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Agricultural mitigation and adaptation to climate change in Yolo County, CA

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ADAPTATION STRATEGIES FOR AGRICULTURAL SUSTAINABILITY IN YOLO COUNTY, CALIFORNIA

A White Paper from the California Energy Commission's California Climate Change Center

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DISCLAIMER

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ABSTRACT

This place-based case study in an agricultural county in California's Central Valley focused on the period of 2010–2050, and dealt with biophysical and socioeconomic issues related to both mitigation of greenhouse gas (GHG) emissions and to adaptation to an uncertain climate. In the past 100 years, changes in crop acreage has been more related to crop price and availability of irrigation water than to growing degree days during summer, and in fact, summer temperatures have increased less than winter temperatures. Econometric analysis indicated that warmer winters, as projected by Geophysical Fluid Dynamics Laboratory-Bias Corrected Constructed Analog during 2035–2050, could result in less wheat acreage, more alfalfa and tomato acreage, and slight effects on tree and vine crops. The Water Evaluation and Planning (WEAP) model showed that these econometric projections did not reduce irrigation demand under either the B1 or A2 scenarios, but a diverse, water-efficient cropping pattern combined with improved irrigation technology reduced demand to 12 percent below the historic mean. Collaboration during development of Yolo County's Climate Action Plan showed that nitrous oxide (mainly from nitrogen fertilizers) was the main source (≅40 percent) of agricultural emissions. Emissions from cropland and rangeland were several orders of magnitude lower than urbanized land per unit area. A survey distributed to 570 farmers and ranchers achieved a 34 percent response rate. Farmers concerned about climate change were more likely to implement water conservation practices, and adopt voluntary GHG mitigation practices. Use of the urban growth model (UPlan) showed that channeling much or all future urban development into existing urban areas will increase ecosystem services by preserving agricultural land and open space, immensely reducing the Yolo County's GHG emissions, and greatly enhancing agricultural sustainability.

Keywords: crop acreage shift, farmer survey, urban growth model (UPlan), Water Evaluation and Planning (WEAP), water conservation

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Executive Summary

This paper examines biophysical and socioeconomic issues related to mitigation of greenhouse gas (GHG) emissions and adaptation to climate change for agriculture in Yolo County, California. Few such place-based studies exist. Instead, most scientific research on agriculture and climate change focuses on management practices to reduce GHG emissions, or on crop vulnerability due to changes in seasonal weather, water supply, pests and diseases, and biophysical factors affecting production. These are only a few of the aspects necessary for climate change planning in agricultural regions. To begin addressing these gaps, this paper provides a science-based exploration of tools for scientists, farmers, policymakers, and the general public to better understand the adaptation and mitigation options for increasing agricultural sustainability in rural landscapes and in particular, in Yolo County. Such tools are particularly important in counties where cropland and grazing land make up the vast majority of total land, as in Yolo they account for 57 percent and 24 percent, respectively. In addition to assembling information and tools necessary for a place-based approach, this paper will serve as a bridge between various stakeholders in order to facilitate discussion and evaluation of long-term planning options in Yolo County. This paper also seeks to generate strategies and planning information applicable to other California counties.

Paper Structure

This paper consists of five studies conducted by an interdisciplinary group of researchers utilizing a series of models, surveys, and stakeholder engagement techniques to understand potential vulnerabilities to climate change and options for adaptive management. They include the following:

- **Study 1**: Econometric analysis of crop choices under future climate change projections
- **Study 2:** Use of a water planning model to assess how future climatic and economic projections will affect the local water supply
- **Study 3:** Assessment of countywide agricultural GHG emissions and engagement in the development of Yolo County's Climate Action Plan
- **Study 4:** Survey of farmers' ideas and attitudes on climate change, and on adoption of climate change mitigation and adaptation strategies
- **Study 5**: Exploration of the impact that future urbanization scenarios might have on county farmland using an urban growth model

Emissions Scenarios

To better understand the potential range of impacts from climate change, this paper utilizes two primary future climate scenarios in its modeling, as developed by the Intergovernmental Panel on Climate Change (IPCC): "A2" characterized by higher population growth, increased land conversion for urbanization as well as economic growth and increased greenhouse gas (GHG) emissions in keeping with the current trajectory; and "B1" characterized by less-intense population growth and limited urban expansion, as well as a reduction in resource intensity, growth in clean technologies, and lower GHG emissions.

Through stakeholder consultation and analysis of local planning documents, these global IPCC storylines were "downscaled" to more clearly represent future scenarios within the region. In the final study, an even greener AB32+ scenario is added, referring to a future characterized by highly compact growth, little population growth, and economic development built around by value-added production, particularly in the agricultural sector.

Findings

Study 1: Using an econometric model, this study examined past crop-climate realtionships to estimate the general magnitude of potential crop responses caused by future climate change.

- Model output shows that changes in acreage of each crop has depended little on growing degree days during summer, partially because summer temperatures have increased much less than winter temperatures over the past century.
- Econometric analysis indicates that warmer winters will decrease wheat acreage and increase alfalfa and tomato acreage, with slight effects on tree and vine crops. Crop price and availability of irrigation water are often more important for crop acreage projections than temperature.

Study 2: This study used the Water Evaluation and Planning (WEAP) system to model the effects of climate change and adaptive management on water resources within the Cache Creek watershed. Using two downscaled climate projections (B1 and A2), three adaptation scenarios were examined. These scenarios included: (1) a shift in local cropping patterns based on dynamic econometric forecasts, (2) a shift towards more diversified and water efficient cropping patterns; and (3) a combination of irrigation technology improvements and a diversified cropping pattern.

- Under both B1 and A2 projections, a gradual increase in temperature and decrease in precipitation leads to significant water supply constraints by the end of the century.
- Irrigation demand increases by 27 percent and 32 percent under the B1 and A2 scenarios, respectively, while the shift in cropping pattern predicted by dynamic econometric forecasts using current trends in acreage does not reduce irrigation demand under either projection.

- A water-efficient, diversified cropping pattern produces modest reductions in irrigation demand, and when combined with improved irrigation technology, reduces demand below the historic mean.

Study 3: In this study, an inventory of agricultural GHG emissions in 1990 and 2008 is presented for Yolo County, using internationally accepted inventory methods modified to accommodate county level activity data.

- Total GHG emissions from land in agricultural production are found to have declined by 10.4 percent during this period due to a reduction in irrigated cropland, a shift towards crops which require less nitrogen, and a reduction in nitrogen rate for some crop categories.
- Growth in the population of livestock and the acreage of rice increases methane emissions by approximately 20 percent.
- Estimates for GHG emissions per hectare of urban land in Yolo County are >70 times greater than for irrigated cropland, which highlights the importance of farmland preservation and smart growth as a strategies to mitigate emissions in California.

Study 4: This study analyzed the results of a survey mailed to 572 farmers in Yolo County.

- A slight majority of farmers agree that the global climate is changing. Far fewer agree that temperatures are increasing and that human activities are an important cause.
- Many farmers believe that climate change poses risks to agriculture globally, but many also believe that climate change presents opportunities for agriculture globally.
- Farmers are most concerned about future climate impacts related to policies and markets, followed by moderate concern about water supply.
- Those in less frequent contact with local agricultural organizations or conservation programs are less likely to implement voluntary mitigation practices and participate in future government programs supporting adaptation and mitigation.

Study 5: This study used UPlan, an urbanization modeling program, to develop scenarios for future urban growth corresponding to the IPCC's A2 and B1 storylines, as well as an AB32+ storyline that assumes stronger state action to reduce GHG emissions.

- The three scenarios vary dramatically in their emissions related to new urbanization, with highest emissions associated with the largest conversion of agricultural land to urban uses, as seen in the A2 scenario.

- The AB32+ storyline produces the lowest GHG emissions from residential development of all three scenarios in light of its reliance on infill growth. AB32+ yields approximately 8 percent of the emissions in A2, or about 14 percent with population held constant.
- The B1 scenario also produces substantial GHG emissions savings, though less than AB32+, mainly through more compact growth. This scenario yields about 36 percent and 50 percent of emissions in A2 under the two different population levels.
- The focus of the B1 and AB32+ scenarios on preservation of rural agricultural land is consistent with increased interest and demand for local food processing, storage, and distribution infrastructure.

Section 1: Introduction

A place-based approach for studying agricultural responses to climate change explores a broad set of biophysical and socioeconomic issues related to both greenhouse gas (GHG) emissions and to adaptation to an uncertain climate. Few such studies exist. Instead, the scientific research on agriculture and climate change has focused on agricultural management practices to reduce the GHG emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (Delgado et al. 2011; Smith and Olesen 2010), or on the vulnerabilities of different crops to changes in seasonal weather, water supply, pests and diseases, and biophysical factors affecting agricultural production (Rosenzweig and Tubiello 2007; Lobell et al. 2008). These are only a few of the aspects necessary for planning for climate change in agricultural regions. As many jurisdictions in the Western United States are now addressing regional impacts of climate change, there is a need for science-based exploration tools for scientists, farmers, policymakers, and the general public to better understand the complexity of vulnerabilities and adaptation options for increasing agricultural sustainability (i.e., achieving agricultural productivity and profitability, environmental quality, and social well-being) in rural landscapes.

California's Climate Change Scenarios Project has focused on determining impacts from plausible climate change scenarios (Cayan et al. 2008a). Use of Global Circulation Models (GCM) for future climate projections have used two scenarios from the International Panel on Climate Change (IPCC) that are based on storylines for high and low GHG emissions (A2 and B1 scenarios, respectively) (Cayan et al. 2008b). For agriculture in California, climate change will have impacts on water availability, crop physiology, production (Cavagnaro et al. 2006), and pest and disease problems (Gutierrez et al. 2008), especially for the A2 scenario by the end of this century.

Addressing agricultural vulnerabilities and adaptive capacity is part of California's new statewide climate adaptation strategy. A place-based vulnerability approach deals with climate change as one of many other long-range issues such as changes in commodity production, stewardship of natural resources, land use, population growth, and urbanization in a regional system. The capacity of a rural population to adapt with climate change and other uncertainties depends largely on its collective ability to assemble and process information and respond in site-specific and context-relevant ways (Adger 2003). Adaptive strategies will require input from many disciplines, including agronomy, ecology, economics, land use planning, and political science. And the involvement of multiple types of stakeholders must inform the assessment and planning process, so that adaptive management can proceed in response to a knowledge base that is continuously developing (Pretty and Smith 2004).

The strong science-policy interface for climate change in California has generated a great deal of agricultural interest in the implementation of the law to reduce statewide GHG emissions, California Assembly Bill 32 (AB 32), known as the Global Warming Solutions Act of 2006.[1]

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[1] Assembly Bill 32 (Nuñez), Chapter 488, Statutes of 2006.

Under AB 32, the state's GHG emissions are to be reduced to 1990 levels by 2020 through mandatory reporting, emission limits, and reduction measures, as implemented by the California Air Resource Board. It also establishes a goal of 80 percent reduction by 2050 and proposes a cap-and-trade policy for GHG emissions. Agricultural GHG emissions will not be included in the cap, but there may be potential for trading carbon offsets from agricultural practices. Senate Bill 375 (SB 375) connects land use planning (and obviously agricultural land use change) with implementation of AB 32. It requires a Climate Action Plan for mitigation of GHG emissions in the unincorporated areas of each county in California. This process is engaging farmers and other agricultural stakeholders in detailed accounting of GHG emissions from production and processing practices, and thereby beginning to create greater awareness of vulnerabilities and adaptation options as well.

In Yolo County, an agricultural county in California's Central Valley, an interdisciplinary group of researchers has worked with a diverse group of stakeholders to understand potential vulnerabilities to climate change and options for adaptive management. The first phase of the project used literature review of management and GHG emissions for various crops, historical records of resource use, and geographic information system (GIS)-based queries of land use to set the stage for analysis of different scenarios (Jackson et al. 2011). The current phase takes a more quantitative approach to understanding adaptation options, and several of the projects utilize GCM data for future climate projections (Tyree and Cayan, unpublished data). The projects include:

- Econometric analysis of crop choices under future climate change projections (Section 2);
- Use of the Water Evaluation and Planning (WEAP) model (Yates et al. 2005a; Yates et al. 2005b) to assess how future climatic and economic projections will impact the local water supply and to test the efficacy of various mitigation and water conservation strategies (Section 3);
- Assessment of countywide agricultural GHG emissions and engagement in the development of Yolo County's Climate Action Plan (Section 4);
- Survey of farmers' ideas and attitudes on climate change, and on adoption of climate change mitigation and adaptation strategies (Section 5); and,
- Exploration of how future urbanization scenarios might impact the county's farmland with the urban growth (UPlan) model (Section 6).

In addition to assembling the information and tools necessary for a place-based approach, this project has served as a bridge between various stakeholders to discuss and evaluate long-term planning options for agriculture in Yolo County. Uncertainty is an inherent part of climate change planning. Our intention is to create planning information that can be used for other California counties, through this document and a website.

1.1 Yolo County: Background on Agriculture as Relevant to Climate Change

Yolo County is in the Sacramento Valley of Northern California. It extends westward from the Sacramento River to the Coast Range Mountains (Figure 1.1). The alluvial plains support a diverse set of irrigated perennial and row crops. The most important crops are tomatoes, alfalfa hay, wine grapes, and almonds. Upland summer-dry grasslands and savannas are grazed by cattle. The few small towns and cities have experienced a changing mixture of urban, suburban, and farming-based livelihoods through the past few decades.

In Yolo County, there are approximately 500 farms with an average size of about 500 acres (Yolo County Agricultural Commissioner's Office; USDA 2009; Richter 2009). Many farms (>25 percent) produce sales ≥$100,000 per year. Yolo County is ranked 23 by value of sales of California's 58 counties (USDA 2007). Roughly 2 percent of the county's production is consumed within the Sacramento region (SACOG 2010).

The 653,452 acres (264,443 hectares) of Yolo County are largely agricultural (538,043 acres or 217,738 hectares) (FMMP 2008). Important farmland (defined as several categories of cultivated land for grains, row crops, orchards, and vineyards) is 57 percent, and livestock grazing land is 24 percent, while urban and built-up land is only 4.6 percent of the county's acreage (FMMP 2008).

During the past few decades, there has been a trajectory toward less crop diversification of county acreage, larger farm sizes, but fairly stable markets for commodities (Jackson et al. 2009; Jackson et al. 2011). Most commodities are managed with high intensification of agricultural inputs (e.g., fossil fuels, fertilizers, and pesticides). The number of organic farms, however, is growing. A recent survey showed that many riparian corridors have low scores for soil quality and riparian health (Young-Mathews et al. 2010), and there is concern about transport of pesticides to the San Francisco Bay delta (Moore et al. 2008). Environmental quality is now receiving more attention, with active participation in programs from several agencies.

Preservation of agricultural land has been a strong priority in Yolo County, and planning is focused on regional land use guidelines that maintain land in agricultural production and concentrate new development into urban areas (Richter 2009). Regions within Yolo County are distinguished by their land forms (plains, hills, or mountains), proximity to the Sacramento River and Delta (and its cooler microclimate), water availability (surface water, groundwater, and the feasibility of irrigation deliveries), and the influence of small towns and cities. The regions differ in crop commodities. There is greater prevalence of wine grapes along the river, processing tomatoes in the alluvial plains, and organic fruits and vegetables in an isolated, narrow valley to the north. The regions also have different trends and targets for urban growth, rural housing, and wildlife habitat creation. Flooding along the Sacramento River poses the most significant regional hazard from climate change; water flows will increase by at least 25 percent by 2050 due to a decrease in snowpack in the Sierra Nevada (Cayan et al. 2008b).

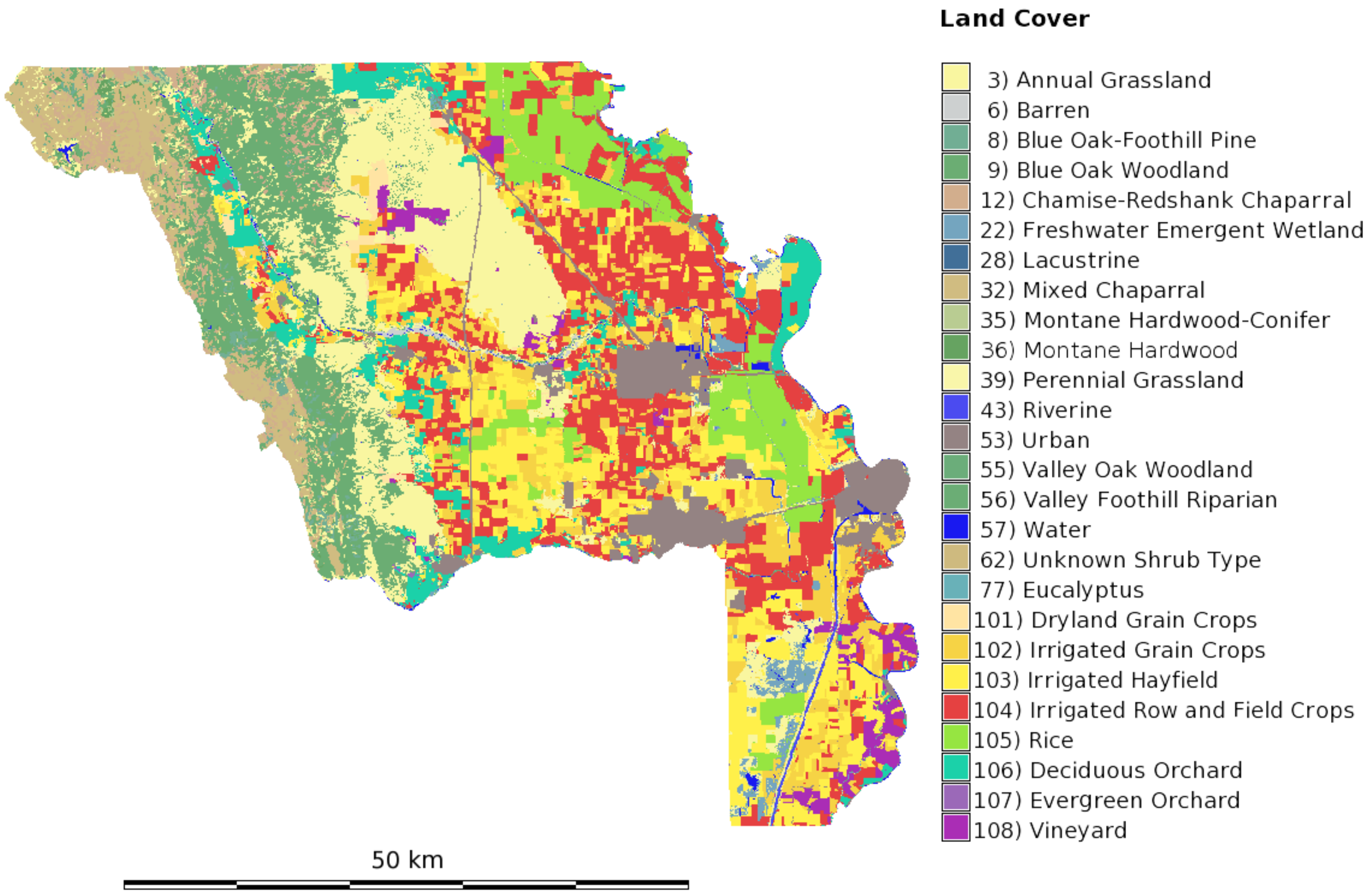
1.2 Previous Work on Climate Change Impacts on Yolo County Agriculture

Climate simulations by Global Climate Models (GCM) show that mean annual temperature will rise by 1°C to 3°C (1.8°F to 5.4°F) by 2050, the time frame of this case study (Cayan et al. 2008b). Heat wave days (i.e., thresholds that exceed the approximate mean maximum summer temperature) will increase two- to three-fold by 2050. Precipitation is likely to decrease toward the end of the century, depending on the assumptions of each GCM. Hydrological changes suggest, however, that drought is already increasing and will become more severe and variable with time (Barnett et al. 2008; Cayan et al. 2010). Water supply has been considered the most uncertain aspect of climate change for farmers in Yolo County, who rely on groundwater for approximately 30 percent of their supply in a normal water year (WRA 2005). It should be emphasized that GCM models are not "predictions," but rather, are plausible scenarios of climate sequences over a long-term period.

The previous phase of this case study examined possible impacts of increased temperature and decreased precipitation on Yolo County crops (Jackson et al. 2011). Horticultural crops will likely experience more problems from heat than field crops, due to greater temperature sensitivity of their reproductive biology, water content, visual appearance, and flavor quality (Backlund et al. 2008; Bazzaz and Sombroek 1996). A warmer temperature regime is likely to shift more "hot-season" horticultural crops, such as melon and sweet potato, into Yolo County's horticultural "warm-season" crop mix (e.g., tomato, cucumber, sweet corn, and pepper). Warmer winter temperatures may allow "cool-season" crops such as lettuce and broccoli, whose short growth seasons could permit two crops per year, unlike winter grains at present. Expansion of citrus production (Reilly and Graham 2001), and of heat and drought-tolerant trees, such as olive (Gutierrez et al. 2008), are likely options especially because reduction in winter chill hours will reduce flowering in stone fruits, nuts, and grapes (Baldocchi and Wong 2008). During the past 25 years, crop diversity has decreased in Yolo County (Jackson et al. 2011). Diversity may increase if farmers find that resilience, especially to extreme events such as heat waves, is enhanced by a species mix that varies in stress tolerance (O'Farrell and Anderson 2010).

Forage production for livestock in upland grasslands and savannas may increase with warmer winter temperatures during the winter rainy season, but field experiments with elevated CO_2 (eCO_2) do not corroborate this expectation (Shaw et al. 2002). More nitrogen (N) limitation will likely occur under eCO_2 (Dukes et al. 2005; de Graaff et al. 2006). If N-fixing legumes become more abundant in response to warmer winter temperatures, however, the N supply will increase. Thus, it is unclear if livestock production on these rangelands will actually increase due to climate change, especially in dry years, which require lower stocking rates, earlier animal removal dates, and transport to irrigated, permanent pasture.

Figure 1.1. Map of Yolo County, California, Showing Land Use Types. The Sacramento River is the eastern boundary of the county. The Coast Range Mountains extend north-south along the western edge.



Source: DWR 1997

Pests and diseases are another major uncertainty: warmer temperatures can increase ranges and population sizes, and change the trophic interactions that currently provide biological control of invasive species (Gutierrez et al. 2008). At present, no comprehensive compilations from California Department of Food and Agriculture (CDFA) or the National Plant Diagnostic Network (NPND) exist to show new invasive species to target for a warmer climate (Richard M. Bostock, personal communication). Some literature suggests that it is more efficient to focus on the spread of already naturalized species rather than from new potential invasive species at the importation stage (Smith et al. 1999). Yet, the Yolo County Agricultural Commissioner, John Young (personal communication), notes that several recently arrived pests are becoming severe problems, such as the European grapevine moth in vineyards, spotted wing drosophila on cherries, and Japanese dodder on a wide range of cultivated and wildland plant species. Quarantines are especially difficult for Yolo County because so little of the crop production is consumed within its boundaries, and thus economic hardship occurs unexpectedly for all growers of a particular commodity.

Discussions with the Yolo County University of California (UC) Cooperative Extension farm advisors indicated special concern for stripe rust on wheat (especially under wetter conditions), insect pests on nuts, medfly, corn earworm on tomato, tomato spotted wilt virus, and earlier activity of perennial weeds such as bindweed (Jackson et al. 2011). Very recently, alfalfa stem nematode has become a serious pest in the Sacramento Valley, possibly because winter minimum temperatures have reached the lower limit of reproduction for the species (Long 2010). On the other hand, some pests may become less serious; high summer temperatures are likely to reduce the fecundity and survival of the olive fly in this area, which will cause olive yields to increase (Gutierrez et al. 2008).

Decisions on strategies for adapting to these types of climate change vulnerabilities are not only made by growers. Public institutions, researchers, and non-governmental organizations (NGOs) become involved in decision-making by gathering information, stimulating awareness, and generating collective action. At present, California's strong emphasis on reducing GHG emissions suggests that mitigation and adaptation should be dual components of climate change decision-making. Some authors have made the case that most categories of adaptation measures have positive impacts on mitigation of GHG emissions (Smith and Olesen 2010). This may be too optimistic. First, agricultural soils may emit more potent GHG (N_2O and CH_4) in a future CO_2-enriched atmosphere (van Groenigen et al. 2011). Second, detailed analysis of crop management may show tradeoffs between mitigation and adaptation goals. An analysis of benefits of different management options for mitigation and adaptation benefits in Yolo County showed that synergies are often complex (Jackson et al. 2009; 2011 and references therein; Table 1.1). Changes in crop diversity, irrigation methods, fertilizer management, and tillage practices often are more beneficial for either mitigation or adaptation. Rather than change a single practice, major changes in cropping systems will be needed to meet production and mitigation goals. For example, a conventional tomato system with furrow irrigation and knife injection of fertilizer emitted 3.4 times more N_2O and had lower yields than an integrated tomato system with drip irrigation, reduced tillage and fertigation on the same soil type (Kennedy 2011). But drip irrigation, unlike furrow irrigation, does not recharge groundwater, leaving farmers more vulnerable to long-term drought. More comprehensive analysis of these complex relationships is needed.

Table 1.1. Analysis of Agricultural Management Options in Yolo County, the Benefits for Mitigation of GHG Emissions vs. Benefits for Adaptation to Climate Change, and Tradeoffs between These Goals. For more detail and specific references, see Jackson et al. 2009 and 2011.

Agricultural Management Options	Benefits for Mitigation of Greenhouse Gas Emissions	Benefits for Agricultural Adaptation to Climate Change	Tradeoffs
Crop diversification	Certain crop rotations can promote the sequestration of soil carbon (C).	Diversity may offset some of the risks from weather variation due to climate change.	Implementation, equipment, and labor are costly. New markets are needed.
Plant tree and vine crops	Perennial woody crops increase C storage, but are not permanent.	Cultivars and species should be less vulnerable to long-term drought and reduced chill hours.	Low permanence of C stocks may pose problems for if a carbon market is established.
Selection of crop genotypes that benefit from eCO_2, WUE[1] and NUE[1]	Lower N and water inputs contribute to decrease N_2O emissions.	New genotypes may increase production under environmental stress.	Suites of beneficial traits need research for each crop, and crop breeding takes time.
Irrigation management	Drip irrigation can decrease N_2O emissions. Deficit irrigation may decrease N leaching and offsite emissions.	Under drought, shifting to drip or deficit irrigation and crops with higher value will increase returns.	Equipment and energy for pressurization are needed. Drip does not recharge groundwater even in wet years.
Fertilizer use	Lower N inputs will decrease N_2O emissions, N leaching, and offsite emissions.	Conventional crop production will be unaffected by a 25% decrease in N fertilizer at present.	N fertilization may help compensate for eCO_2 effects on crop physiology and lower protein.
Winter cover crops	Soil C sequestration may increase, and fertilizer N may decrease N_2O emissions.	Higher soil organic matter increases soil health, water infiltration, and other benefits.	Cool-season cash crops are not possible. Soil water recharge for summer crops is reduced.

Table 1.1 (continued)

Agricultural Management Options	**Benefits for Mitigation of Greenhouse Gas Emissions**	**Benefits for Agricultural Adaptation to Climate Change**	**Tradeoffs**
Tillage	Low-till or no-till show few GHG mitigation benefits here but decrease fossil fuel inputs.	Reduced fossil fuel use will become important if fuel prices rise.	Likely production problems are seed establishment and efficient movement of irrigation water.
Manure management	Methane digesters convert dairy manure-derived CH_4 to electricity.	Use of on-farm renewable energy reduces dependence on purchased inputs.	Yolo County has only one dairy, and manure cannot be managed for rangeland cattle.
Farmscaping	Perennial vegetation on marginal lands can increase C storage and reduce N_2O emissions.	Benefits from habitat and biodiversity may indirectly increase pest control.	Research is needed to show co-benefits and justify cost-share programs for implementation.
Organic production	Soil C sequestration can increase and N_2O emissions can decrease, depending on management.	Diversity may offset risks. Some pests may increase without pesticide. More crops per year are common.	New markets are needed to support expanded organic production.
Biomass utilization for energy and fuel production	Use of farm waste as feedstocks is a source of renewable energy which is currently dumped or inefficiently used.	Agricultural wastes rather than biofuel production may increase make farmers more energy independent.	Efficient use of clean renewable energy requires new technology and infrastructure to allow metering on the grid.

[1]WUE = Water Use Efficiency; NUE = Nitrogen Use Efficiency

Phase I of this project also considered agricultural adaptation strategies that addressed regional issues such as hydrology, growers' attitudes toward climate change, and urbanization vs. preservation of farmland (Jackson et al. 2011). These topics are explored in more quantitative ways here in Phase II.

