing the diversity of mycorrhizal communities (Fenn et al. 2003), and potentially their functionality.

Agriculture also can be an important determinant of air quality. Recognizing agriculture's impact on air quality, California has placed stringent regulations on agriculture, relative to the rest of the United States, to comply with the Clean Air Act of 1990. For instance, the California Air Resources Board (CARB) recently tightened rules governing emissions from engine-powered irrigation pumps (California Air Resources Board 2005), to curb smog-forming constituents and GHG emissions.

The direct effects of the two most prominent greenhouse gases (CO_2 and CH_4) on GWP and radiative forcing have been addressed above in Section 3. This section reviews the effects of O_3, aerosols, and oxides of nitrogen (NO_x) on climate and agriculture in the California context.

4.2. Types of Air Pollutants: Aerosols, O_3, VOCs, and NO_x

4.2.1. Ozone and oxides of nitrogen (NOx)

Ozone has potentially wide-ranging but only moderately well–understood effects on climate change, due to the non-linear and multiplicative interactions involved in its formation. In the upper troposphere, O_3 effectively reflects UV radiation, and in the lower atmosphere—in addition to being harmful to human health—O_3 is a well-documented phytotoxin (Mauzerall and Wang 2001). Ozone enters plants through stomata and disrupts biochemical functioning, leading to decreased productivity, lowered fertility, and accelerated senescence (Mauzerall and Wang 2001), all of which can cause significant economic losses within California croplands (Murphy et al. 1999). Integration of agricultural crop production models and a motor-vehicle emissions model, (Murphy et al. 1999) revealed significant crop production losses in different commodities at regional and national levels.

A complex series of reactions between VOCs and NO_x gases (see below also), catalyzed by sunlight and heat, produce O_3 (Figure 4.1). At low concentrations, tropospheric NO_x causes a net destruction of O_3, while at higher concentrations it causes a net production. However, global O_3 production efficiency (OPE) is greater at lower NO_x concentrations, and anthropogenic NO_x is known to contribute less than natural sources to global O_3 budgets (Fiore et al. 2002; Liang et al. 1998). Furthermore, background GHG concentrations, such as CO_2 and CH_4, could accelerate O_3 formation through radiative forcing, and the ratio of NO_x to VOCs can be more important in determining O_3 production than absolute concentrations (National Academy of Sciences 1991). This myriad of reactions can confound local air quality initiatives that do not account simultaneously for NO_x and VOC concentrations as O_3 precursors. Such local effects may be of particular significance to agriculture, given the phytotoxicity of O_3 (see below). The above interactions and their impacts upon agriculture are as yet poorly understood, however, it is apparent that an integrated approach to the regulation of these various atmospheric constituents affecting air quality is necessary.

4.2.2. Aerosols

The preponderance of current research agrees that the overall impact of aerosols on climate change is a cooling effect, countering the warming effects of GHGs (IPCC 2001; Ramanathan et al. 2001). Aerosols directly influence the climate system by absorbing and scattering solar radiation and indirectly by providing cloud condensation nuclei (CCN). An increase in cloud droplet concentrations and a reduction in cloud droplet size is often observed when clouds are fed by air with enhanced levels of CCN, creating the so-called "first indirect effect" through which aerosols effect climate (Menon 2004; Ramanathan et al. 2001). As a result, the optical properties of clouds are rendered more reflective, and solar insolation is increased. However, the magnitude of aerosol cooling is poorly quantified; a recent study found increased solar insolation over the past 15 years, and attributed this result to improvements in air quality (Wild et al. 2005). Given the projected increases in the population of California and consequential aerosol production coincident with urbanization (see Section 2), the effects of increased CCN may be of particular significance to climate and California agriculture, especially in the Central Valley, where much of the urbanization is projected to take place.

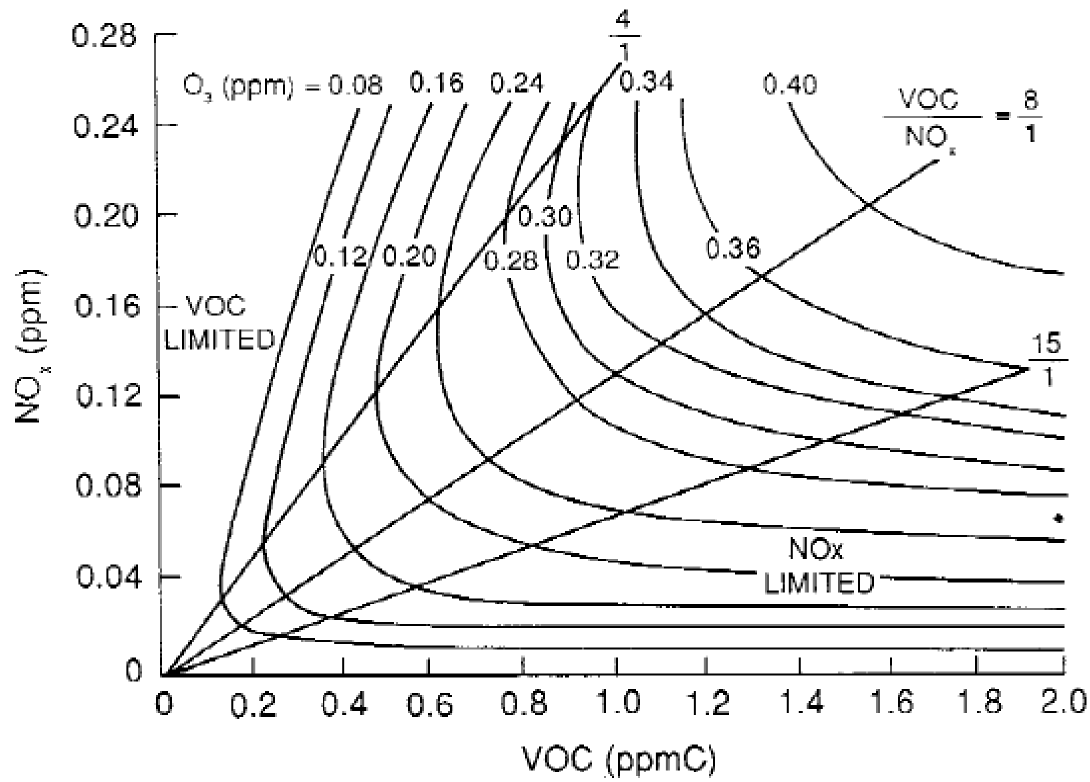

Figure 4.1. VOCs and NOx relationship to O_3. Typical O_3 isopleths used in EPA's Empirical Kinetic Modeling Approach (EKMA). The NO_x-limited region is typically downwind of urban and suburban areas; whereas the VOC-limited region is typical of highly polluted urban areas. Key sources of NO_x and VOCs include agriculture, wildfires, and transportation emissions. Figure excerpted from National Academy of Sciences (1991), formal permission not obtained.

In addition to increased cloud reflectivity, an increase in CCN has been found to decrease the average radius of atmospheric liquid-water droplets, which hinders cloud droplet coalescence and retards precipitation, leading to the "second indirect effect" through which aerosols effect climate (Menon 2004; Ramanathan et al. 2001). Thus, aerosols can decrease the precipitation efficiency of clouds, notably decreasing incidence and amounts of precipitation (Chameides et al. 1999; Durkee et al. 2000; Ramanathan et al. 2001). Increased aerosol concentrations downwind of major urban centers (for example, arising from transportation) in both California and Israel are suggested to have reduced precipitation by 15%–25% during the last several decades, based upon calculations of the orographic enhancement factor using a time course of precipitation data downwind and sidewind of urbanized areas (Givati and Rosenfeld 2004). Atmospheric particulate matter (PM_{10}) within the San Joaquin Valley is correlated with annual precipitation patterns (Franco et al. 2005) (Figure 4.2), possibly suggesting that this relationship led to increased CCN, less atmospheric scrubbing (see below), or a feedback between the two. Agriculture is an important source of dust in California. However, the amounts of dust can be reduced by employing conservation or minimum tillage practices. In the San Joaquin Valley, conservation tillage (with no cover crop) decreased amounts of both total and respirable dust to approximately one third of that compared to adjacent standard tillage treatments (with no cover crop) (Baker et al. 2005). Inclusion of a cover crop reduced this difference to approximately two thirds and three quarters of total and respirable dust, respectively (Baker et al. 2005).

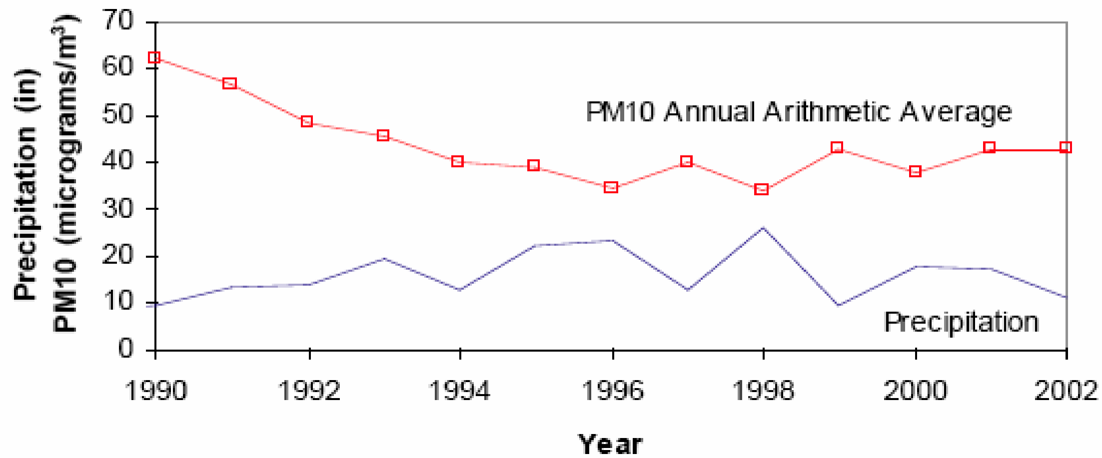

Figure 4.2. Average annual PM_{10} concentrations and precipitation patterns over San Joaquin, Stanislaus, Merced, and Fresno Counties. Figure excerpted from Franco et al. (2005), formal permission not obtained.

Precipitation is the main agent removing aerosols from the atmosphere, particularly smaller aerosols, which are more effective at scattering light. Thus, as more aerosols enter the atmosphere, potentially decreasing precipitation events by the "second indirect effect," aerosol concentrations could increase as the rain's natural scrubbing ability is lessened. This may be exacerbated in summer, especially if precipitation decreases in California are the result of climate change (see Section 2). However, as predicted surface temperatures increase, water vapor entering the atmosphere through evaporation will also increase (Trenberth et al. 2005), which could potentially cause increases in precipitation as global warming takes effect. The net effect upon precipitation is difficult to predict accurately, as it is a function of many factors, which are understood and predicted with differing degrees of confidence. Although there are large uncertainties associated with precipitation (Section 2), changes in the absolute volume of precipitation, in the number and/or duration of storm events, or a lengthening of the rainy season, could affect air quality.

4.3. Interactions Between Agriculture, Climate Change and Air Quality in California

The complex interactions between agriculture, climate change, and air quality are a product of the mechanisms involved with source(s) (both biogenic and antropogenic) (Chandler et al. 2004; Lammel et al. 2004), sink(s) (for example, soils for C and N sequestration, see Section 3), and the feedbacks between air quality constituents (for reviews, see California Air Resources Board 2004; California Air Resources Board 2005; Krupa 2003; Mennon 2004). For instance, black carbon (BC) and organic carbon (OC) aerosols are formed in similar combustive processes, yet BC aerosols are generally associated with global heating, whereas OC aerosols are associated with global cooling, because of their respective absorptive and reflective properties (Menon 2004).

Although vegetation generally reduces climate change by sequestering C (Section 3), isoprene emissions from vegetation, including crop and grassland (but most prominently California oak stands), are nearly three times as reactive in smog formation than a weighted average of VOCs emitted from vehicle exhaust (Carter 1994; Scott et al. 2002). Isoprene production from oak stands growing along the western slope of the Sierra Nevada, mixed with a combination of anthropogenic VOCs and NO_x emissions blown up-wind from the Central Valley, produce high levels of O_3 concentrations in the Sierra foothills (Dreyfus et al. 2002). Furthermore, both biogenic isoprene emissions (Guenther et al. 1991; Tingey et al. 1980) and O_3 formation can be accelerated from increased sunlight and heat, and the contribution of both to future exacerbations of air quality, irrespective of current anthropogenic source reductions, are important variables in California climate change scenarios. Based upon data from the South Coast Air Quality Management District, a slight increase in tropospheric O_3 concentrations over the Los Angeles Basin, as a result of increased surface temperatures, is projected (Franco et al. 2005). Conversely, increased temperatures shift the solid form of ammonium nitrate, a dominant wintertime PM constituent, to its gaseous precursors, thereby reducing atmospheric PM concentrations (Franco et al. 2005) and altering the adsorptive quality of reactive atmospheric N in ecosystems. The processes outlined above not only contribute to climate change, but their rates and extents, and hence, their impacts upon California agriculture, may be altered (see below).

4.3.1. Sunlight and photosynthesis

The amount of sunlight available for photosynthesis directly affects crop growth (Stansel and Huke 1975, cited in Chameides et al. 1999), and can be increased or decreased through cloud-aerosol interactions (Chameides et al. 1999; Cohan et al. 2002). For example, the direct effect of aerosols in China may be reducing current yields of rice and winter wheat by between 5% and 30%, by reducing the amount of light available to drive photosynthesis (Chameides et al. 1999). However, since aerosols both scatter and absorb light, depending on their relative optical and absorptive properties (Menon 2004), they are also predicted to have positive effects on net primary productivity (NPP), with increased light scattering resulting in increased productivity on understory leaves, and on cloudy days (Cohan et al. 2002). While the air over the Central Valley is likely cleaner than that over China, crops with sufficient sun exposure can be expected to show similar negative growth trends, as estimated by Chamiedes et al. (1999), as the rate of aerosol production increases in California. Aerosols also play a role in determining the nature and magnitude of changes in the precipitation cycle, and their indirect effects (see above), and as such represent a significant source of the uncertainty in current precipitation models.

4.3.2. Aerosols and precipitation

Changes in the hydrological cycle may result in unexpected challenges for the ability of California to maintain its current agricultural productivity, and could be heavily influenced by aerosol levels. Agriculture complicates the interaction of aerosols and cloud formation by affecting the latter mechanism directly. In southeastern Australia, Lyons (2002) found there to be many more clouds over native vegetation than over agricultural fields—probably because native vegetation is typically darker than cropland, leading to convective cloud formation. Another factor is that native vegetation is more "rough" than cultivated fields, slowing down wind more effectively. In California, however, summer drought may change these relationships, as grasslands are lighter colored and more even in stature than irrigated cropland—especially perennial fruit and nut crops. As with the effects of CCN and increased temperatures on precipitation patterns, feedbacks between aerosols emitted over agricultural fields, particularly through tillage (machinery exhaust and PM), may counteract any decreases in precipitation by promoting cloud formation. However, the net effects remain highly uncertain.

4.3.3. Ozone

Ozone exposure leads to reduced plant growth and crop yields, hindered nitrogen-fixation, compromised disease resistance, and increased susceptibility to insect damage (Andersen 2003; Mauzerall and Wang 2001); see Section 6.3 also. Vegetative growth reductions of 5%–10 % can be reached through ozone toxicity at different plant-specific threshold concentrations, generally between 50–70 parts per billion (ppb) for agricultural crops (Chameides et al. 1994), and 35 ppb for native vegetation (Taylor et al. 1994), depending on plant sensitivity and exposure duration. Background concentrations of ozone in rural forests in the United States range from 30 ppb to 45 ppb; in the Sierra Nevada, the concentrations range from 50–70 ppm, with some concentrations in the San Bernardino Mountains to the east of Los Angeles exceeding 90 ppm (Takemoto et al. 2001). This is expected to increase in California with urbanization, more livestock production, and with the possibility of transpacific N transport from Asia (Fenn et al. (2003).

4.3.4. Reactive nitrogen

Increased fuel combustion and fertilizer production during industrial times have approximately doubled the amounts of reactive nitrogen (N), relative to natural N fixation, introduced to the biosphere (Galloway et al. 1995; Vitousek 1994). Nitrogen deposition (Fenn et al. 2003) can shift ecosystems from N-limited to phosphorus-limited, to higher potential for carbon sequestration through increased photosynthesis (Galloway et al. 1995), and to reduced species diversity by favoring N-responsive plant communities (Vitousek 1994).

Globally, about 11 teragrams (Tg) of NO_X-N from atmospheric exchange is returned to agricultural land according to model estimates of Holland et al. (1997). This amount is equivalent to 14% of N fertilizer applied to farmlands in 1990 (Mosier et al. 2001). In California, N deposition is most prominent on the west slope of the Sierra Nevada, which includes grazed grasslands, as polluted air moving inland from the coast and Central Valley is forced up, and water vapor and other pollutants are washed out. Atmospheric N deposition inputs in the low- and mid-elevation chaparral and mixed conifer forest zones of California range from 20 to 45 kilograms per hectare per year (kg ha^{-1}/$year^{-1}$) (Fenn et al. 2003). N deposition in the Central Valley was approximately 6 kg N ha^{-1} $year^{-1}$ (1996), based upon model simulations (Fenn et al. 2003).