1.3 Climate Change Scenarios for Agriculture in Yolo County

Global Climate Models (GCM) of the IPCC A2 (high GHG emission) and B1 (lower GHG emission) scenarios in 2050 are relatively similar in temperature regime (Cayan et al. 2008b). Yet the IPCC storylines that underpin these two scenarios vary immensely due to their assumptions about different socioeconomic responses to climate change (Nakicenovic and Swart 2000). In the first phase of this research, "downscaling" the global IPCC storylines to local situations was based on regional planning documents, input from various stakeholders, and discussion with the project's steering committee (Jackson et al. 2009). In the current phase, our sub-projects use the A2 and B1 scenarios in different ways. The econometric analysis and water resource modeling sub-projects use the projected temperature and precipitation of GCM models (Sections 2 and 3), whereas the urbanization model uses the downscaled narrative storylines (Section 6), which can be summarized as follows (Jackson et al. 2009 and 2011):

A2. "Regional Enterprise." Increased population growth and doubling of urban land occurs in this rapid growth and economic development. Agricultural production remains mainly as large-scale monocultures, with some reduction in the intensity of soil, fertilizer, and water management that reduce energy use and GHG emissions. Little advance planning for extreme events results in larger variation in production from year to year due to climate change-induced water shortages and flooding risk.

B1. "Global Sustainability." Lower population growth and more compact urban development preserve agricultural land. Growers diversify their crop mix for resilience, and reduce intensity of N-based fertilizer use and tillage. Organic-based practices emphasize renewable inputs and nutrient retention, and carbon (C) storage. Water stewardship is tuned to annual variation in precipitation, water-use efficiency, and groundwater recharge. Conservation practices create wetlands in flood-prone areas and vegetated corridors along waterways and farm margins.

These downscaled storylines are intended to expand the analysis of agricultural responses to climate change to include many sectors of society and a wide set of ecosystem services. A landscape approach is utilized in each of the subsequent sub-projects to examine the larger set of regional issues that affect the options for adaptive management, using these scenarios as guidelines for plausible outcomes.

1.4 References

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1.5 Glossary

AB 32	California Assembly Bill 32, California Global Warming Solutions Act of 2006
C	carbon
CDFA	California Department of Food and Agriculture
CH_4	methane
CO_2	carbon dioxide
eCO_2	elevated CO_2
FMMP	Farmland Mapping and Monitoring Program
GCM	Global Circulation Model
GHG	greenhouse gas
GIS	geographic information system
IPCC	Intergovernmental Panel on Climate Change
N	nitrogen
N_2O	nitrous oxide
NGO	non-governmental organization
NPND	National Plant Diagnostic Network
SACOG	Sacramento Area Council of Governments
SB 375	California Senate Bill 375

UC	University of California
USDA	U.S. Department of Agriculture
WEAP	Water Evaluation and Planning
WRA	Water Resources Association

Section 2: Climate-Induced Changes in Acreage of Crops, Including Projections to 2050

H. Lee and D. Sumner

2.1 Introduction

Analyzing changes in past crop acreages in relation to local climate history can provide a set of projections of potential climate-induced changes in cropping patterns based on how farmers have responded to past climate change. The analysis in this section uses data from 100 years of local climate history and 60 years of crop acreages in Yolo County, California, to establish statistical relationships between climate change and changes in the crop acreage pattern. Most of the land in Yolo County is devoted to field crops such as alfalfa, rice, and wheat. Vegetables, primarily processing tomatoes, orchard and vine crops, and seed crops are also important.

Econometric models can relate the evolution of acreages of each major crop to changes in relative prices and climate variables through time. This provides a way to investigate how farmers have responded to the central tendencies of weather, and to test if their responses have been strong enough to affect changes in acreages of either annual crops and perennial crops in Yolo County. Such models are not designed to fully account for all of the year-to-year fluctuation in acreage or to link acreage to the full complement of expected prices and other drivers. But they can be used to guide projections about future acreage patterns, utilizing climate projections from scenarios provided by Global Climate Models (GCM) (Cayan et al. 2009). Of particular interest to this project are the B1 (low GHG emissions) and A2 (high GHG emissions) scenarios from 2010 to 2050.

Past crop-climate relationships help us understand the general magnitude of potential crop responses caused by future climate change. Such historical relationships can inform planning, even though future crop patterns will also be heavily influenced by changes in market conditions and policies, including policies for resource management (such as water stewardship) and environmental quality.

2.2 Profile of Yolo Agriculture

In 2009, farmers in Yolo County sold $462 million worth of farm products on 330,000 acres of cultivated cropland (Table 2.1). About 80 percent of this revenue is divided almost evenly among orchard crops, field crops, and vegetables.[2] Animal-related products represent only about 5 percent of the revenue, and the rest (14 percent) is accounted for by organic, nursery, and seed crops. Field crops occupy two-thirds of farmland, and orchard crops and vegetables

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[2] Fruit and nut crops are also commonly referred to as *tree and vine crops* or *orchard and vine crops.* In this paper, we use these terms interchangeably. Occasionally, when it is clear from the context, orchard and vine crops are simply referred to as orchard crops.

together cover only 23 percent of cropland. We include irrigated pasture among the field crops, but exclude dry land pasture from the cropland. Dry land pasture (mainly on upland annual grassland and savanna) was >100,000 acres in 2009, but contributed only $1.0 million dollars of revenue (<$10 per acre). Organic acreage or revenue is reported as a single category and not separated by commodity. Therefore, organic production is included with the "other" category.

Field crops have a much larger share in the value of output in Yolo County than in California as a whole (Figure 2.1); 26 percent versus 10 percent, respectively. Animal-related products account for 5 percent versus 22 percent, respectively. While farming is one of the leading businesses in Yolo County, it represents only about 1.3 percent of California farm revenue, ranking about 23rd among the 58 counties in the State.

Table 2.1. Yolo County Agriculture in 2009: Cropland and Crop Value by Commodity Category and by Major Crop in Each Category

Commodity category	Acreage 1,000 acres	Share of total acres	Value $million	Share of total value
Fruit and nut crops	38	0.11	113	0.25
Grapes	13	0.04	56	0.12
Almonds	12	0.04	25	0.05
Walnuts	10	0.03	19	0.04
Field crops*	223	0.67	122	0.26
Rice	37	0.11	53	0.11
Alfalfa	49	0.15	30	0.07
Wheat	28	0.08	12	0.03
Vegetables	41	0.12	136	0.30
Tomatoes	38	0.11	128	0.28
Organic production	6	0.02	23	0.05
Nursery products	0.5	0.00	10	0.02
Seed crops	26	0.08	33	0.07
Animal products		0.00	25	0.05
TOTAL	335	1.00	461	1.00

* Includes irrigated pasture and other miscellaneous crops; does not include non-irrigated pasture.

Source: 2009 Yolo County Agricultural Crop Report

In each crop category, only a few crops account for a large share of crop revenue: 80 percent of field crop revenue comes from alfalfa, rice, and wheat; close to 90 percent of orchard crop revenue is from wine grapes, almonds, and walnuts; and 90 percent of vegetable revenue is from a single crop: processing tomatoes. In terms of economic importance, processing tomatoes are by far the largest revenue crop, followed by wine grapes and rice.

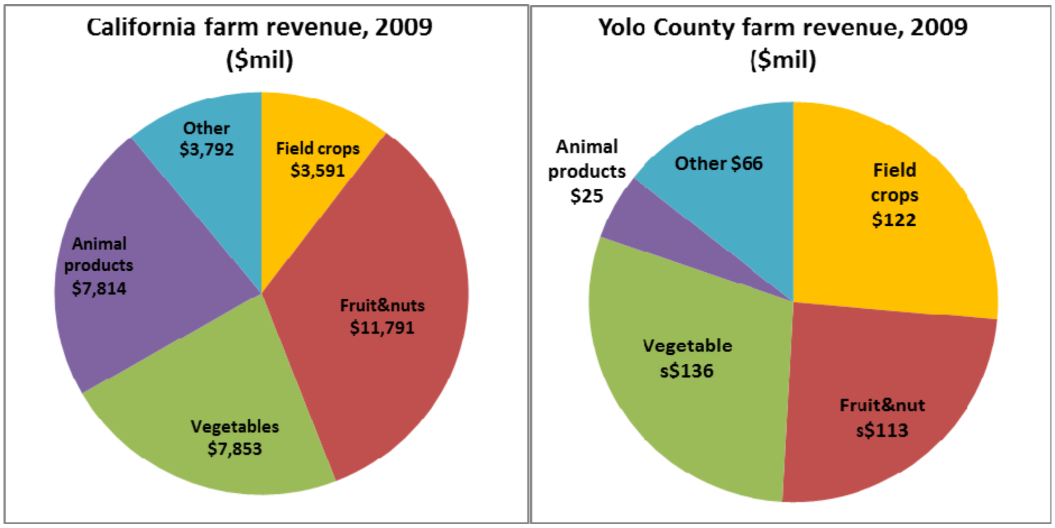

Figure 2.1. California Farm Revenue ($ million) and Yolo County Farm Revenue in 2009 by Commodity Category

Source: California Agricultural Resource Directory (2010-2011); 2009 Yolo County Agricultural Crop Report (2009)

Historical Perspective

A consistent time series on crop acreage, production, and revenue in Yolo County covers the period from 1950 through 2008 (Yolo County Agriculture Department, Agricultural Crop Report 1937–2009). Data are available as early as 1937, but were discontinued during the Second World War, and there were many missing values before 1950.

Since 1960, total crop acreage in Yolo County has been declining. Vegetable and orchard crop areas have increased, while field crop acreage has declined (Figure 2.2). There has been an increase in higher-revenue-per-acre crops, especially a shift out of barley, and an increase in processing tomatoes, wine grapes, and walnuts.

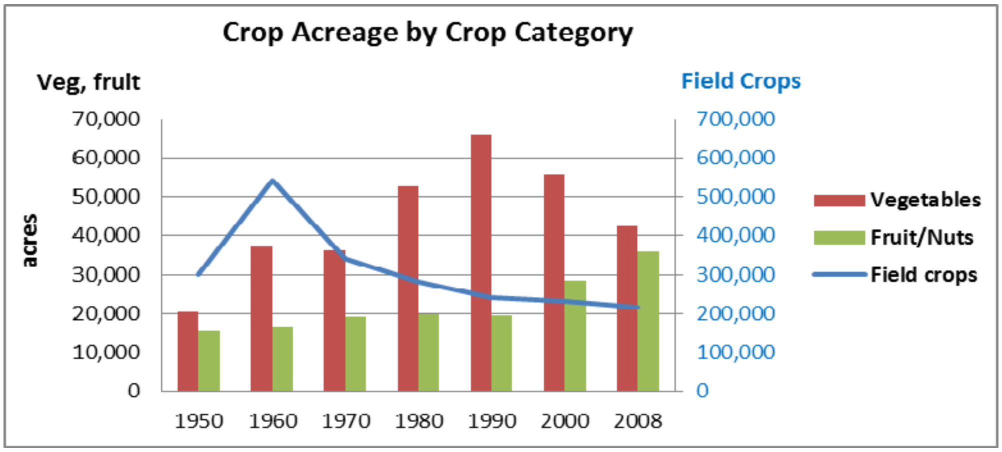

Figure 2.2. Historical Crop Acreage by Crop Category for Selected Years during 1950–2008

Source: Yolo County Agricultural Crop Report (1950–2008)

Field crop acreage in Yolo County rose from 300,000 acres in 1950 to >500,000 acres by the end of the1950s. Since then, it has continued to decline—first rapidly until the end of the 1960s and then slowly, reaching about 200,000 acres currently (Figure 2.2). Even a small change in field crop acreage dominates any other acreage changes in Yolo agriculture. The very high prices since 2008 may stimulate more field crop acreage.

The most important change in terms of acreage has been a massive shift out of barley (with that land reverting to pasture) in the 1960s (Figure 2.3). These shifts can be explained by changes in relative prices and farm structure. When barley prices stagnated, alfalfa increased. Dairy, which uses alfalfa rather than barley as feed, had expanded in California. The virtual disappearance of sugar beet acreage was due to lack of competitiveness with other regions in the United States and costs of production and processing that were far above import prices.

Almonds were the single most important orchard crop in Yolo County for more than half a century, but the rise of grape acreage (1990 to the present) put the almond crop in the second place in terms of acreage (Figure 3.4). Wine grape acreage increased from 1,700 acres in 1993 to >10,000 acres in 2001. Grapes have mainly replaced row crop acreage. For grapes, a main driver behind the rapid expansion in acreage is an increase in wine consumption in the United States. For the last several decades, walnuts have become the third most important orchard crop in Yolo County. Declines in crops such as apricots have been a statewide phenomenon, due to very high labor costs, reduction in demand for processed fruits, and availability of imports of dried fruit.[3]

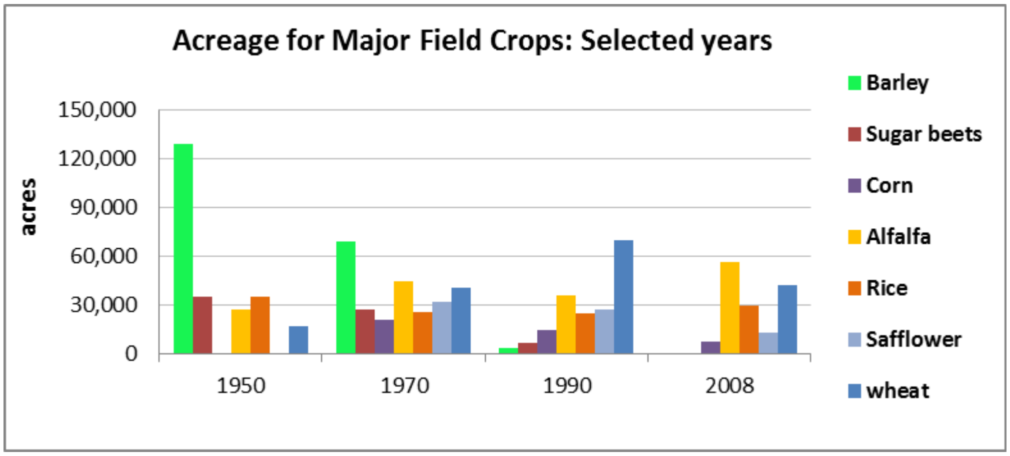

Figure 2.3. Crop Acreage by Major Field Crop for Selected Years, 1950–2008. Corn acreage in the early 1950s was not available.

Source: Yolo County Agricultural Crop Report (1950–2008)

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[3] The import share of domestic consumption of dried apricots was about 30 percent in 1975. However, since 1995, this share has been more than 90 percent (Source: Economic Research Service, USDA).

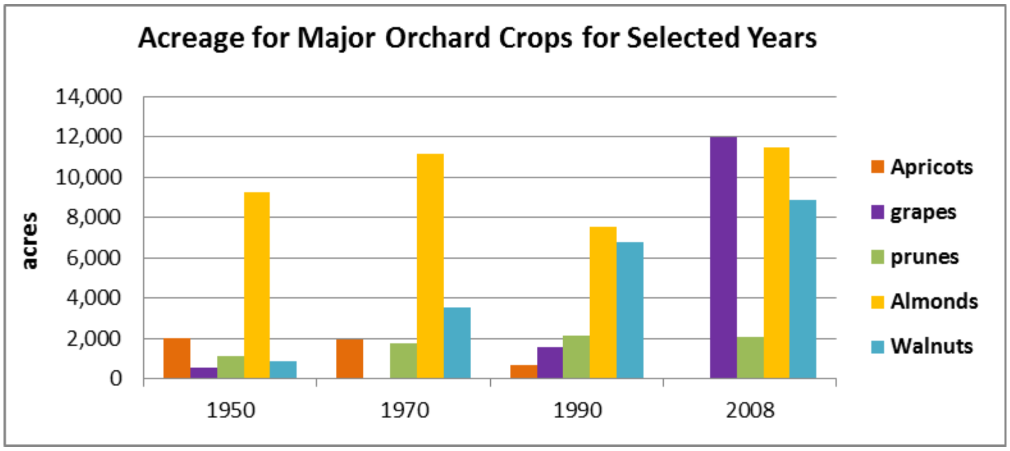

Figure 2.4. Acreage by Major Orchard and Vine Crop for Selected Years During 1950–2008. Grape acreage was not available in 1970.

Source: Yolo County Agricultural Crop Report (1950–2008)

Since the 1950s, processing tomato acreage has dominated vegetable area in Yolo County (Figure 2.5). After acreage peaked at nearly 70,000 acres in 1994 (data not shown), processing tomato acreage has been about 40,000 acres. The Yolo reduction exceeded the broad decline in statewide acreage. This acreage decline in the Yolo County roughly coincided with the expansion of tomato acreage in the southern San Joaquin Valley where some cotton acreage was replaced (Carter 2006). The southern San Joaquin Valley also benefits from larger-scale farming and newer processing facilities.

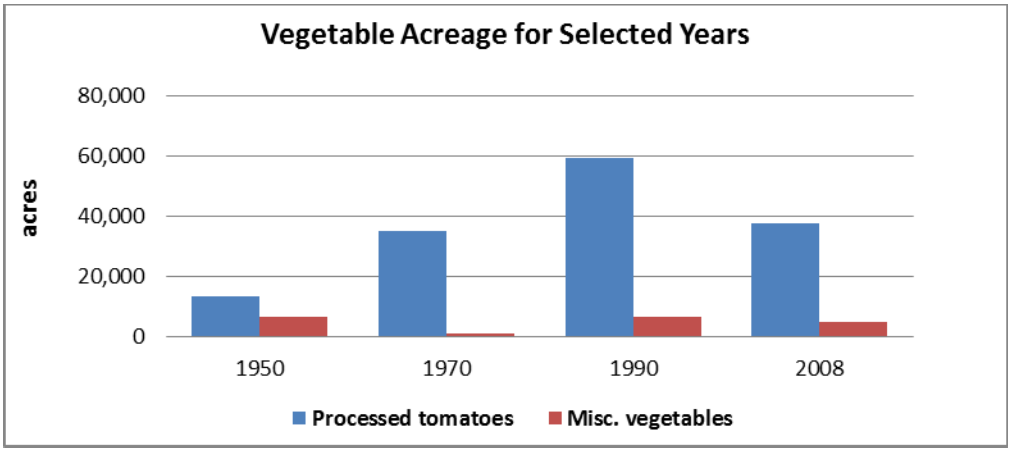

Figure 2.5. Historical Crop Acreage by Major Vegetable Crops, 1950–2008

Source: Yolo County Agricultural Crop Report (1950-2008)

2.3 Climate in Yolo County

Daily data on maximum and minimum temperatures and precipitation for Yolo County cover a period of 100 years (1909 to 2009) (National Climatic Data Center [NCDC] of the National Oceanic and Atmospheric Administration [NOAA]). Three weather stations currently operate in Yolo County (Davis, Winters, and Woodland). However, none of these stations has complete time series data, and the Davis station has the least number of unreported days. We chose the Davis station as the main database and unreported days were filled in by generating data either using data from other stations or by interpolating Davis data (for the data generation procedure, see Appendix 1).

To summarize historical climate data, aggregation is necessary. Daily minimum and maximum temperatures were averaged, and the mean of daily temperatures for the year is shown as annual average temperature (Figure 2.6). For the period of 1910–2009, a long-term upward trend is unmistakable. If a linear assumption is made, the annual temperature has risen from approximately 59°F to 61°F (15°C to 16.1°C) over the past century, indicating an annual average increase of 0.02°F (0.01°C).

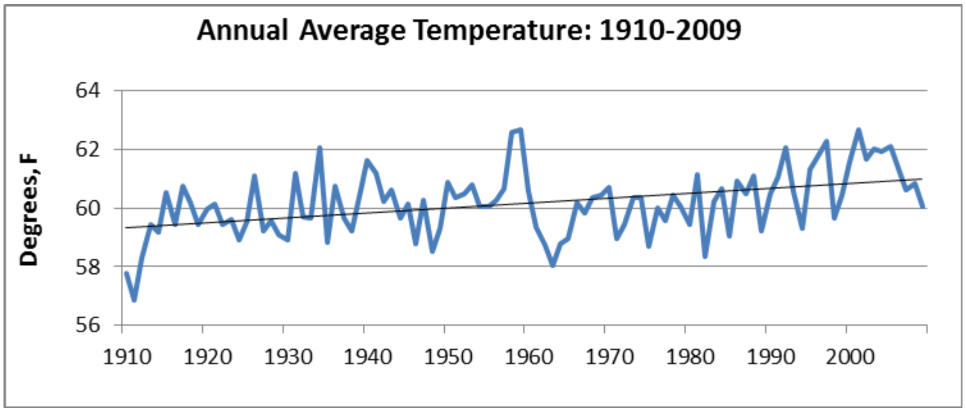

Figure 2.6. Annual Average Temperature, Computed Using Daily Minimum and Maximum Temperature for the Period of 1910–2009

Source: NCDC/NOAA

The average monthly temperatures for both summer and winter months have been increasing. Based on linear trend lines for summer months (Figure 2.7a), the average July temperature rose about 0.9°F (0.5°C) (from 74.2°F to 75.1°F [23.4°C to 23.9°C]) over the century, and the August temperature rose about 1.4°F (0.7°C) (from 72.6°F to 74°F [22.6°C to 23.3°C]). These century-long changes translate into annual summer average increase of 0.009°F (0.005°C) or (0.012 percent) for July and 0.014°F (0.007°C) (or 0.02 percent) for August.

For the two coldest winter months, the average temperature in January rose from 44.2°F (6.8°C) to 46°F (7.8°C) and in February from 49°F (9.4°C) to 50.3°F (10.2°C) during the 100-year period (Figure 2.7b). These increases translate into an annual average increase of 0.018°F (0.01°C) degrees (or 0.04 percent) for January and 0.013°F (0.008°C) degrees (or 0.03 percent) for February.

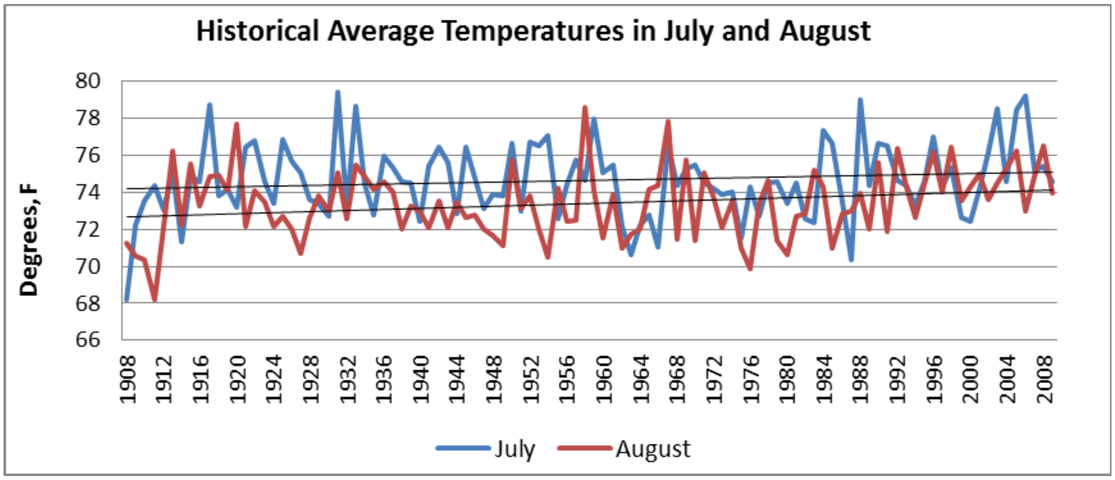

Figure 2.7a. Historical Average Monthly Temperature (°F) for July and August, Computed Using Daily Minimum and Maximum Temperatures for the Period of 1908–2008

Source: NCDC/NOAA

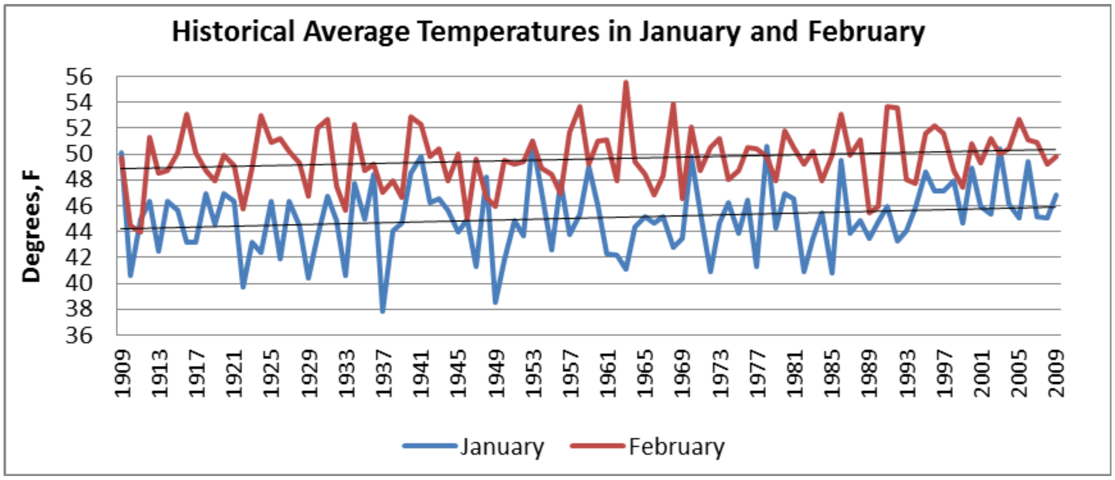

Figure 2.7b. Historical Average Monthly Temperature (°F) for January and February, Computed Using Daily Minimum and Maximum Temperatures for the Period of 1909–2008

Source: NCDC/NOAA

During the past century, the increase in annual temperature (Figure 2.1) appears to be accounted for more by warmer winters than by warmer summers (Figures 2.7a and 2.7b). The actual annual temperature increase for January is twice that of July. In percentage, the annual increase in average temperature for January is about three times larger than that for July. Also, closer examination of non-linear trend lines suggests that the rate of increase seems to have been accelerating in the last several decades (data not shown). This is consistent with global trends of recently increased warming (Trenberth et al. 2007).

We next examine minimum and maximum temperatures separately. Minimum temperatures have risen from 52°F to 56.7°F (11.1°C to 13.7°C) during the same summer months (July and

August), and from 36.5°F to 39.5°F (2.5°C to 4.2°C) for the same winter months (January and February). This translates into an annual increase of 0.047°F (0.026°C) in summer and 0.03°F (0.017°C) in winter (Figure 2.8). Contrary to the findings on the minimum and average temperatures, maximum temperatures have remained roughly constant (Figure 2.9).

Another study examining the period of 1910 to 2003 has observed higher minimum temperatures in the San Joaquin Valley (Christy et al. 2006), i.e., 0.45°F (0.25°C) from 1910 and 2003, which coincides with the higher end of our data. They attribute these trends partially to changes in irrigation and land use, which alter heat transfer and evaporation.

Growing Degree Days

Plants require an adequate amount of sunlight hours to grow and mature, and an immediate implication of climate warming for crop agriculture is a longer growing season. Growing degree days (GDD) are based on daily air temperature, which is converted into a heat accumulation measure. Daily GDD are calculated using two key factors: the daily average temperature and a base temperature below which plant growth is impaired. That is,

Daily GDD = (min temperature + max temperature)/2 – base temperature

However, there are also physiological tolerances for high temperatures, such as reduction in photosynthetic rates. Therefore, following Deschenes and Greenstone (2007), Schlenker et al. (2006) and Ritchie and NeSmith (1991), our GDD calculation employs an upper bound temperature in addition to the lower bound, base temperature. These two threshold temperatures may differ by plant species and cultivar, but we set these two values at 46.4°F (8°C) and 89.6°F (32°C) following Deschenes and Greenstone (2007). Thus, daily mean temperature <46.4°F (8°C) generates zero degree days and the daily mean temperature >89.6°F contributes no additional GDD. Values for daily GDD are between zero and 43.2°F (6.2°C).

The GDD were calculated for summer (April 1–August 31) and winter (November 1–May 31) growth seasons. These time spans are fit for the planting to crop maturity for most summer and winter crops, respectively, produced in Yolo County.

Consistent with our findings on average temperature, GDD for the summer growth season have been slowly increasing by three units per year, which is about 0.09 percent of annual increase. According to the trend line, GDD increased from 3230 to 3515 during the period of 1909–2009 (Figure 2.10a). Other studies have also found the growth season to be lengthening across North America and California (Feng and Hu 2004; McKenney et al. 2006).

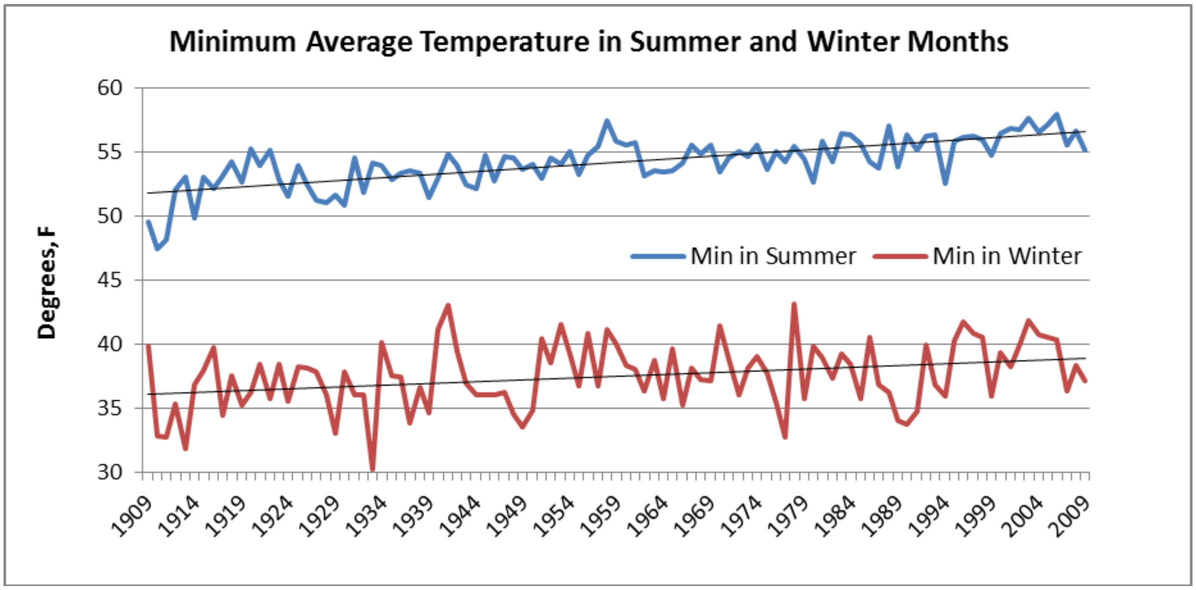

Figure 2.8. Minimum Average Temperature in Summer (July and August) and Winter (January and February) Months, Computed Using Daily Minimum Temperature for the Period of 1909–2008

Source: NCDC/NOAA

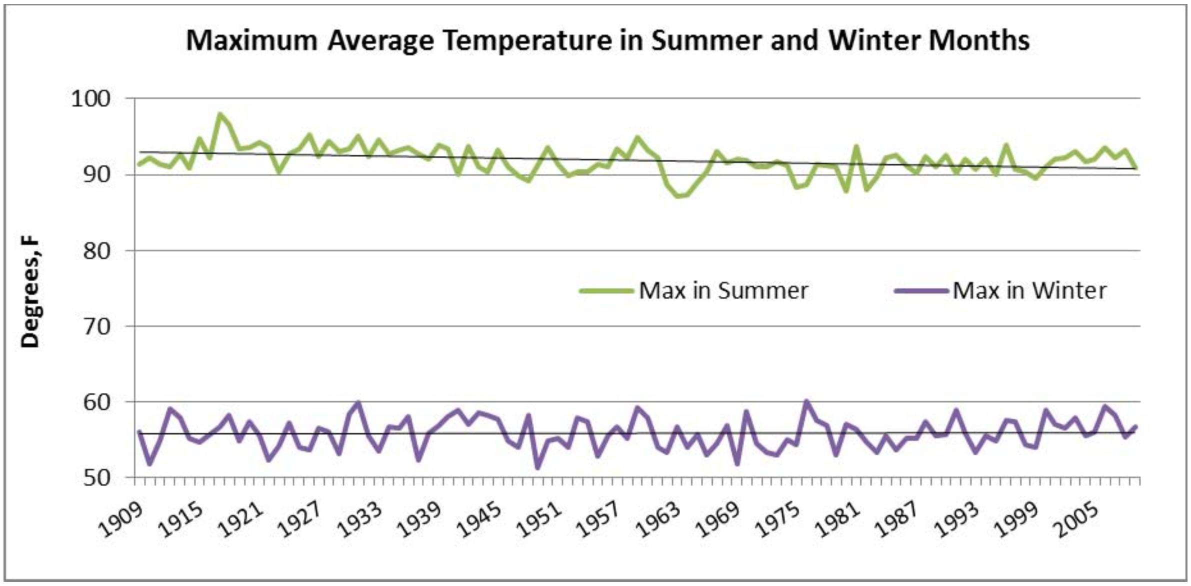

Figure 2.9. Maximum Average Temperature in Summer (July and August) and Winter (January and February) Months, Computed Using Daily Maximum Temperature for the Period of 1909–2008

Source: NCDC/NOAA

For the winter growth season, GDD has increased about three units of annual increase on average (Figure 2.10b). Note that the growth season for winter crops involves two consecutive years and is plotted for the year in January. According to the linear trend line, the GDD increased from 1425 to 1710 during the period of 1912–2009, a rate of annual increase about twice that of GDD for summer crops.

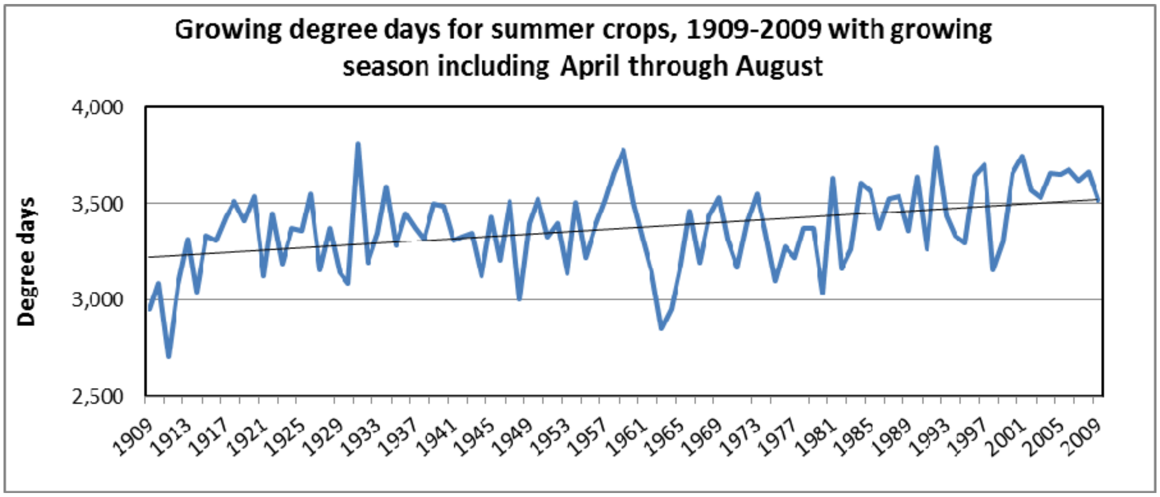

Figure 2.10a. Growing Degree Days for Summer Crops for 1909–2009, with Growth Season Including April through August

Source: Authors' calculation using data from NCDC/NOAA

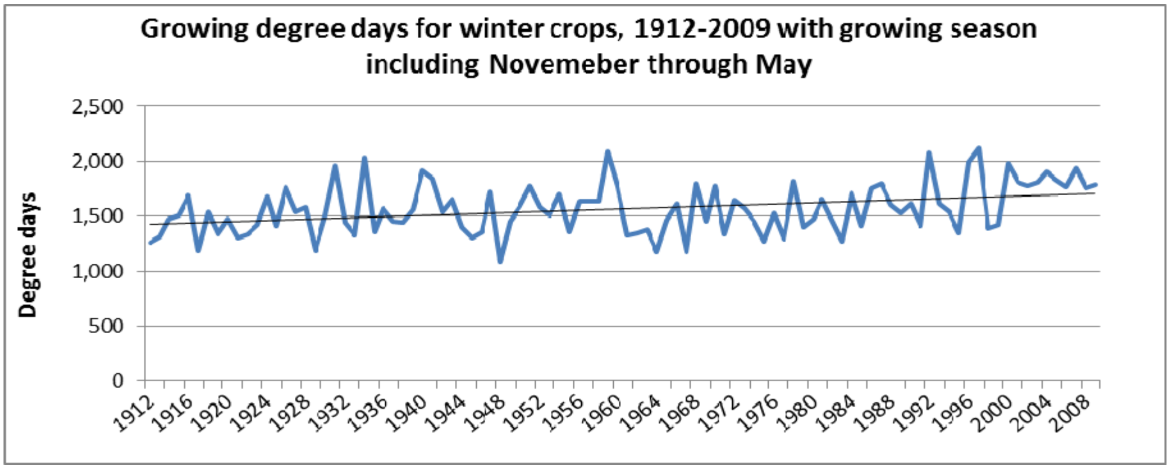

Figure 2.10b. Growing Degree Days for Winter Crops for 1912–2009, with Growth Season Including November through May in the Following Year

Source: Authors' calculation using data from NCDC/NOAA

Corn Heat Units

Corn heat units (CHU) are an alternative heat accumulation index with different upper and lower bounds than GDD (Brown 1969). Since the initial use by Brown, CHU has been widely used (Brown and Bootsma 1993; Easson and Fearnehough 2003; Pearson et al. 2008; Major et al. 1978). The seasonal CHU is the sum of daily heat units calculated from a quadratic function of maximum temperature above a base of 50°F (10°C) and a linear function of minimum temperature above 39.9°F (4.4°C). Denoting daily maximum and minimum temperatures in Celsius degrees as Tmax and Tmin, the CHU can be expressed as (Major et al. 1978):

$$\text{CHU} = 0.5\ (\text{Ymax} + \text{Ymin}),$$

where $\text{Ymax} = 3.3\ (\text{Tmax} - 10) - 0.084(\text{Tmax} - 10)^2$, for $\text{Tmax} > 10°\text{C}$,

$\text{Ymin} = 1.8(\text{Tmin} - 4.4)$, for $\text{Tmin} > 4.4°\text{C}$

otherwise, $\text{Ymax} = \text{Ymin} = 0$.

Typically CHU is calculated for April, May, June, and July. Given the relatively long months of summer in California, where corn can be harvested as early as June and as late as September, we calculated the CHU for the April 1–August 31, making it comparable to GDD.

The upward trend of the annual accumulated CHU (Figure 2.11) is almost linear, suggesting that the CHU has been increasing steadily at a constant rate over the observed period. Over the last century, annual CHU increased by about 300 units for the four-month growing season (data not shown) and about 400 units for the extended growing season, i.e., 3 and 4 CHU of annual average increase annually, respectively. These increases in CHU are equivalent to 0.13 percent of the average annual accumulated CHU, slightly higher than 0.09 percent for the equivalent value for GDD.

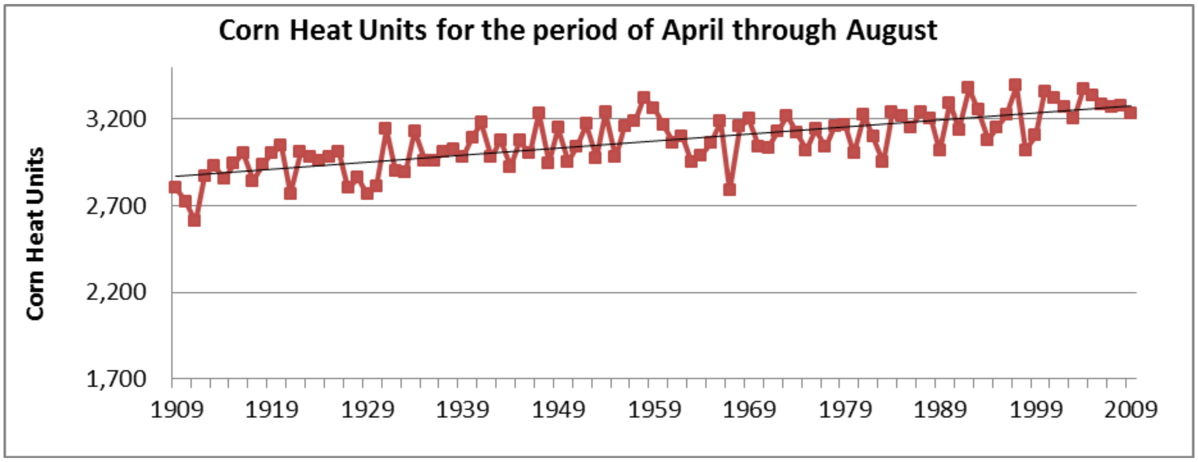

Figure 2.11. Corn Heat Units for 1909–2009 for a Season Beginning on April 1 and Ending on August 31, Computed Using Daily Minimum and Maximum Temperature

Source: Authors' calculation using data from NCDC/NOAA

Winter Chill Hours

After shedding their leaves in the fall, most trees and vines enter dormancy, and to emerge from dormancy and to resume growth in the spring, they must receive a certain amount of winter chill during their dormancy. Requirements for winter chill hours differ by species or cultivar. In general, fruit trees need to experience between 200 and 1,500 chill hours during dormancy (Rattigan and Hill 1986; Samish 1954). Insufficient winter chill does not provide enough physiological stimulation to renew growth, causing a delay in the development and opening of leaf and flower buds, excessive shedding of flower buds or smaller blossoms, which all result in reduced fruit yield (Aron 1983).[4]

Winter chill hours are the number of hours below a critical temperature, which is widely accepted as 45°F (7.2°C) (Aron 1983). Annual chill hours are computed as a sum of daily chill hours for the entire winter season. This requires extensive data, namely, time series of hourly temperatures, which are not available here. Thus, estimates of chill hours follow Baldocchi and Wong (2008), who use daily maximum and minimum temperatures. They assume that temperature changes over a 24-hour period are gradual, and bounded by the daily maximum and minimum temperatures (Figure 2.12). Hourly temperature changes within a 24-hour period can be described as a process in which the daily mean temperature declines down to the minimum, rises up to the maximum, and falls back to the mean temperature. Algebraically, the daily chill hours are calculated as, denoting Tref, Tmin, Tavg, and Tmax, as the reference chill temperature (45°F), daily minimum temperature, average temperature, and daily maximum temperature, respectively,

If $Tref < Tavg$ chill hours $= 12hr * [(Tref - Tmin)/(Tavg - Tmin)]$

If $Tref > Tavg$ chill hours $= 12hr + [12hr*(Treg - Tavg)/(Tmax - Tavg)]$

If $Tref < Tmin$ chill hours $= 0$

If $Tref > Tmax$ chill hours $= 24$ hours

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[4] Flowering time is particularly critical for trees such as walnuts and pistachios that depend on male and female flowering occurring at the same time to ensure pollination and a normal yield (Aron 1983).

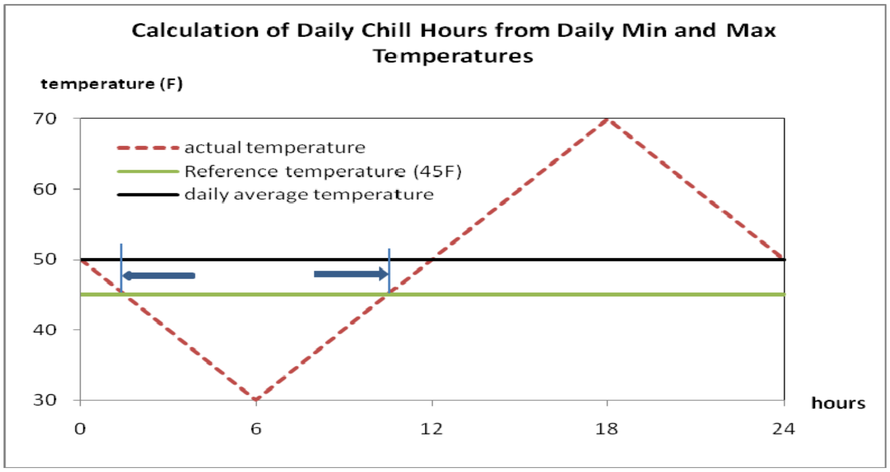

Figure 2.12. Calculation of Daily Chill Hours from Daily Minimum and Maximum Temperatures. The example illustrates the case when the daily minimum temperature is 30°F (-1°C), and the daily maximum temperature is 70°F (21°C).

Annual winter chill hours for November through February coincides with the usual dormant season for California's tree fruit and nut crops. The long-term trend indicates that the annual chill hours are decreasing (Figure 2.13). Over the century, the total decrease, based on the linear trend line, was about 150 hours, which is a decrease of about 1.5 hours in annual chill hours per year.

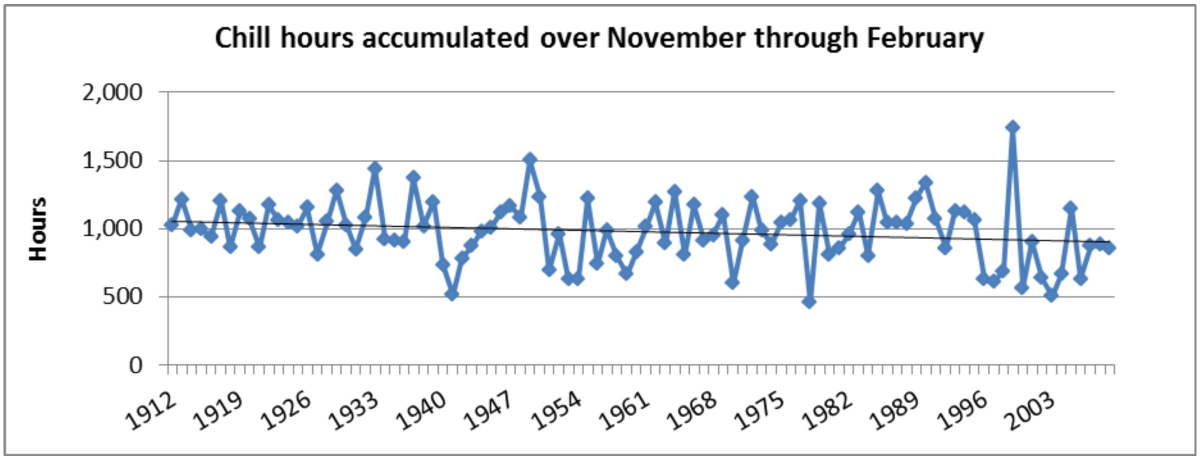

Figure 2.13. Annual Chill Hours Accumulated over November through February for the Period of 1912–2009 Computed Using Daily Minimum and Maximum Temperature

Source: Authors' calculation using data from NCDC/NOAA

Winter chill hours required for major California tree crops in Northern California vary considerably (Table 2.2). Three crops (almonds, walnuts, and grapes) together occupy more than 90 percent of fruit and nut acreage in Yolo County. Walnuts require the largest amount of chill hours, while almonds require only about half of chill hours required by walnuts. Among the three crops, grapes require the least.

Table 2.2. Winter Chill Hours Required for Tree and Vine Crops

Crop	Range in Chill Hours		Crop	Range in Chill Hours
Almond	400–700		Peach	200–1,200
Apricot	350–1,000		Persimmon	100–500
European pear	600–1,500		Pistachio	800–1,000
European plum	700–1,800		Pomegranate	100–200
Fig	100–500		Quince	100–500
Grape	100–500		Raspberry	100–1,800
Kiwi	400–800		Sweet cherry	600–1,400
Nectarine	200–1,200		Walnut	400–1,500

Source: Baldocchi and Wong (2008).

Note that winter chill hours refer to accumulated cold-season hours <45°F (7°C). A wide range in chill hours indicates that varieties for some of the above crops differ. The University of California reports lower chill hours (hours under 45°F) as 200–350 hours for almond.

We can compare our chill hour data with those of Luedeling et al. (2009) who investigated the winter chill hour reduction in many sub-regions of the Central Valley of California. Taking a period comparable to our analysis, they estimated chill hours for the Sacramento Valley to be 993 in 1950 and 870 in 2000. Our chill hour calculations for the same years were 1000 in 1950 and 920 in 2000 (following the linear trend line in Figure 2.13), suggesting that the decline in chill hours in our data is moderate compared to the decline estimated by Luedeling et al. (2009) for nearby regions.

2.4. Empirical Estimation of Crop Acreage Decisions

This section provides econometric estimates of crop acreage based on historical data, with emphasis on the role of climate change. These models account statistically for changes in crop acreage using explanatory variables such as market prices, water availability, and climate conditions, which are described in detail below. We first present the specifications including details about the explanatory variables for each crop acreage equation. Each acreage equation is estimated separately using regression techniques, which establish the quantitative relationship between the change in acreage and the change in each explanatory variable.

The specification of the acreage equations was designed for a specific purpose. We want to isolate any potential effects of climate change on acreage across crops in Yolo County. Therefore, we focus on climate variables that may have influenced acreage while controlling statistically for other factors such as prices that may also affect acreage. However, developing a model that precisely estimates the effect of all these factors (especially prices) requires complex modeling, and developing such modeling is beyond the scope of the current study.[5] Given our focus is on estimating how climate change has affected acreage, we do not develop a fully articulated model of acreage response to all explanatory variables.

Model Specification

We specify 13 acreage equations, each associated with an individual crop that currently has significant acreage in Yolo County. Each equation includes acreage of a specific crop as the dependent variable and a set of climate variables, prices, and other factors as independent (or explanatory) variables. Below, acreage is expressed as a function of these independent variables. Our guiding principle, in specifying each equation, is that crop acreage depends on market conditions, water availability, climate considerations, and other agronomic factors such as crop rotations which may be specific to the crop in question (further discussion on explanatory variables for each equation is provided later).

For the estimation models used for each product, the following conventions in denoting variables are used: Acreage and prices (real price deflated by a gross domestic product deflator) variables begin with capital letters, A for acreage and P for the price. This capital letter is followed by the commodity name in lower case. We denote precipitation as Prcp. The subscript at the end of the variable denotes the year for which the data are used. So, for example, the subscript, t-i, indicates that the variable is lagged by i periods. More definitions follow the presentation of these 13 acreage equations that describe historical changes in acreage are as follows:

$Arice_t = f(Price_{t-1}, Pcorn_{t-1}, Dind, Prcp_{t-1}, Prcp_{t-2}, GDDsummer)$

$Acorn_t = f(Pcorn_{t-1}, Pbarley_{t-1}, Palfalfa_{t-1}, Dind, Prcp_{t-1}, Prcp_{t-2}, GDDsummer)$

$Awheat_t = f(Pwheat_{t-1}, Atomato_{t-1}, Dind, Prcp, Prcp_{t-1}, Prcp_{t-2}, GDDwinter)$

$Aalfalfa_t = f(Palfalfa_{t-2}, Dind, Prcp_{t-1}, Prcp_{t-2}, Prcp_{t-3}, GDDwinter)$

$Asafflower_t = f(Psafflower_{t-1}, Pcorn_{t-1}, Dind, Prcp_{t-1}, Prcp_{t-2}, GDDsummer)$

$Apasture_t = f(Ppasture_{t-1}, Pbarley_{t-1}, Pwheat_{t-1}, Dind, Prcp_{t-1}, Prcp_{t-2}, GDDsummer)$

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[5] Estimating full models of supply response, especially to changes in relative prices, is inordinately complex in a system with many crops and with the potential for perennial crop decisions. There is a huge acreage response literature, including a classic article by Nerlove (1956) and more recent perennial crop estimation by Alston et al. (1980), or the recent dissertation by Hendricks (2011) that emphasizes crop rotations.

$\text{Atomato}_t = f\,(\text{Ptomato}_{t-1}, \text{Arice}_{t-1}, \text{Psafflower}_{t-1}, \text{Dind}, \text{Prcp}_{t-1}, \text{Prcp}_{t-2}, \text{GDDwinter})$

$\text{Aotherveg}_t = f\,(\text{Atomato}_{t-1}, \text{Pcorn}_{t-1}, \text{Pwheat}_{t-1}, \text{Dind}, \text{Prcp}_{t-1}, \text{Prcp}_{t-2}, \text{GDDsummer})$

$\text{Aprune}_t = f(\text{Pprune}_{t-5,6,7}, \text{Pgrape}_{t-6}, \text{Dind}, \text{Prcp}_{t-1}, \text{Prcp}_{t-2}, \text{Chill})$

$\text{Agrapes}_t = f(\text{Pgrape}_{t-1,2,3}, \text{Aprune}_{t-2}, \text{Dind}, \text{Prcp}_{t-3}, \text{Prcp}_{t-4}, \text{Chill})$

$\text{Amfruit}_t = f(\text{Pmfruit}_{t-1,2,3}, \text{Palmond}_{t-5}, \text{Dind}, \text{Prcp}_{t-3}, \text{Prcp}_{t-4}, \text{GDDsummer}, \text{Chill})$

$\text{Aalmond}_t = f(\text{Palmond}_{t-5,6,7}, \text{Pwalnut}_{t-3}, \text{Pprune}_{t-3}, \text{Dind}, \text{Prcp}_{t-1}, \text{Prcp}_{t-2}, \text{Chill})$

$\text{Awalnut}_t = f(\text{Pwalnut}_{t-5}, \text{Palmond}_{t-3}, \text{Pprune}_{t-3}, \text{Dind}, \text{Prcp}_{t-4}, \text{Prcp}_{t-5}, \text{Chill})$

Further variable definitions are as follows:

A $\mathit{commodity}_{j\ t}$ = acres of $\mathit{commodity}_j$ at period t, where j = rice, corn, wheat, alfalfa, safflower, pasture, tomato, other vegetables (denoted as otherveg), prune, grape, other miscellaneous fruit (denoted as mfruit), almond, and walnut.

P $\mathit{commodity}_{j\ t-i}$ =real (deflated) price of $\mathit{commodity}_j$, at period t-i (lagged by i periods)

Dind = binary variable that separates the period between before and after Indian Valley reservoir, if year<1975, Dind = 1, otherwise Dind = 0.

GDDsummer = ten year moving average of growing degree days for spring and summer months, beginning on April 1 and ending on August 31

GDDwinter = ten year moving average of annual growing degree days for winter and spring months, beginning on November 1 and ending May 31

Chill = ten year moving average of annual winter chill hours

Prcp_{t-i} = total precipitation at period t-i

$\text{Pprune}_{t-5,6,7}$ = three year moving average of lagged prices, Pprune_{t-5}, Pprune_{t-6}, Pprune_{t-7},

$\text{Pgrape}_{t-1,2,3}$ = three year moving average of lagged prices, Pgrape_{t-1}, Pgrape_{t-2}, Pgrape_{t-3},

$\text{Pmfruit}_{t-1,2,3}$ = three year moving average of lagged prices of miscellaneous fruits, Pmfruit_{t-1}, Pmfruit_{t-2}, Pmfruit_{t-3},

$\text{Palmond}_{t-5,6,7}$ = three year moving average of lagged prices, Palmond_{t-5}, Palmond_{t-6}, Palmond_{t-7}

In each acreage equation, product market conditions are represented by own product price and prices of substitute crops. Price data used in our analysis are obtained from the U.S. Department of Agriculture (USDA) sources (USDA/National Agricultural Statistics Service [NASS]). The USDA publishes prices of major agricultural commodities, and the state level is the smallest geographic unit for which consistent price data are available. Statewide, markets are spatially integrated and price is highly correlated within relatively large regions allowing us to use California prices for Yolo County. All prices are converted into real prices using the gross domestic product deflator (Bureau of Economic Analysis). Note that in many annual crop equations we used prices that were lagged one period because acreage decisions are usually made based on the information available prior to the crop year, with an exception of alfalfa, which usually is grown for multiple years once the field is developed. For perennial crops, we used prices of much more distant lags, since many orchard crops take three to seven years from the time of planting until commercial harvest. Nevertheless, the specific lag may differ for each orchard crop and is not known with certainty. Multiple lags form a moving average of own prices. The concept is that the perennial crop acreage harvested in year *t* is based largely on planting decisions made several years in the past.

The climate variables used are annual growing degree days and winter chill hours, mostly with the former for annual crops and the latter for perennial crops. Note that climate variables here are intended to represent the general trend of climate rather than year-to-year short-term changes in weather. Thus, to smooth out short-term fluctuations and identify a long-term trend, we use a ten-year moving average of each climate variable. The effects of irrigation water supply are captured by two lagged precipitation variables and a variable for the effect of water availability from a nearby reservoir (Dind). Most California crops are irrigated, and precipitation here is used as a proxy representing irrigation water availability. In California, one important supplier of irrigation water is reservoirs, and previous years' rainfall is important for replenishing water supply in reservoirs.[6] The dummy variable, Dind, captures the effect of the Indian Valley reservoir, which began operating in 1976 and increased flexibility in supplying water in Yolo County farmland (see Section 3). The reference period for this binary variable is the period of post-Indian Valley reservoir.