4.3.5. Coupled effects

Additive and synergistic interactions between global climate change and air quality on California agriculture will likely have a large effect on crop and animal production in California. For example, it might be expected that California grasslands will respond to the direct effects of increased N deposition, coupled with rising atmospheric CO_2 concentrations, and warmer winter temperatures. A recent study found that aboveground NPP in a California grassland increased in response to the single or multiplicative responses of increased precipitation, N deposition, and temperature, but these increases were dampened by CO_2 enrichment (Shaw et al. 2002). Within the same grassland, after three years of treatments, grass species abundance varied widely across all treatments. The abundance of forbs, however, increased under elevated atmospheric CO_2, temperature, and precipitation and generally had a negative response to N deposition (Zavaleta et al. 2003). Furthermore, grass and forbs species richness were both reduced most by a combination of increased N deposition and CO_2; whereas species richness of grasses increased most by a combination of increased temperature, precipitation, and N deposition and the single effect of increased precipitation in forbs (Zavaleta et al. 2003). These complex responses point towards the need of future research to move beyond single-effect studies in order to encompass the multiplicative phenomena occurring in the responses of plants in the context of global climate change

4.4. Mitigation and Adaptation

California agriculture has the potential to improve air quality, and help mitigate climate-based plant and animal stresses, by implementing best management practices such as reduced till farming (see below), water conservation (Section 5), and crop rotations. High-input intensive agriculture has the potential to adversely affect air quality and climate stability by increasing smog formation, aerosol production, and reactive N introduced to the biosphere. Efforts to reduce tillage, lower soil N concentrations, maximize N use efficiency and optimize manure management, are simple approaches that could be implemented Decisions need to be made, and policies developed and implemented, if we are to effectively mitigate climate change impacts upon air quality and California agriculture.

Statewide, one of the most promising agricultural practices that could enhance air quality is to reduce tillage, a best-management practice that minimizes the number times a field is cultivated. Reduced tillage has the potential to mitigate poor air quality by limiting soil disturbance and formation of atmospheric aerosols (for example, dust and particulates), reducing fuel combustion, and decreasing NOx formation. Baker et al. (2005) found conservation tillage in the San Joaquin Valley to decrease amounts of both total and respirable dust, compared to adjacent standard tillage treatments. Currently, only 16% of California's total farm acreage employs conservation tillage practices (Conservation Technology Information Center 2002), creating a large potential for air quality improvement through reduced tillage incentives.

Regulations are also a critical means to achieve air quality mitigation, specifically regarding tropospheric O_3 reductions. Ozone concentrations in the San Bernardino Mountains peaked in 1978, and have been decreasing ever since, despite large increases in both vehicle miles traveled (VMT) per capita and population in Southern California. Improvements in vehicle efficiency (and reduced emissions), as mandated by the California legislature, account for this trend (Lee et al. 2003). Complete elimination of O_3 precursors from motor vehicles are estimated to remove $2.9 billion in crop damage in California (Murphy et al. 1999).

Ozone mitigation is a classic example of a strategy that requires careful consideration of aspects other than just lowering the concentration of its precursors (i.e., VOCs). Volatile organic compounds differ largely in their reactivity (O_3 forming potential) (EPA 2004). While some VOCs are essentially unreactive (for example, acetone), others are very potent O_3 precursors (for example, isoprene). Therefore, policy makers should not solely consider total VOC concentration alone as an effective mitigation strategy, but rather concentrate on those precursors that are highly reactive.

The production of O_3 depends on the relative concentrations of VOCs to NO_x (see above). For this reason, anthropogenic production of VOCs is controlled by state law, along with NO_x production. Under current regulatory standards in California, dairy cattle are assumed to produce 12.8 lbs/cow/yr of VOCs. This dairy emission factor means that dairies have surpassed all other sources as smog (O_3) producers (even cars and trucks). However, this dairy emission factor is based on a 1938 study (Ritzman and Benedict 1938) in which methane (not VOC) from cows and other ruminant animals were measured. Recent VOC research conducted (Mitloehner 2005) indicates that this number is greatly inflated, and that the emission factor for dairies should be closer to 2–3 lbs cow^{-1} $year^{-1}$. They also found that most VOCs produced from dairies are compounds like acetone, acetic acid, and several alcohols that are known to be low in their ability to form O_3. Be that as it may, cattle do play an important role in climate change, because both animals and their manure produce a large portion of agriculture's 38% contribution to statewide methane emissions (Franco et al. 2005). Mitigation efforts to reduce global warming effects from livestock production should focus on methane, rather than VOC emissions.

4.5. Conclusions: Data Gaps and Future Research Questions

The above sections highlight the need for mitigation strategies to be predicated upon the latest and most complete scientific understanding. Interactions between climate change, air quality, and agriculture will have significant effects unseen in typical single-effect studies. Future studies will need to be broader in scope; they should involve several gases (National Academy of Sciences 1991) and look at the interaction between above- and below-ground processes (Fenn et al. 2003). Furthermore, models must be integrated to account for process-based interactions at varying temporal scales and community-level structures (Zavaleta et al. 2003).

Specific gaps in air quality studies include O_3-shoot-root interactions (Fenn et al. 2003), the contribution of agriculture to the VOC constituents of the atmosphere, the duration and movement of aerosols in the atmosphere and the effect of aerosols' in suppressing precipitation (Menon 2004), all at various local and global scales. The pursuit of such research will require top-down support from federal, state, and regional agencies, as well as bottom-up collaborations between stakeholders involved with the issues.

5.0 Water Resources and Climate Change: Implications for California Agriculture

Kraig Kraft, Kathleen Reed, Roy Peterson

5.1. Known Climate Change Impact Trajectories for California Water in Agriculture

While the numerous predictions of climate change scenarios are in general agreement in projecting a rise in the mean temperature of California (the magnitude of which is still under dispute), the predictions for changes in the future precipitation patterns of California vary widely (Hayhoe et al. 2004; Miller et al. 2003). In comparing the three most recent precipitation predictions from the PCM, HadCM2, and HadCM3 models under a range of IS92 emissions scenarios, they range from mildly drier than present (PCM) to a slightly more wet climate scenario (HadCM2) and an extremely dry climate scenario (HadCM3) (Miller et al. 2003). The large disparity in estimates reflects the difficulty of extrapolating predictions of GHGs and temperature to climatic patterns that generate precipitation. However, one trend is present in all scenarios: as temperatures rise, precipitation type changes increasingly from snow to rain (Cayan 2005).

Higher temperatures will produce reductions in snowpack accumulation in the Sierra Nevada Mountains, with subsequent effects on water storage, streamflow, and supply (Department of Water Resources 2005; Hayhoe et al. 2004; Vanrheenen et al. 2004). Water stored in the snowpack is a major natural reservoir for California. It is the presence of this large snowpack that provides the majority of the irrigation water for the dry Central Valley during the growing season. Additionally, the shift in precipitation type may increase the risk of winter flooding, especially in the Delta region, where a series of levees keep the subsided delta islands dry. The frequency of flooding and other "extreme" weather events, such as El Niño and heavier winter storms, has been projected to increase with rising temperatures (IPCC 2001), but this issue has not been adequately addressed by climate models.

In this section, the issue of climate change and its potential effects on California agricultural water resources will be treated as an issue of future scarcity. Even in scenarios with higher precipitation levels (Miller et al. 2003), earlier snowmelt and flood control allocation in reservoirs decreased surface water storage and the subsequent ability for water deliveries during the growing season (Zilberman et al. 2002). This section identifies the potential impacts, then discusses potential mitigation and adaptation strategies and data gaps in current analyses.

5.2. Potential Impacts of Climate Change on California Agricultural Water Resources

The earlier snowmelt and runoff from increased temperatures and decreased snowpack will likely create some challenges for state reservoir managers. Managers would be forced to operate storage space conservatively, losing more water downstream and leaving less water for deliveries during the summer growing season (Zilberman et al. 2002). Projecting future water use for California, Tanaka and colleagues (2005) predict that agricultural water allocation in California will continue to decline relative to urban and environmental uses. Apart from environmental flows, 70% of California's water is currently directed towards agricultural production. The rise in demand for water from the urban and industrial sectors will result in decreased water allocation to agriculture. Escalating water demand will require shifts in water sources as the reservoir system reaches capacity (Lund, pers. comm., 2005). Conjunctive water use will increase with less surface water from decreased snowpack and snowmelt capture. Greater groundwater use will result in subsidence and in higher pumping costs. Desalination in coastal regions for urban use and for aquifer treatment is expected as technology improvements reduce energy costs for treating water, and as water costs increase (Tanaka et al. 2005). Taken together, these eventualities represent a significant challenge to water resource managers and California agriculture.

Sea level rise may have a major impact on California water transfers through the Sacramento-San Joaquin Delta. Increased salinity intrusion into the San Francisco estuary and potential failure of levees protecting low-lying land may degrade the quality and reliability of fresh water transfer supplies pumped at the southern edge of the Delta, or may require more fresh water releases to repel ocean salinity (Department of Water Resources 1993, 2005; Kiparsky and Gleick 2003). Levee breaches on deeply subsided islands draw brackish water into the Delta during rapid flooding, temporarily degrading water quality over a large region. However, long-term degradation of water quality may result from flooding of subsided islands, which affects tidal prism dynamics within the Delta (Department of Water Resources 2002; Mount and Twiss 2005). In addition to sea level rise, the effects of a warmer climate such as reduced snowpack storage, higher flood peaks during the rainy season, and reduced warm-season flows after April increases the risk of contamination of California's freshwater supplies by salinity intrusion (Knowles and Cayan 2004).

5.2.1. California water storage and delivery infrastructure and its operation

California has an extensive network of water storage, transfer, distribution, and use systems. The primary infrastructure for agriculture water includes the California State Water Project, the Federal Central Valley Project, and the Colorado River Project. These systems, together with local water districts, are expected to become more coordinated, using water transfers as one of means for providing water where it is most desired (Department of Water Resources 2005).

Water transfers are described in the Water Code as a transfer or exchange of water or water rights that result in a temporary or long-term change in the place of diversion, place of use, or purpose of use. Water transfers have increased over the past 20 years and are expected to accelerate in the future. Transfers came to prominence with the drought in the 1980s when 80,000 acre–feet were transferred in 1985, and by 2001, 1,250,000 acre–feet were transferred (Department of Water Resources 2005). The transfers are mostly local, with 25% within the same county, almost 50% within the same the same basin, and the remaining 25%–30% of the transfers between regions (Department of Water Resources 2005). Most transfers come from agriculture and go to either environmental or urban use. With higher water values, there are concerns about a net agricultural loss. Concerns about these losses have prompted requests for a balanced approach to regulating transfers.

5.2.2. Infrastructure operational limits for water delivery

Reliability of water delivery is critical for agriculture and some transfers have failed. For instance, the Los Angeles Metropolitan Water District was unable to complete a water transfer from a water source in the Sacramento Valley because water pumping from the San Francisco Delta was at a maximum and spring storms had left no reservoir storage space. Sea level rise in the Delta could aggravate operation of the State and Central Valley projects, making reliability an increasingly important issue.

5.2.3. Analytic optimization tools for agricultural water use during climate change

The California value integration network model (CALVIN) is an engineering optimization of surface water, ground water, and water infrastructure below 1000 feet elevation (Lund et al. 2003). Most of California's agricultural land is covered in the model, with the exception of the coastal regions. Coupled with the CALVIN model is the Statewide Water and Agricultural Production model (SWAP) (Howitt et al. 2003). The CALVIN model uses monthly estimates of water for 25 regions of the SWAP to determine the statewide allocation of water for 72 years of variable hydrology. It assumes a freely operating water market. Climate change is incorporated into SWAP by modifying crop yields and amount of irrigated water used by the predominant 17 crops in several regions, based on quadratic response functions for yield and ET that examined the effect of elevated CO_2 (as estimated from typical modeling responses), technological advances (0.25 or 1.0% change in yield growth per year), and a range of temperature and precipitation scenarios (Adams et al. 2003b).

SWAP uses economic rules for its optimization solution. The rules include endogenous principles that are beyond the producers' reach, such as world grain prices, exogenous principles, and technological factors such as on-farm water delivery and plant breeding developments in water use efficiency optimizing the assimilation-to-transpiration ratio. Through quadratic crop yield function expressions, yield is related to seasonal temperature, precipitation, land quality measures, and technology progress. The quadratic expressions account for both crop gains such as an increase from cold to warm, and to crop declines such as from warm to hot (Adams et al. 2003a). This is a simple modeling approach that does not take into consideration crop-specific developmental responses to temperature, or effects of extreme events (see Section 6). This crop modeling effort is the most comprehensive to date in California, and suggests a low impact on crop productivity in response to climate change, through adaptation via technological innovations and land use changes in response to a large range of climate change scenarios.

5.2.4. Model results, agricultural water, and land use

The combined CALVIN and SWAP modeling tools found that although agriculture adjusts to climate change, there will be less land under cultivation and growers will switch to higher value crops. Currently, due to their geographic location, current climatic conditions and the commodities grown in the region, agricultural water users in the Central Valley are the most vulnerable to climate warming and could be devastated by severely dry forms of climate warming. Some Central Valley regions would lose or sell about half their desired water use. According to Tanaka and colleagues (2005) and Lund (pers. comm. 2005), climate change could reduce Valley agricultural water deliveries by 37% from current deliveries in a dry climate warming scenario (and 24% from 2100 urbanization-corrected agricultural demands) and raises Valley water scarcity costs by $1.7 billion. With a shift to higher value crops, agriculture income only falls 6% while sustaining about a 24% decrease in agriculture water deliveries on 2100 urbanization adjusted water demands (Tanaka et al. 2005). Currently, when environmental (statute mandated) water is excluded, agriculture uses 70% of the state's water and results in 10% of the state's gross domestic product (GDP) (Lund et al. 2003; Lund, pers. comm. 2005).

If climate change results in an increase in water availability at appropriate times, farmers may benefit. However, if water availability decreases, farmers are likely to be affected more than urban and industrial users, who can pay more for water. Some farmers may benefit if they hold senior water rights and are allowed to sell or transfer them (Gleick et al. 2003).

Evapotranspiration (ET) will change with increasing temperatures. This is the vaporization of water to the atmosphere from the terrestrial landscape. There are two parts to ET: (1) evaporation, the vaporization of water from the soil and wet plant surfaces, and (2) transpiration, the vaporization that occurs within the leaves, with the water vapor diffusing through pores (stomata) in the leaves to the atmosphere. Several investigators have used an energy budget in the form of the empirically derived Penman-Monteith equation to calculate an expected climate changed ET for the California landscape. Increasing air temperature causes the weighting factor of the radiation-term of the Penman-Monteith equation to increase, but, because of the effect on stomatal closure, increasing CO_2 concentration causes it to decline. Hidalgo et al. (2005) derived a 6% increase in ET when considering a 3ºC (5.4ºF) temperature increase but they did not include any factoring for an increase in CO_2. Peterson et al. (2006, in review) found a 4.5% increase in ET with a 3ºC (5.4ºF) in minimum and maximum temperature increase when not considering CO_2 changes. The ET was reduced to 3% when an elevated CO_2 was factored for by using an expected canopy resistance increase calculated from Free Air Enrichment experiment measurements. It is difficult to accurately estimate the direct affect of climate change on ET because there are no measures of ET at elevated temperature and CO_2 at a canopy scale the derived value is thus uncertain. More research is need on the influence of elevated CO_2 and air temperature on canopy resistance. While the magnitude of ET change at an elevated CO_2

and air temperature is uncertain, there appears to be consensus that it will increase to some extent, and that this will increase the water demand per unit of biomass production. When extrapolated over the entire growing region of California, even a small increase in ET could result in a considerable amount of added water required for agricultural production.

5.2.5. Water conservation and water use efficiency

Due to growing constraints on new water supply, California is exploring improved water use efficiency (WUE) in all sectors. Improvements in both agricultural and urban WUE may offer sources of new water supply by reducing overall demands for water in every sector (Gleick 2003), although this needs to be balanced against the projected increases in the population of California. Wastewater reuse, seawater desalination and water conservation show promise as water supply sources, in particular in southern California where cheaper alternatives may not be available (Department of Water Resources 2005; Tanaka et al. 2005). Under a drier climate scenario, about 1.35 million acre feet (maf) year^{-1} comes from wastewater reuse and about 0.24 maf year^{-1} comes from seawater desalination (Tanaka et al. 2005). Increased winter rainfall could result in increased groundwater recharge; however, higher evaporation and a shorter season of rainfall may reduce recharge to deep aquifers (Kiparsky and Gleick 2003).