The GDDwinter variable reflects the winter growing season. Most wheat produced in Yolo County is spring wheat that is planted in winter.[7] The GDDwinter is also used for tomatoes and alfalfa, even though these crops are mainly summer-harvested crops. In Yolo County, tomatoes intended for early harvest are planted as early as February. Alfalfa is a perennial crop and the first harvest occurs in April in California (planted in October) (University of California Cooperative Extension 2003). The GDD during the winter season is particularly relevant to

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[6] We had to use a proxy for the reservoir storage level because a time series for reservoir storage that was long enough to match with our production data was not available.

[7] The Sacramento Valley produces a large share of California's fall-sown hard red wheat, along with fall-sown hard white wheat, barley, oats, and triticale. Most wheat cultivars have a late fall-sown and spring-grown habit and are day-length insensitive. In Sacramento Valley, wheat is planted in November and harvested in June (University of California Cooperative Extension 2009).

these crops because they usually have sufficient growing degree days during the summer in California.[8]

We also include variables representing prices of substitute or rotation crops where these are relevant. In Sacramento Valley, irrigated small grains are grown in rotation with alfalfa, cotton, corn, rice, safflower, and a wide range of vegetable crops. The choice of rotation crops also depends on the specific site and the economic prospects for the rotation crops (March and Jackson 2008; University of California, Division of Agriculture and Natural Resources 2006). For each equation, we report the models that include variables which had significant effects and explained more of the variation in acreage.

Finally, a just few comments on technical issues related to econometric methods are needed. For the regression techniques to generate unbiased parameter estimates, the data must be transformed to meet certain statistical properties. Of particular relevance here, explanatory variables used in the model are transformed to have constant mean and variance over time. We conducted specification tests which evaluate statistical properties of all the time series. We report the test procedure and results in Appendix 2. In order to satisfy the needed conditions, we used each variable in a first difference form. For example, the dependent variable in each model is the year-to-year change in acreage, and the explanatory variables are also represented as year-to-year changes. That is, in the estimated models, we regress the first difference in acreage (i.e., change in acreage) on the first differences of explanatory variables.

Estimation Results

Among the field and vegetable crops, own prices are found to be important for rice and wheat acreage decisions ($P \leq 0.01$) (Table 2.3). For these crops, the favorable own price contributes to the expansion of acreage, and likewise, the unfavorable own price has a negative effect on acreage. Own price of tomatoes is found statistically significant at $P \leq 0.1$. Irrigation water availability also affects acreage decisions. Our regressions use previous years' precipitation as a proxy for irrigation water availability; the effects are positive for alfalfa and corn, and negative for wheat and safflower ($P \leq 0.06$). Among the field crops considered here, the most water-intensive crops (per acre basis) are rice and alfalfa (see Section 3). For rice, own price is significant but precipitation variables are not, indicating the relative importance of economic variables over water availability for rice acreage. This conjecture is supported by crop values per acre, which, averaged over the last ten years, (1999–2008) were $738 for alfalfa and $1,019 for rice. The results on wheat and safflower are also consistent with their low dependence on irrigation and low per-acre value. Thus, abundant water supply would induce farmers to shift away from these crops and the opposite would occur with constrained water supply. Note that the wheat equation includes current period precipitation, as well as two previous years' precipitation, because the current year's precipitation season ends in April which is many months before the wheat planting time in November.

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[8] While the summer GDD may still contain some relevance, we decided to include only the winter GDD, due to the correlation between these two GDD variables.

Summer temperatures (as represented by the GDDsummer variable) did not directly affect the allocation of acreage among crops in Yolo County.[9] The minor changes in temperature during the months of April, May, June, July, and August for the past 100 years apparently have had little effect on the planting pattern. Winter temperatures (as represented by the GDD winter variable) had significant effects on acreage equations for both alfalfa and wheat ($P \leq 0.01$ and 0.02, respectively).[10] Warmer winter growing seasons (November 1 through May 31) have had a negative effect on wheat acreage, but a positive effect on alfalfa acreage. In many winter wheat growing regions in the United States, winter kill caused by a harsh winter is a major risk (Wiersma 2006), but this is not a problem in California. In California, spring wheat varieties do not require a period of cool growing conditions (vernalization) to trigger reproductive growth (Chouard 1960). Negative effects of GDDwinter on wheat acreage are difficult to explain physiologically. Wheat is successfully adapted to conditions in the southern Central Valley where it is generally warmer in the winter than it is in Yolo County. For alfalfa production, a warmer winter is expected to provide favorable conditions, particularly since alfalfa varieties commonly planted in northern California are either semi-dormant or non-dormant (Putnam et al. 2007). In the Sacramento Valley, alfalfa is harvested six to seven times a year, with its first harvest beginning in April, thus warmer conditions in the spring would increase production and income.

For orchard crops, the prune and grape acreage equations have significant own price effects ($P \leq 0.05$). For grapes, this may be due to increased wine consumption and demand in the United States. Precipitation variables show some differences between annual and orchard crops. Orchard crops may be more resilient to water availability, since they tend to use drip irrigation and use a smaller share in total costs for irrigation than annual crops. Finally, no one plants orchards without already securing access to water, and this is a very long-term consideration, not dependent on short-run fluctuations.

The data also indicate that winter chill hours have statistically significant relationships with acres of prunes and miscellaneous fruits ($P \leq 0.05$), and for walnuts ($P \leq 0.08$). These effects indicate that an increase in winter temperatures is associated with a decrease in acreage for these crops. Walnuts and prunes are among the fruits that require significant numbers of chill hours (Table 2.2). Further calculation indicates that 1 percent change in chill hours induces also about 1 percent change in acreage for prunes and walnuts, but about 1.7 percent change for miscellaneous other fruits.

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[9] "Summer temperatures," here indicate the temperatures during the growth season for summer crops, which actually includes spring and summer seasons (April through August).

[10] Likewise, winter temperatures also indicate the temperatures during the growth season (from sowing to harvest) for winter crops which includes winter and spring seasons (November through April)

Table 2.3. Estimation Results of Crop Acreage Regression for Rice, Wheat, Safflower, Alfalfa, Corn, Irrigated Pasture, Tomatoes, Other Vegetables, Grapes, Prunes, Almonds, Walnuts, and Miscellaneous Fruit. (Detailed variable definitions are provided in the previous subsection dealing with model specifications).

Field crops

Arice	Coefficient	t-ratio
Price$_{t-1}$	620.8427	3.62***
Pcorn$_{t-1}$	-214.704	-0.48
Dind	-4472.87	.
Prcp$_{t-1}$	0.856056	0.8
Prcp$_{t-2}$	1.347797	0.99
GDDsummer	-16.8889	-0.62

Sample years: 1953–2008

Log likelihood = -562.121

Aalfalfa	Coefficient	t-ratio
Palfalfa$_{t-2}$	13.78913	0.46
Dind	13685.94	.
Prcp$_{t-1}$	1.764353	1.88*
Prcp$_{t-2}$	1.583242	1.62*
PRCP$_{t-3}$	0.770328	0.98
GDDwinter	48.05577	2.35**

Sample years: 1950–2008

Log likelihood = -578.813

Awheat	Coefficient	t-ratio
Pwheat$_{t-1}$	95.28042	4.09***
Atomatoes$_{t-1}$	0.363334	1.83*
Dind	-4036.08	.
Prcp$_{t}$	-3.80139	-2.21**
Prcp$_{t-1}$	-3.56303	-1.47
Prcp$_{t-2}$	-3.30991	-1.96**
GDDwinter	-118.848	-2.45**

Sample years: 1949–2008

Log likelihood = -629.893

Acorn	Coefficient	t-ratio
Pcorn$_{t-1}$	148.6254	0.21
Pbarley$_{t-1}$	58.08705	1.49
Palfalfa$_{t-1}$	-91.3938	-2.09**
Dind	1009.279	.
Prcp$_{t-1}$	-0.23377	-0.21
Prcp$_{t-2}$	2.868617	2.66***
GDDsummer	-6.76962	-0.17

Sample years: 1953–2008

Log likelihood = -571.187

Table 2.3 (continued)

Field crops

	Coefficient	t-ratio
Asafflower		
Psafflower $_{t-1}$	3.440266	0.64
Pcorn $_{t-1}$	-575.098	-1.07
Dind	-5093.05	.
Prcp$_{t-1}$	-2.05275	-1.92**
Prcp$_{t-2}$	-2.22706	-1.59
GDDsummer	30.49686	0.98

Sample years: 1953–2008

Log likelihood = -571.390

	Coefficient	t-ratio
Apasture		
Ppasture $_{t-1}$	-0.65549	-0.41
Pbarley $_{t-1}$	9.906607	1.32
Pwheat $_{t-1}$	-14.9011	-2.98***
Dind	2118.416	.
Prcp$_{t-1}$	0.308552	1.25
Prcp$_{t-2}$	0.325629	1.22
GDDsummer	6.978067	0.93

Sample years: 1949–2008

Log likelihood = -509.689

Vegetables

	Coefficient	t-ratio
Atomatoes		
Ptomatoes $_{t-1}$	120.8775	1.69*
Arice $_{t-1}$	-0.15493	-1.37
Psafflower $_{t-1}$	10.88645	1.75*
Dind	6130.501	.
Prcp$_{t-1}$	1.460655	1.25
Prcp$_{t-2}$	-0.57176	-0.47
GDDwinter	46.56023	1.51

Sample years: 1952–2008

Log likelihood = -582.584

	Coefficient	t-ratio
Aoveg		
Atomatoes $_{t-1}$	0.029865	1.51
Pwheat $_{t-1}$	-1.619	-0.33
Pcorn $_{t-1}$	71.09365	0.58
Dind	515.3696	.
Prcp$_{t-1}$	0.335129	1.43
Prcp$_{t-2}$	0.171505	0.69
GDDsummer	6.552722	1.25

sample years: 1953–2008

Log likelihood = -478.31

Table 2.3 (continued)

Orchard crops

	Coefficient	t-ratio
Aprunes		
$\text{Pprunes}_{t-5,6,7}$	0.559267	2.03**
Pgrapes_{t-6}	-0.39062	-1.44
Dind	72.60092	
Prcp_{t-1}	0.046843	1.29
Prcp_{t-2}	0.057166	1.76*
Chill	1.93071	2.36**

Sample years: 1954–2008

Log likelihood = -362.99

	Coefficient	t-ratio
Agrapes		
$\text{Pgrapes}_{t-1,2,3}$	10.53052	2.18**
Aprunes_{t-2}	-0.60576	-0.95
Dind	-2138.09	.
Prcp_{t-3}	0.157157	0.75
Prcp_{t-4}	0.099304	0.36
Chill	-3.10026	-0.7

Sample years: 1952–2008

Log likelihood = -246.905

	Coefficient	t-ratio
Aalmonds		
$\text{Palmonds}_{t-5,6,7}$	404.4613	0.55
Pwalnuts_{t-3}	0.887461	2.45**
Pprounes_{t-3}	-0.6479	-0.64
Dind	26.60237	.
Prcp_{t-1}	0.17063	0.78
Prcp_{t-2}	0.123223	0.68
Chill	-5.92143	-0.98

Sample years: 1954–2008

Log likelihood = -457.363

	Coefficient	t-ratio
Awalnuts		
Pwalnuts_{t-5}	0.08268	0.31
Palmonds_{t-3}	-55.759	-0.33
Pprunes_{t-3}	-0.3399	-1.05
Dind	-936.82	.
Prcp_{t-4}	0.07215	0.55
Prcp_{t-5}	0.12415	0.88
Chill	4.67149	1.73*

Sample years: 1952–2008

Log likelihood = -438.918

Table 2.3 (continued)

Orchard crops

	Coefficient	t-ratio		Coefficient	t-ratio
Amfruit					
Pmfruit $_{t-1,2,3}$	0.029641	1.61*			
Palmonds $_{t-5}$	-26.8818	-0.73			
Dind	41.78882	.			
Prcp$_{t-3}$	-0.038	-1.19			
Prcp$_{t-4}$	-0.02073	-0.56			
GDDsummer	0.83654	0.82			
Chill	1.876831	2.15**			

Sample years: 1952–2008

Log likelihood = -372.818

Notes: The number of asterisks indicates different levels of significance: *** (P≤0.01), ** (P≤0.05), and * (P≤0.1).

2.5. Projection of Climate-induced Changes in Crop Acreages, 2010–2050

Based on the regression results provided above, projections of GDDsummer, GDDwinter, winter chill hours, and precipitation can be used as drivers for acreage changes over the next four decades (2009–2050). This assumes that the same general types of production systems and markets occur as at present. Downscaled climate projections (GFDL-Bias Corrected Constructed Analog [BCCA]) from two IPCC emissions scenarios (A2 and B1) were used to until 2050, a time-frame consistent with using past crop-climate relationships to guide future decision-making. All independent variables other than Yolo County climate variables are held constant at the value in the last year of actual data (2008). By holding all other variables except for climate variables, we focus on the acreage effects of the changes in temperature and precipitation in the A2 and B1 scenarios.

These are projections of plausible scenarios that are based solely on past responses of growers. No attempt is made to forecast relative prices, technical changes, new markets, or other factors that will also surely affect how much of each crop is planted. Notice also that we do not consider the direct or indirect effects of climate elsewhere on acreage in Yolo County. So, for example, we do not incorporate potential impacts of a smaller snow pack on irrigation water availability. Nor do we consider indirect price effects of global and national supply adjustments in response to climate change in other parts of California or in other regions that may produce crops that compete with crops in Yolo County.

Projection of Climate Variables

Using daily GFDL projections for 2010–2050 under A2 and B1 scenarios, we estimated the values of our climate indices (GDDsummer, GDDwinter, and chill hours) following the procedures used for the historical data above. These same data are used in Section 3 for climate change projections for hydrological modeling. Use of the climate indices (GDDsummer, GDDwinter and chill hours) with GFDL data for 2010–2050 produce acreage projections that are generally consistent with the historical trends of the past century (Figures 2.14a–d).

The temperature patterns for the A2 and B1 scenarios are remarkably similar for the period from 2009–2050, except for an unexpected decrease in the A2 (higher GHG emissions) scenario after 2035, with a concomitant increase in B1 (lower GHG emissions). This is mainly due to winter temperatures, as is evident from lower GDDwinter and higher winter chill hours in A2 versus B1 in this time period (Figure 2.14b). Note that GDD summer (Figure 2.14a) and precipitation (Figure 2.14c) show very similar patterns for the scenarios. The greater winter warming in B1 derives directly from the climate data in the GFDL-BCCA output runs. It appears to be an artifact of the climate downscaling or and clearly does not reflect the long-term pattern of greater warming in A2 by the end of the century (see Section 3). Statewide projections from several other GCMs (Cayan et al. 2009) show similar trajectories for A2 and B1 until mid-century reflecting the expectation that our current actions to mitigate GHG emissions may have little effect in the near future.

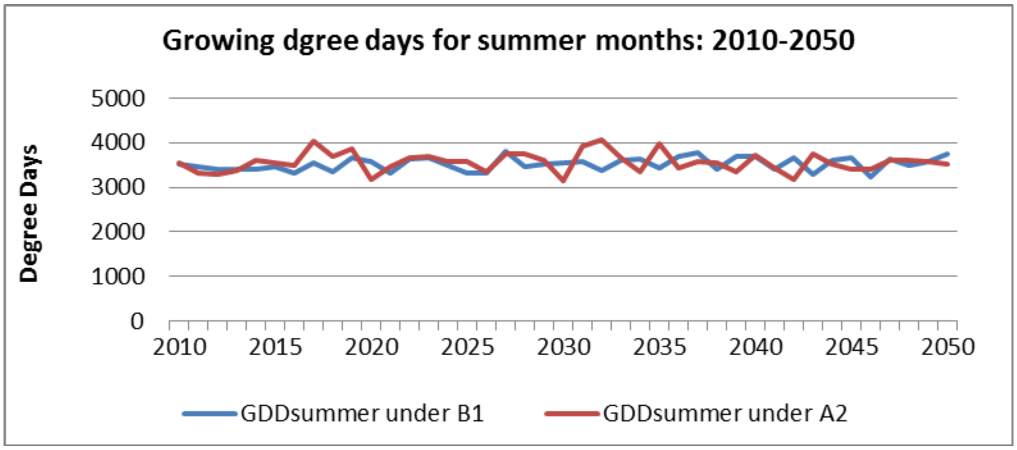


Figure 2.14a. Annual Accumulated Growing Degree Days for Summer Months, April through August, for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

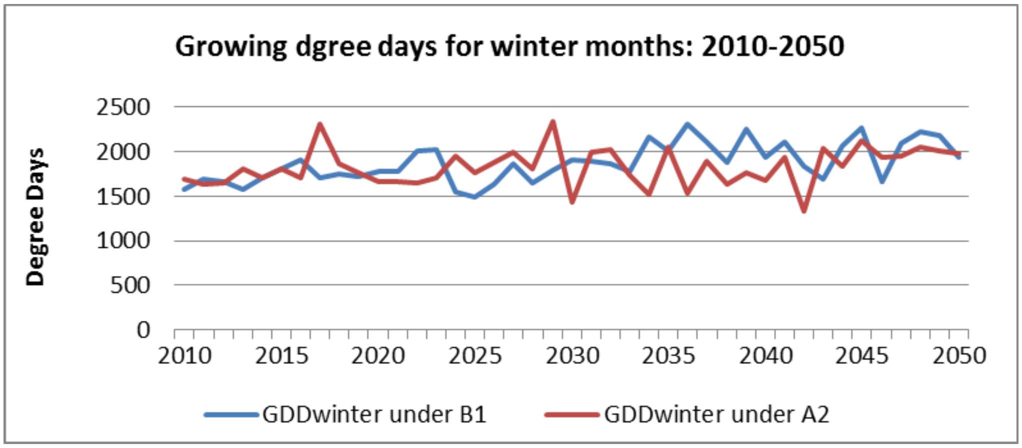


Figure 2.14b. Annual Accumulated Growing Degree Days for Winter Months, November through May for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

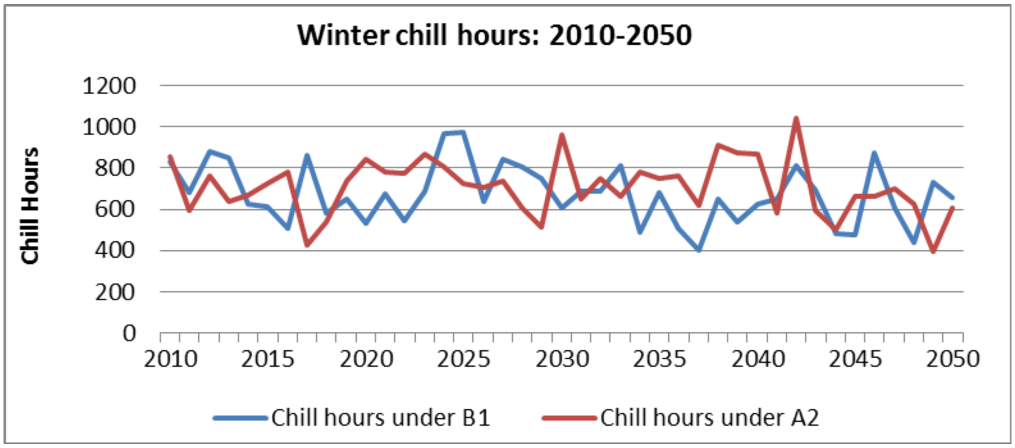


Figure 2.14c. Annual Accumulated Chill Hours (for November through February) for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

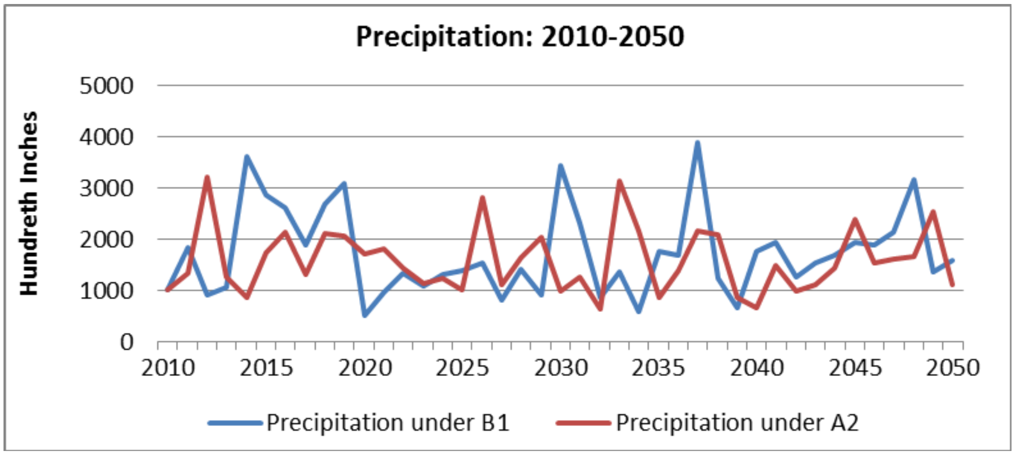


Figure 2.14d. Annual Precipitation (Hundredth Inches) for the Period from November through April for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

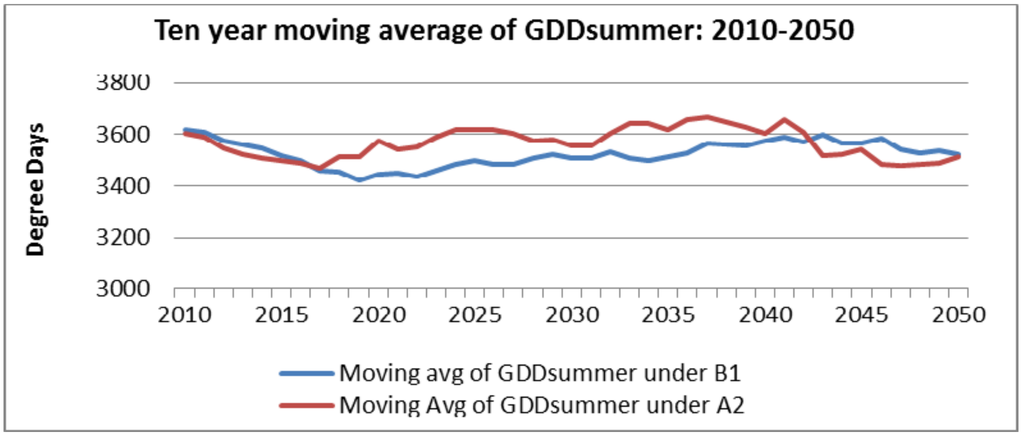


Figure 2.15a. Ten-Year Moving Average of Growing Degree Days (GDD) in Summer Months (April through August) for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

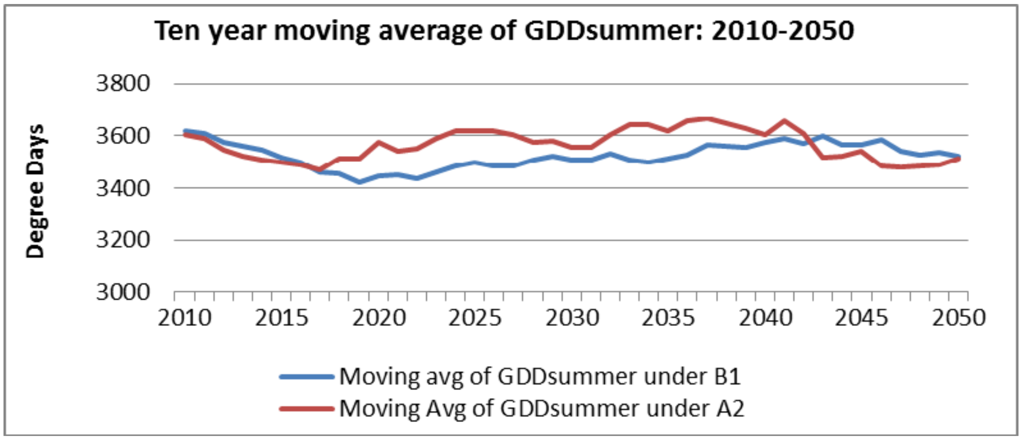


Figure 2.15b. Ten-Year Moving Average of Growing Degree Days (GDD) in Winter Months (November through May) for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

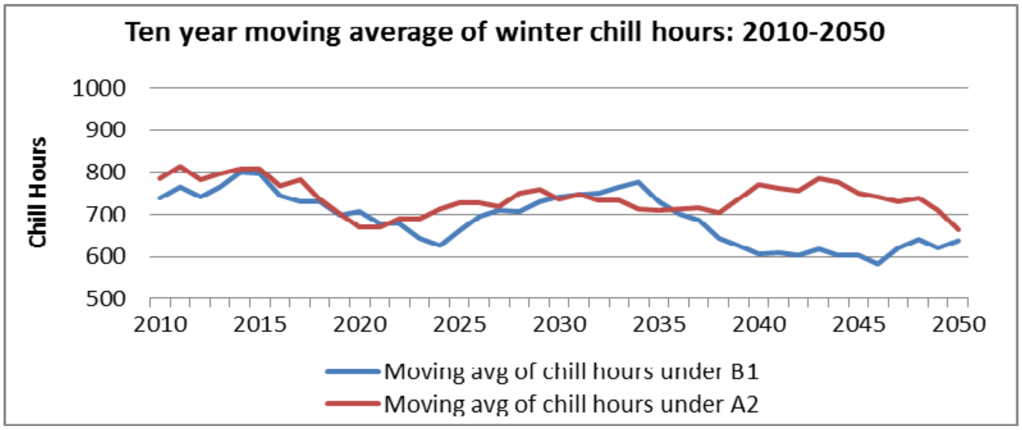


Figure 2.15c. Ten-Year Moving Average of Chill Hours for 2010–2050 under B1 and A2 Scenarios Using GFDL Climate Data

The 10-year moving averages portray broad trends more clearly and represent climate in a way consistent with grower perceptions on climate change (Figures 2.15a–c). These amplify the effect of the A2 winter cooling trend by extending its effect over several years. The 10-year moving average of GDDsummer is more similar between the scenarios than GDDwinter or winter chill hours.

Acreage Projections: Field Crops

The estimated acreage tracks the actual acreage well over the historical period for the field crops (rice, wheat, safflower, corn, and irrigated pasture), indicating that our regression results do fit the data well (Figures 2.16a–f). The acreage projections into the future use the estimates obtained in our regressions, which are based on historical data, and do not include unanticipated shocks, such as new pests or changes in relative prices. Therefore, compared to the previous 50 years, our acreage projections vary less from year to year than do the historical data or the fitted values over the historical period. This smoothing follows because future acreage was projected by varying only future climate, holding all other variables constant, and seeking broad patterns of change consistent with growers' expectations about future climate.

Compared to current acreage, future rice acreage tends to be slightly higher, but with no clear trend (Figure 2.16a). Recall from our regression results that the rice own price is a more significant determinant of rice acreage than climate. Wheat acreage decreases significantly under the warming of the B1 scenario in the final 15 years of the projection period (2035–2050) (Figure 2.16b). The opposite is true for alfalfa (Figure 2.16c). Increasing GDD in winter is favorable for alfalfa and alfalfa acreage increases significantly during this warming period.