5.2.6. Agricultural water conservation

To understand water conservation options, a distinction in Water Use Efficiency (WUE) between basin and on-farm scale is useful in visualizing the hydrological cycle. A higher percentage of water is recycled at the basin level than at the on-farm level. Infrastructure distinctions are also apparent at the district level vs. the on-farm level. Regional WUE includes regulating reservoirs, canal lining, additional system automation, and spill prevention. On-farm WUE is dependent on crop type and irrigation system, which determine how much is "lost" to irrecoverable flows such as flows to saline sinks and non-beneficial evapotranspiration (Department of Water Resources 2005).

Agricultural WUE improved considerably from 1980 to 2000 in terms of agricultural production per unit of applied water (tons acre-foot^{-1}) by 38% for 32 important California crops (Department of Water Resources 2005). However, major WUE improvements are still possible in the agricultural sector, particularly through implementation of more efficient irrigation practices. Micro-irrigation can achieve a WUE of up to 95% versus 60% or less for flood irrigation, one of the simplest, yet most inefficient methods. More efficient sprinkler systems, such as the low-energy, precision application (LEPA) system, reduce evaporative losses by discharging water just above the soil surface. Laser leveling of fields can decrease water use and by allowing water to be distributed more uniformly. Precision irrigation is one of the most effective water conservation techniques but also the most expensive, and perhaps best suited for high value crops, such as vegetables (Gleick 2003). Other benefits of precision irrigation are increased fertilizer application efficiency through fertigation, and decreased potential for leaching of nitrate, some pesticides, and other soluble compounds.

Case studies of successful use of drip irrigation in row crops showed mixed economic results. Drip irrigation in cotton was sometimes less profitable than furrow irrigation (Hanson et al. 2000). However, a study of buried drip irrigation of pepper compared with traditional sprinkler irrigation in two locations in California resulted in higher yields (30% and 37%), lower water use (2% and 19%), higher energy use (18% and 21%), but higher energy use efficiency (18% and 13%), and higher net returns by \$4,288 ha^{-1} and \$2,265 ha^{-1} (Irrigation Training and Research Center 1996a; 1996b). Using the above examples, Hanson et al. (2000) also suggest that drip irrigation is most suited to higher cash value crops.

History has shown that as a drought becomes more severe, farmers increasingly adopt water conservation technologies in California (Figure 5.1), fallow land with relatively low-value crops, and increase ground water pumping. Previous droughts also caused decision makers to introduce mechanisms that rely on market forces and financial incentives to encourage water conservation (Zilberman et al. 2002). The U.S. Department of Agriculture Natural Resources Conservation Service provides growers with incentives to conserve water through the Conservation Security Program, and the California Ground and Surface Water Initiative (United States Department of Agriculture 2005). Though some economic incentives exist at the state level, increased state support of local agencies in developing incentives for water conservation may improve water use efficiency in California (Department of Water Resources 2005). Because higher water costs may encourage conservation, the state may influence water use by instituting rates that support better water management (Department of Water Resources 2005).

5.2.7. Urban water conservation and water recycling

Given California's projected population increase (See Section 2), promoting urban water conservation may reduce the amount of water diverted from agriculture. In addition to augmenting the water supply, water recycling may offer several benefits to farmers such as providing a more secure water supply during droughts, and supplying more reliable local sources of water, nutrients, and organic matter for agricultural soils. Currently, California recycles about 500,000 acre-feet of wastewater annually, of which approximately 250,000 acre-feet $year^{-1}$ is used by California farmers on 52 different crops (Department of Water Resources 2004). There is a potential to obtain 0.9 million to 1.4 million acre-feet annually of additional water supply from recycled water by the year 2030. Recycled water is also used for groundwater recharge, with 15% of all recycled water in 2002 used for groundwater recharge (Department of Water Resources 2004, 2005).

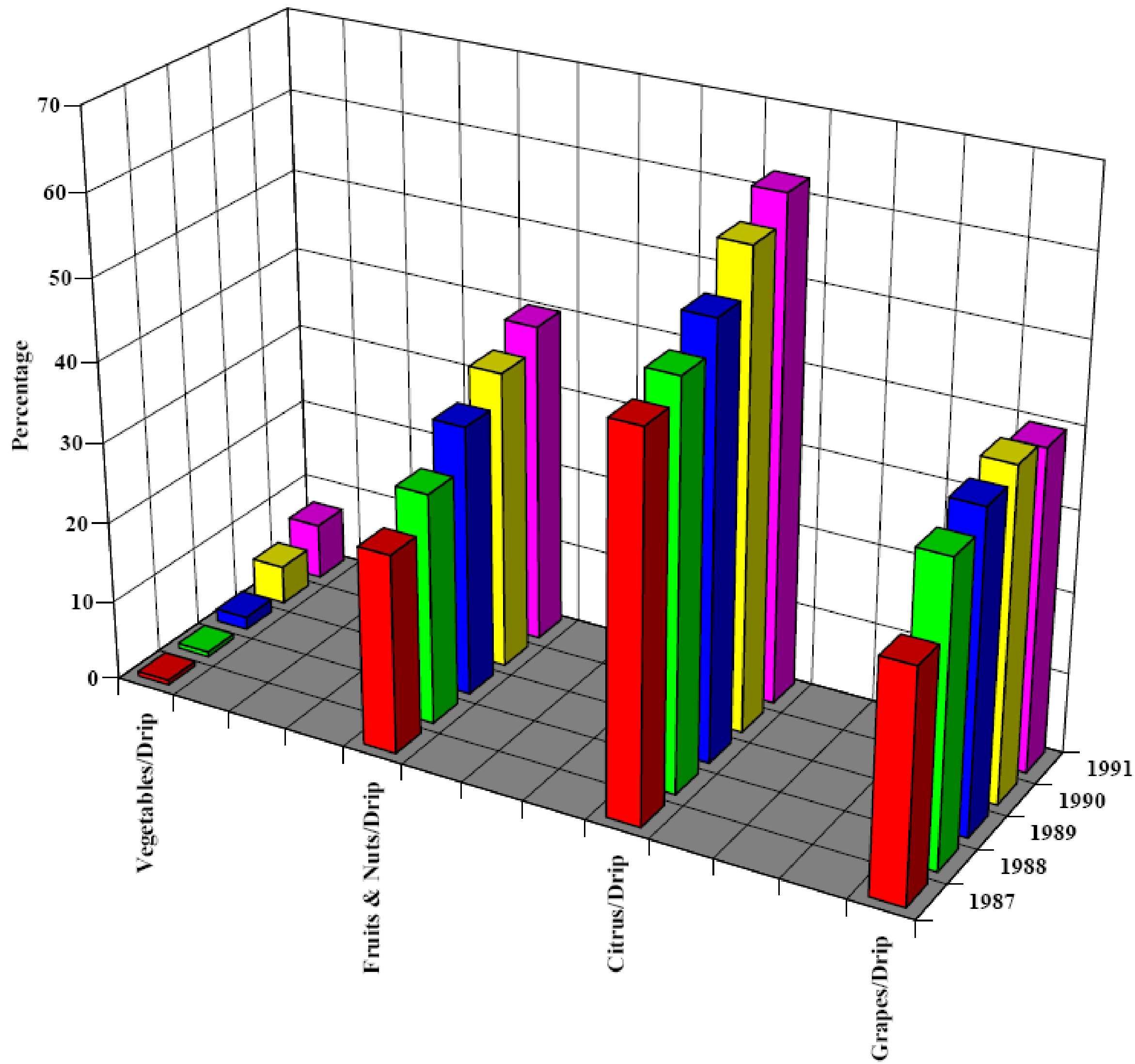

Figure 5.1 Use of drip irrigation on selected crops, 1987–1991. Figure excerpted from: Zilberman et al. (2002), formal permission not obtained.

Some water resource management strategies, aside from new water-supply infrastructure, are: wastewater reclamation and reuse, water marketing and transfers, and desalination; however, none of these alternatives are likely to alter the trend toward higher water costs (Kiparsky and Gleick 2003). The increased cost of traditional water sources (including storing or transporting water long distances), and the reduced costs of desalinization due to improvements in technology, have resulted in greater consideration of this option as a water source in some areas of California (Department of Water Resources 2005) and elsewhere.

Under a wet climate change scenario, Central Valley flooding will become a serious problem. Widening the lower American River floodway, raising levee heights, and potential levee relocation due to increased urbanization are possible strategies for dealing with increased flooding. In a recent study (Tanaka et al. 2005), the most extreme case considering urbanization and the increase in land value, as well as flood damage costs and frequency due to climate change, the height of levees and their setback would need to be 65 feet (20 meters) and 500 feet (150 meters), respectively; which has implications for other infrastructure projects.

5.3. Data Gaps and Future Research Questions

Given the large discrepancy in current precipitation prediction models, an immediate need is improved prediction of precipitation amounts and spatio-temporal patterns. Refinement of nested regional models that can assess change and responses at a scale that matters to agricultural producers are also needed. These models will provide a better analysis of evapotranspiration demand, and water management at the landscape scale. Precipitation and windspeed are not expected to be well-described in any models in the near future, yet these models are important both for understanding extreme weather events and for optimizing crop breeding and agronomic technologies to make best use of available water resources (Snyder et al. 2004). Results from improved regional models can enhance the precision of input data sets for the water infrastructure operational optimization models such as CALSIM (a California DWR water resource planning tool that provides input to CALVIN), as well as contributing directly to the CALVIN and SWAP models.

Currently plant physiological processes, such as drought tolerance at different plant water potentials, are of limited use because quantitative descriptions are not available in a form compatible with the quadratic response functions for individual crops in the SWAP model. Evapotranspiration in the model is treated as single static value rather than a dynamic variable that responds to changes in climate. In addition, there are many developmental processes in plants that are affected by temperature that are not included in this approach (see Section 6). New models with the capacity to integrate physiological and developmental processes for high-cash value specialty crops are a high priority.

5.4. Conclusions

Water conservation in agricultural production results in a direct mitigation for GHGs because of the decrease in fossil energy used to pump and deliver water to crops. Specifically, there should be a focus on high-value, water-efficient agricultural commodities. For example, Pimental et al. (2004) described commodity water use using the volume of water required to produce a particular mass of product. Alfalfa, which is a C3 plant that prefers a milder climate, was found to require 1100 liters per kilogram produced of yield. Wheat is a C3 plant that evolved in a semiarid environment and prefers a relatively dry climate. It was reported to require 900 liters per kilogram. Corn, a C4 plant that originated in a hot dry climate requires 650 liters per kilogram. Rice, which is a C3 plant that evolved in a tropical environment, requires 1600 liters of water per kilogram of rice. California agriculture has developed considerably more water-efficient rice production than the worldwide average. Because of shallower water submergence and better management, California rice is estimated to require 1080 liters of water per kilogram of rice (J. Hill, pers. comm.). Incentives to decrease water use should be considered. California's water system will adapt to future population growth and increased demand; however, it may be at the expense of agriculture, with Central Valley agricultural users being most susceptible to climate change related impacts upon water resources.

6.0 Impacts of Climate Change on Crop and Animal Physiology in California Agriculture

Roberta Gentile, Martin Burger, Danielle Pierce, Dave Smart

6.1. Introduction

There are several predicted environmental changes of pertinence to crop development in California as a consequence of global climate change. Changing climate variables will impact crop and animal physiology with respect to yields and quality of cropping and animal systems. These climate variables include increases in temperature, atmospheric CO_2 and O_3 concentrations, changes in the amount and seasonality of precipitation, the availability of water resources, and climate uncertainty (Sections 2, 3, 4, and 5). Major physiological impacts of these anticipated climatic changes include diminished yields from increased temperatures during crop and animal development (Peng et al. 2004; Sato et al. 2000; West 2003), shorter periods of crop development (DeJong 2005; Moya et al. 1998; Wheeler et al. 1993), reduced product quality from unseasonal precipitation or adverse temperatures during fruit development (Southwick and Uyemoto 1999), shifts in growing regions suitable for specialty crops (Reilly and Graham 2001), and decreased incidence of frost damage (Reilly and Graham 2001). This section will review our current understanding of crop and animal physiological responses to the predicted changes in climate, highlighting California agricultural commodities of greatest economic importance.

6.2. Crop Response to Increased Temperature

California's unique environment allows for the production of a diverse range of crops, many of which are high-value specialty crops for which California is the sole producer in the United States. We selected several of California's top economically important crops to review individual crop physiological responses to increased temperature (summarized in Table 6.1). Temperature influences crop growth and development through its impact on enzyme- and membrane-controlled processes. Carbon acquisition by photosynthesis typically has a temperature optimum close to the normal growth temperature for a given crop, while the carbon loss via respiration increases with temperature (Lambers et al. 1998). Therefore, crop growth will be indirectly controlled by temperature due to the balance between photosynthesis and respiration rates. Temperature also serves as a controlling factor for developmental processes, and the accumulation of low or high temperatures often serves as cues for flowering and fruit maturation stages (Atkinson and Porter 1996).

Table 6.1. Responses of economically important California crop commodities to increased temperature

Crop	Response	Reference
Tomato	Reduced fruit number	(Peet et al. 1998; Sato et al. 2000)
Lettuce	Shortened growing season	(Wheeler et al. 1993)
	Increased incidence of tipburn	(Saure 1998)
	Early bolting (flowering onset)	(Waycott 1995)
Rice	Reduced yields	(Moya et al. 1998; Peng et al. 2004; Ziska et al. 1997)
	Increased spikelet sterility	(Matsui et al. 1997)
Stone fruits	Decreased fruit size and quality	(Ben Mimoun and DeJong 1999; DeJong 2005)
Citrus	Reduced frost losses and increased yields	(Reilly and Graham 2001; Rosenzweig et al. 1996)
Grapes	Premature ripening and possible quality reduction	(Hayhoe et al. 2004)
	Increased yield variability	(Bindi et al. 1996)

Tomato

Optimal temperature for tomato (*Lycopersicon esculentum* Mill.) growth is between 19°C–24°C (66°F–75°F) (Geisenberg and Stewart 1986). At growth temperatures of 32ºC (90°F) day/26°C (79°F) night, fruit number and seed number per fruit were only 10% and 16%, respectively, compared with those at 28ºC (82°F) day/22ºC (72°F) night (Peet et al. 1998). Pollen development and release appear to be the most important causes for decreased fruit set as a result of elevated growth temperatures (Sato et al. 2000). Heat spells of a few days with maximum temperatures > 38ºC (> 100°F), as in 2005, substantially decrease harvestable fruit. An increase in mean temperature of only a few degrees would likely affect tomato production in California negatively with currently used cultivars.

Lettuce

For lettuce, an increase in temperature results in shorter crop duration, and thus, a reduction of intercepted radiation and decreased biomass at harvest. For example, the final weight of heads of lettuce (*Lactuca sativa* L.) and the time from transplanting to marketable fresh weight will likely decrease under elevated temperatures. An increase of 1.2ºC (2.2°F) to 5.6ºC (10.1°F) compared to a control (baseline climate for 15 years at Rothamsted between 1968 and 1991) resulted in significant decrease in time for lettuce to reach a fresh weight greater than 200 grams (g) (Wheeler et al. 1993). Growers may benefit from such circumstances, since the effects in final yield are projected to be relatively small. However, extreme temperatures, especially if the onset of such temperatures is rapid, may present greater challenges to growers in controlling bolting and tipburn (Saure 1998). The incidence of tipburn appears to be higher when plants are suddenly exposed to stress, such as high heat, because higher levels of physiologically active gibberellins under prior stress-free growth raise the permeability of cell membranes and disturb calcium transport into rapidly growing tissues (Saure 1998). Bolting is a day-length response, but high heat mediates this response (Waycott 1995). Not surprisingly, most of summer lettuce production is in the cool, foggy valleys of the Central Coast, with fall and winter production in the desert and Central Valley. Climate change may thus reduce summer production of this important crop.

Rice

Increased temperature can accelerate the development of rice (*Oryza sativa* L.), resulting in lower yields, which tends to offset any increase in yield stimulated by increased atmospheric CO_2 (Moya et al. 1998; Ziska et al. 1997). For field production in the Philippines, grain yields were found to decline 10% for each 1°C (1.8°F) increase in minimum temperature (Peng et al. 2004). Additionally, high temperatures induce spikelet sterility in rice and elevated CO_2 levels may exacerbate this effect (Matsui et al. 1997). An elevated atmospheric CO_2 concentration of 300 micro liters per liter ($\mu l\ l^{-1}$) CO_2 above ambient decreased the critical air temperature for sterility by 1°C (1.8°F) (Matsui et al. 1997). This interactive effect was hypothesized to be due to higher canopy temperatures that resulted from decreased stomatal opening and transpirational cooling under elevated CO_2. Rice cultivars currently grown in the United States may be more sensitive to temperature stress than Asian cultivars, with upper temperature thresholds of 32°C–35°C (90°F–95°F) (Baker 2004).