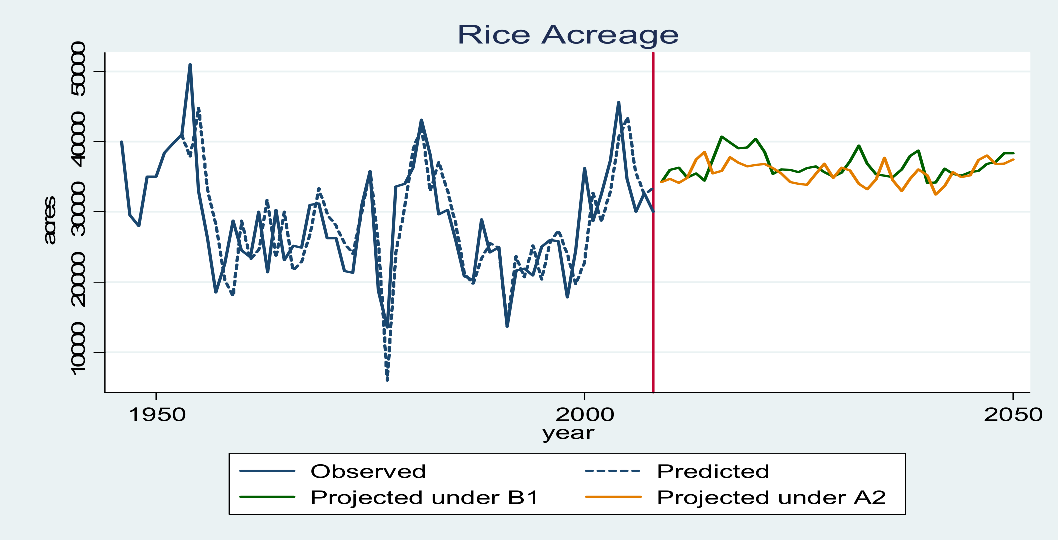


Figure 2.16a. Rice Acreage in Yolo County, in the Past and as Projected with an Econometric Model Based on Historical Data. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

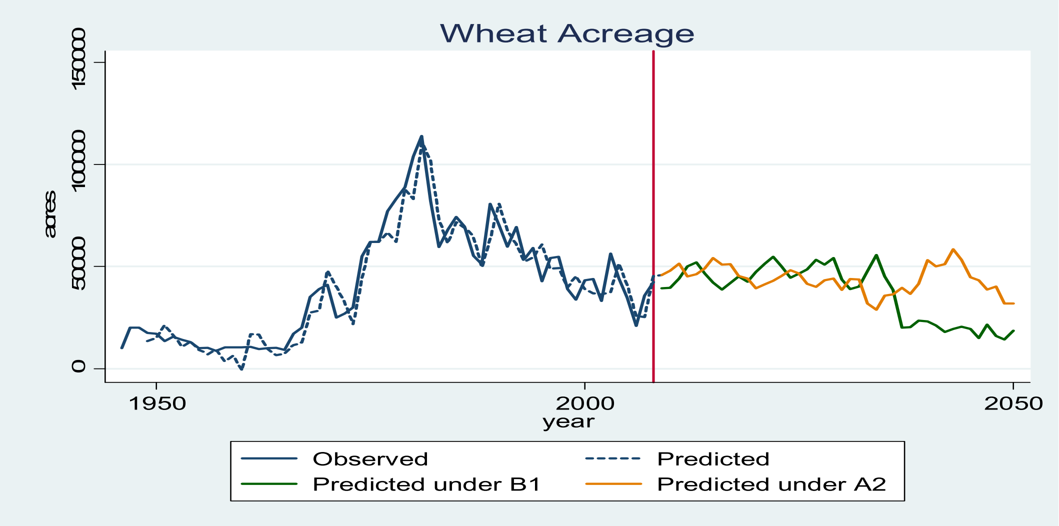


Figure 2.16b. Wheat Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

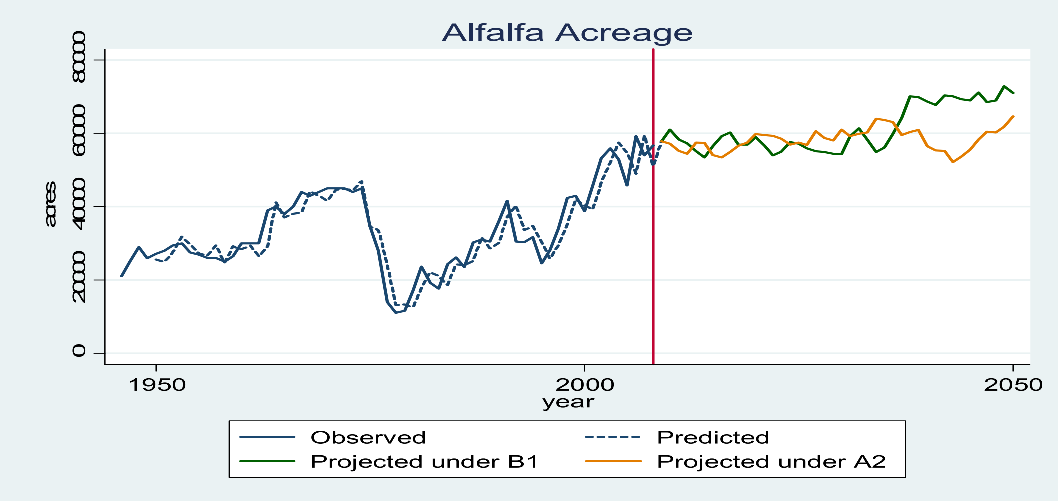


Figure 2.16c. Alfalfa Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

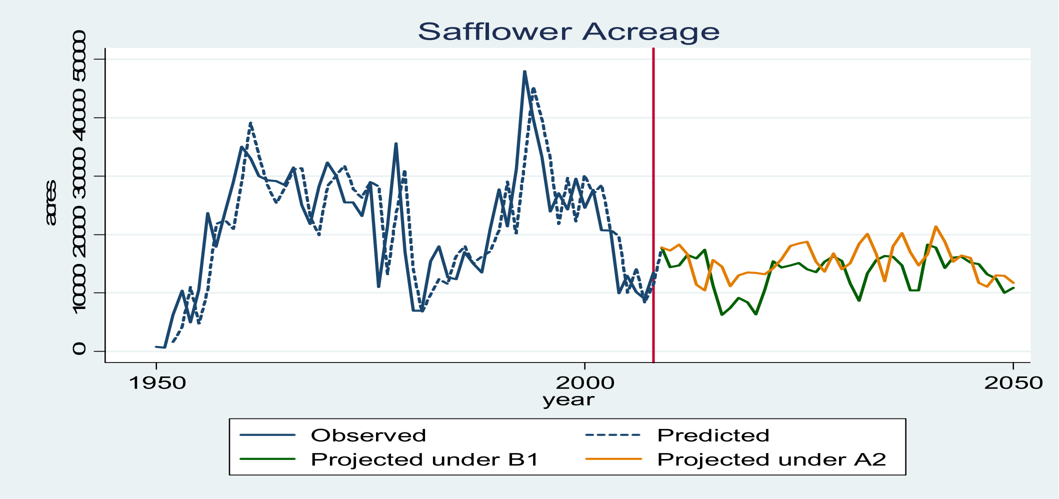


Figure 2.16d. Safflower Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

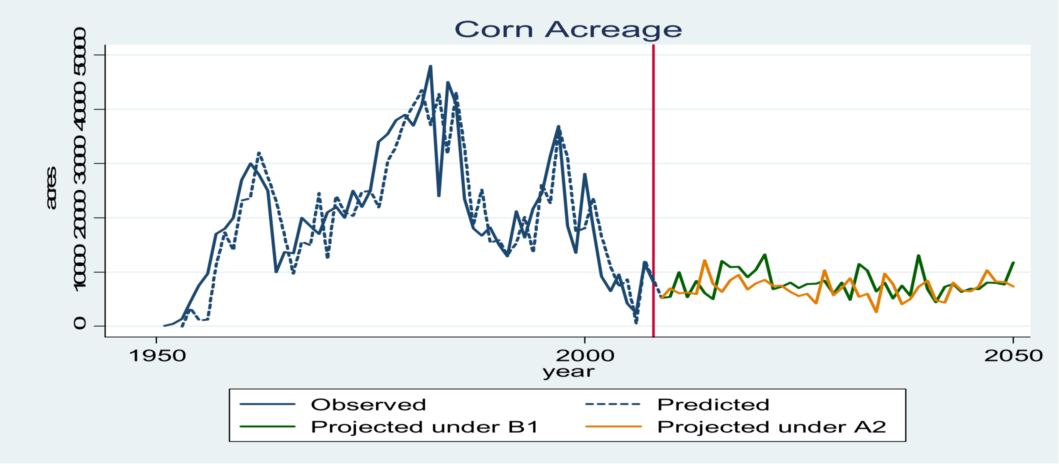


Figure 2.16e. Corn Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

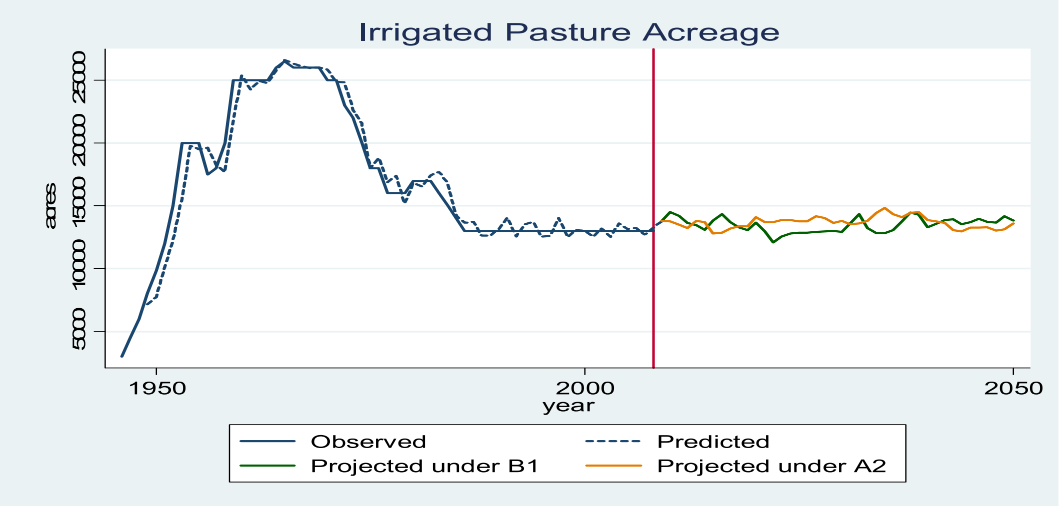


Figure 2.16f. Irrigated Pasture Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

Safflower acreage tends to fluctuate over a wider range than other crops during the projection period (Figure 2.16d). Our regressions showed that safflower acreage increases when water availability is restricted. Safflower is one of the least irrigated crops, and the fluctuations in safflower acreage are related to precipitation. Corn acreage also fluctuates around the current level with no major trend (Figure 2.16e). Corn acreage may well increase in Yolo County if prices are much higher (and which are predicted by many economists for corn over the future decades), but such a scenario is not incorporated in this study. Irrigated pasture acreage also varies little from the current level over the projection period (Figure 2.16f).

Displaying all field crops together allows us to readily compare across crops (Figures 2.17 a–b). Under both scenarios, rice, alfalfa, and wheat remain as major field crops throughout the period to 2050, although wheat acreage is much lower in 2040 and 2050 compared to earlier decades in response to warming. A concomitant projected increase in alfalfa acreage presents an interesting implication for water use. Wheat is one of the least water-using crops because much of its growing season coincides with the rainy season in California. Alfalfa, on the other hand, is one of the more intense water users. Thus, any significant decline in wheat acreage combined with an increase in alfalfa acreage is expected to increase regional irrigation water demand.

Winter warming between 2035–2050 reduced field crop acreage, and was mainly related to loss of wheat acreage. In 2008 wheat covered the second most acreage among the field crops, following alfalfa (Figure 2.3). Even though the warmer winter under the B1 scenario increases alfalfa acreage, the decline in wheat acreage caused by warmer winter is larger, leading to a decline in overall field crop acreage.

Acreage Projections: Vegetable Crops

Tomato acreage is projected to increase compared to the current level, mainly in the latter half of the projection period under the B1 scenario (Figures 2.18a). This projected increase is related to the increase in the GDD in the winter months. A warmer climate in the late winter (or equivalently the early spring) has a positive effect on tomato production because it allows early planting and provides favorable conditions for establishment. In Yolo County, growers plant tomatoes every week during the late winter and spring. Projected acreage for other vegetables is small and changes little (Figure 2.18b). Since tomatoes dominate vegetable acreage in Yolo County, any change in other vegetable acreage, even if it were significant, would have little effect on total vegetable acreage.

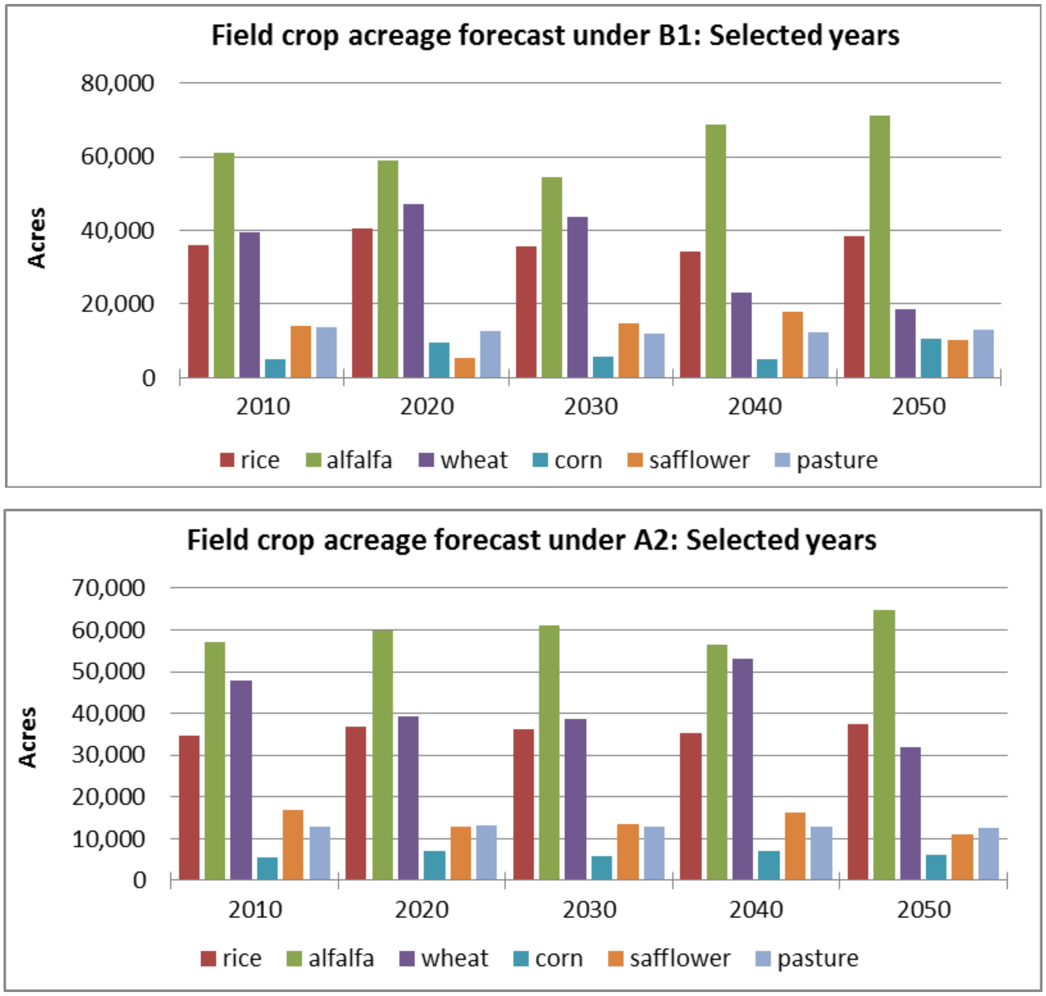


Figure 2.17. Field Crop Acreage Projections by Crop and by Climate Scenario for Selected Years over 2010–2050, as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. Crop acreages for 2008 were the starting point for the future modeling, and all other factors except climate were held constant until 2050.

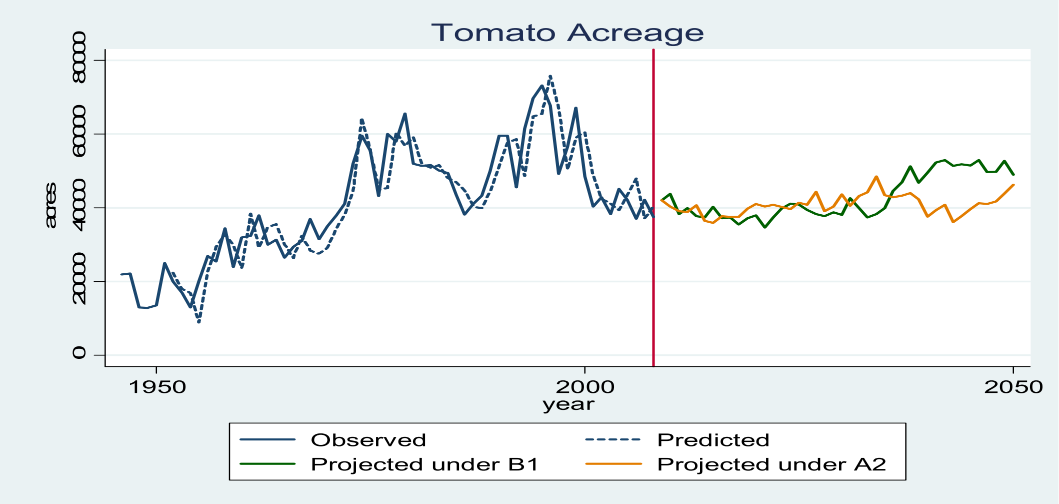


Figure 2.18a. Tomato Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

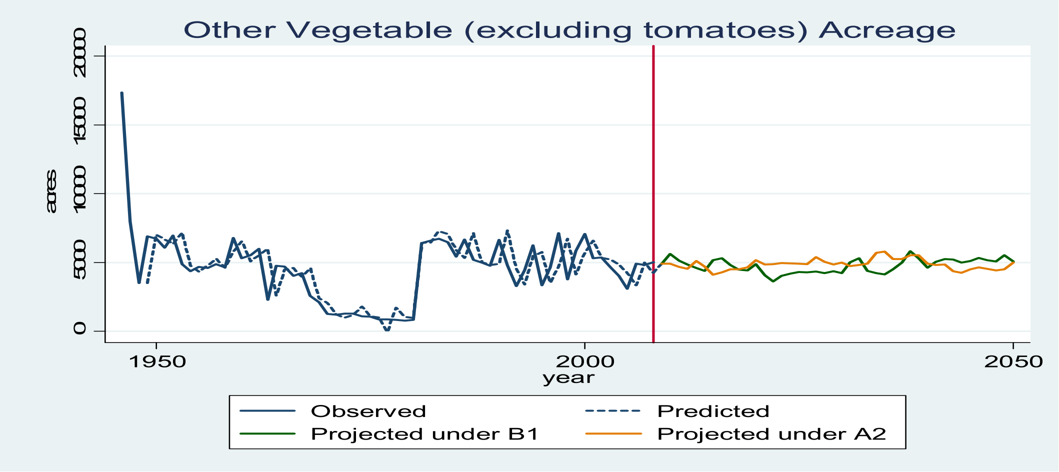
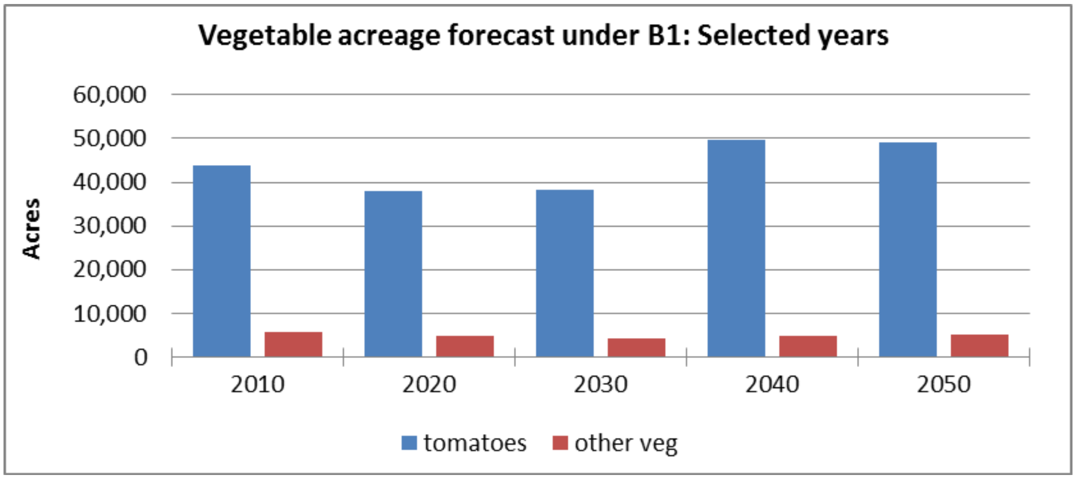


Figure 2.18b. Other Vegetable Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.



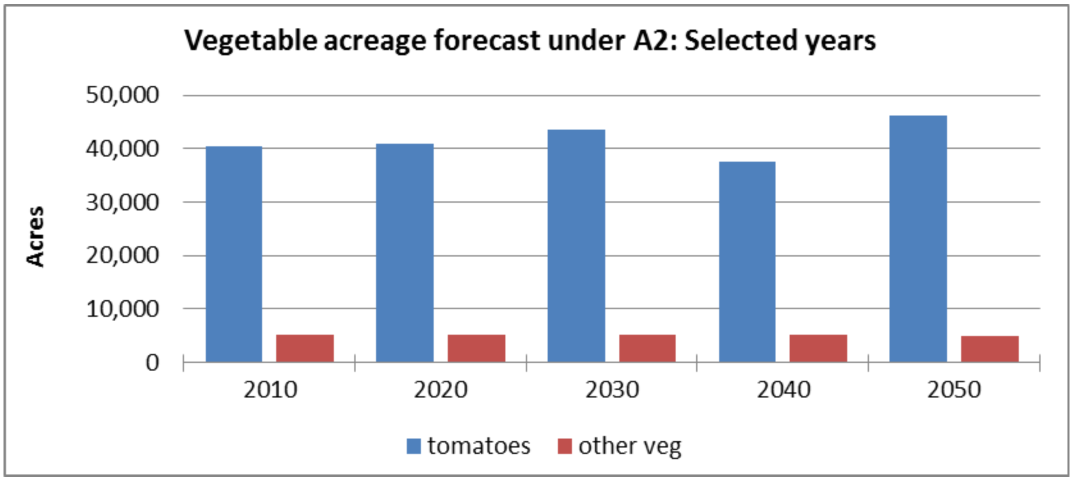


Figure 2.19. Vegetable Acreage Projections by Crop and by Climate Scenario for Selected Years over 2010-2050, as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

Acreage Projections: Tree and Vine Crops

Projected prune acreage shows a downward trend under both scenarios, which is a result of reduction in winter chill hours (Figure 2.20a). However, prune acreage fluctuates more under the B1 scenario than under A2. Grape acreage is almost constant over the projected period (Figure 2.20b); changes in grape acreage are induced by changes in factors other than climate.

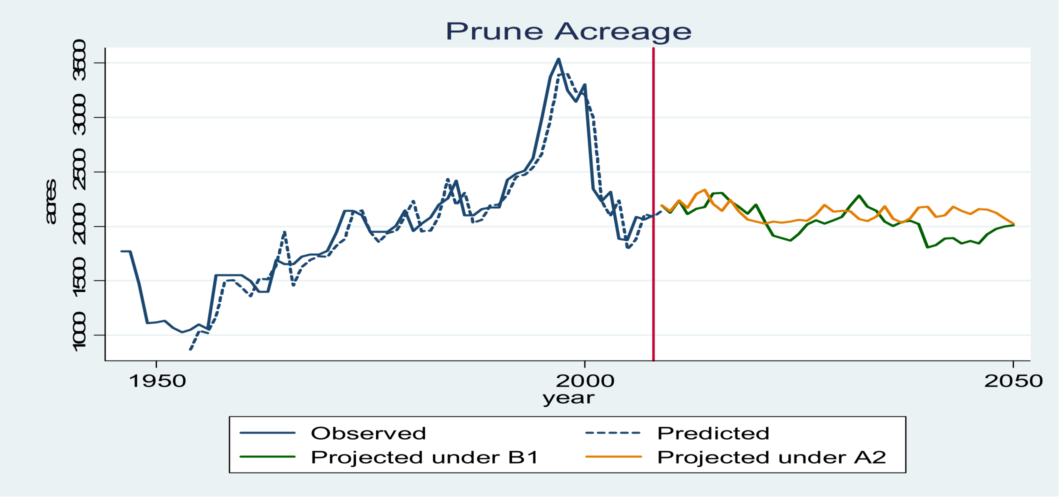


Figure 2.20a. Prune Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 arethe starting point for the future modeling, and all other factors except climate are held constant until 2050.

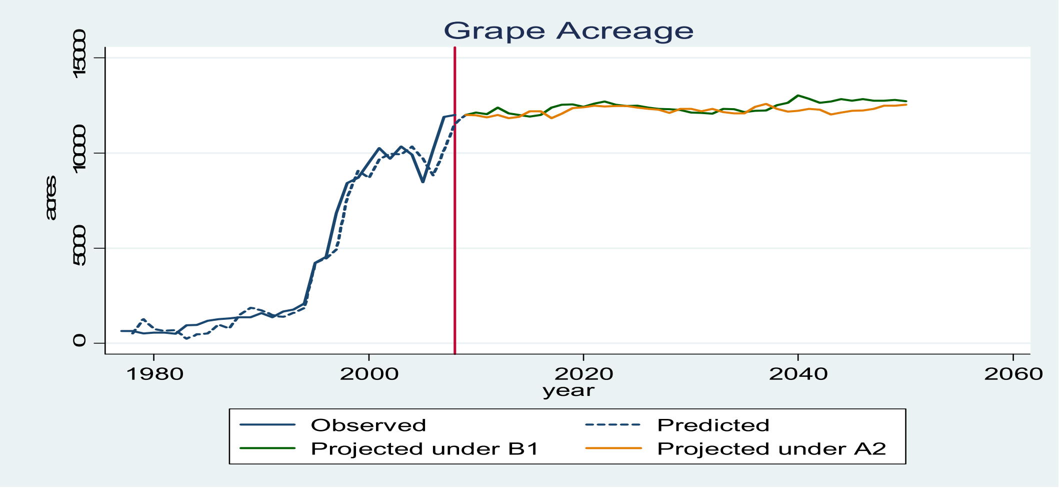


Figure 2.20b. Grape Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

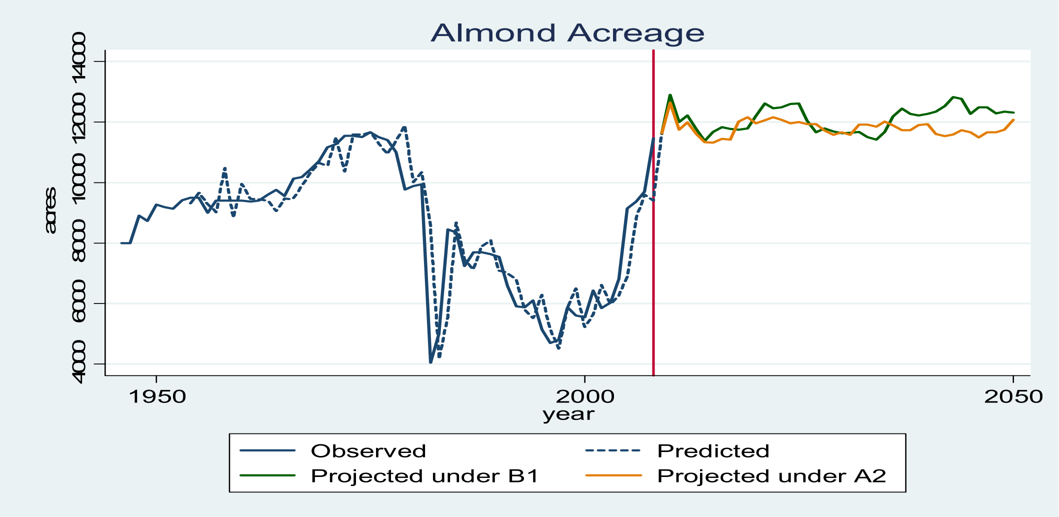


Figure 2.20c. Almond Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

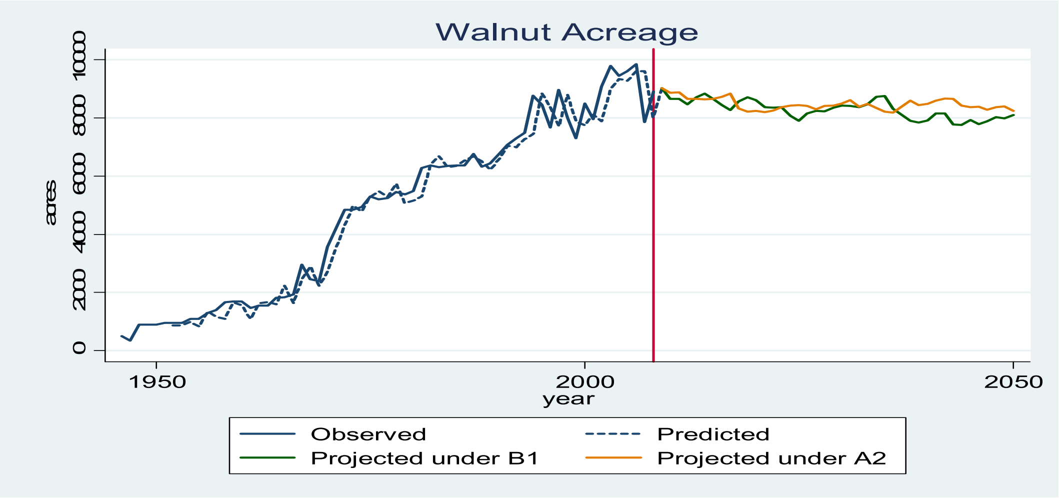


Figure 2.20d. Walnut Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

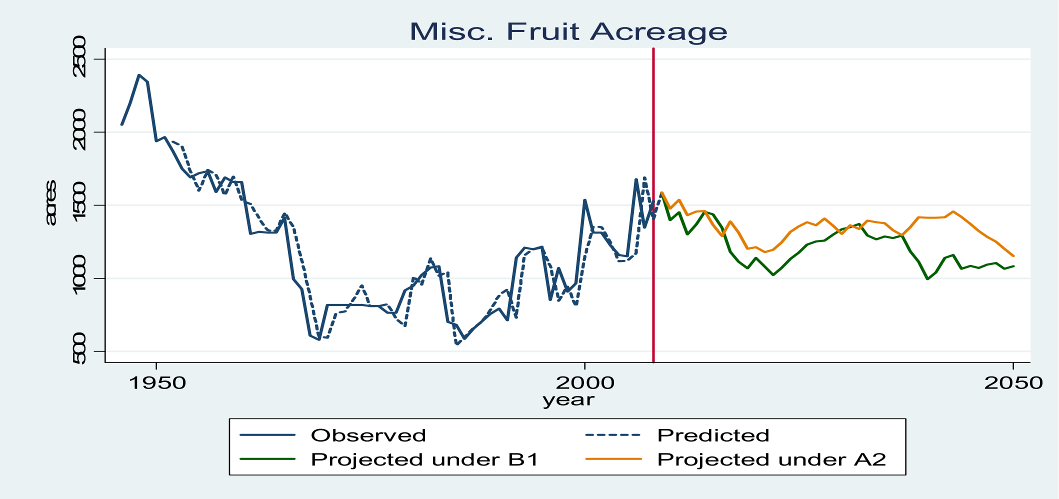
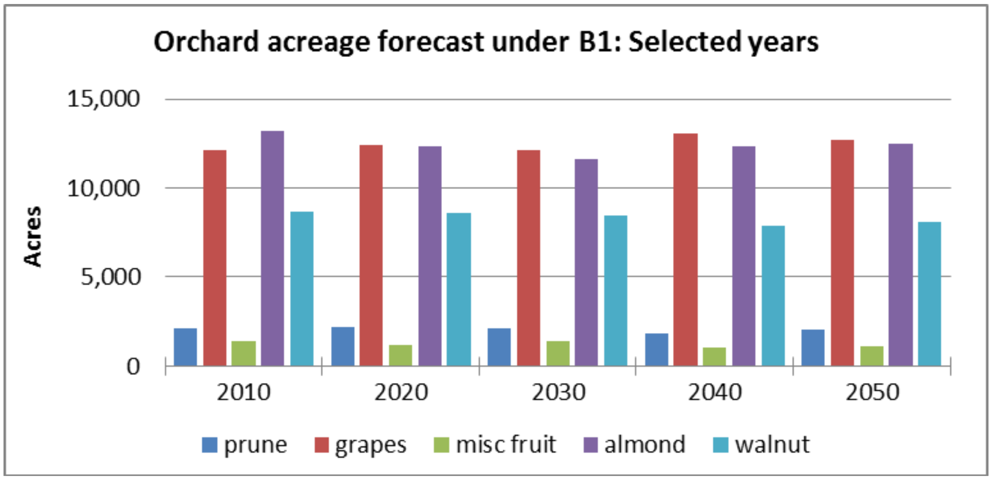


Figure 2.20e. Miscellaneous Fruit Acreage in Yolo County, in the Past and as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. The left half of the graph presents actual and projected acreage values in solid and dotted lines, respectively, and the right half presents projected acreage for the B1 and A2 scenarios for 2010–2050 using GFDL climate data. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

Almond acreage, unlike the rest of orchard crops, increases in the latter half of the projected period when winter warming occurs under the B1 scenario (Figure 2.20c). Almond has relatively a low winter chill hour requirement, and appears to be little affected by the lower chill hours that are projected. For walnut and miscellaneous fruit (Figures 2.20d and e), reduced chill hours are found to be a contributing factor, and acreage tends to decrease more under the B1 scenarios.

Figures 2.21a and 2.21b present crop specific orchard crop acreage for selected years under A2 and B1 scenarios, respectively. Only small differences exist between the two scenarios and the acreage variations over the projection period are small overall. Climate change is of second order importance in determining orchard crop acreage. For the entire projection period, total orchard crop acreage changes little, and there is little difference in acreage exists between B1 and A2 scenarios. In the second half of the projection period, the acreage reduction for prunes, walnuts, and miscellaneous fruits under the B1 scenario is offset by the acreage increase for almond and grapes. Thus, climate-induced changes in composition of tree and vine crop species are more likely than loss or gain of acreage. Reduction in the 10-year moving average of winter chill hours does not appear to be a major factor that will contribute to acreages at least until 2050, reinforcing the point that climate change is of second-order importance in determining orchard crop acreage.

Once again, it is important to keep in mind that our projections in acreage changes are driven solely by forecasts of climate indices (10-year moving averages of weather variables) with no other drivers of acreage change included in the model. Further, the effect of this future climate



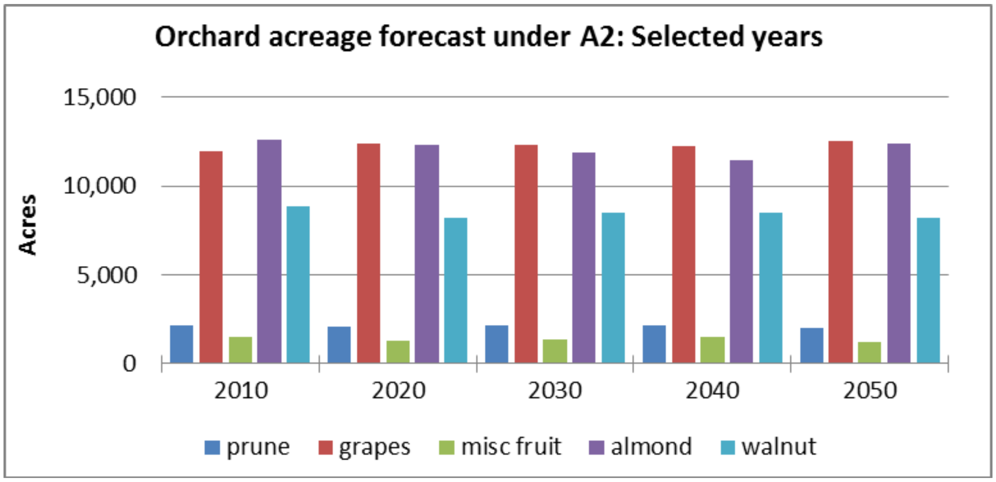


Figure 2.21. Orchard and Vine Acreage Projections by Crop and by Climate Scenario for Selected Years over 2010–2050, as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

change was evaluated based on farmers' past history on how climate expectations may have affected their acreage decisions. Thus, as with any analysis, these projection results should be understood within the model framework.

Crop Acreage Shares in 2008 and 2050

Recall that projection of climate-induced acreage changes use the relationships between climate change and acreage that were established over the past 60 years. Based on this observed behavior the projected climate-induced changes in acreage shares among crops in 2050 differ from the shares in 2008 (Figures 2.22a–c). Significant changes in acreage shares are found mainly with annual crops; particularly rice, alfalfa, wheat, and tomatoes. Under both climate scenarios, acreages of tomatoes and rice increase. The tomato share increases from 15.5 percent to up to 20.6 percent by 2050. Rice acreage increases from 12.4 percent to as much as 16.2 percent. The alfalfa acreage share increases from 23.4 percent to up to 26.1 percent. Wheat now accounts for a major share of Yolo Country crop acreage, but climate change would induce significant declines in wheat acreage by 2050. Again, these projections do not include anticipated changes in relative prices, pests, climate variability or other drivers that are not themselves driven by climate indices in Yolo County. These econometric models are based on continuing into the future with the same patterns of decisions that have influenced farmers' past history, using the 2008 starting point for crop acreages. Therefore, these projections do not include anticipated changes in relative prices, pests, climate variability, short-term extreme events in climate, or other drivers that are not themselves driven by climate indices in Yolo County.

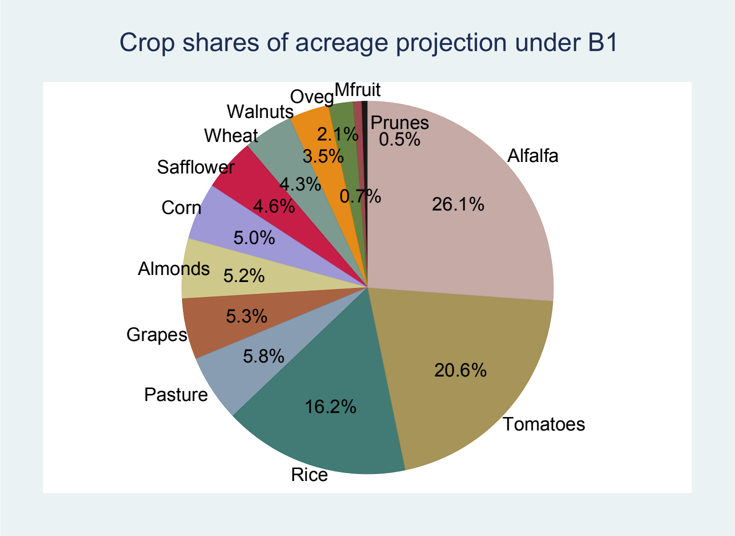


Figure 2.22a. Crop Specific Shares in 2050 Under the B1 Scenario, as Projected Based on the Estimates of an Econometric Model Using Data for 1950–2008. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

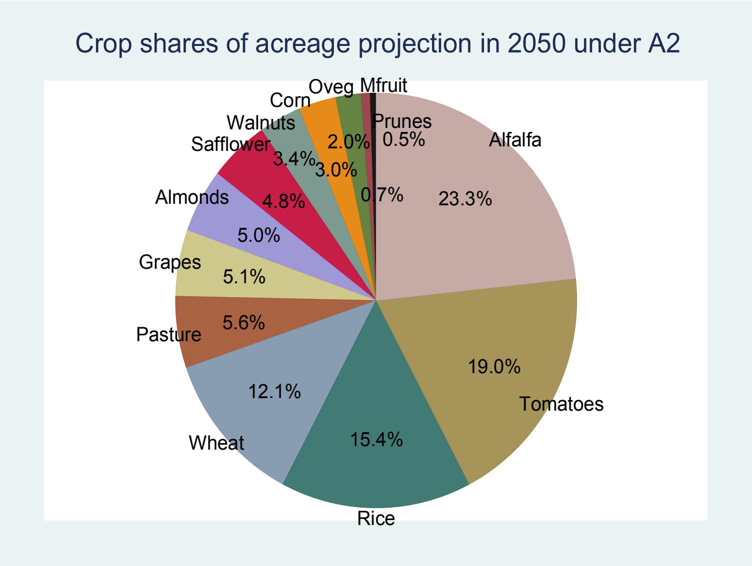


Figure 2.22b. Crop specific shares in 2050 under the A2 scenario, based on the estimates of an econometric model using data for 1950–2008. Crop acreages for 2008 are the starting point for the future modeling, and all other factors except climate are held constant until 2050.

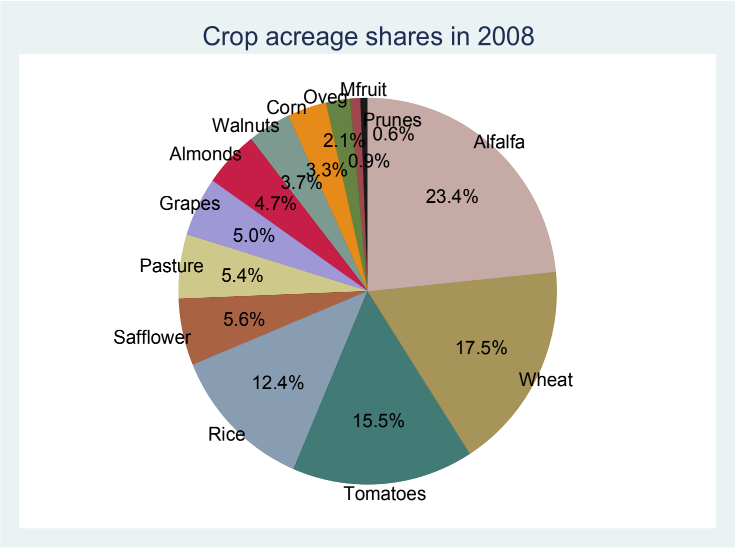


Figure 2.22c. Crop specific shares in 2008 using actual acreage in 2008

2.6. Conclusions

Our research developed unique sets of data on agricultural climate aggregates and crop acreages to establish statistical relationships between climate and the pattern of crops planted over the past six decades. Estimates of parameters that characterize these relationships guide projections about how alternative climate changes forecasted under the two (high and low) GHG emission scenarios affect acreage patterns in Yolo County from 2010 to 2050.

The agriculturally relevant climate in Yolo County has changed over the past century. Growing degree days (which is an aggregate measure of warmth over the season) have risen, especially for the winter season, while the number of chill hours (a summation of time that the temperature is below a critical value) has declined. The specific crop mix has changed over the decades, while these overall patterns have continued.

Our econometric models related acreages of each major crop to relative crop prices and key climate variables that are expressed as 10-year moving averages to represent the recent memory of growers' decision making. In general, the data indicate significant influences of prices and only moderate influences of expected growing degree days, chill hours and precipitation on acreage of individual crops. Overall the data indicate that Yolo County climate change has played a moderate role in the evolution of crop acreage in Yolo County in recent decades. The models did not investigate many other factors that affect Yolo County crop acreages, such as irrigation water effects of climate change outside Yolo County, extreme events, or the potential influence of statewide or global climate change on relative prices,.

We applied the estimated parameter values to downscaled GFDL climate projections to assess how future climate change in Yolo County may affect crop acreage patterns from 2010 to 2050. The results should not be interpreted as acreage forecasts. For example, we took no account of recent trends or expected changes in prices, technology, or other factors in projecting acreage change. Instead, we invesitgated the acreage impacts of two paths for climate change (B1 and A2 scenarios), holding constant the relative prices and other relevant drivers of crop acreage. An underlying assumption in our approach was that the basic relationships between climate and acreage that were estimated using the data from 1950 to 2008 apply to projected climate effects on acreage from 2010 to 2050.

Average temperature is projected to rise in Yolo County under both scenarios, associated with winter temperature increases and the reductions in winter chill hours. The two climate scenarios diverge for the period after 2035 with the A2 scenario cooler during this period, despite a long-term increase in temperature compared to B1. Among field crops, warmer winter temperatures (2035–2050) are projected to cause wheat acreage to decline and alfalfa acreage to rise. This led to a small projected decline in total field crop acreage and projected increase in tomato acreage. Climate change has relatively moderate impacts on projected tree and vine crop acreage. The largest impact of warmer winter temperatures is for projected wheat acreage. Using the historical relationships, climate change induces a decline in projected wheat acreage share from about 17.5 percent of crop acreage in 2008 to as low as 4 percent of acreage in 2050. Even though the projected change was significant for the acreage of certain crops, the overall impact on total crop acreage has been moderate.

Some care must be exercised in interpreting our results. Our projections focused exclusively on the using historical patterns to project relationships between acreage change and climate change. They are not year-to-year forecasts. Further, our projections were based on the statistical estimates derived solely from historic data, meaning that factors other than climate do not change from their historic values. In terms of adaptation to climate change, however, these results indicate that farmer decisions may now need to be based more on uncertainty of climate than in the past, which is not incorporated in our projection (see Section 3).

In summary, the major findings of Section 2 on historical and projected effects of climate on crop acreage in Yolo County are:

- Over the most recent 60 years, the most significant crop acreage changes in Yolo County have been the shift out of barley (especially in the 1960s), the virtual disappearance of sugar beet acreage, and a rapid rise in wine grape acreage. Other important acreage shifts include an increase in alfalfa, wheat, and walnut acreage, and decline in apricot acreage. Since the 1950s, processing tomatoes have dominated vegetable acreage in Yolo County (>90 percent of vegetable acreage), and four crops (alfalfa, tomatoes, rice, and wheat) have accounted for close to 70 percent of the total crop acreage in Yolo County.
- The annual average temperature has risen by an average of 0.02°F (0.01°C) per year over the past century (1909 to 2009). This increase in average temperature has been driven by warmer winters rather than by warmer summers, with three times larger percentage increases in the average temperature in January than that in July. Moreover, daily minimum temperatures have risen considerably, while daily maximum temperature has remained roughly constant.
- Climate warming variables deemed relevant for Yolo agriculture include growing degree days (GDD) for summer crops (April through August), growing degree days for winter and spring crops (November through May), and winter chill hours (November through February). We find that GDD in both seasons have been increasing and chill hours have been decreasing. Moreover, the increase in GDD for winter crops has been double the GDD for summer crops (annual rates of 0.18 percent and 0.09 percent). Winter chill hours, computed as a sum of daily chill hours for the entire winter season, have declined by about 1.5 hours per year over the last century.
- Statistical relationships between climate, water availability, relative prices, and crop acreage by crop reveal several significant impacts: a higher price for the crop raises acreage of rice, wheat, prunes, and grapes. More irrigation water availability raises acreage of alfalfa and corn, and lowers acreage of wheat and safflower. The increase in GDD for summer crops had little effect, but the increase in GDD for winter crops reduced wheat acreage and raised alfalfa acreage. Reduced winter chill hours decreased the acreage of prunes, miscellaneous fruits, and walnuts.
- Using historical reationships between climate and acreage allows investigation of how projected climate change in Yolo County may affect Yolo acreage patterns; the downscaled B1 and A2 IPCC scenarios are used to project changes in acreage patterns for 2010 to 2050 (holding constant other relevant drivers of crop acreage). Based on historical relationships, projections of warmer winters from 2035 to 2050 cause lower wheat acreage and more alfalfa and tomato acreage. In aggregate this implies less field crop acreage and more vegetable acreage. Projections also imply small changes in tree

and vine crop acreage over the 2010 to 2050 period. This analysis suggests that alfalfa, tomatoes, rice, and wheat will continue to dominate Yolo County crop acreage, assuming that all other factors are held constant as at present.

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Section 3: Simulating the Effects of Climate Change and Adaptive Water Management on the Cache Creek Watershed: Alternative Agricultural Scenarios for a Local Irrigation District

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3.1 Introduction

In California, demand for water from agriculture, industry, urban areas and the environment has meant that most watersheds in the state are consistently over-allocated (DWR 1998). In the near term, projections suggest that by 2020 demand for water will exceed the available supply by >2.4 million acre-feet in average rainfall years and up to 6.2 million acre-feet in dry years (DWR 1998). In the long term, climate change and population growth will place additional demands on the state's water resources (Hanak et al. 2011).While there is uncertainty regarding the extent to which climate will change in any given location, there is a growing consensus that the impacts on California's water resources will be outside the range of past experience (Kiparsky and Gleick 2003; Milly et al. 2008). Consequently, state agencies such as the Department of Water Resources (DWR) and the California Energy Commission have urged water managers at the regional, district, and local levels to examine the potential impacts of and responses to climate change as a part of their planning efforts (DWR 2008; Kiparsky and Gleick 2003).

Past climate and hydrologic records provide ample evidence that climate change is already having a measurable effect on California's water supply (Hidalgo et al. 2009). For instance, statewide weather records show that mean annual temperatures have increased by roughly 0.6–1.0°C during the past century, with the largest increases seen in higher elevations (Anderson 2008; DWR 2008). This warming trend has contributed to a 10 percent decline in average spring snowpack in the Sierra Nevada over the same period, which equates to a loss of approximately 1.5 million acre-feet of snow water storage (Barnett et al. 2008; DWR 2008). Global climate models suggest that this warming trend will accelerate, with temperatures expected to increase by 2 to 6°C by the end of this century (Brekke et al. 2008; Cayan et al. 2008; Dettinger 2006). While there tends to be less agreement among the climate models as to whether mean annual precipitation in California will increase or decrease, inter-annual variability is already on the rise and projected to increase further during the latter half of this century (Anderson et al. 2008; Cayan et al. 2008; Cayan et al. 2010). Since the relationship between precipitation and surface runoff is non-linear, a minor decrease or increase in precipitation could have disproportionate effects on the state's water supply (Cayan et al. 2008). Some of the water supply vulnerabilities for agriculture and other sectors can be mediated through traditional infrastructure improvements or alternative water policies; for instance by expanding water storage, updating levies and aqueducts, interstate transfers, modifying the existing operating rules, expanding conjunctive use or groundwater banking (Tanaka et al. 2006; Medellín-Azuara et al. 2008). Many of these supply side adaptations also have important tradeoffs, namely high capital costs and/or significant environmental impacts (Kiparsky and Gleick 2003; Medellín-Azuara et al. 2008).

Shifts in temperature and precipitation are also projected to have significant implications for the demand side of California's water balance. Higher temperatures will increase the demand for water from agriculture, as well as the losses associated with water storage, delivery and irrigation. Since agriculture accounts for approximately 80 percent of California's water use, methods to manage and minimize agricultural water demand are seen as an important way to adapt to climate change (Levite et al. 2003; Joyce et al. 2006; Joyce et al. 2010). Local conservation strategies implemented by water managers and agricultural users tend to also be more economical than developing new supplies (Kiparsky and Gleick 2003). Demand management options may include water pricing and markets, allocation limits, improved water use efficiency, public and private incentives for irrigation technology adoption, reuse of tail-water, shifting to less water-intensive crops, and fallowing (Tanaka et al. 2006).

The degree to which climate change will impact both water resources and agriculture is likely to vary considerably throughout California (Cayan et al. 2008). Thus, for climate impact assessments to be useful they must be conducted at a scale which is fine enough for regional and local water managers to integrate research findings into their planning and adaption efforts. One tool that has helped water resource managers integrate climate change projections into their decision making process is the Water Evaluation And Planning (WEAP) system (Yates et al. 2005a; Yates et al. 2005b; Purkey et al. 2007). WEAP is a modeling platform that enables integrated assessment of a watershed's climate, hydrology, land use, infrastructure, and water management priorities. In California, WEAP has been used to model the impact of various climate change, land-use and adaptation scenarios on the Sacramento and San Joaquin River Basins (Joyce et al. 2006; Joyce 2009; Purkey et al. 2008). Likewise, Mehta et al. (2011) used WEAP to evaluate potential climate warming impacts on hydropower generation in the Sierra Nevada. Joyce et al. (2010) combined these regional models into a statewide WEAP application that is being used for integrated scenario analysis by the California Department of Water Resource. While these large-scale hydro-climatic models have proven useful for state and regional water managers, their spatial resolution is often too coarse to be of immediate value to local irrigation districts. The WEAP framework has the potential to address this limitation by developing local applications that use more refined input data (e.g., downscaled climate sequences, stream flow records, land-use patterns, infrastructure) and greater spatial disaggregation. Models developed at the district scale would also provide an opportunity to improve communication between water managers and climate scientists, cultivate a better understanding of the risks and uncertainties, and ultimately enhance the community's capacity to adapt (O'Conner et al. 1999; Dow et al. 2006; Kiparsky and Gleick 2003).

In this study we use WEAP to build a hydrologic model of the Cache Creek watershed and to assess the potential effects of climate change and adaptive management on the water resources dispensed by Yolo County Flood Control and Water Conservation District. This district was chosen for several reasons. First, most studies examining climate impacts on the state's water resources have focused on watersheds fed by the Sierra Nevada, while those originating in the

Coast Range have received little attention. Examining the Cache Creek watershed therefore provides an opportunity to investigate how watersheds that are not reliant on Sierra Nevada snowmelt may be affected by climate change. A second reason is that Yolo County is the site of an ongoing interdisciplinary case study on agricultural adaptation to climate change carried out by the University of California at Davis and the California Energy Commission. As such, the hydro-climatic analysis is further informed by locally relevant agronomic and socioeconomic data. While several integrated water management plans have been formulated for the District over the past decade (Borcall and Associates Inc. 2000; WRA 2005; WRA 2007; WRIME 2006), our work adds value in several ways. Unlike past studies, we simulate the hydrology of the catchments in Lake County which form the headwaters of Cache Creek. Since this analysis is conducted at the district scale, we are also able to capture the explicit operating rules and legal decrees (e.g., Solano Decree for Clear Lake) which govern local water management decisions. We then use downscaled climate projections (GFDL-BCCA) from two IPCC emissions scenarios (A2 and B1) to simulate the District's future water supply and projected demand under one baseline and three hypothetical adaptation scenarios.

3.2 Study Area

Between 1970 and 2008, total irrigated agricultural area in the county averaged 332,000 acres, varying between a maximum of 395,000 acres in 1980 and a low of 280,000 in 1982 (YCAC, various years). As indicated in the economics section above, there has been an overall downward trend in total agricultural area. The county covers a portion of two geomorphic provinces: the Coastal Range and Central Valley. Surface water supply comes from a number of drainages: the eastern and northern parts of the county depend on the Sacramento River, Colusa Basin Drain, and Yolo Bypass, while the western part depends on Cache Creek (with minor contributions from Willow Slough). Most of the water in Putah Creek supplies neighboring Solano County. Agriculture accounts for almost 95 percent of the approximately 1 million acre feet of the county's total water demand. About 70 percent of that water is estimated to be supplied by surface water; the remaining is pumped from groundwater (but pumping is not monitored) (WRA 2005).

The Yolo County Flood Control and Water Conservation District (henceforth, "the District") service area covers 41 percent of the county's irrigated area and is located in the western and central portion of the county (Figure 3.1). The District was established in 1951 and supplies surface water for irrigation from Cache Creek. The upstream reaches of the Cache Creek watershed are wetter and cooler than the valley floor. For example, average (1971–2000) annual rainfall and temperature in areas upstream of Clear Lake are 988 (±386) millimeters (mm) and 13.3 (± 0.56)°C respectively, compared to 560 (+/- 223) mm of precipitation and 16.5 (±0.65)°C respectively in the valley. Snow does not occur in the watershed, except intermittently in high elevations. Upland soils to the west are well drained but shallow to bedrock composed of marine shales, siltstones, and sandstones. Lowland soils are part of alluvial fans, underlain by the Tehama formation (DWR 2006). In the District, alfalfa, tomatoes, wheat, almonds, walnuts, wine grapes, and rice are the dominant crops.

Two reservoirs located upstream in neighboring Lake County are critical for District water deliveries: Clear Lake and Indian Valley. The District purchased water rights from Lake County in 1967, amounting to a maximum of 150,000 acre feet annually. The actual amount available for District release in any given year is strictly controlled by the stipulations of the Solano Decree (Solano Decree 1978) (described below). In 1976, the Indian Valley reservoir was completed. Since it is owned and operated by the District, it allows greater flexibility in supplying water to its downstream customers. Water is delivered to customers via a network of canals and ditches downstream of Capay diversion dam. The District does not own or operate any groundwater wells for the purpose of meeting customer demands. However, many privately owned wells exist throughout the District, and landowners rely on these wells for domestic purposes and to add flexibility to their farming operations. The groundwater basin experienced some depletion of storage in the 1960s and early 1970s. The increased storage and provision of surface by Indian Valley Reservoir has been identified as a key factor in the recovery of groundwater levels in Yolo County in recent decades (Borcalli and Associates Inc. 2000).

The Clear Lake release schedule (1978 Solano Decree, modified 1995) specifies how much water is available annually and monthly to the District during the peak agricultural season from April to September. The decree's "Quantity" criteria sets allowable seasonal withdrawal limits (ASW) based on April 1 (with a revision on May1) water levels recorded at Rumsey, known as the *Rumsey gauge.* If the Rumsey gauge is at or above 7.54 feet, then 150,000 acre feet of water is available for the growing season from April 1 to October 31. Monthly percentages of the ASW are available for release each month. If Rumsey levels are below 3.22 feet, no water can be released that year apart from flood flows. For in-between levels, ASW are set in the release schedule that increases to a maximum of 150,000 acre feet in what is known as the quantity criteria. As per these stipulations, the District did not make any releases in the severe drought of 1976–1977, as well as in 1990 at the end of several dry years. The Solano Decree also stipulates "Stage criteria" that set limits to drawdown, posing an additional constraint to the District's withdrawal of water in any given month. Clear Lake releases in the winter are also controlled by the 1920 Gopcevic Decree for flood control operation. The highly controlled nature of this lake can be attested by the historical monthly average lake levels which have varied only 5.7 ft on average (1970–2000) within a water year, with a maximum range of 10.9 ft and a minimum of only 2.3 ft.