Stone fruits and nuts

Temperature influences the development of stone fruits and nuts with regards to chilling requirements, heat accumulation, and heat stress damage. *Chilling* is generally defined as the accumulation of hours between 0°C–7°C (32°F–45°F) during the period of bud dormancy in fruit and nut crops, which is from November to March in California; California is currently classified as a moderate to high chill region. Decreased chilling can result in late or straggled bloom, decreased fruit set and poor fruit quality, which will decrease the marketable yield of these commodities (Weinberger 1950). Heat accumulation refers to the summation of hours between 7°C–35°C (45°F–95°F), and length of time of fruit development has been strongly correlated with the units of heat accumulation during 30 days after bloom (Ben Mimoun and DeJong 1999). Enhanced rate of fruit development due to increased temperatures at this time can result in decreased fruit size. For example, warm spring temperatures in 2004 caused early fruit development and harvest, and small fruit size for peaches and nectarines, reducing the quality categories of these fruits (DeJong 2005). Heat stress can cause fruit damage and reduced quality during bud and fruit development leading to double fruits, fruit sutures, and heat burn (Southwick and Uyemoto 1999).

Citrus

The effects of temperature on yield and quality of citrus are comparable to other perennial tree crops in that citrus require a cool period for dormancy, but are also subject to freezing or heat stress losses during critical fruit development periods (Rosenzweig et al. 1996). Crop models have been used to simulate citrus responses to increasing temperatures and atmospheric concentrations of CO_2 in the United States (Reilly and Graham 2001; Rosenzweig et al. 1996). Simulated citrus yields increased 20%–50% nationwide depending on the climate change scenario, with a 65% reduction in crop loss due to fewer periods with freezing temperatures (Reilly and Graham 2001). In response to temperature increases of up to 5°C (9°F), simulated yields increased for northern regions of California, but decreased in southern growing areas of the state (Rosenzweig et al. 1996). Including the effect of elevated atmospheric CO_2 concentrations on citrus production counteracted the yield decreases in southern locations. The production region for citrus may be able to expand northward under predicted climate change conditions (Reilly and Graham 2001).

Grapes

The potential response of grapevines to increased temperatures due to climate change is relatively unknown. Increasing temperatures may result in premature ripening and thus decreases in quality for some cultivars in some major California wine grape growing regions based on modeling approaches that calculated threshold temperature impacts by using downscaled temperature projections for key counties relative to monthly average temperatures (Hayhoe et al. 2004). Additionally, modeling of climate change scenarios has shown that grapevine yields may become more variable, which will increase economic risk for growers (Bindi et al. 1996). Climate change and its physiological impacts upon grapes may also influence terroir, an important quality and marketing characteristic that is especially important in this industry (pers. comm., M. Mathews).

6.3. Crop Responses to Elevated CO_2 and O_3

The predicted increases in photosynthesis for most C3 species due to elevated CO_2 have been widely accepted (Pritchard and Amthor 2005). However, the direct outcome of increased photosynthetic rates is uncertain in terms of increasing crop growth and allocation to harvestable yield (Sinclair et al. 2004). For example, wheat yields of 156 experiments under elevated CO_2 were highly variable (-20% to +70%), probably because of interactions of elevated CO_2 with other environmental factors, such as temperature, water and nutrient availability (Amthor 2001). Concentrations of mineral nutrients in plant tissues grown under elevated CO_2 decrease, even when nutrient supply is not restricted (Newbery et al. 1995; Prior et al. 1998). Of particular interest is the decrease in the concentration of nitrogen (N), because N plays a central role in plant metabolism and biogeochemical cycles. In a meta-analysis comparing 69 different C3, C4, and N-fixing species grown under elevated CO_2, C3 species showed an average decrease in N concentration of 16% (Cotrufo et al. 1998), compared to a decrease of only 7% in C4 and N-fixing plants. There is a close relationship between photosynthetic capacity and concentrations of leaf N, soluble protein, and the carboxylating enzyme, Rubisco (Ellsworth et al. 2004). Photosynthesis down-regulation after initial stimulation by elevated CO_2 ("acclimation") occurs with a simultaneous decrease in the concentration of Rubisco (Hymus et al. 2001; Sicher and Bunce 1997). Several hypotheses to explain the decrease in shoot N concentration and photosynthetic acclimation have been put forth. First, nutrient limitation could be the result of increased N immobilization by soil microorganisms receiving more plant-derived C under elevated CO_2, or by increased sequestration of N into long-lived biomass (Norby and Iversen 2005; Shaw et al. 2002). Second, plant N demand of C3 species may be lower because the decrease in photosynthesis under elevated CO_2 leads to higher efficiency of the photosynthetic apparatus, thus requiring less Rubisco and diversion of N into enzymes of the photorespiratory pathway (Drake et al. 1997). Acclimation of photosynthesis might occur because a build-up of carbohydrates triggers a feedback regulation of transcription factors for enzymes involved in photosynthesis (van Oosten et al. 1995) Third, elevated CO_2 decreases nitrate (NO_3^-) assimilation in C3 but not in C4 species (Bloom et al. 2002; Cousins and Bloom 2003; Rachmilevitch et al. 2004). This situation may contribute to decreased Rubisco concentration and carbon gain when the plant N supply is in the form of NO_3^-, since NO_3^- reduction to NH_4^+ appears to compete with photosynthesis for reductant (Bloom, 2005 talk). Conversely, N fixation by symbionts and by free-living rhizobia, is stimulated by elevated CO_2 (Serraj et al. 1999; Zanetti and Hartwig 1997).

In short, elevated CO_2 interacts with environmental variables and plant physiological responses that differ among species, making it difficult to predict plant productivity, species composition and nutrient cycling, especially in natural ecosystems and rangelands. In California grasslands, for example, elevated CO_2 decreased net plant productivity, when temperatures, precipitation or soil N in the form of NO_3^- addition were increased compared to ambient levels (Shaw et al. 2002). In a grazed pasture on the west coast of the North Island of New Zealand, species composition changed as a consequence of elevated CO_2. The proportion of legumes increased, while the N concentration of the other species decreased (Allard et al. 2003). Total N intake by ruminants was not changed, but the N recycled by the animals was more susceptible to losses due to ammonia volatilization because the higher proportion of legumes in the diet of the grazers leads to a greater proportion of N excreted as urea (Allard et al. 2003). Thus, a change in forage quality and a shift in the relative abundance of plant species induced dietary changes that may enhance loss of nitrogen and increase release of N trace gases.

The consequences of elevated CO_2 for crop plants are decreases in grain protein and in the case of wheat, breadmaking quality (Kimball et al. 2001; Pleijel et al. 2000). Elevated CO_2 has been shown to increase grape yield without altering wine quality, but more research is needed to consider the interaction between increased CO_2 and temperature

(Bindi et al. 2001). Other crops, such as strawberries (*Fragaria* x *ananassa*), will likely benefit from elevated CO_2 concentration. The fruit flavor of strawberries was superior in those grown in elevated CO_2 during a three-year open top chamber experiment (Wang and Bunce 2004). Fruit dry matter, fructose, glucose, and total sugar contents—as well as volatile aroma compounds and antioxidant properties—were increased. Malic and citric acid contents were decreased on the other hand, compared to those in strawberries grown under ambient CO_2 (Wang and Bunce 2004; Wang et al. 2003).

Elevated CO_2 may alleviate the harmful effects of elevated O_3 concentrations on plants. Many crop species are sensitive to elevated O_3, including cotton (Heagle et al. 1999), watermelon (Gimeno et al. 1999), alfalfa (Renaud et al. 1997), and plum (Retzlaff et al. 1997) (see Section 4.3.3). In a meta-analysis of 53 studies of soybeans (*Glycine max*) exposed to O_3 concentrations of > 60 ppb, a decrease in biomass of 34% and seed yield by 24% was observed (Morgan et al. 2003). Elevated CO_2 ameliorated damage caused by O_3 at 60 ppb, probably because elevated CO_2 decreases stomatal conductance, and thus lowers O_3 concentrations inside the leaf (Morgan et al. 2003). However, growth of paper birch (*Betula papyrifera* Marsh) and sugar maple (*Acer saccharum* Marsh) was severely reduced after long-term (6-year) exposure to elevated O_3 under both ambient and elevated atmospheric CO_2 concentrations (Karnosky et al. 2005). Therefore, effects of elevated O_3, in combination with elevated CO_2, may only be fully assessed after long-term exposure of perennials to the altered atmospheric conditions. This may be of particular significance to tree crops, which in some cases, California is the primary or sole producer in the United States.

6.4. Crop Responses to Environmental Variables

In a report to the California Energy Commission, Adams et al. (2003b) used climate and crop data to model the impacts of changing climate, increasing CO_2, and technology on California crops (see Section 5 also). In this report, they indicated that warmer temperatures during the crop-growing season were favorable to the cooler regions of California, but unfavorable to the arid regions. This result was consistent with national studies (for example, Adams et al. 1995; 1998) that showed that crop productivity increased with temperature in more northern latitudes of the United States, and decreased with increased temperatures in some of the southern regions of the country. This may be explained by crop productivity in cooler regions benefiting from additional degree-days of warming; whereas crops in warm regions may already be at the heat threshold level (Adams et al. 2003b). As discussed above, there are shortcomings with the simple quadratic equation approach, and crops may actually respond more strongly to increased temperature and CO_2 than indicated in these studies (see Section 5)

For specialty crops such as stone fruits and grapes, water stress, temperature, and the timing of precipitation can be extremely important for sustainable yields and maximizing fruit quality (Bazzaz and Sombroek 1996). However, for rain-fed crops and grazed lands, where the most productive seasons are late fall, winter, and early spring, water use patterns may change markedly as a result of higher evapotranspiration (ET). Adams et al. (2003b) found that most regions and climate change scenarios for California indicated an increased demand for water over time. Also, increased precipitation did not affect water use or crop yields because many California crops are irrigated (Adams et al. 2003b). For some crops, increased precipitation in the summer or fall would result in an increased incidence of fruit rot and decreased fruit quality. However, elevated levels of CO_2 reduce crop ET, primarily through a reduction in stomatal aperture, and controlled experiments that measured crop water use (ET) under elevated CO_2 have shown that most crops produce similar or increased yields with less water (Rosenzweig and Hillel 1998).

Future crop water use is difficult to predict because of climate variability, increasing temperatures, and increasing CO_2 concentrations. Increasing CO_2 and temperatures may balance ET overall, however, water storage in California's snowpack is predicted to decrease (Section 2), which will alter the amount and timing of water available to agriculture for irrigation (Section 5). As a result, California will need to cope more effectively with the constraints of its Mediterranean-type climate than it has done in the past. Even if precipitation increases, water storage will remain an important problem, and issues will arise that require that more research is devoted to understanding crop water responses, and effects of rainfall on crop quality.

6.5. Climate Change and Animal Physiology

In California, there are about 5.2 million cattle, 1.7 million of them lactating (USDA 2002) (see Section 2). Most of them are located in the Central Valley. To maintain homeothermy, mammals dissipate heat by conduction, convection, radiation, and evaporation. The latter is the principal cooling mechanism of cattle in a hot environment. At high ambient temperatures (> 35°C, or > 95°F), metabolism generates about a third of the total heat load (Blackshaw and Blackshaw 1994). Therefore, reduced feed intake is an immediate response to heat stress. Above 35°C (95°F), feed intake may fall 10%–35% (Conrad 1985), but maintenance expenditures increase by 20% compared to thermoneutral conditions (NRC 1981). Thus, dairy cows with elevated body temperatures have lower milk yield and produce milk with lower efficiency (West 2003).

The Temperature-Humidity Index (THI) is a widely used stress indicator:

$$THI = T_{db} + 0.36 * T_{dp} + 41.2 \qquad (1)$$

where T_{db} is the dry bulb temperature and T_{dp} is the dew point temperature in °C. At THI 72-76, milk yield and dry matter intake start to decline (West 2003); at THI 79–84, cattle weight gain decreases (Klinedinst et al. 1993). Mortality can occur at THI > 84 (Klinedinst et al. 1993), which in the Central Valley is reached at about 39°C (102°F), assuming a dew point of 15°C (59°F). Although the well-being of California's cattle may be less affected by global warming in comparison with other, more humid areas of the United States (Klinedinst et al. 1993), the projected significant increase in mean temperature and the increased frequency of heat wave days will pose great challenges for cattle operations, which is California's most economically valuable agricultural commodity, (Section 2), and the need for adaptation.

6.6. Mitigation and Adaptation

California agriculture can ultimately respond to the physiological impacts of climate change through cultivar selection and crop management practices designed to respond to changes in crop development. Observed cultivar variation in heat tolerance and access to germplasm from regions with higher temperatures may provide opportunities to breed better-adapted cultivars for a variety of crops (Baker 2004; Moya et al. 1998; Sato et al. 2004; Sinclair et al. 2004; Waycott 1995). Better understanding of plant physiological responses to elevated CO_2 and the interacting effects of mineral nutrition, temperature, and O_3 are required to effectively guide breeding for crop performance in a changed atmosphere. Additionally, management practices such as the manipulation of planting dates and timing of thinning can be adjusted to take advantage of changes in crop development and available resources (Bindi and Howden 2004; DeJong 2005). However, adoption of new cultivars and timing of management practices will be more easily implemented for annual than perennial crops, which require more time and greater investment for cultivar development and crop establishment.

Heat stress in cattle is alleviated by shade because it reduces the external radiant heat load (Blackshaw and Blackshaw 1994). Cooling of the drinking water (Blackshaw and Blackshaw 1994) and acclimation of the animals are other useful strategies to help cattle maintain homeothermy. Adjustment in the diet to reduce the heat increment and minimize yield loss is a subject of intense research (West 2003). Selection for heat tolerance may be in conflict with maximizing high yield. In the last 50 years, metabolizable energy for milk production and heat energy have been steadily increasing. Thus, breeding for increased milk production has also changed the thermal regulatory physiology of cows (Kadzere et al. 2002).

6.7. Conclusions

While the responses of California-specific cultivars to predicted regional changes in growing conditions remains largely unknown, anticipated climate changes will likely have both positive and negative effects on the yield and quality of currently produced commodities. For example, increased temperatures may adversely affect yields of tomato (Sato et al. 2000), rice (Moya et al. 1998; Ziska et al. 1997), stone fruits (DeJong 2005), grapes (Hayhoe et al. 2004), and milk (West 2003), but allow for more crops of lettuce outside of the coastal regions (Wheeler et al. 1993) and expansion of citrus production (Reilly and Graham 2001), as well as heat and drought- tolerant trees, such as olives. Concurrent increases in CO_2 levels may also have positive or negative influences on yield and quality depending on the crop. Decreased protein contents of cereals will lower product quality (Kimball et al. 2001; Pleijel et al. 2000), while strawberries may become more flavorful (Wang and Bunce 2004). Adaptation strategies for commodities with potentially negative responses to climate change include: cultivar development of stress-tolerant cultivars, changes in management practices, and provision of shade and cooling water for livestock. These strategies will take time to implement, and cultivar adaptation to warmer climates should be a pertinent concern, especially for long-lived perennial crops. As the physiological adaptation and continued production of many of California's commodities seems possible in the face of increasing temperature, and atmospheric concentrations of CO_2 and O_3, it appears as though water availability for irrigation and animal production (Section 5) will pose a larger risk to future agricultural production in California.

7.0 Agricultural Invaders, Pests, and Disease in California's Changing Climate

Michael Bower, Jason Sexton, Vanessa Carne-Cavagnaro

7.1. Introduction

Climate change, both within California (Field et al. 1999; Hayhoe et al. 2004; Wilkinson 2002) and globally (IPCC 2001; Scherm et al. 2000), is likely to have a significant impact upon the types, abundance and impacts of agricultural weeds, pests, and diseases. While climate change may be advantageous to some species that provide ecosystem services (for example, through CO_2 fertilization of plants or increased abundance of some beneficial invertebrate species such as pollinators or biological control agents), such benefits will likely be offset by population increases in groups such as invasive exotics, invertebrate pests and disease causing microbes (McCarty 2001). Predicting these changes rests on better understanding of their ecophysiology and the complexity of the multi-trophic and multi-factor interactions in which they are involved. Here we review literature on agricultural weeds, pests, and disease-causing microbes and how they may be impacted by climate change in the context of California agriculture.

7.2. Invasive Plants and Agricultural Weeds

7.2.1. Introduction

Noxious and invasive weeds infest over 20 million acres in California and are estimated to cost hundreds of millions of dollars in control expenses and lost productivity annually (Schoenig 2005). Both the direct economic impacts and many of the indirect impacts of these plants such as reduced plant diversity, threatened rare and endangered species, reduced wildlife habitat and forage, altered fire frequency, increased erosion, and depleted soil moisture and nutrient levels (DiTomaso 2000) may well be exacerbated by interactions with a changing climate (Dukes and Mooney 1999). The nature of these interactions, and their variation between different commodities and growing regions, poses a serious problem for decision–maker's response to changes in California's climate, but are germane to achieving agricultural sustainability in California.