3.3 Methods

Hydrology Routines in WEAP

The WEAP software consists of modules for simulating hydrology and infrastructure operations (Yates et al. 2005a; Yates et al. 2005b). WEAP's rainfall-runoff hydrology routine consists of a lumped, one-dimensional, two-storage soil water accounting that uses empirical functions to describe evapotranspiration, surface runoff, interflow, and deep percolation. Additionally, WEAP provides three routines for handling groundwater: a connection to MODFLOW models if available, a groundwater-surface water interaction routine, and a simple linear reservoir representation of groundwater in which percolation from the top soil layer recharges the groundwater reservoir. The surface hydrological balance is typically performed by discretizing the model area into hydrologic response units which in WEAP are referred to as "catchment" objects. Multiple catchment objects can recharge a single or several groundwater objects. Details on the specific routines for the hydrologic balance, infrastructure operations, and allocation are provided in Yates (1996) and Yates et al. (2005b).

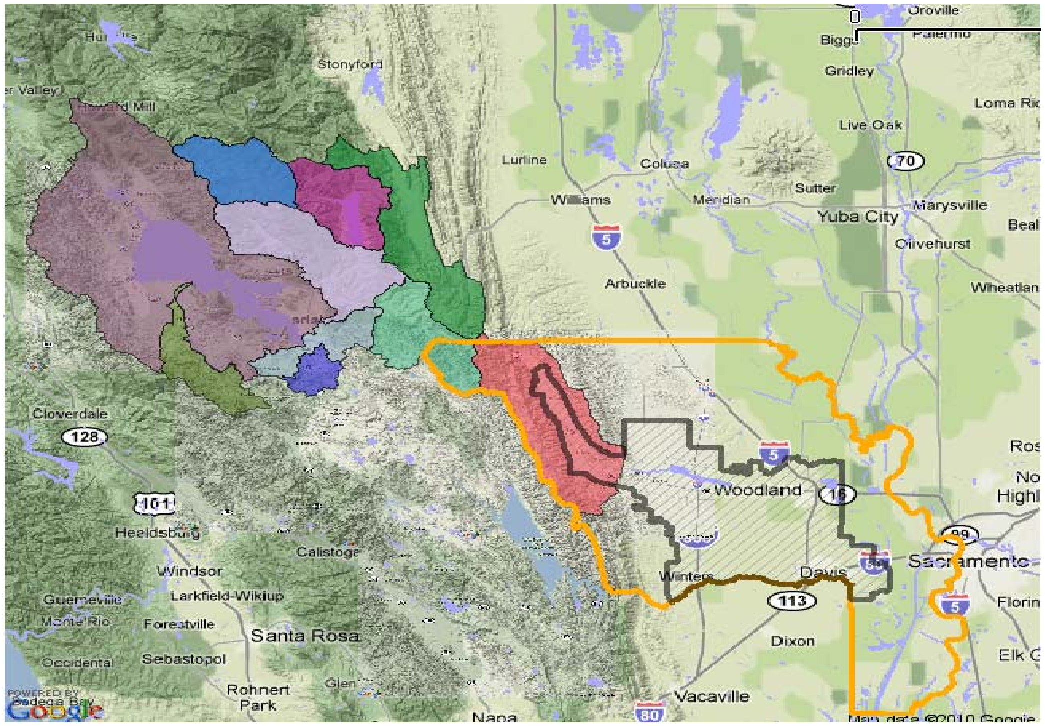

Figure 3.1. Map of the Study Area Modeled Using WEAP. Colored polygons are independently characterized catchments. The hatched polygon is the Yolo County Flood Control and Water Conservation District.

Model Build and Verification over the Historical Period

The Cache Creek model, run at a monthly time step, uses climate and land cover information to simulate the water balance. It uses the results to simulate the management of Clear Lake and Indian Valley Reservoirs and water supply for irrigation downstream. The model simulates irrigation demand for 20 crop types within Yolo County, which is met through surface (higher priority) and groundwater sources (lower priority). The model was calibrated to a historical run from 1971–2000, which formed the baseline scenario. The calibrated model was then run under various combinations of climate and agricultural land use (i.e., crop proportions) projections as described below.

Figure 3.1 shows the study area along with the spatial discretization of the model. The spatial domain of the model covers 5027 square kilometers (km^2) and includes the Cache Creek watershed up to Capay (colored polygons), and all of Yolo County. The focus of the irrigation water demand and supply analysis is on the District service area (the hatched polygon), although the model can also simulate irrigation demand for the rest of the county. Table 3.1

summarizes each catchment's characteristics. A water balance simulated for each catchment. Spatial data on elevation, watersheds, and land use were acquired and used to define and characterize each catchment. Elevation data were extracted from the Digital Elevation Model (DEM) provided by the U.S. Geological Survey. Land cover information was assembled from two sources. For the non-agricultural landscape, the National Landcover Data Set (NLCD) was used (Homer et al. 2007). For the agricultural areas, county reports and DWR Land Use Surveys were used (YCAC, various years; DWR 1997). Upstream catchments were aggregated from the DWR watersheds layer. This aggregation was based on climate considerations, the locations of major infrastructure (reservoirs), in-stream flow requirements, and flow gauges. Historical monthly climate data were averaged for each catchment from a gridded dataset (Maurer et al. 2002).

Hydrology

Parameters of the rainfall-runoff module were calibrated against the longest available continuous data from gauges in unimpaired watersheds. These were at Kelsey Creek (WY 1975–WY 2000) and Hough Springs on the north fork of Cache Creek (WY 1975–WY 1994), in the headwaters of Clear Lake and Indian Valley, respectively. Goodness of fit metrics (bias and Nash-Sutcliffe index [Nash and Sutcliffe 1970]) were computed for each set of simulated and observed hydrographs.

Two groundwater objects were defined and conceptually aligned to the groundwater sub-basins delineated by DWR: one below Capay Valley receiving recharge as infiltration from the Capay Valley catchment, the other below the Yolo Valley floor, receiving recharge from the catchments downstream of Capay. Our model's treatment of groundwater is similar to the Central Valley application (Joyce et al. 2010). It is capable of relative comparison among scenarios of groundwater recharge (from infiltration and conveyance leakage) and extraction volumes, but not of simulating absolute groundwater depths.

Infrastructure and Operations: Reservoirs and Conveyances

The model simulates the operations of Clear Lake, Indian Valley, and the water delivery through canals. Detailed description of how WEAP simulates reservoir releases through conservation storage and flood rules is available in Yates et al. (2005b). Reservoir physical characteristics (e.g., storage capacities, volume-elevation curves) were obtained from California Department of Water Resouces California Data Exchange Center (CDE) and the District. Indian Valley operating rules (flood rules and priorities) were obtained from the District. Clear Lake operating rules were obtained from the District, and from documentation of the Solano and Gopcevic Decrees described earlier (See "Study Area"). Details, including the stepwise procedure on implementing the Solano Decree, are available in public documents and through the District. Clear Lake releases during the wet season are controlled by the Gopcevic Decree, for which target storage levels come into play from January to March. These target storages were set as WEAP's "Top of Conservation" in the model's Clear Lake reservoir object. The second operating constraint, also from the Solano Decree, is its stage limitation criteria. These criteria were programmed and set as "Top of Buffer" in the reservoir object. The third constraint is the hydraulic capacity of Clear Lake's outlet channel. Hydraulic capacity varies by the stage; data obtained from the District was used to develop a hydraulic capacity constraint as a function of stage. This expression was set as a hydraulic constraint on the releases from Clear Lake in the model. Outlet flows were then constrained to be a minimum of the hydraulic capacity constraint, and the allowable monthly withdrawal as determined by the Solano decree's Quantitative criteria—the latter also entirely encoded within WEAP.

Clear Lake does not provide carryover storage for irrigation demand. Although Indian Valley does provide carryover storage, typically it is operated with no carryover storage (Borcall and Associates Inc. 2000). In general, the District attempts to utilize all its Clear Lake allocation each year. This means that Clear Lake usage is prioritized over Indian Valley as much as possible. In the model's setting of supply priorities, this translates to a lower filling priority for Clear Lake over Indian Valley. Simulation of reservoir operations was verified by comparing simulated versus observed reservoir levels.

The District's main conveyance is in the form of 175 miles of mostly unlined canals and arterial ditches that run off the West Adams and Winters Canals from Capay Diversion Dam on Cache Creek. In the model, these conveyances are aggregated into a single transmission link object, with capacity set to the total distribution's capacity of 750 cubic feet per second (cfs), and with an estimated leakage of 40 percent of conveyance flows obtained from calibration attempts and informed by District estimates of mass balances (Borcall and Associates Inc. 2000).

Historical Crop Acreage and Irrigation Water Demand

Seventeen crop categories were modeled for the catchments dominated by agriculture. Table 3.3 lists the different crop categories considered along with county-wide acreages from four selected years. The crop categories are informed by DWR's irrigated crop acres and water use portfolio,[11] taking into consideration both the crop categories and corresponding acreages available through the county reports as well as estimates of the District scale cropping pattern. An annual time series of total irrigated acreage and irrigated crop areas was assembled at the county level (YCAC, various years). Individual crop acreages were spatially distributed among the four agricultural catchments using GIS datasets available for 1989 and 1997 through the DWR Land Use Surveys (DWR 1989; DWR 1997). This allowed a cropping pattern to be represented in the model for the historical period for each agricultural catchment.

Each crop's irrigation water needs were simulated using crop-specific crop coefficients, irrigation schedules, and irrigation thresholds. Crop-specific parameters pertaining to irrigation were adapted from the Central Valley application by Joyce et al. (2011), who calibrated the crop and irrigation parameters at the spatial scale of the DWR Planning Area level against four

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[11] DWR. irrigated crop acres and water use. http://www.water.ca.gov/landwateruse/anaglwu.cfm#.

Table 3.1. Characteristics of the Catchments Used to Discretize the WEAP Model of the Cache Creek Watershed

ID	Area (km^2)	Catchment	Description	Dominant land use
CC-01	150	Upper Indian Valley	Twin Valley and Bartlett Creeks	Forest
CC-02	162	Middle Indian Valley	Spanish Creek and Indian Valley Reservoir	Forest
CC-03	268	Lower Indian Valley	Wolf, Long Valley, Hog Hollow and Grizzly Creeks to confluence with Cache Creek	Forest
CC-04	115	Kelsey Creek	Kelsey Creek	Forest
CC-05	1149	Clear Lake	Clear Lake except Kelsey Creek, Copsey Creek and Siegler Canyon	Forest, grassland, some urban
CC-06	45	Copsey Creek	Copsey Creek	Forest, grassland
CC-07	93	Seigler Canyon	Seigler Canyon which ends below gauge at confluence with North Fork	Forest
CC-08	183	Upper Cache Creek	From North Fork confluence to Bear Creek confluence, including Rocky and Davis Creek	Forest
CC-09	266	Bear Creek	Bear Creek to confluence with Cache Creek	Forest, grassland
CC-10	349	Capay Valley	Capay Valley to Capay Diversion Dam	Forest, grassland, some agriculture
YC-01	186	Willow slough	Willow Slough headwaters outside District service area	Grassland, forests
YC-02	753	YCFCWCD Lower	District service area below Capay Dam	Agriculture
YC-03	1308	Yolo East	Yolo County portion outside District service area	Agriculture

annual estimates of applied water published by DWR for 1998,1999, 2000, and 2001 (i.e., DWR portfolio cropping pattern).

In our model, we also used DWR portfolio data available for the same years, but at a finer spatial level—the Detailed Analysis Unit (DAU). The irrigation threshold parameter in WEAP was calibrated for each crop to match DWR's applied water estimates for 1998, 1999, 2000, and 2001 for the DWR's Lower Cache Creek DAU (ID 162) which closely follows the county boundaries. Figure 3.2 presents the calibrated irrigation schedules and thresholds for each crop.

The model's estimation of water demand represents a departure from the operations of the District. The District solicits water demands from its customers every year in March, and then decides by April how much total quantity will be available. This decision is based on water levels in the two reservoirs and a projection of the season ahead. Since our goal was to look to the future, we used a simulation approach instead of hard-coding the historical demand based on the District's historical roster. The latter would not have provided us the means of projecting demand into the future.

Adaptation Scenarios Based on Climate, Land Use, and Irrigation Technology Projections

Three types of future projections were investigated: climate, land use, and irrigation technology. To characterize future climatic conditions of the study area (present–2099) we used projections from a global climate model produced by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Dynamics Laboratory; referred to here as the GFDL CM2.1 (Delworth et al. 2006; Knutson et al. 2006). Climate sequences from the GFDL model were generated for two greenhouse gas emissions scenarios: A2 (medium-high emissions) and B1 (low emissions), which have been outlined previously by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic and Swart 2000). Monthly climate data (temperature, precipitation, wind speed, and humidity) were downscaled and extracted for each of the 13 catchments in the watershed using the Bias Corrected Constructed Analog (BCCA) method, which was chosen due to its superiority amongst other downscaling methods (Maurer et al. 2010). The GFDL model is one of several that were used in the IPCC Fourth Assessment, and has been found to produce a realistic representation of California's recent historical climate, as well as the spatial distribution of temperature and precipitation within the region (Cayan et al. 2008). Relative to other global climate models, the GFDL model is generally more sensitive to greenhouse gas forcing processes (Cayan et al. 2006). Consequently, the climate projections produced for California using the GFDL model tend to be warmer and drier than other models (Cayan et al. 2008). For these reasons, the GFDL model is useful for long-term planning to address plausible extremes in the future climate of California.

Two projections of agricultural land use were developed to evaluate the potential for future adaptation to climate driven changes in water availability by shifting local cropping patterns. The first projection is based on an econometric analysis of cropping area trends in Yolo County (see Section 2). To summarize briefly, time series models were developed for individual crops in

Table 3.2. Historical Crop Proportions and Average Annual Irrigation Demand by Crop Type for Yolo County's Irrigated Agricultural Area. Irrigation demand estimates simulated using WEAP are compared to Department of Water Resources (DWR) portfolio data at the detailed analysis unit scale.

	Historical Crop Proportions				Average Annual Irrigation Demand 1998–2001	
Crop Type	1980	1990	2000	2008	DWR	WEAP Model
	---------- % irrigated area ----------				----- acre feet -----	
Grain	37.3	25.3	18.3	19.2	1.2	1.1
Alfalfa	4.7	10.5	11.6	17.5	5.3	5.2
Other Field	6.6	12.0	12.0	16.4	2.5	2.3
Tomatoes	14.2	17.3	14.5	11.6	3.1	3.1
Rice	9.9	7.3	10.8	9.3	5.4	5.3
Vine	0.2	0.8	3.4	4.2	1.9	1.9
Safflower	1.9	8.0	7.3	4.2	0.7	0.7
Pasture	4.6	3.8	3.9	4.0	5.7	5.4
Other Deciduous	2.6	3.0	4.0	3.9	4.2	4.2
Almond	2.7	2.2	1.7	3.5	4.3	4.3
Other Truck	0.3	1.0	1.2	3.4	4.2	4.1
Corn	10.1	4.4	8.4	2.5	2.9	2.8
Cucurbits	0.0	1.5	1.3	0.4	1.7	1.7
Sugarbeets	3.9	2.0	0.3	0.0	3.1	3.1
Dry Beans	1.2	1.0	0.0	0.0	3.0	3.0
Cotton	0.0	0.0	1.2	0.0	2.3	2.4
Subtropical Orchards	0.0	0.0	0.0	0.0	4.1	4.1

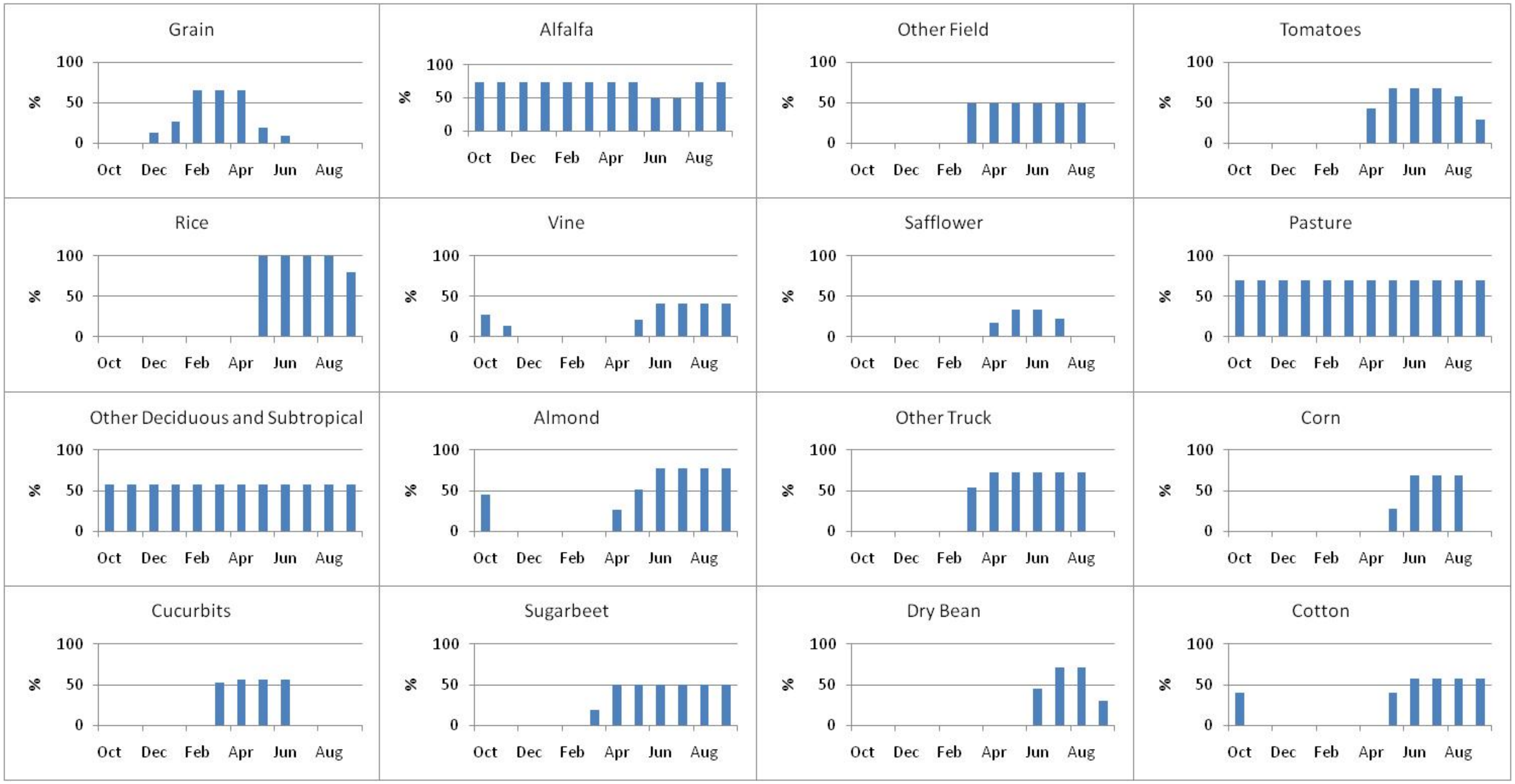

Figure 3.2. Irrigation Schedules and Thresholds (%) for Each Crop Type Used to Simulate Irrigation Demand During the Historical Period

Yolo County based on the relationship between historical crop acreage, a set of economic variables (e.g., commodity prices), and climate variables (e.g., temperature, precipitation, growing degree days, chilling hours).

To forecast cropping area from the present to 2050, climatic variables were calculated from daily climate projections for the A2 and B1 scenarios generated by the GFDL climate model described above. The second land use projection was based on a hypothetical scenario envisioning an agricultural landscape which adapts to climate change in two ways: (1) by allocating a smaller fraction of land to crops that require large amounts water; and (2) by increasing crop diversity. For example, the acreage of rice, alfalfa, and other water intensive field crops were gradually reduced to the lows observed during a period of severe drought in the mid-1970s (Figure 3.4). Likewise, an increase in crop diversity over time was simulated by progressively allocating a larger fraction of land to vineyards, winter grains, almonds, deciduous orchards, subtropical orchards, tomatoes, cucurbits, and truck crops (Table 3.3). Since this crop diversification projection is a hypothetical construct, rather than a statistically derived forecast, a future time frame of 2009–2099 was used. It should also be noted that this approach assumes gradual changes in crop acreage and did not attempt to capture the year to year variability reflected in the historic record.

Statewide there has been a notable shift in irrigation methods from surface water applied using flood or furrow irrigation towards low-volume sprinkler and drip irrigation, particularly for vegetable crops, orchards, and vineyards (Orang et al. 2008). These methods can potentially reduce soil evaporation and applied water (Kallenbach et al. 2010). Furthermore, a recent survey of grower perspectives on water scarcity and climate change in Yolo County indicates a strong inclination to expand their use of drip and low-volume irrigation among local farmers (See Section 5). Likewise, incentive programs to promote adoption of improved irrigation technology are seen as a politically feasible water demand management strategy. However, one criticism is that, in some watersheds, such policies have failed to curtail groundwater extraction as some farmers use the “water savings” to expand irrigated acreage or grow more water-intensive crops (Pfeiffer and Lin et al. 2009; Ward and Pulido-Valazquez 2008). As such, we included a conceptual scenario which assumes that irrigation technology and efficiency will continue to improve in coming decades but overall irrigated acreage in the district will not. We reflect these trends in the model, by decreasing the irrigation threshold parameter, in a manner similar to the work of Joyce et al. (2006) and Purkey et al. (2008). Beginning in 2010, irrigation thresholds for each crop, except for wine grapes, winter grains, and safflower, were assumed to decrease linearly so that by 2099 they reached 70 percent of the historic reference threshold. For the latter crops, no change in water-saving irrigation technologies was assumed because vineyards are already on drip irrigation, winter grains are mostly supplied by rain and stored soil water, and safflower is already a low water consuming crop.

These projections were combined into four scenarios to investigate the potential effects of climate change and adaptation as follows:

Table 3.3. Future Land Use Projections by Crop Type in Yolo County's Irrigated Agricultural Area. The econometric projections (used in Adaptation 1) are based on downscaled climate data from the GFDL general circulation model for the B1 and A2 emissions scenarios. The hypothetical land use projections (used in Adaptation 2 and 3) assume a more diverse cropping pattern and gradual shift towards crops that require less water.

	Historic	Econometric Projections				Hypothetical Land Use Projections			
		GFDL B1		GFDL A2					
Crop Type	2008	2025	2050	2025	2050	2025	2050	2075	2099
	-- % of irrigated area --								
Grain	19.2	18.8	17.5	18.8	18.2	20.3	21.9	23.5	25
Alfalfa	17.5	17.4	19.9	17.3	18.8	15.0	11.3	7.6	4.0
Other Field	16.4	16.2	14.9	16.0	15.5	13.5	9.3	5.1	1.0
Tomatoes	11.6	12.6	13.7	12.4	13.5	12.1	12.7	13.4	14.0
Rice	9.3	10.8	10.7	10.2	10.9	8.3	6.9	5.4	4.0
Vine	4.2	3.8	3.6	3.7	3.7	5.3	6.9	8.5	10.0
Safflower	4.2	4.4	2.9	5.4	3.1	3.8	3.2	2.6	2.0
Pasture	4.0	3.7	3.6	3.9	3.7	4.0	4.0	4.0	4.0
Other deciduous	3.9	3.4	3.1	3.6	3.3	4.1	4.4	4.7	5.0
Almond	3.5	3.7	3.5	3.5	3.6	4.2	5.1	6.1	7.0
Other truck	3.4	3.4	3.1	3.4	3.3	4.1	5.1	6.1	7.0
Corn	2.5	1.5	3.0	1.3	1.8	3.9	6.0	8.0	10.0
Cucurbits	0.4	0.4	0.4	0.4	0.4	0.7	1.1	1.6	2.0
Sugarbeets	0	0	0	0	0	0	0	0	0
Dry beans	0	0	0	0	0	0	0	0	0
Cotton	0	0	0	0	0	0	0	0	0
Subtropical	0	0	0	0	0	0.9	2.3	3.7	5.0

1. Climate only: The potential impacts of climate change alone, under the two IPCC emission scenarios (GFDL B1 and A2). Land use is held constant at the 2008 pattern. *What is the likely impact of climate change only?*

2. Adaptation 1 (Climate and dynamic cropping): These correspond to the econometric model that simulates future cropping patterns based on the B1 and A2 climate sequences. *What is the combined impact of climate change and a cropping pattern adaptation driven by similar forces as the past?*

3. Adaptation 2 (Climate and crop diversification): These correspond to a run of the hypothetical diversified cropping pattern, under the two Climate only scenario runs. *What is the adaptive potential of a diversified cropping pattern dominated by increasing proportions of low-water consuming crops?*

4. Adaptation 3 (Climate, crop diversification and technology): This corresponds to a run of the diversified land used projection from Adaptation 2 and the irrigation technology projections described in the paragraphs above. *What is the combined adaptive potential of a diversified cropping pattern (as in 3) plus water-conserving irrigation technology improvements?*

3.4 Results and Discussion

Model Performance over the Historical Period

Unimpaired hydrology

Unimpaired hydrology was simulated reasonably well in Kelsey Creek and Hough Springs, located upstream of Clear Lake and Indian Valley, respectively (Figure 3.3a and 3.3b). At Kelsey Creek, monthly flows from WY 1975–2000 were simulated with a bias of 2 percent, Nash-Sutcliffe of 0.65 and $R^2 = 0.78$ ($n = 300$ months). At Hough Springs, monthly flows from WY 1975–1994 were simulated with a bias of 2.2 percent, Nash-Sutcliffe of 0.55 and $R^2 = 0.67$ ($n = 228$ months).

Reservoir levels

Figure 3.3c shows simulated and observed reservoir storage volumes for Clear Lake and Indian Valley. Clear Lake storage simulations were excellent with a bias of -1.9 percent and $R^2 = 0.87$ ($n = 840$ months from WY 1970–WY2005). The model was adept at simulating severe 1976–1977 droughts, as well as the successive dry years of the late 1980s. Indian Valley storage was also simulated well with a bias of 4.3 percent and a $R^2 = 0.70$ ($n = 720$ months from WY 1976–WY 2005).

Irrigation water demand

Table 3.2 provides a comparison of each crop’s simulated average annual irrigation demand from 1998–2001 in the District’s service area below Capay Dam, against DWR’s portfolio data for DAU 162 (Lower Cache Creek). The mean deviation of the model across all crops was only 0.2 percent: the mean absolute deviation was 2.7 percent. This calibration leads to a District-wide estimate of total annual average irrigation demand of 380,875 acre feet over the historic period (1971–2000). The model estimated that on average groundwater supplied 49 percent of irrigation demand over the same period. This corresponds well with the District's water management plan and local water resource managers who estimate that 50 percent of demand is met by groundwater (M. Stephenson, personal communication). However, two important points should also be noted. First, supply from groundwater varies substantially year to year (e.g., coefficient of variation is 50 percent, with a maximum above 80 percent during the severe drought of 1976–1977). Second, post-Indian Valley construction, the dependence on groundwater has eased (DWR 1987). Hence on average, groundwater supplied 43 percent of irrigation demand from 1978–2000. For the county as a whole, simulated irrigation demand for 1971–2000 averaged 1.04 million acre feet (data not shown).

Climate and Adaptation Scenarios

The District's annual temperature and precipitation during the historic and future periods are summarized in Figure 3.4 and Table 3.4. The B1 and A2 climate projections are warmer and drier than the historical period. The A2 emissions scenario (medium to high emissions) diverged from B1 after mid-century, and projected somewhat warmer temperatures thereafter (Figure 3.4; Table 3.4). Both projections also show a decrease in precipitation after mid-century.

Surface water supply

The Solano Decree presents a hard limit of 150,000 acre-feet from Clear Lake releases for the District's use. Since April 1 lake levels recorded at the Rumsey gauge are the primary determinant of ASW from Clear Lake releases, they can be used as an indicator of surface water availability for the District. Table 3.5 shows that during the historic period, April 1 Rumsey gauge levels were less than 7.56 feet during 18 of 30 years and thus below what is required for full allocation. The model records for Hough Springs, Kelsey Creek, and Indian Valley do not cover the entire historical period.