7.2.2. Competition

Atmospheric CO_2 concentration is one of the many factors that can influence the competitive ability of plants. Many weedy species in California's irrigated row crop and orchard production systems are C4 plants; particularly problematic species include: redroot pigweed (*Amaranthus retroflexus*), johnsongrass (*Sorghum halepense*), and common ragweed (*Ambrosia artemisiifolia)* (DiTomaso 2005). As C4 species, they are expected to experience a relative decrease in competitive ability compared with C3 plants when exposed to increased concentrations of CO_2, due to less disparity in efficiency on CO_2 assimilation pathways (Ziska 2001). This has been verified by numerous weed-crop competition studies in which C3 crops have experienced a relative increase in competitive ability compared with their C4 weed counterparts under elevated atmospheric CO_2 concentrations (Alberto et al. 1996; Patterson 1986), although exceptions do exist (Ziska 2001). By itself, increasing atmospheric CO_2 concentrations would therefore tend to disfavor most weedy species. However, changes in the earth's atmosphere and climate are a combination of many factors which cannot be taken in isolation (see below).

Although increased atmospheric concentrations of CO_2 may favor C3 species thereby altering competitive interactions between C3 and C4 species (see above), higher temperatures are expected to favor plants utilizing the C4 photosynthetic pathway (Pritchard and Amthor 2005). Some efforts to understand these interactions have been made; for example, Tremmel and Patterson (1993) studied the growth and allocation of five weed species treated with a gradient of CO_2 concentrations and two temperature regimes. Their results demonstrate that generalizations about interactions are difficult; different species and different populations within the same species showed different responses to the same treatment. Similarly, Taylor and Potvin (1997) demonstrated that even single factor experiments yield unpredictable outcomes when conducted in an ecosystem context. In summary, though the effect of individual factors on specific functional groups is well understood, interactions between these factors often yield unpredictable outcomes, which are likely to become even less predictable in natural settings.

One example of how such changes could manifest themselves in California involves experiments conducted on *Hemizonia congesta,* a late-season California native which is similar in phenology and in other respects to *Centaurea solstitialis* (yellow starthistle), a late-season problematic Californian weed that is unpalatable except when young. Elevated atmospheric concentrations of CO_2 can benefit *H. congesta* by increasing its late-season water availability (Reynolds 1996), but the weed could also benefit from this moisture. This may be reason for concern because many invasive plants share traits with this endemic species (Dukes and Mooney 1999) and because water is often limiting in hot, dry summers typical of a Mediterranean climate.

7.2.3. Range shifts

Many invasive plants and agricultural weeds are expected to expand their range in response to climate change in a fashion which will likely increase their impact in California. One way to assess northern range limits of tropical and warm temperature annual species is by accumulated heat sum, measured in degree days (the total amount of heat required, between the lower and upper developmental threshold temperatures for an organism, to develop from one point to another in its life cycle), during the growing season (Patterson 1995). Since the number of degree days are expected to increase (Hayhoe et al. 2004), new invaders and weeds may become prevalent as appropriate habitats develop and these species extend their range. It has been suggested, for example, that C4 grass weeds which are problematic in the southern United States, may expand into higher latitudes as a result of global warming (Patterson 1995; Rahman and Wardle 1990); similar effects may be seen with elevation. Given the prolific nature of most weeds and invasive plants and their exceptional colonization capacities (Baker 1974), these C4 grass weeds may be among the first to exhibit such range expansion. The effects of a warmer, more extreme climate, and the relatively disturbed nature of much of California, especially in the Central Valley, may predispose susceptible agricultural systems to quickly encounter new and more vigorous weeds (Williams et al. 2005).

A complimentary contraction of southern range boundaries of weed species is not necessarily expected. It is now known that detectable adaptive divergence evolves on a time scale comparable to change in climate; within decades for herbaceous plants and within centuries or millennia for longer-lived trees (Davis et al. 2005). Because many weeds become reproductive at an early age and are highly fecund, rapid rates of evolution will likely play a significant role in their response to climate change. While range expansions are to be expected for many species, range contractions are less likely in rapidly evolving species with significant populations already established. Similarly, should range contractions occur, it is likely that new or different weed species will fill the emerging gaps/niches.

Many successful invaders and weeds such as field bindweed (*Convulvulus arvensis*), giant reed (*Arundo donax*), and jubatagrass (*Cortaderia jubata*), reproduce primarily asexually; therefore their populations may be more readily reduced due to climate change, given their clonal nature. However, asexually reproducing clonal plants on average are not less genetically variable than non-clonal plants (Eckert 1999; Ellstrand and Roose 1987; Hamrick and Godt 1989), and thus the potential for an evolutionary response exists. There are however, large knowledge gaps regarding the evolutionary genetics of clonal plants, making any definitive conclusion difficult (Eckert 1999).

7.3. Invertebrate and Vertebrate Pests in Agriculture

7.3.1. Introduction

California farmers contend with thousands of crop-damaging invertebrate and vertebrate pest species. As a result of adaptation to climate change, their abundance, types, and activities will likely be altered in the future (Davis et al. 2005). This is especially true of invertebrate pests which have rapid generation times, and as such an ability to change to a gradual shift in selection pressures, almost certainly more rapidly than their host plant species (Cannon 1998; Field et al. 1999), and that of weeds (see above). In 2003 the reported pesticide use in California was 175 million pounds (California Department of Pesticide Regulation 2005). In recent years California agriculture has adopted Integrated Pest Management (IPM), an ecosystem-based strategy that focuses on long-term prevention of pests through a combination of biological control, changes in cultural practices and the use of resistant varieties, as well as chemical control when necessary (rather than prophylactory), for pest management. The efficacy of these different control measures are to a certain extent determined by climate.

Invertebrates (for example, insects and nematodes) cause problems such as crop damage, vectoring disease, contamination of food and fiber, and export and quarantine problems. Vertebrate pests (for example, mammals and birds) transmit diseases and parasites, burrow and disturb crop plants and pastures, and damage trees resulting in sap loss and allowing infestation by harmful insects and/or pathogens. Any pest management strategy must be carefully designed, so that beneficial organisms are not negatively impacted and are able to persist. For example, many Californian farmers use IPM, including encouraging bats, burrowing owls, and kestrels onto their properties in order to help control damaging insects, rodents, and other pests. Biological control agents, such as parasitoids and predators—and other beneficial species such as pollinators—provide important services to agriculture (Flint and Dreistadt 2005; Hanna et al. 2003; Heinz et al. 1999; Heinz and Zalom 1996; Norris and Kogan 2000). Impacts of a changing climate on pest species (with an emphasis upon invertebrate species) and their control are discussed here.

7.3.2. Pest species and climatic interactions

Agriculture impact assessments often do not account for potential yield losses due to changes in pest dynamics and density under climate change (Scherm 2004). While the Agricultural Assessment Group with the U.S. Global Change Research Program considered the effect(s) of pesticides in their model, they did not account for the effect(s) that changing pest populations had on yield losses (Reilly 2001). This consideration deserves further attention. For example, in a study of a pest aphid species in Britain—*Aphis gossypii* Glover (Hom., Aphididae)—the aphids migrated 3–6 days earlier as temperatures increased by 0.4°C (0.7°F) over 25 years, which has significant implications for epidemiology of aphid-vectored virus diseases in economically important crops such as barley and sugar beet (Harrington 2002). Accurate prediction of insect development and emergence are essential for effective pest management, but can be challenging, as it is virtually impossible to measure the microenvironments in which pests actually live. Pest management decisions should take into consideration quantitative information on dispersal of invertebrate pests, but such information is often lacking (Turchin and Thoeny 1993). Additionally, invertebrate pests are hard to detect and monitor. Farmed landscapes may need to provide opportunities for natural enemy species to disperse between habitats (Marshall et al. 2003; Tscharntke et al. 2005). However, great diversity of crops along with their own complement of pests creates logistical challenge for planning and implementing successful pest management programs, in a changing climate. This is especially true of California given its many different agricultural commodities and regions (see Section 2).

7.3.3. Pest development and climate change

Changing pest dynamics as a result of changing atmospheric conditions are of ecological and economic importance (Fuhrer 2003). While little is known about the direct effects of changing precipitation patterns upon invertebrates, it is known that increased rainfall can increase insect mortality (Thacker et al. 1997). Information on direct effects of elevated atmospheric concentrations of CO_2 on insects is limited (Agrell et al. 2000; Coviella and Trumble 1999; Stange 1997), as are studies of the consequences of changing ultraviolet-B (UV-B) levels on insect herbivores (McCloud and Berenhaum 1994) and other invertebrates. Existing studies suggest that direct effects of temperature are likely to be larger and more important than any other factor associated with climate change

(Bale et al. 2002). Given the predicted increase in temperatures in California in the coming century, this is a key area upon which attention should be focused.

Invertebrates (as with plants, see above) require a certain number of degree days to develop from one point in their life cycle to another. The survival, range, and abundance (Bale et al. 2002) of many invertebrate pest species is mediated by temperature. Furthermore, temperature is the dominant abiotic factor that directly affects herbivory (Bale et al. 2002). Consequently, the diversity and intensity of insect herbivores increases with rising temperatures and constant latitude (Bale et al. 2002). In multivoltine species (producing several generations per year), such as the Aphididae and some Lepidoptera, development time is expected to increase with climatic warming, allowing for increased generations within a year (Pollard et al. 1995). A 2˚C (3.6˚F) temperature rise, which is at the lower end of temperature increases predicted for California in the coming century (Section 2), may result in 1–5 additional generations/year for a range of invertebrates such as insects, mites, and nematodes (Yamamura and Kiritani 1998). It is also likely that many pest species will expand their geographical range in a warmer climate, seen already in Britain in several butterfly species (Hill et al. 1999; Parmesan and Yohe 2003; Pollard et al. 1995). The effect of higher temperatures on overall abundance of herbivorous insects remains unknown in the absence of equivalent data of their natural enemies (Davis et al. 2005). While warming speeds up the lifecycles of many insects, suggesting that insect pest problems could increase (Cannon 1998), herbivorous insects may grow more slowly, as they feed on the typically protein poor leaves produced under conditions of elevated atmospheric concentrations of CO_2 (see Section 6). The increase in C:N ratio in plant tissue (Cannon 1998) may cause insects to eat more herbaceous material, thereby causing more damage or change their feeding preferences to satisfy their dietary N requirements, slowing larval development and increasing mortality (Coviella and Trumble 1999).

Climate change may impact host species in ways that make them more vulnerable to pests (Harrington et al. 2001). Adaptation to changing climate would be more rapid for insects than host plants, due to generation time (Lawton 1995), and the spread of insect pests may be accelerated if host ranges change rapidly due to environmental change or to socioeconomic incentives (see Section 8). For example, the temporal synchrony of larval emergence of the Winter moth, *Operophtera brumata,* and bud burst of its host plant, sitka spruce *Picea sitchensis* are important. A temperature increase of 2˚C (3.6˚F) is not expected to dramatically impact bud burst date; however, larval emergence is likely to advance ahead of bud burst (Sibly et al. 2005), which may negatively impact the capacity to plants to resist/avoid some pest damage. However, temperature does not act in isolation to influence pest status. Some insects are unable to cope in extreme drought, while others are disadvantaged by extreme wetness. However, the present projections of California's future precipitation patterns are uncertain, making predictions of this nature difficult. Taken together, these examples highlight the complex climatic and trophic interactions that California agriculture will need to begin to consider in a changing climate (Figure 7.1).

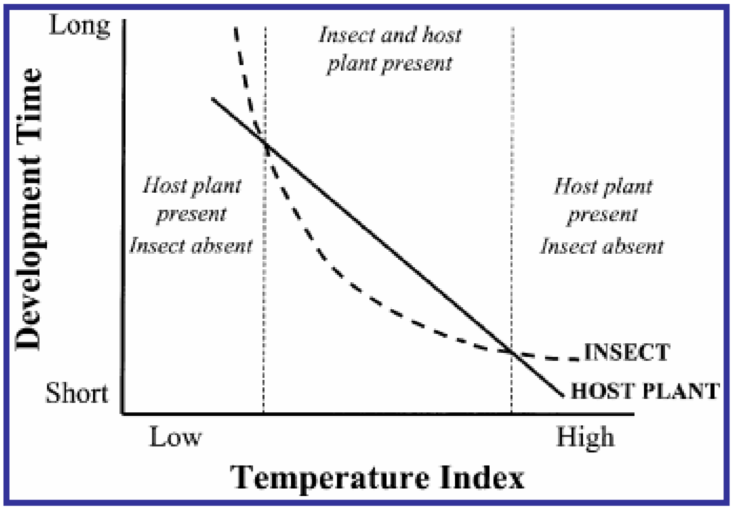

Figure 7.1. Model showing how the relative development rates (time) of an insect and its host plant at different temperatures might set the distribution limits of host-specific insect herbivore species in the northern hemisphere (after MacLean 1983). In the northern part of the range (low temperature index), the host plant grows too slowly to support insect development; whereas in the south (high temperature index), the plant develops too quickly. Only over the mid-part of the range is the insect herbivore able to match its phenology to that of its host plant. Figure excerpted from Bale et al. (2002), formal permission not obtained.

7.3.4. Pest control and climate change

The global pesticide market was valued at $29 billion in 2000, with herbicides, insecticides and fungicides representing 48%, 27%, and 19% of expenditure, respectively (Marshall et al. 2003). In addition to the high costs of chemical control, there are growing environmental and health concerns about the use of pesticides and their regulation (especially as the interface between agricultural and urban areas increases), and applications must be timed precisely to maximize efficiency and minimize undesired impacts. Under climate change scenarios (with increased temperature), the number of days that will be suitable for spraying is likely to increase where it is drier and decrease where it is wetter; however, as a result of increased pesticide application, invertebrate pests may build resistance to the chemical or its active ingredient (Harrington et al. 2001). Furthermore, the toxicity and/or stability/volatility of the chemical are likely to change under different climatic conditions (especially increased temperature). An important consequence of chemical spraying is that natural enemies present in the ecosystem are killed, further increasing the need for chemical applications to control pest populations. Health risks to workers and consumers, associated with increased pesticide usage in Californian agriculture, are also of importance.

The efficacy of other control methods such as biological control and the use of genetically modified organisms are likely to be affected by climate change. Factors that impact the abundance and activity of invertebrate pests will similarly impact beneficial invertebrates such as predators, parasitoids, and pollinators. Thus, biological control efforts will need to consider the impacts of climate change on complex pest/natural enemy dynamics. For example, high temperatures tend to decrease the efficacy of the entomopathogenic fungus (biocontrol agent) *Beauvaria bassiana* in controlling wax moth (*Galleria* sp.) in soil treated with certain pesticides (Mietkiewski et al. 1997). In Australia, the effectiveness of Ingard cotton, which has been genetically modified to produce a Bt toxin precursor, appears to be greater at a given node when that node is produced at a higher temperature (Harrington et al. 2001). This adds an additional layer of complexity that needs to be considered as GM crops are grown in some instances to not only reduce pest pressure but to also decrease insect vectored plant pathogens (Gatch and Munkvold 2002). Taken together, these examples highlight the need for multitrophic studies of pest, biological control agent, and host plant dynamics in a changing climate.

7.3.5. Climate change and vector borne diseases

Invertebrates not only cause direct damage to crops, but can also act as vectors of disease-causing organisms. Environmental conditions play a significant role in vector-borne diseases, and the impact of climate change has the potential to shift geographical ranges (Henry et al. 2005). Some examples of vectored diseases include *beet curly top virus,* which affects several hundred varieties of ornamental and commercial crops in California and is vectored by the sugar beet leafhopper; *tomato spotted wilt virus*, vectored by western flower thrips; and Pierce's Disease, vectored by the glassy-winged sharpshooter. These will be considered in more detail in the following section.

7.4. Disease-causing Microbes

7.4.1. Introduction

The risk of agricultural yield losses due to disease, weeds and insects, is likely to increase with climate change, but is rarely considered in climate assessments (Anderson et al. 2004; Reilly et al. 2001; Rosenzweig et al. 1995). Disease onset requires a susceptible host, a virulent or infective pathogen, and a favorable environment. Disease-causing microbes are dependent on temperature and moisture optima for establishment and reproduction, with most diseases occurring in warm and wet conditions (Agrios 2005). Pathogenicity, or the degree to which the host is harmed by its parasite, depends on this three-part interplay. Disease often occurs outside of the temperature optima of the pathogen *and* the host, and often results from the host organism being more susceptible than the pathogen to being outside of these optima (Agrios 2005). Climate change in California, especially in the context of increased temperatures, and its impact upon plant disease development is likely to be of great consequence to California agriculture.

Climate factors that affect microbial diseases are multifarious and multiplicative. An increase in average temperatures of just a few degrees can hypothetically lengthen the growing season as well as the growth rate of a pathogen dramatically (Harvell et al. 2002). While increased CO_2 may increase plant growth, it may also increase pathogen fecundity, thereby negating or reversing positive effects on plant growth, should conditions conducive to disease development, such as increased temperatures, manifest

(Manning and Tiedemann 1995) (Figure 7.2). Similarly, increased O_3 and UV-B levels, while harmful to plant tissues, may also harm obligate host pathogens, decreasing plant disease (Manning and Tiedemann 1995).

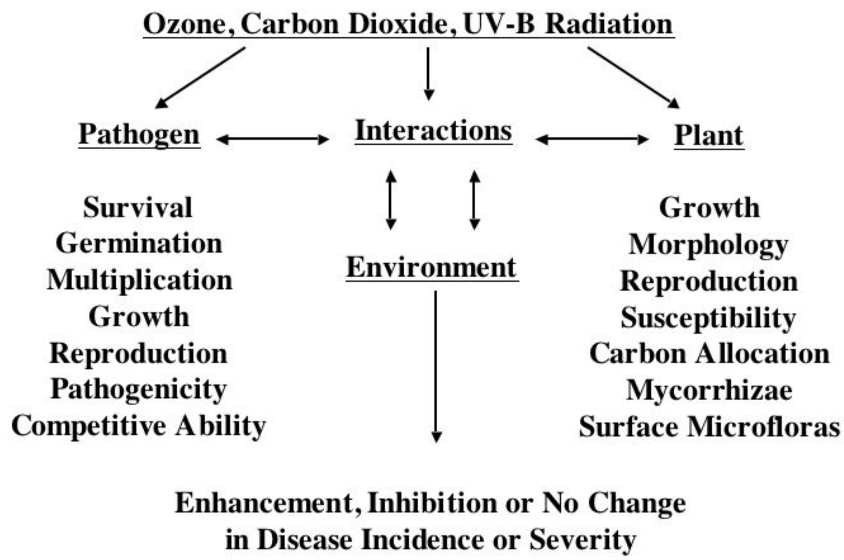

Figure 7.2. Changes in disease incidence and severity due to CO_2, O_3, or UV-B and by affecting plant or pathogen. Figure excerpted from Manning and Tiedemann (1995), formal permission not obtained.

The global impacts of pathogen outbreaks in agriculture have been profound (Scherm and Coakley 2003). Plant pathogenic organisms have been responsible for many instances of devastating crop losses (e.g., Anderson et al. 2004). Since the 1960s, millions of livestock and poultry have been destroyed in response to combined outbreaks of Influenza A Virus, Foot and Mouth disease, and Mad Cow Disease alone (Tilman et al. 2002), with anomalous climate patterns often flagged as alleged triggers to such natural economic disasters (Scherm and Yang 1995). The introduction of new agricultural pathogens through species range shifts will undoubtedly be a major effect of changing climates (Scherm and Coakley 2003). Climate-driven pathogen range extensions in terms of both latitude and elevation have been widely reported in mosquito-borne human diseases such as malaria and dengue and yellow fevers (Epstein et al. 1998); however, debate exists on whether such range expansions are better attributed to anthropogenic causes (Reiter 2001). Similar climate-range interactions have been anticipated in aphids (vectors of a variety of important crop pathogens, see above) by influencing winter survival and spring flight timing (Anderson et al. 2004; Coakley et al. 1999; Scherm and Coakley 2003).

Evolutionary responses of pathogens are an additional source of uncertainty in changing agricultural systems. It is well known that microbial agents can quickly evolve resistance to antibiotics and herbicides, often within time scales less than a decade (Palumbi 2001). However, adaptation potentials are not unlimited, and interactions between pathogen evolution and their environment have seldom been studied. Changes in fungal disease severity in crop plants at increased atmospheric CO_2 concentrations have been demonstrated (Coakley et al. 1999); however, the direction of response shifted depending on point of inoculation, whether occurring in the field or in controlled environments, making extrapolation difficult. Chakraborty and Datta (2003) demonstrated a lag in the increase of fungal pathogen aggressiveness over 25 infection cycles in twice ambient CO_2 environments, but speculated on the potential for accelerated pathogen evolution in such environments via observed increases in pathogen fecundity. Interactions between host and pathogen genotypes and the environment further increase uncertainty of outcomes. Furthermore, climate change will enable plant pathogens to survive outside their historical geographic range; consequently, climate change may lead to an increase in the significance of pre-existing pathogens as disease agents, or provide the climatic conditions required for introduced pathogens to emerge (Anderson et al. 2004).

7.4.2. Potential pathogen shifts and forecasting disease risk in California

In the multi-billion dollar grape industry of California (Section 2), Pierce's Disease has caused Riverside County alone $13 million in damage as of 2002, and the state has aided the industry with more than $65 million in control efforts since 1998 (Wine Institute 2002). Pierce's Disease is a prominent bacterial disease of California grapes that is caused by *Xyllela fastidiosa* and vectored by the glassy-winged sharpshooter, a native to the southeastern United States that is more mobile than leafhoppers already present, and is limited to climates with mild winters such as southern California (Purcell and Hopkins 1996). The optimum temperature for growth of the Pierce's bacterial pathogen is 28°C (82°F) (Feil and Purcell 2001). Consequently, northern and coastal California grape-growing regions are currently sub-optimally cool for Pierce's Disease. However, under climate change, these regions may face increased risk of establishment of Pierce's disease. The threat of the glassy-winged sharpshooter is not limited to grapevines; its host range includes more than 100 species of plants, including almonds, citrus, peaches, plums, alfalfa, and ornamental plants produced by the state's commercial nursery industry, and therefore has the potential to disrupt the state's agricultural economy, especially if it increases under future climate scenarios. In 2004 West Nile virus (WNV) was reported in horses in more than half of California counties, resulting in a 42% mortality rate of infected animals (CDFA 2005). Assuming that warming climates lower developmental thresholds for mosquito vectors (Epstein 2001), WNV incidence could potentially increase in California in areas historically less prone to mosquito outbreaks. Similarly, changes in amounts and timing of precipitation, snow melt, and stream flow dynamics (for example, standing water), may lead to an increase in the abundance of mosquitoes in California, and hence, WNV.

Disease forecasting models are essential in order to be able to respond quickly to high-risk trends. In California several crop disease models have been developed and are in use. Downy mildew in lettuce is an example of a disease whose incidence can be predicted by a very simple model; morning leaf wetness after 10 a.m., influenced by low midday temperature and high relative humidity, directly affect disease incidence (Scherm and Van Bruggen 1994; Wu et al. 2005). In this system, warming alone may actually reduce disease risk for this pathogen in certain areas; however, with future precipitation patterns uncertain at best, there is need for further information. Interactive risk assessment and forecast models are currently available through the University of California Integrated Pest Management Program for powdery mildew on grapes and tomatoes (University of California 2005a). The fungal mildews in these systems, as well as others, such as the devastating late blight in potato and tomato (Hansen and Nazarenko 2004), are tightly linked to temperature and precipitation, with severe disease outbreaks occurring in relatively wet winters with mild temperatures such as in El Niño years (R. Michael Davis, pers. comm.). Esca, a fungal disease in California table and wine grapes, appears to respond to above-normal rainfall and summer temperatures (Eskalen et al. 2003). Several California crop disease climate models are in development and are available, including fire blight (apple and pear), scab (pear), alternaria leaf blight (carrot), and brown rot (stone fruits) (University of California 2005a).

7.5. Mitigation and Adaptation

For the farmer, potential adaptation strategies for pests include choice of crop, growing season, manipulative cultural practices, fertilization, pest control, and irrigation—or a combination of these (Liebman et al. 2001), many of which are currently used to control weeds in agriculture. Yet, there are often tradeoffs involved that can benefit pests as well (Harlan 1975; Patterson 1995). An effective adaptation plan depends on accurately casting predictions, but such predictions are difficult when the impact of undesirable organisms is based on a complex network of interacting factors. Maladaptation can result in negative effects that are as serious as the climate change-induced effects being avoided (Scheraga and Grambsch 1998).

Nonetheless, two endeavors stand out as productive methods of ultimately reducing the impact of invasive plants and weeds in California's changing climate: an increase in our understanding of interactions in an ecosystem context and increased vigilance. Though many competition experiments have been conducted on the effect of rising CO_2 on weed-crop competition (Pritchard and Amthor 2005), both our understanding of how such effects change in an ecosystem context and how such an effect interacts with other aspects of climate change is rudimentary (Dukes and Mooney 1999) and is insufficient to formulate respectable predictions in California's future climate. This is further confounded by uncertainty associated with future precipitation patterns and those of El Niño events in California. As a second adaptation, increased vigilance will serve to identify new invaders early, thus dramatically increasing the potential for successful eradication (Rejmanek and Pitcairn 2002). The Western Plant Diagnostic Network, of which California is a member, is an example of such a network (Western Plant Diganostic Plant Network 2006). In terms of increased vigilance, the "guilty until proven innocent" approach (Ruesink et al. 1995), in which each threat is assumed to be dangerous, shows promise. Where resources are limited, likely problem areas should be targeted, such as disturbed habitat, especially along roadsides and other dispersal corridors and points of entry.

The impact of climate change on pest and disease outbreaks is difficult to predict because it involves changes in both the vigor of the predator and the vulnerability of its prey. Plants do not experience climate change alone, but as part of a wider ecosystem incorporating their pests, pathogens, symbionts, and competitors (Newman et al. 2003). Although arthropod pests and weeds do interact with each other, strategies aimed at managing one or other of these classes of threats, rarely consider such interactions (Norris and Kogan 2000). Furthermore, the great diversity in commodities produced in California, coupled with the abundance of natural vegetation and weeds can provide an important refuge for pests and diseases causing microbes to survive in, at times when their primary crop host plant may be absent. Species with small geographic ranges are more vulnerable to climate change than widespread ones (Sibly et al. 2005). This is also true of specialist pest species versus generalist pest species. One possible adaptation is to modify planting dates or the selection of cultivars that are resistant to emerging pests and disease-causing microbes. As with weeds this dictates the need for vigilance and accurate predictions of pest/disease outbreaks. Implementation of multifaceted pest and disease management strategies such as those applied in IPM will likely enhance the adaptive capacity of producers in a changing climate. Many of the strategies currently used to control disease and pest outbreaks will likely be successful in the future climate.

Human responses to climate-induced pestilence need to be adaptive and inventive. Agricultural pest control is already a complex and expensive endeavor. For example, increased pesticides are an obvious adaptation; however, this approach has many drawbacks (see above). When combating Pierce's disease, for example, in addition to conventional methods such as inspection, pesticides, and host removal, other technologies are being employed to better control the disease in California, including biological control, sequencing the pathogen genome (to help develop targeted pesticides that do not harm the grape vines), and identification and breeding of disease-resistant vines (Wine Institute 2002). In order to buffer against the unknown interacting effects of climate change, bet-hedging strategies should be used that reduce host pools, such as maximizing spatial and temporal crop intra-specific genetic variation (Zhu et al. 2000). The judicious use of genetic technologies may also prove important in stemming invasions and epidemics by adding to our range of available tools to deal with such challenges.

7.6. Data Gaps and Future Research Questions

Issues of precipitation are critical. A warmer, drier California will likely have a very different pest, weed, and disease landscape than a warmer, wetter California. Furthermore, research is needed to understand the effects of climate change on the ecology and evolution of agricultural pests. The effects of climate variability on co-evolution, virulence, and resistance to control methods are at best poorly understood. For example, does the efficacy of taxon-specific chemical control (including evolution of adaptive resistance) shift, if at all, in warmer and/or more variable environments? This question is important across all taxonomic levels, from vertebrate pests to microbial pathogens. Changes in competitive balance and trophic interactions are difficult to predict for future climates. Nevertheless, field experiments can be conducted across existing climate gradients representing current and future conditions. Such studies are lacking. Landscape surveys are also instructive in pointing out the value of non-crop habitat in pest control, and in determining spatial and temporal gradients that affect pest distribution (Tscharntke et al. 2005).

The effect of higher temperatures on overall abundance of herbivorous insects remains unknown in the absence of equivalent data of their natural enemies (Davis et al. 1998). Furthermore, efforts to link information specific to California weather to disease and pest outbreaks are limited in their number (see exceptions above). Concerted efforts are needed to monitor and compile data, including historical records. The development and validation of prescriptive control models depend on these data. Currently, climate-disease models in California are developed on an as-needed basis, with temporary funding often provided by private agricultural interests (R. Michael Davis, personal communication). Hence, no long-term efforts or programs exist.

Thus, development of continuing programs, such as the disease warning systems recommended by Wu et al. (2005), is necessary.

Long-term sharing, coordination, and modeling of pest outbreak and environmental data among the diverse climate regions within (or neighboring) California would greatly improve our understanding and ability to prepare for, adapt to, and mitigate against future pest risks and disease causing agents. Pests and pathogens that may become significant in California agriculture need to be identified and appropriate quarantine and inspection measures implemented to avoid introduction. Looking to other regions where the climate is similar to that predicted for California in the coming century will also likely be instructive.

7.7. Conclusions

With the forecasted climate warming over this century, California agriculture is facing a significant threat in shape of weeds, pests, and microbial diseases. Warmer and wetter climates generally support more species and higher growth. Hence, climate warming in California, if accompanied by precipitation during key growth periods, will cause increased immigration, growth rates, and developmental windows of problematic species. Unfortunately, determining when and where increased pestilence and biological invasions will manifest is not yet possible because of a significant lack of information and programs.

The interacting effect of climate factors (for example, temperature, CO_2, and O_3) on host-pest dynamics renders species-specific predictions based on single-factor analyses tenuous at best. Many factors, including species interactions, drive outcomes. Hence, the need for ecosystem-context (or *in situ*) studies and experiments in changing climate scenarios is clear, albeit challenging to achieve. Additionally, the fact that organisms adapt and evolve, often quickly given sufficient genetic variation, further confounds prediction. As climate change reshapes the agricultural pest landscape, humans need to be adaptive, finding new tools to cope with increasing uncertainty.

Investment in research and response systems is essential to understanding and adapting to climate change. Increased statewide and interstate cooperation in the form of shared databases, dedicated modeling programs, and outbreak and invasion warning and detection programs would vastly improve our current ability to adapt to the many biological threats to agricultural systems. A continuing challenge over the coming century will be finding ways to control problematic species while simultaneously maximizing ecological services (for example, pollination, and predation) from limited and stressed native ecosystems.

8.0 Land Use Change in California's Agricultural Landscapes in Response to Climate Change

Angela Kong, Kim Cahill, Krassimira Hristova, Louise Jackson

8.1. Current Understanding of Climate Change Effects on Land Use Change

Land use refers to the management regime humans impose on the biophysical attributes of the earth's surface. Temperature or rainfall patterns associated with climate change may alter land use and land-cover distributions (Dale 1997), and consequently basic patterns of productivity, stability, and sustainability in agroecosystems (Viglizzo et al. 1997). Conversely, the effects of human-induced greenhouse gas (for example, CO_2 and N_2O) fluxes and C sequestration that is attributed to land use and management can, in turn, impact the rate and magnitude of climate change (Dale 1997; Houghton and Hackler 2000a; Houghton et al. 1999). For example, cultivation of forest and grassland soils accounts for approximately 25% of the net loss of C in the United States, while N fertilization, no-till farming, and grassland restoration have only slightly reduced these losses (Houghton and Hackler 2000b). Issues of agricultural land use change are particularly interesting in regions with Mediterranean-type climates; they have typically experienced high population growth, urban expansion, and decreasing self-sufficiency in terms of producing their own food, due also to the export value of the many specialty commodities they produce (Rosenzweig and Tubiello 1997; Scheuring 1983). In California, these issues raise questions related to the sustainability of agriculture, both economically and environmentally.

Given the potential growth of California's population to 90 million people by the end of the twenty-first century, urbanization is probably the single largest factor driving land use change in California's agricultural landscapes, farmland loss, and the increasing utilization of wetlands and riparian corridors that serve as wildlife corridors (Landis and Reilly 2004). Urbanization could result in a loss of 35% of the prime agricultural land in San Joaquin Valley counties, and much of the remaining agricultural land in coastal counties, even when climate change is not considered in the projections (Table 1) (Landis and Reilly 2004). This section will: (1) introduce the approaches commonly used to assess climate change effects on land use, (2) discuss the fundamental drivers of land use change, and (3) evaluate knowledge gaps in current mitigation and adaptation strategies for climate change-induced land use shifts in California.

County (sorted in order of absolute loss, 1998-2100)	1998 Prime Farmlands (ha). Source: CFMMP	Projected Loss due to Urbanization, 1998-2020		Projected Loss due to Urbanization, 1998-2050		Projected Loss due to Urbanization, 1998-2100	
		Hectares	%	Hectares	%	Hectares	%
Fresno	148,584	3,818	3%	25,589	17%	51,552	35%
Kern	217,093	7,930	4%	24,375	11%	42,081	19%
San Joaquin	173,331	5,678	3%	16,416	9%	29,088	17%
Monterey	69,068	3,025	4%	14,593	21%	26,559	38%
Riverside	64,517	9,533	15%	16,579	26%	24,710	38%
Stanislaus	67,478	1,077	2%	9,055	13%	18,842	28%
Imperial	80,722	53	0%	1,781	2%	12,844	16%
Merced	116,887	3,519	3%	8,351	7%	12,562	11%
San Bernardino	12,110	5,769	48%	7,016	58%	9,467	78%
Ventura	20,935	1,103	5%	4,617	22%	8,661	41%
Solano	60,730	673	1%	3,926	6%	8,079	13%
Santa Barbara	29,128	486	2%	4,056	14%	7,879	27%
Kings	57,624	1,853	3%	4,561	8%	7,402	13%
Madera	41,350	1,011	2%	3,502	8%	7,035	17%
Santa Clara	12,951	1,257	10%	4,095	32%	6,482	50%
San Benito	13,874	281	2%	1,954	14%	3,271	24%
Sonoma	14,450	95	1%	1,438	10%	2,848	20%
Yolo	107,582	104	0%	1,304	1%	2,837	3%
Orange	4,524	946	21%	2,139	47%	2,593	57%
San Diego	4,323	1,466	34%	2,257	52%	2,526	58%
Contra Costa	16,036	386	2%	1,473	9%	2,213	14%
Santa Cruz	6,960	427	6%	2,172	31%	2,172	31%
San Luis Obispo	16,159	255	2%	1,011	6%	2,080	13%
Alameda	3,081	573	19%	1,334	43%	1,573	51%
Tulare	34,365	347	1%	578	2%	788	2%
Los Angeles	9,949	212	2%	435	4%	636	6%
Napa	12,117	34	0%	161	1%	283	2%
Sacramento	49,317	1	0%	1	0%	9	0%
Yuba	18,465	0	0%	0	0%	0	0%
Placer	3,964	0	0%	0	0%	0	0%
San Mateo	1,082	0	0%	0	0%	0	0%
El Dorado	490	0	0%	0	0%	0	0%
Nevada	153	0	0%	0	0%	0	0%
Marin	71	0	0%	0	0%	0	0%
Mariposa	12	0	0%	0	0%	0	0%

Table 8.1. Anticipated losses in prime farmland due to projected urbanization, for selected counties, 1998–2100. Excerpted from Figure 13 Landis and Reilly (2004), formal permission not obtained.

8.2. Approaches for Modeling Climate Change Impacts on Land Use

Climate change impact assessments commonly employ a hierarchy of models (Parry 1990) which, ideally, are integrated to simulate the most important processes, interactions, and feedbacks in the systems. At the top of the hierarchy are Global

Circulation Models (GCMs), which simulate global climatic patterns on a grid with cells sized between 2° and 9° longitude and/or latitude and several vertical layers thick. Results from GCMs are then used as inputs to biophysical models, which also rank at the top tier of the hierarchy. Outputs from biophysical models (i.e., crop yields) are subsequently used as inputs to economic models at, for example, the farm level (second tier). Models at the regional scale are more suitable to estimating climate change effects on land use.

While some GCM predict gains of 20%–50% in potential agricultural land for North America (Schlenker et al. 2005), regional models provide projections at greater resolution and detail. Regional models have forecast that certain crops will be forced to shift out of their current geographical range due to increasing temperatures (Adams et al. 1990; Parry 1990), but these losses in productivity may be partially offset by increased productivity from increased CO_2 levels (Blasing and Solomon 1985; Ramankutty et al. 2002; Reilly and Schimmelpfennig 1999; Reilly et al. 2003). Other crops, especially C4 plants (for example, maize), might suffer lower yields due to elevated atmospheric CO_2 levels (Rosenzweig et al. 2000), though California produces few C4 commodity crops. As Section 6 points out, less is known about how temperature and CO_2 concentrations affect key developmental phases of horticultural crops, and thus their vulnerability to climate change.

Climate analogs can provide some insights into land use change. Using the hot, dry decade of the 1930s as an analog of the possible climate that might occur in the Missouri, Iowa, Nebraska, and Kansas (MINK) region as a consequence of climate change, Easterling and Apps (2005) modeled crop responses. They found that farm management changes and slight increases in productivity of some crops (for example, irrigated wheat) could eliminate 80% of the negative impact of the analog climate, thus minimizing potential land use change. In California, an analogy of climate change, the drought of 1987–1991 demonstrated that farmers increased their reliance on ground water, adopted water-conserving technologies, reduced water use per acre, moved away from water-intensive crops, and fallowed more land (Zilberman et al. 2002). The drought instigated the official approval of water trading (see Section 5) and demonstrates how extreme events can trigger rapid changes in land use and social institutions that increase adaptation to climate change.

Different approaches have been used to predict climate change impacts on the agricultural landscape, sometimes resulting in very different outcomes. The first approach is a process-based one that arbitrarily or synthetically forecasts a specific climatic change by varying temperature, precipitation, or another model parameter (Reilly 1999) and is likened to a simple sensitivity analysis (Leemans 1997). One advantage of this process-based approach lies with its reliance on simple regressions. Some weaknesses of this approach include: (1) the utilization of significant amounts of primary data that are constrained in time and/or space; (2) requisite stable equilibrium conditions; (3) omission of changes in crop physiology and ecosystem productivity, adaptive human behavior, and land use; and (4) neglect of interactions with land use and responses to environmental change (Leemans 1997). The California SWAP/CALVIN model (Section 5) is similar to this approach, and it predicts relatively feasible changes in terms of crop management and land use change to maintain crop productivity (Howitt et al. 2003; Lund et al. 2003; Tanaka et al. 2005). A second approach models the responses of crops and farmer behavior based on extrapolation of responses of varying climates observed at other sites to the system of interest, and does not necessarily consider unique adaptations that may increase success during transition to a new climate regime (Parry 1990; Reilly 1999). This latter approach is more akin to the approach of Hayhoe et al. (2004). In this case, predicted effects of climate change on wine grape production are more negative than what would be indicated by the SWAP/CALVIN model, suggesting more problems associated with adaptation, and greater changes in land use patterns. Thus, different potentials for land use change emerge from different modeling efforts.

More work is needed to improve the accuracy of modeled projections of climate change, and to produce results that are accessible and will allow a wide range of user communities in agriculture to adapt to climate change. A recent analysis by the World Meteorological Organization (Garbrecht et al. 2005) concluded that uptake of climate projections by agricultural communities has been low due to lack of a clear understanding of their needs and insufficient interaction and communications among all involved stakeholders.

8.3. Tracking Land Use Change in California's Agricultural Landscape

California's past history suggests that agriculture has the capacity to effectively transition to new climate regimes with economic success, but it may be only after a tortuous journey. Since 1850, California's agriculture has been in a perpetual state of growth, transition, and adjustment (Williams et al. 2005). Large changes have occurred within the last 150 years in terms of acreage for California's commodities, beginning with early mission attempts to raise livestock, grow grains, and develop horticulture; followed by the era of ruminants and then extensive wheat and barley production; then, the beginnings of intensive fruit, nut, and vegetable agriculture and large-scale beef and dairy production; ending with the present management-intensive, technologically dependent agricultural industry (Johnston and McCalla 2004; Mikkelsen 1983).

During the past 40 years, the total acreage of agricultural land, including grazed land, has decreased from 37,000,000 to 28,000,000 acres, reflecting urbanization and greater intensification of existing agricultural lands. The production of horticultural crops has increased, while field crops have remained stable in acreage since the 1960s (Brunke, Agricultural Issues Center, UC Davis, pers. comm.). Lettuce, tomatoes, rice, and almonds have increased in acreage by more than 50% in the last 30 years, while two major crops of past production eras—barley and sugarbeets—have declined by almost 100% during this period. Major shifts in production areas have occurred; for example, almond production in California has moved northwards over the past several decades (Figure 8.1). Within California, as the climate warms, production patterns will shift latitudinally northward, to higher elevations, or out of the state. A warmer and drier climate and expanding growing seasons (allowing for early planting of cold–sensitive crops) could benefit olive and citrus production by extending their cultivation range northward (Morettini 1972). If crops are to decline or disappear from the Californian landscape with climate change, it is most likely to be those that use large amounts of water to produce crops of limited economic value (for example, alfalfa and cotton; (Field et al. 1999)).

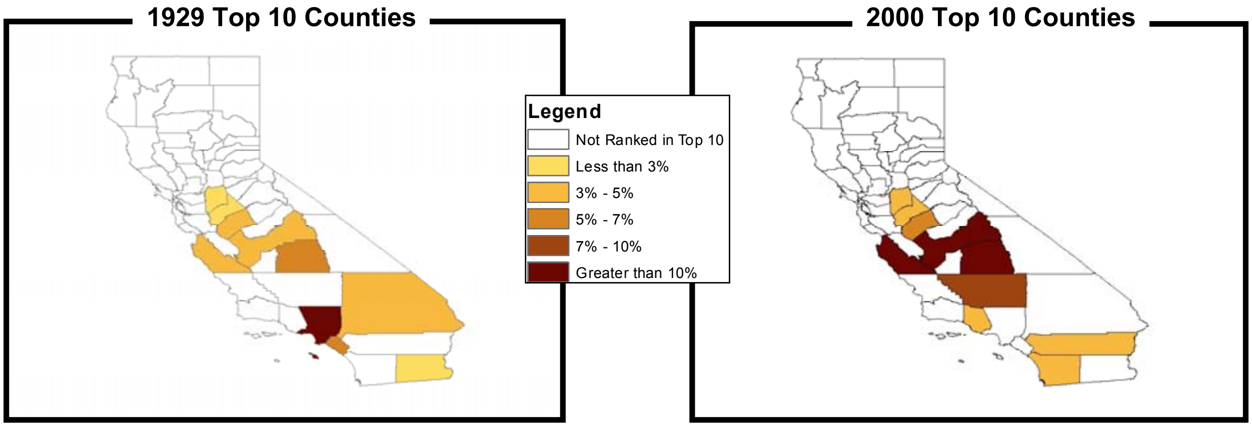

Figure 8.1. The intensity of almond acreage in California has shifted in our short history, highlighting the ongoing shifts in agricultural production areas. Legend: counties marked with color represent the top 10 almond-producing counties in California. The color gradient represents the relative contribution of these counties to the total Californian almond production. Maps were produced by Kurt Richter of the Agricultural Issues Center at UC Davis.

Many commodities in California have experienced highs and lows during the last century. Disease and market changes are two important factors for these changes. Wheat production, for example, declined steadily through the twentieth century due to bunt and stem rust diseases, loss of foreign markets, and competition with irrigated crops, until the 1970s when new disease-resistant varieties were introduced (Scheuring 1983). For grapes, Prohibition in 1919 caused a nearly total demise of the wine grape industry, which had already experienced shifts in production due to outbreaks of the invertebrate pest, phylloxera, by that time. The industry has now obviously rebounded to the point of being one of the main drivers of agricultural land use change in California. For apricots, statewide production has decreased steadily in the past 40 years, especially since shifts (spurred by urbanization in the Santa Clara Valley) occurred as the result of less advantageous weather conditions in the San Joaquin Valley. However, competition with foreign markets also decreased the demand for dried fruit products. Potato production historically has moved extensively around the state, experiencing fluctuations in production due to tuber-borne diseases and changes in processed versus fresh consumption patterns. These examples show that California agriculture has the capability and agility to maintain agriculture productivity despite obstacles related to urbanization, pest, and market changes for individual crops. It may mean converting to dry land or minimal irrigation of oil seed and forage crops and/or development of salt-tolerant crops. Yet, the concern is that a changing climate may accelerate the rate at which producers must cope with specific management problems that arise—especially heat waves, water scarcity, and pests (Sections 2, 5, and 7). A sequence of unfavorable years may force these land users to switch from horticultural to lower-income field crops, or to sell land for urbanization or ranchettes with affiliated small-scale agricultural enterprises.

If the supply of a given commodity decreases as the result of climate change, and the price of that commodity increases, producers with the capacity to maintain production because of their microclimate or to technological ability may increase their profits (Sumner 2005). But, less-adaptable producers will suffer greater losses, especially for high-input crops with large costs of production. These producers will shift commodities.

8.4. Factors of Land Use Change

Land use changes are driven not only by environmental factors such as climate, topography, and soil characteristics, but also by synergetic combinations of the five fundamental land use drivers (Lambin et al. 2003). First, *resource scarcity*, which can lead to an increase in the pressure of production on resources, has profound implications for land use change. It has been suggested that climate change may have either a "fertilization" effect, leading to increased yields or a "land-area" effect on crop production that would reduce arable land area and, subsequently, production (Parry 1990). Water resources will likely be the primary environmental variable determining shifts in crop distribution (Field et al. 1999), since California's water reserves are largely allocated for cropland irrigation (see Section 5). Salinization of deeper aquifers, however, will continue to increase as a result of irrigation, causing lower crop productivity, and retirement of some agricultural lands, especially in the San Joaquin Valley (Schoups et al. 2005). The loss of prime agricultural land to urbanization may also move production areas to lower quality soils, and to areas without sufficient water supplies (Landis and Reilly 2004).

Second, *changing opportunities and constraints,* which are created by local and national markets and policies, can also affect new land uses. Agriculture in California has been historically "demand-driven," with shipping products to the rest of the U.S. and international markets bringing profits to California (i.e., \$6.5–\$7 billion over 1997 to 2001 (Johnston and McCalla 2004). Depending on the cost of production and supply, either consumers or producers could gain from climate change (Zilberman et al. 2004). Climate change-induced alterations in agricultural productivity in one region can affect productivity in another region (Dale 1997)—such as the recent loss of California garlic production to China (Stanford 2003)—possibly leading to collapses in one set of product markets that might trigger collapses or changes in those production systems (Lambin et al. 2001).

Third, *outside policy intervention,* motivated by improving or worsening agricultural conditions in different areas affected by climate change, could lead to protectionist policies seeking to improve domestic production (both in California, the United States, and abroad) and increase subsidies for irrigation or other inputs (Reilly 1999). Such policies can have the long-term effect of slowing economic growth, encouraging unsustainable practices, and/or increasing food insecurity. Nevertheless, incentives can potentially give rise to experimentation with new crops and products (Lambin et al. 2001).

Fourth, *loss of adaptive capacity* associated with increases in climate variability can greatly determine shifts in land use. Adaptation is defined by the IPCC as "adjustments in practices, processes or structures in response to actual or expected climatic stimuli or their effects, with an effort to reduce a system's vulnerability and to ease its adverse impacts" (IPCC 2001). Adaptive capacity refers to a system's increased options and capacity to reorganize after change or disturbance, which is conferred by resilience, and is enhanced by diversification within agricultural landscapes, as well technology and access to information that increase options for successful responses (Swift et al. 2004). In California, for example, vegetable growers tend to minimize risks by diversifying production (only 26% produce one sole commodity), while 70% of orchard producers produce only one commodity and are much more likely to rely on crop insurance as a risk-management tool (Lee and Blank 2004). Both finding ways to produce the same crop at a profit, and relocating employment outside of agriculture, may be considered adaptation (Reilly 1999).

Lastly*, changes in social organization and attitudes* towards climate change consequences might play a large role in determining land use shifts. Two examples are the Standard Williamson Act (SWA) and the newer Farmland Security Zone (FSZ), which compensate landowners for 10–20 year commitments to agricultural land use by property tax reductions (Sokolow and Bennett 2004). Another example is the USDA cost-sharing and reserve programs, which compensate farmers for practices that increase water and air quality, wildlife habitat, or grassland conservation. Another issue is that cultural values, and even just the belief that climate change is actually taking place, strongly motivate the social response to climate and land use change (Pretty and Smith 2004). Other social changes may also include a shift in demand for renewable energy sources, including bioenergy crops and other technologies compatible with agriculture (wind and solar). Stakeholders need to decide which risks should be retained and managed adaptively versus which risks should be shared through risk-sharing contracts. Social and economic impacts of climate change must be evaluated at larger scales than site-specific studies, i.e., landscape or regional scales, to provide useful information (Easterling and Apps 2005; Reilly 1999).

8.5 Mitigation and Adaptation to Climate Change Effects on Land Use Change

Agricultural land in California has gradually shifted to urban or other non-agricultural uses, driven by population growth and non-agricultural force. From 1990–2000, approximately 500,000 acres (202,350 hectares) were converted from agricultural to non-agricultural uses (Kuminoff et al. 2001). A recent analysis predicts that although there will be a 10% net loss of farmland and irrigation water resources by 2030, this loss will be offset by yield growth attributable to climate change, crops with high value per acre, and growth in production per acre due to technological improvement (Brunke et al. 2004). This analysis relied on the predictions of crop production with simple quadratic models that were described in Section 5 (Adams et al. 2003b), and assumed yields of California crops to increase by approximately 15%. As was discussed previously, however, effects of climate change on crop yields may be more complex. For example, if higher temperature plus higher CO_2 has a detrimental effect on allocation patterns, developmental timing, or fruit maturation, or if pest problems increase, yields may decrease. Essentially, this view builds on the high degree of past success that California has had in developing production strategies and markets for a diverse array of different types of commodities, as exemplified in Figure 8.2 by the changing geographic distribution of the top 10 counties in terms of agricultural production since 1929. The demand for California vegetables, fruit, and nuts is expected to grow, and cotton, alfalfa, and irrigated pasture acreage in the state is likely to shift to these crops. As long as relative prices and policy adjustments favor these shifts, and technological advances increase, a gradual increase is predicted in the value of food production in California, and net food exports to the rest of the world is expected to expand, rather than contract.

Alternatively, such successful adaptation of California agriculture to climate change might require a more cautious approach. There may be surprises in terms of weather events, for example, short-term heat waves (Meehl and Tebaldi 2004), floods, or pest outbreaks. Recent modeling has shown that California will experience longer heat waves, and more summer heat waves based on fine-scale, regional processes (Diffenbaugh et al. 2005). In fact, extreme events may dictate outcomes from climate change more definitively than the expectation that gradual increases in mean temperatures and CO_2 fertilization effects will reliably boost crop productivity.

Adaptive capacity and resilience may be enhanced by taking a cautious strategy that acknowledges the need for land use changes that will assure productivity during gradual changes in climate, but also when extreme weather events, or unexpected surprises, occur. Based on the ecological literature, diversification is a key element to resilience in response to change or disturbance. Biodiversity, for example, can provide "insurance" or a buffer against environmental fluctuations (Loreau et al. 2001). Since different species respond differently to change, more species can lead to more predictable aggregate community or ecosystem properties. Although certain species may appear to be functionally redundant for an ecosystem process at a given time, they may no longer be redundant through time. Based on this analogy, and the recognition that diversity in crops and farming systems lend economic and ecological resilience at the landscape level (Swift et al. 2004), it seems reasonable to adopt a diversification strategy as one element in the necessary technological advances for agriculture to cope with climate change in California. But while crop diversification can act to reduce farm business risks, there are start-up costs and problems for achieving economies of scale.

Other risk-reducing strategies, such as crop insurance or the securing of off-farm income, may be readily available and preferred by producers (Bradshaw et al. 2004).

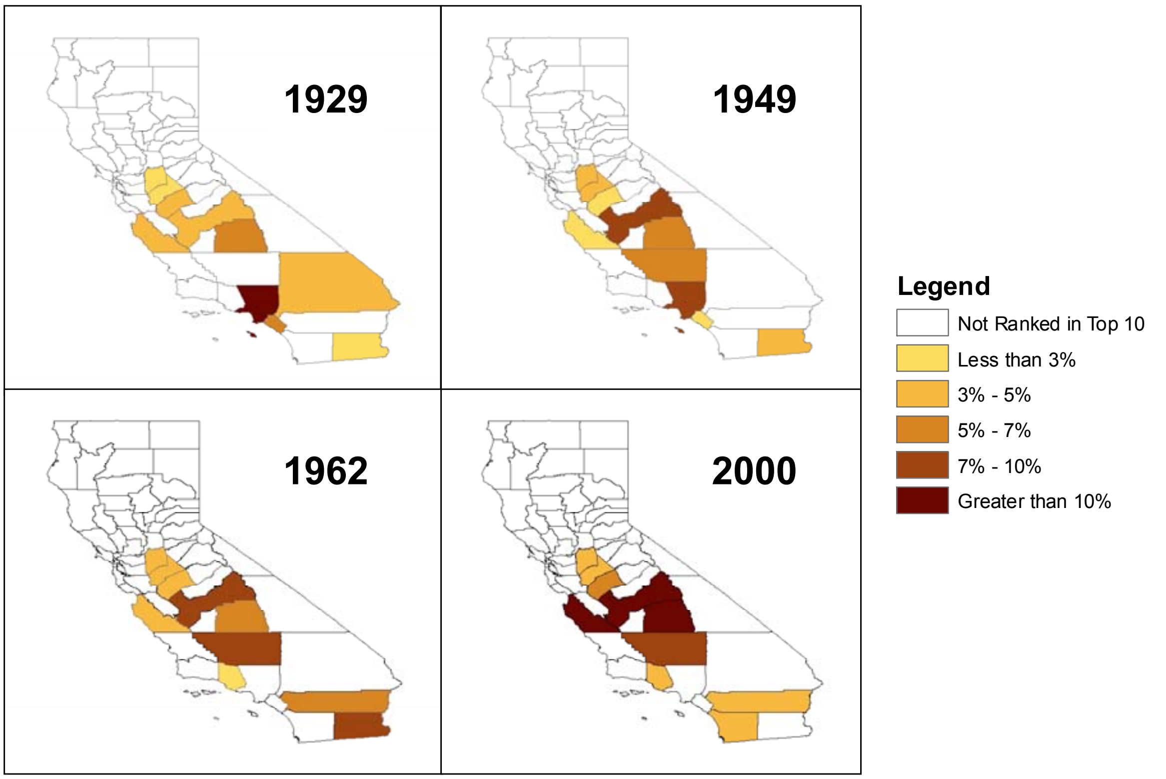

Figure 8.2. Shifts across California of the top 10 producing agricultural counties in the last century. Legend: counties marked with color represent the 10 most productive agricultural counties in California. The color gradient represents the relative contribution of these counties to the total agricultural production in California. Maps were produced by Kurt Richter of the Agricultural Issues Center at UC Davis.

Another issue is the loss of wetlands, riparian corridors, and the fragmentation of farmland that is predicted to occur in California's agricultural landscapes during the next century due to urbanization, and to water projects that must build levees and storage reservoirs to cope with higher stream flows (Section 5). Not only do impacts on species protected by the Endangered Species Act need to be considered in planning land use strategies, but impacts on other ecosystem services provided by these habitats (for example, water filtration, soil retention, or erosion regulation) need to be considered as well. Thus, it will be necessary to address whether adaptations to climate change by growers and institutions, will be at the expense of sustainable land use practices and extant natural ecosystems (Polsky and Easterling 2001).

8.5. Data Gaps

Sustainable land use is identified by most stakeholders as a priority for California, i.e., that tradeoffs between agricultural productivity, environmental quality, and human livelihoods and well-being be assessed for the greatest long-term benefits to society as a whole. A major risk is that sustainability may be lost when climate change and urbanization increase the pressure for short-term financial gain from current agricultural lands, especially given a range of potential scenarios for climate change range between positive to problematic. For this reason, alternate coping strategies must be assessed for their short- and long-term feasibility and sustainability. The immense breadth of commodities in California indicates that it will be necessary for industry groups and government to prioritize ways to deal with these changes. Insurance programs may also change if the insurance industry perceives a threat from climate change in the form of extreme events, such as Hurricane Katrina in New Orleans, 2005.

At present, practical implications for agriculture are lagging behind the science that is predicting climate change. As pointed out by the World Meteorological Organization (Garbrecht et al. 2005), neither farmers nor policy makers have good access to information for decision-making, beyond that offered by general climate projections. This is particularly important for repercussions of land use change that will result from the combined effects of urbanization and climate change. Although technological advances have great potential for adaptation (Brunke et al. 2004), they should be more clearly specified by joint efforts between agriculturalists and economists, so that land use changes are planned rather than reactionary to surprise events. The practicality of moving crops from one area to another area is not simple (Easterling et al. 1997; Hansen and Nazarenko 2004; Lambin et al. 2001). Shifts in land-use are not considered a market impact and therefore, are not included in most global models (Mendelsohn et al. 2000), but they potentially have large economic and environmental effects on people and the resource base in agricultural landscapes. For this reason, a cautiously optimistic approach would emphasize agricultural research and land use planning that would examine novel scenarios for agriculture to minimize risks, facilitate coping strategies for extreme events, and ensure long-term productivity, perhaps at the expense of short-term financial gains by agricultural producers or urban developers.

9.0 Synthesis, Emerging Trends, Future Directions and Conclusions

Timothy Cavagnaro, Louise Jackson, Kate Scow

9.1. Climate Change and California Agriculture: Interdependence and Cascade Effects

The potential impacts of climate change are varied, multifarious and occur across a range of temporal and spatial scales. California is a highly populated state, rapidly growing, with dwindling resources already subject to extensive competition. In the previous sections, although the discussions of climate change impacts were organized into specific categories, it was already evident that many issues crossed over the different categories. This section synthesizes some of the issues identified above to demonstrate the interdependence and chain effects associated with different aspects of climate change, by developing several targeted examples of climate change impacts on California agricultural landscapes. There are and will be other such interactions, many of which are not yet apparent.

Water resources: Agriculture, urbanization, and agricultural employment

Users of agricultural water in the Central Valley are among those most vulnerable to climate change and could be devastated by severely dry forms of climate warming (Sections 5 and 2). The allocation of water resources across the state is in part based upon estimates of crop water use efficiency from a limited number of crop species (Sections 5 and 6). Urbanization of the Central Valley (Section 8) will place increasing pressure on water resources and reduce their availability to agriculture. Farmers are more likely to be impacted than urban and industrial users, who can pay more for water. Farmers may benefit, however, if climate change results in an increase in water availability at critical times (Section 5). At present, agriculture represents approximately 7.4% of total Californian employment; however, in the Central Valley it accounts for 25% (Section 2). Farming is already a precarious occupation for some and challenging resource limitations may be all it takes for some to give into urbanization pressures and sell to developers. The confluence of changing availability of water resources, increasing urbanization, and the high dependence upon agriculture as a source of employment, may lead to disproportionately large effects of climate change upon the Central Valley of California (Sections 2 and 5).

CO_2 fertilization, plant nutrition and physiology, pest and pathogen dynamics

Increased growth in response to CO_2 fertilization is well documented for many plant species (Sections 4 and 6). Increased photoassimilation of C can lead to decreased concentrations of leaf N, soluble protein, and of the carboxylating enzyme, Rubisco; and nitrate reduction may be inhibited at high CO_2 concentrations, such that growth is reduced. A reduction in protein and nutrient content of plant tissue may decrease the nutritive value of food for all consumers, including herbivorous pest invertebrate species (Section 7). While warming accelerates the lifecycles of many invertebrates, and thus negative impacts associated with invertebrate pests, herbivorous invertebrates may actually grow more slowly because their food source is nutrient- and protein-poor. In response, these pests may increase their feeding rates to satisfy their nutritional requirements. Furthermore, decreased plant nutritional status actually decreases resistance of some plants to pathogenic organisms. These examples highlight the importance of exploring multiple effects of elevated atmospheric CO_2 concentrations on crop growth and pest communities.

Temporal synchrony: Plant growth and pest dynamics

Temperature influences key developmental stages of many important tree crops (Section 6), for which California is the country's sole producer (Section 2). Decreased chilling can result in late or straggled bloom, decreased fruit set and poor fruit quality (Section 6). Heat waves may also cause early bolting, or reduce pollination success. Climate warming may lead to faster developmental rates, decreased generation times, and range expansion of some pest invertebrate species (Section 7). Thus, climate change may have implications (positive and negative) for integrated pest management, other control measures of such pests, and their natural enemies. In a warmer climate, whereas development of some tree crop species may be slowed, that of their pests may be increased, making these crops highly vulnerable to pest damage. Rapid rates of adaptation to climate change by invertebrates may exceed the slow rate of development of resistant germplasm available to growers, thus further exacerbating this situation.

Soil organic matter decomposition and nutrient supply

Soil organic matter (e.g., from crop residues, cover crops, or manures) is an important source of nutrients, especially in organically managed agroecosystems. Under a warming climate the rate of soil organic matter decomposition is predicted to increase (Section 3). This may lead to enhanced nutrient availability to plants, provided nutrient release and plant demand are temporally synchronous, but may also reduce the efficacy of soil C sequestration (Section 3). Soil moisture is another key driver of soil organic matter decomposition (Sections 2 and 5), whose availability with climate change remains hard to predict. If carbon trading markets develop in California, tradeoffs between enhanced nutrient supply and decreased carbon sequestration may become significant, especially given the high energy requirements for producing inorganic fertilizers.

Climate change impacts on beneficial species

Beneficial organisms and their processes (e.g., N fixation by symbiotic and free-living rhizobia) are stimulated by elevated CO_2. Conversely, ozone exposure reduces plant growth and crop yields, hinders nitrogen-fixation, compromises disease resistance, and increases susceptibility to invertebrate damage. Although ozone is phytotoxic, elevated atmospheric concentrations of CO_2 can ameliorate damage caused by O_3 in some circumstances. The interacting effect of different climate factors on multitrophic interactions are uncertain, making species-specific predictions based on single-factor analyses tenuous at best. Ecosystem-context, especially on-farm or *in situ* studies, and experiments in changing climate scenarios are required.

While by no means exhaustive, the examples developed above are intended to act as stimuli for future research to identify linkages both within and beyond agriculture to understand climate change impacts and plan adaptive strategies.

9.2. Adapting to Climate Change

The vulnerability of California agriculture to climate change is a function of many factors, including exposure to climate change itself, sensitivity to such changes, and the ability to respond and mitigate changes without losing future options. Based on this review, a cautious approach is warranted in developing coping strategies that achieve reliable productivity and sustainability of California agriculture. Adaptive capacity indicates greater potential options for successful reorganization following change; some of these options are outlined in the following section.

1. Increased pressure upon the state's water resources will require greater adoption of existing technologies, and the development of new technologies, that enhance the efficiency of irrigation and water use. This may result in intervention in the form of incentives, such as green credits, or may be market-driven by rising costs of water. There may also be the need to build a diverse portfolio of water resource supply options to maintain supply at the state level.
2. Increased temperatures will pose substantial challenges to plant breeders and farmers familiar with a different climate regime. The impacts of increased temperature, especially warmer winter temperatures, on crop development and their vulnerability to pest and pathogen damage, pose a particular challenge for long-lived tree crops and other perennials. Tolerance of annual crops to extended periods of high maximum temperatures is also a priority. Given the long time frame (decadal) required to develop new germplasm of physiological tolerant or pest-resistant crops, breeding efforts to respond to climate change need to be undertaken now. Development of different management strategies for, and possibly diversification within, this sector may be required.
3. The complexity of agricultural systems dictates the need for more comprehensive and complete models that better represent the diversity of commodities produced in the various regions of California. Furthermore, shifts in the policy (e.g., agricultural subsidies, trade, global carbon trading markets) in other regions will have enormous implications for California agriculture, both in terms of markets, trade, prices, and competition. A better basic understanding and modeling of biophysical processes, coupled with economic modeling, resource allocation modeling, and inclusion of the social sciences, are required. Development of incentives and policies that foster such activities may be necessary.
4. Technological advances are needed that not only increase production under gradually increasing temperature and CO_2 fertilization, but increase resilience during extreme weather events. These will be unique for different crops, involving a variety of management, rotation, mulching, pollination, or other options not yet in place. Efforts must be made now to assess the types and extent of climate change

impacts that may potentially occur, rather than assume that California can cope successfully in the same reaction-based manner as in the past.

5. Encouraging diversification of agricultural production may enhance the adaptive capacity of individual farmers, commodity groups, agricultural regions and California agriculture as a whole. This requires information relating to the management of such diverse farming systems, as well as an appropriate marketing, trade and economic analysis to be undertaken and made available to producers. Particularly relevant to the mitigation of GHGs, and reduction in California's reliance on petroleum, is the emerging role of agriculture as a source of renewable energy. Bioenergy crops—managed vegetative systems that provide habitat, water management (supply and quality), and biomass for energy—are examples of emerging cropping systems that could play an important role in California's strategy in responding to climate change.
6. Impacts of climate change upon the frequency and magnitude of extreme weather events, such as drought, flooding and winds, are of critical importance to agriculture (and other sectors). Where climate change occurs over a decadal time scale, catastrophic events occur over much shorter periods of time. Consequently, there may be a need to enhance the capacity of the existing economic (e.g., insurance, emergency relief) and social framework to deal with such eventualities, especially if their frequency and/or magnitude increases.
7. Climate change does not occur in isolation. With greater rates of urbanization, the interface between urban and agricultural lands will increase. Similarly, maintaining areas of natural vegetation such as wetlands and riparian corridors may be more difficult, yet even more essential than at present. Adaptation by agriculture needs to be approached in this larger context. For example addressing issues of non-point source pollution, water quality and the judicious use of agrichemicals, as well as sharing of resources (e.g., water). This will require an integrated approach that considers the costs and benefits to all stakeholders.

With time, predictions of the future climate of California will change. The same is true of our ability and capacity to adapt. Be that as it may, there is an urgent need to address many of the data gaps identified throughout this report coupled with adaptive management, iterative decision making, and risk analysis.

9.3. Concluding Remarks

Impacts of climate change, irrespective of scale, land use and sector, will be wide ranging and varied. Climate change will affect California (and California agriculture) differently than it will other parts of the United States. National policies may not always be entirely appropriate, easily implemented, or in the best interests of the state. Consequently, impacts and our response(s) must be assessed in the context of climate change impacts and responses both within the United States and globally. Furthermore, climate change and its impacts need to be taken in the context of a world that is rapidly changing in many ways. Population growth, urbanization, and shifting patterns of agricultural production, decreased water resource supply and increased competition for those resources are areas of high priority. Recognition of the fact that actions taken now and in the near future will play a critical role in mitigating and minimizing impacts, as well as maintaining flexibility and adaptive capacity, is essential.

California agriculture faces serious challenges in the coming century and beyond. Be that as it may, it has shown considerable adaptive capacity in the past, and with the right information and a suitable policy environment and infrastructure, it can continue to do so into the future. California agriculture's potential as a net mitigator of climate change is substantial, and as such is an avenue worthy of detailed investigation. Impacts of action and inaction in limiting and/or responding to climate change will be felt well into the future. The climate is changing. California agriculture stands to be affected substantially. The time to act—with well informed, flexible, and sustainable approaches—is now.

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