Relative to the historic period, the model projected a lower frequency of shortfalls in response to the climate-only scenarios (B1 and A2) in the near and mid term. The climate change only scenarios did, however, result in more frequent shortfalls in the far term (Table 3.5). Since water demand is low in April, the lake levels are largely a hydrologic response to intra-annual variability in climate. As such, adaptation scenarios generally differed little from climate change only scenarios in the frequency of years below full allocation (± one yr). Notable exceptions are Adaptation 2 and 3 scenarios during the far term of B1, which had slightly lower frequency relative to the climate-only scenario (a difference of two and three years, respectively). How these downstream adaptation scenarios might have influenced Clear Lake storage levels remains unclear.

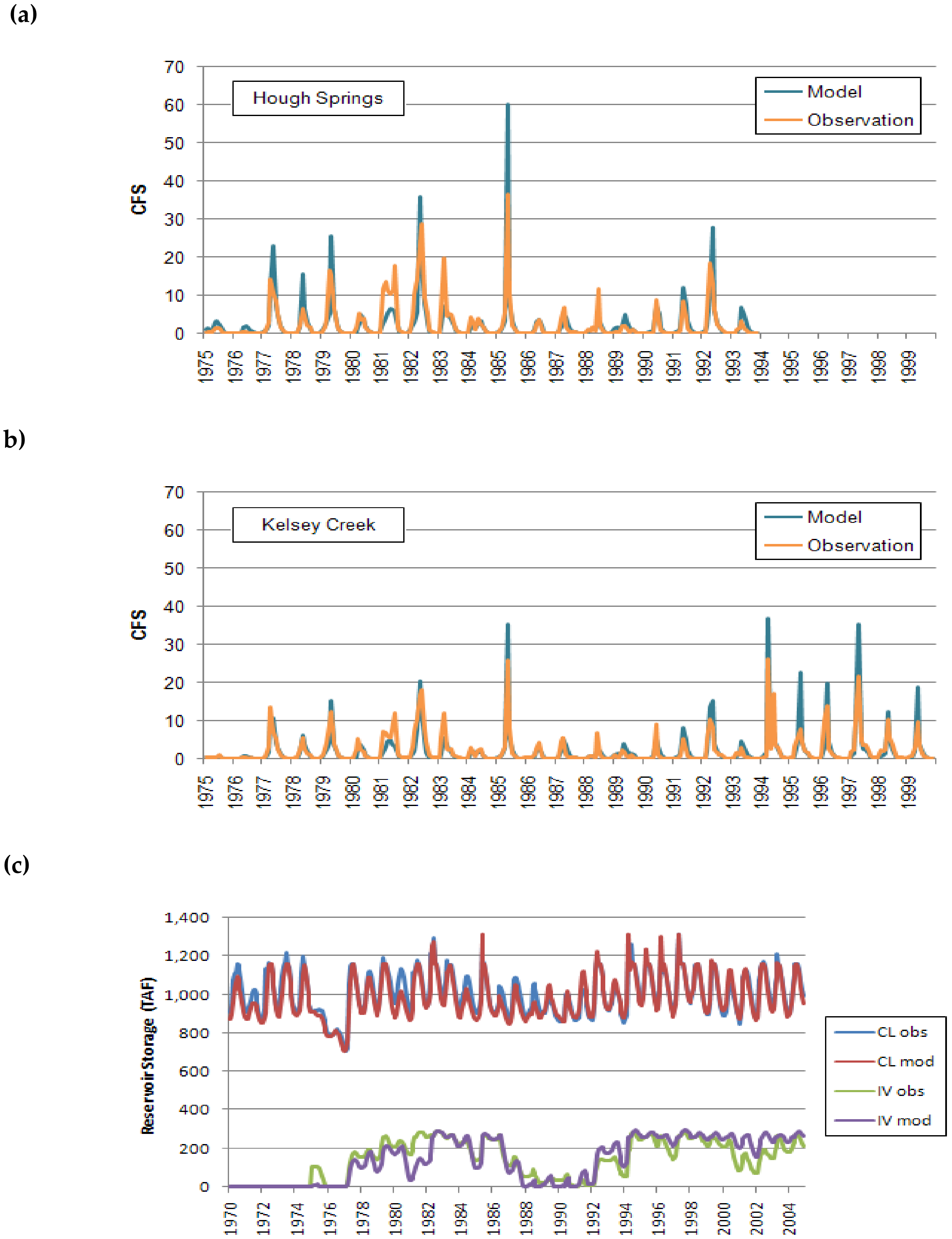

Figure 3.3. Observed and Modeled Stream Flow Hydrographs (cubic feet per second) for (a) Hough Springs and (b) Kelsey Creek and Reservoir Storage Volumes (thousand acre feet) for (c) Clear Lake (CL) and Indian Valley (IV) during the Historical Period (1970–2005)

Table 3.4. Precipitation, Temperature, Irrigation Demand and Groundwater Supply for the Yolo County Flood Control and Water Conservation District During the Historical, Near-Term, Midterm, and Far-Term Periods. Projections for the future periods are simulated in WEAP using downscaled climate data from the GFDL climate model for the B1 and A2 emissions scenarios. Each time period represents 30 years.

	Historical 1971–2000	Near term 2010–2039		Midterm 2040–2069		Far term 2070–2099	
		B1	A2	B1	A2	B1	A2
Precipitation (mm yr^{-1})	561	446	428	430	417	349	342
Temperature (°C)	16.5	17.2	17.2	17.7	18	18	19.5
Annual irrigation demand (TAF yr^{-1})	381	466	463	460	471	483	501
Annual groundwater supply (%)	49	50	49	47	51	55	61

TAF = thousand acre feet

Another measure of water shortage is the frequency of years receiving no water allocation from Clear Lake. For example, if the Rumsey gauge is below 3.22 feet, the initial ASW assessment is for no allocation of water that year. During the historical period the model predicted 6 such years (Table 3.5). Model projections for the climate only scenario suggest that the number of years receiving no allocation will increase gradually with time, particularly during the latter half of the century. In the far term under A2, reservoir inflows are very low in some years in response to the warmer and drier conditions. The main exception to this general trend is the near term of A2, which showed an unexpected lower frequency of no allocation years (e.g., a drop from 6 to 4 no-allocation years out of 30).

Irrigation water demand

Under the climate only scenarios, where land use is held constant at 2008 crop proportions, future irrigation demand is projected to increase in the District (Table 3.4, Figure 3.4). In the near and medium term, average demand is expected to increase by 80 to 90 thousand acre feet, with no notable differences between the B1 and A2 projections (Table 3.5). The increase in demand is expected to continue in the latter part of the century, were the warmer and drier A2 climate sequence ultimately prompts higher irrigation demand than B1 (e.g., B1 and A2 project that demand will increase by 102 and 120 thousand acre feet, respectively). Relative to the historical period, this is an increase in irrigation demand of approximately 26 to 32 percent due to climate alone. Increased demand and greater impact of the GFDL A2 scenario observed in this study are consistent with previous projections for the Sacramento Valley as a whole (Joyce et al. 2006).

Table 3.5 and Figure 3.5 compare the difference in irrigation demand among the three adaptation scenarios relative to the historic period and climate only scenarios. Under Adaptation 1, demand varies to a small extent above and below the zero lines (Figure 3.5). This suggests two things. First, it indicates that A2 and B1 cropping patterns predicted by the econometric model, which are based on historic weather and market drivers, have less impact on irrigation demand than climate change alone. For example, increases in demand from climate alone are on the order of tens of thousands of acre feet, while the relative impact of Adaptation 1 is only a few thousand of acre-feet (Table 3.5). Second, since demand in the B1 scenario shows a slight increase with Adaptation 1, the cropping trend projected by econometric model may be less water efficient than the current cropping pattern. In short, the econometric model predicts a cropping pattern that is likely to be the most economical or profitable in the short-term rather than what might be the most water efficient. Differences between the A2 and B1 climate sequences highlight this possibility. Since the econometric model predicted similar cropping patterns for B1 and A2 prior to 2036, irrigation demand was also similar. However beginning in 2036, the acreage of alfalfa (and to a lesser degree tomatoes) expands significantly under the B1 climate (which is unexpectedly warmer than A2 at this time interval [Figure 3.4]). Since alfalfa has high water requirements, its expanded acreage leads to a corresponding increase in total irrigation demand for B1 relative to A2 and the historic period (Figure 3.5).

Adaptation 2 also shows increased demand compared to the historical baseline across all periods and emissions scenarios (Table 3.5; Figure 3.5). However, the model indicates that the increase in demand can be minimized to some extent by shifting to a more diverse and water efficient cropping pattern. That said, the marginal savings towards the end of the century are still less than half of the increase in demand due to climate change alone (Figure 3.5).

Adaptation 3 also shows a near-term demand slightly greater than the historical period. However, as the diversified cropping pattern and improvements in irrigation technology are gradually implemented, far-term demand declines to approximately 12 percent less than the historical mean for both the B1 and A2 climate sequences (Table 3.5; Figure 3.5). This illustrates that "game-changing" water savings—savings of the same order of magnitude of climate-induced increases—can occur through a combination of progressive irrigation technology improvement, and cropping patterns which are more water efficient and diversified.

Groundwater pumping

Because of an overall increase in irrigation demand, groundwater pumping also tends to increase in the far term under both the B1 and A2 climate (Table 3.4, Table 3.5). Under A2, the groundwater proportion of the District's supply (i.e., the fraction pumped by private landowners) rises from a historical mean of around 49 percent in the near term to as high as 61 percent in the far term (Table 3.4). It should be mentioned that this historic estimate includes years prior to the operation of Indian Valley reservoir, thus the present fraction is somewhat lower than 49 percent. Overall, this corresponds to a volume of 118 thousand acre feet above the historical mean (Table 3.5). Relative to the climate only scenarios, the marginal benefits of Adaptation 1 and Adaptation 2 are somewhat limited in the near and mid term (>20 thousand acre feet). Only in Adaptation 3 are substantial marginal benefits observed in total demand over time. In short, by integrating cropping pattern changes and improvements in irrigation technology, groundwater pumping was maintained at levels close to the baseline in the near term and yielded reductions of 30 to 50 TAF in the far term. The survey of growers indicates that these are types of practices that growers foresee as potential adaptation measures in the future (see Section 5). Groundwater pumping, and building more pumps and wells, are adaptation practices that farmers seem likely to adopt in the future, and these are discussed further in Section 5.

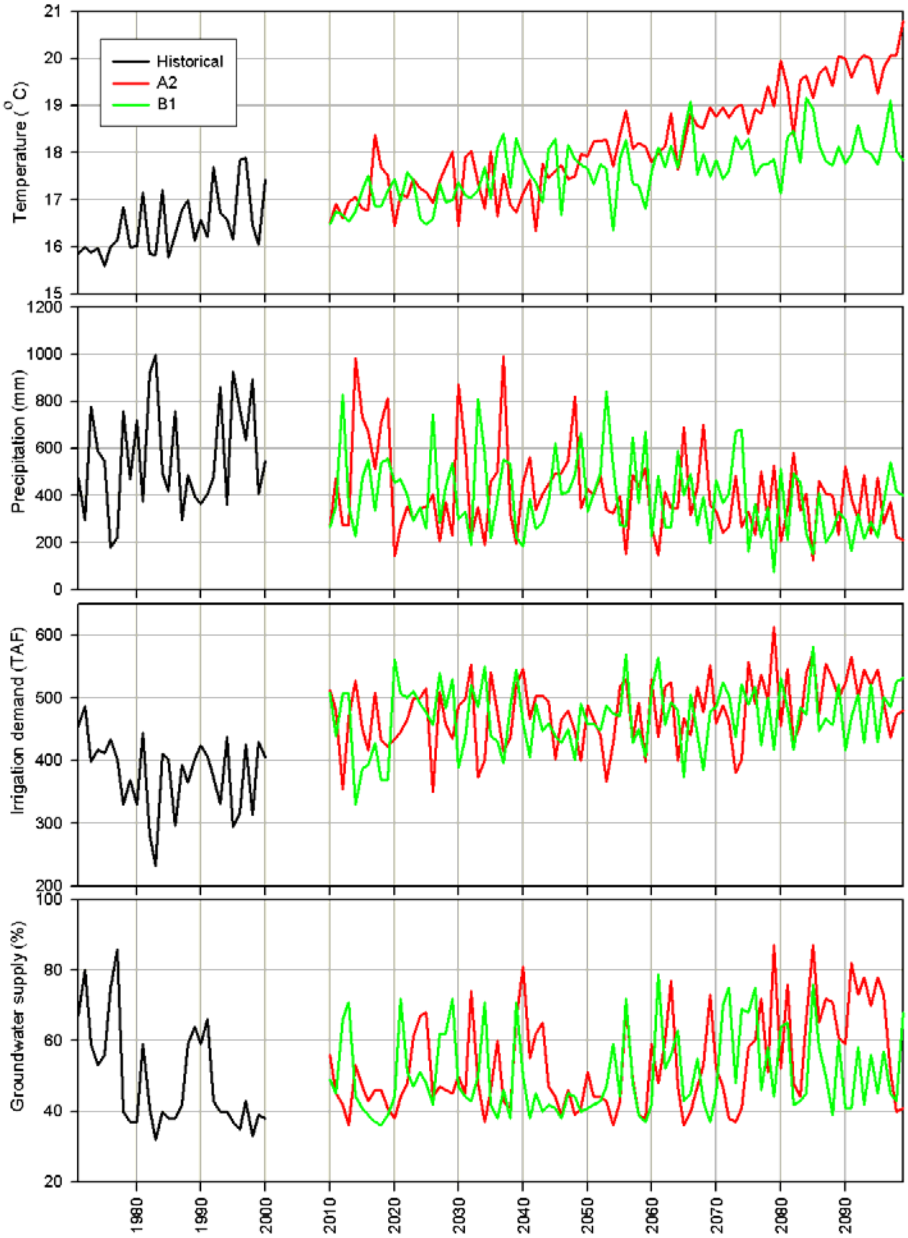

Figure 3.4. Precipitation, Temperature, Irrigation Demand and Groundwater Supply (as a Percent of Total Irrigation Supplied) for the Yolo County Flood Control and Water Conservation District During the Historical, Near-Term, Midterm, and Far-Term Periods. Surface water supply makes up the fraction of total irrigation supplied not accounted for by ground water. Projections for the future periods are simulated in WEAP using downscaled climate data from the GFDL general circulation model for the B1 and A2 emissions scenarios and no adaptation scenarios.

Table 3.5. Comparison of Water Years below Full Allocation, Water Years with No Allocation, Annual Irrigation Demand, and Annual Groundwater Supply for the Historical and Future Periods under Various Climate and Adaptation Scenarios. The B1 and A2 climate scenarios are derived from downscaled projections of the GFDL general circulation model. Each time period represents 30 years.

				B1 Climate + Adaptation				A2 Climate + Adaptation		
Indicator	Period	Historical	B1 Climate	1[c]	2[d]	3[e]	A2 Climate	1[c]	2[d]	3[e]
			------------------------ difference relative to historical period ------------------------							
Freq. of water years below full allocation[a]	1971-2000	18								
	near term		-3		-3	-3	-3		-3	-3
	midterm		-1	1	-2	-3	-3	1	-3	-4
	far term		3		1	0	7		7	6
Freq. of water years with no allocation[b]	1971-2000	6								
	near term		2		2	2	-2		-2	-2
	midterm		4	1	4	3	3	1	3	2
	far term		7		5	4	7		7	7
Annual irrigation demand (TAF)	1971-2000	381								
	near term		85		79	51	82		76	46
	mid term		79	81	62	-15	90	81	72	-13
	far term		102		72	-47	120		88	-45
Annual groundwater extraction (TAF)	1971-2000	187								
	near term		46		38	16	39		32	9
	midterm		29	34	12	-48	53	44	35	-40
	far term		78		48	-57	118		85	-33

[a] Water years below full allocation occur when the Rumsey gauge for Clear Lake reads < 7.56 feet on April 1.

[b] Water years with no allocation occur when the Rumsey gauge for Clear Lake reads < 3.22 feet on April 1.

[c] Adaptation 1 is based on land use projections derived from an econometric model. Since the econometric model only covered the 2009–2050 period only midterm data are presented.

[d] Adaptation 2 uses hypothetical land use projections that assume a gradual shift towards a more diverse and water-efficient cropping pattern.

[e] Adaptation 3 combines the diversified cropping pattern and a projected increase in irrigation technology adoption.

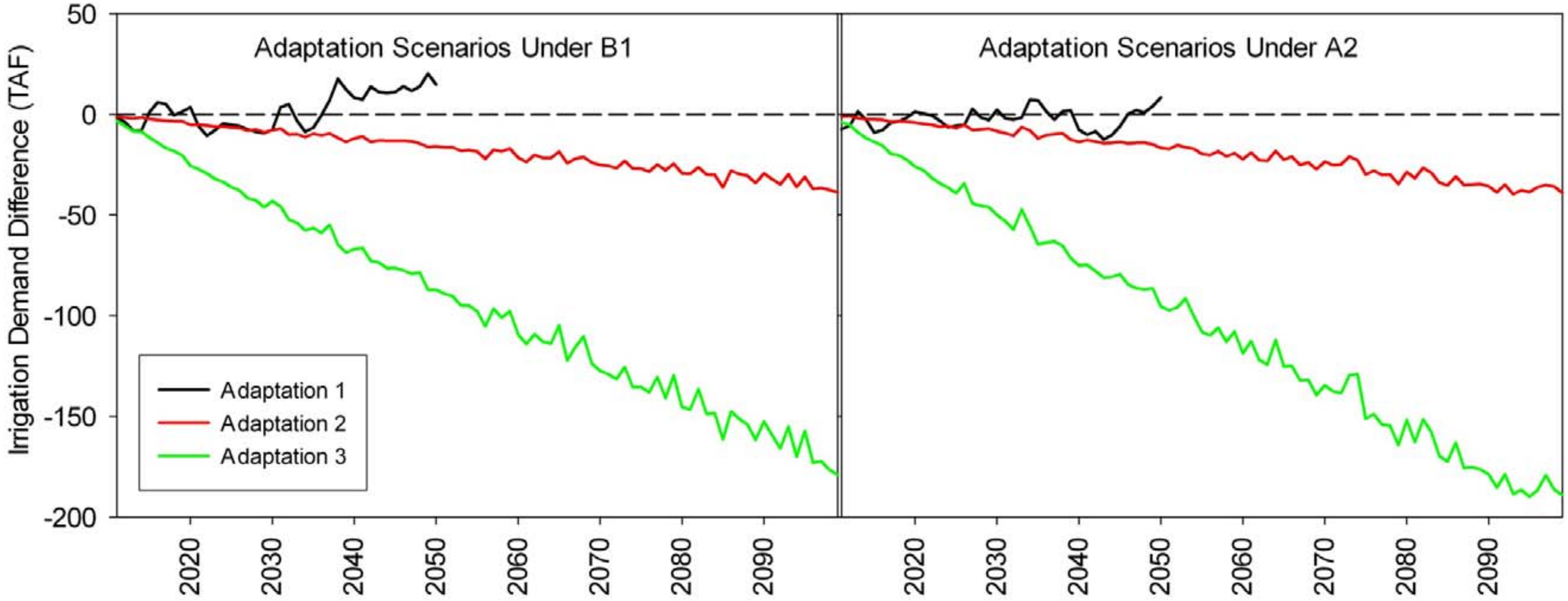

Figure 3.5. Difference in Projected Irrigation Demand for Three Adaptation Scenarios Relative to the Impact of Climate Alone (2009–2099). The B1 and A2 climate scenarios are derived from downscaled projections of the GFDL general circulation model. Adaptation 1 is based on land use projections derived from an econometric model for the 2009–2050 period. Adaptation 2 uses hypothetical land use projections, which assume a more diverse and water-efficient cropping pattern. Adaptation 3 combines the diversified cropping pattern and with a projected increase in irrigation technology adoption.

3.5 Conclusions

The overall conclusions of this section are as follows:

- Climate-driven impacts on surface water supplies, irrigation demand, and groundwater pumping are expected to be substantial under a projected warmer and drier climate. Projected impacts are greatest under A2 conditions in the far term.
- The District is likely to face more frequent years with water supply constraints in the latter part of this century (e.g., greater frequency of years where water deliveries are either below full allocation and/or no-allocation).
- Adaptation through future cropping patterns predicted by an econometric model of climatic and market variables (Adaptation 1) has little or no capacity to minimize the increase in demand or groundwater pumping driven by climate change alone.
- An adaptation scenario which projected a gradual shift to less water-demanding crops and a more diversified countywide cropping pattern (Adaptation 2) minimized the increase in demand and groundwater pumping to a limited extent (e.g., an order of magnitude less than climate change impacts alone).
- By combining the water-efficient diversified cropping pattern with improved irrigation technology/efficiencies (Adaptation 3) it may be possible to keep irrigation demand and groundwater pumping at or below mean levels for the historical period.

Some caveats arise that could have important effects on the results of the study:

- While this research suggests greater impact of climate change over cropping pattern changes on water demand, we should note that the land use projections do not fully capture the year to year variability in crop acreage reflected in the historical record. Adaptation 1 captures some of this variation but not all, while Adaptation 2 and 3 assume gradual change over time. The model should not be expected to account for large-scale crop acreage shifts in response to global commodity demand.
- The irrigation technology scenario is highly conceptual and could encompass many other plausible changes that could bring about reductions in field and/or landscape scale hydrologic demand.
- The cost of irrigation technologies such as drip irrigation has been coming down in recent years, which may accelerate adoption over time and may lead to "rebound" effects on the use of various types of irrigation technology and water management strategies. For the sake of simplicity, this study assumes a gradual linear rate of technology adoption over the course of the study period. Future

iterations of this WEAP model may benefit from modeling the effects of non-linear growth in irrigation technology adoption.

- We have assumed that surface water will continue to be the highest priority for growers in the District. However, research has shown that a shift in supply source often accompanies (or is even the driver of) a shift in irrigation technology (Negri and Brooks 1990; Burt et al. 2000; Shuck and Green 2001; Burt et al. 2003). For example, groundwater is often preferred for drip irrigation because it is reliable and contains less sediment. Likewise, a large scale shift to drip and microsprinkler irrigation may have other tradeoffs, such as an expansion of irrigated acres and/or reduced groundwater recharge (Pfeiffer and Lin et al. 2009; Ward and Pulido-Valazquez 2008). All of these factors, if they were to occur, could lead to a depletion of future groundwater supplies.
- Further studies aimed at developing local conjunctive use policies that attempt to balance the benefits and tradeoffs of changing land use, irrigation technology, and irrigation source are needed.

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3.7 Glossary

ASW	allowable seasonal withdrawal limits
BCCA	Bias Corrected Constructed Analog
CDE	California Data Exchange Center
cfs	cubic feet per second
DAU	Detailed Analysis Unit
CM	climate model
DEM	Digital Elevation Model
DWR	Department of Water Resources
GFDL	Geophysical Fluid Dynamics Laboratory
IPCC	Intergovernmental Panel on Climate Change
km^2	square kilometers
NLCD	National Landcover Data Set
NOAA	National Oceanic and Atmospheric Administration
TAF	Thousand Acre Feet
WEAP	Water Evaluation And Planning
WRA	Water Resources Association
YCAC	Yolo County Agricultural Commissioner

Section 4: Involving Local Agriculture in California's Climate Change Policy: An Inventory of Agricultural Greenhouse Gas Emissions in Yolo County

V. R. Haden, M. Dempsey, S.M. Wheeler, W. Salas, and L. E. Jackson

4.1 Introduction

With the passage of the Global Warming Solutions Act of 2006 (AB 32),[12] California has shown, in the absence of cohesive federal leadership, that local governments are able to adopt a bottom-up approach to greenhouse gas mitigation (Victor et al. 2005; Lutsey and Sperling 2008). Specific targets set by AB 32 aim to reduce California's GHG emissions to 1990 levels by 2020 and a further 80 percent by 2050. Recognizing the key role that land-use planning will play in achieving these goals, legislators also passed Senate Bill 375 (SB 375)[13] in 2008, which requires regional administrative bodies to develop sustainable land-use plans that are aligned with AB 32 (Hettinger 2011).

Agriculture currently occupies 25.4 percent of California's total land area and generates approximately 6 percent of the state's total GHG emissions (NASS 2007; CARB 2010). By contrast, urban areas in California makeup only 4.9 percent of the land area but are the primary source of the state's transportation and electricity emissions, estimated at 39 percent and 25 percent, respectively (de la Rue du Can et al. 2005; Hanak et al. 2011; CARB 2010). Moreover, rapid urbanization in California has contributed to the loss of nearly 3.4 million acres of farmland over the last decade and has increased the emissions associated with urban sprawl (NASS 2007; Liu et al. 2003; Norman et al. 2006). At present, AB 32 does not require agricultural producers to report their emissions or to implement mandatory mitigation measures as it does for California's industrial sector (CARB 2008b; Niemeier and Rowan 2009). The state is, however, encouraging farmers to institute voluntary mitigation strategies through various public and private incentive programs (CARB 2008b). For example, voluntary mitigation projects within California's agriculture and forestry sectors may be permitted to sell offset credits in a carbon market that has been proposed in the scoping plan laid out by the California Air Resources Board (CARB) (Niemeier and Rowan 2009).

While CARB and other state agencies have taken the lead in defining these policies, much of the responsibility for climate change planning and policy implementation has been delegated to local governments. For instance, AB 32 and SB 375 now require local

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[12] Assembly Bill 32 (Nuñez), Chapter 488, Statutes of 2006.

[13] Senate Bill 375, Steinberg, Chapter 728, Statutes of 2008.

governments to either address greenhouse gas (GHG) mitigation in the environmental impact report that accompanies any update to their general plan or to carry out a specific “climate action plan” filed separately (CAGO 2009). Consequently, conducting an inventory of GHG emissions is now among the first steps taken by local governments as they plan for future development.

To help local governments improve the quality and consistency of their emissions inventories, CARB has collaborated with several organizations to develop tools to standardize inventory methods. For example, the International Council on Local Environmental Initiatives has developed a software package known as the Clean Air Climate Protection Model to better align local methods with national and international standards (Kates et al. 1998; Ramaswami et al. 2008). Such inventory tools are suitable for appraising emissions from government or municipal operations, but are less useful for “community-wide” assessments. In particular, the emissions from agriculture are often missing from existing inventory tools geared to local planners due to problems of complexity, data availability, boundary effects, and consistency with methods designed for larger spatial scales (Ramaswami et al. 2008). Methods to estimate emissions from agriculture within a local inventory framework would be a valuable asset for those developing mitigation and adaptation strategies in rural communities.

In this paper, a local inventory of agricultural GHG emissions in 1990 and 2008 is presented for Yolo County, California. Recent mitigation and adaptation initiatives in Yolo County thus provide the policy context for this analysis (Yolo County, 2010). The main objectives of this inventory of agricultural emissions are to: (1) prioritize voluntary mitigation strategies; (2) examine the benefits and trade-offs of local policies and on-farm practices to reduce agricultural emissions; and (3) discuss how involving agricultural stakeholders in the planning process can strengthen mitigation efforts and lay the groundwork for future adaptation.

4.2 Materials and Methods

Inventory Methods and Data Sources

In this study, an inventory of Yolo County’s agricultural GHG emissions was conducted for both the AB 32 base year (1990) and the present period (2008). To address the wide range in data availability and analytical capacity that exists across different national or regional scales, the Intergovernmental Panel on Climate Change (IPCC) advocates a three-tiered approach for identifying the appropriate inventory methods used for the agriculture sector (IPCC 2006). This tiered system refers to the complexity and geographic specificity of the inventory method in question; with the Tier 1 methods using a simplified default approach and relatively coarse activity data, while the Tier 3 methods involve more sophisticated models and higher resolution activity data (IPCC 2006). The Tier 1 methods used here have been adapted for local activity data from three main sources: (1) the CARB Technical Support Document for the 1990–2004 California

GHG Emissions Inventory (CARB 2009b); 2) the U.S. EPA Emissions Inventory Improvement Program Guidelines (U.S. EPA 2004, 2010); and 3) the 2006 IPCC Guidelines for National GHG Inventories (IPCC 2006). Supplementary materials (see Appendix 2), provide detailed equations, activity data, and emissions factors for each emissions category (Table 4.1). While strategies to adapt inventory methods to local data were exchanged with the Yolo County Planning Division during the preparation of their recent climate action plan, the present study is an independent assessment of agricultural GHG emissions.

Direct and Indirect Nitrous Oxide (N_2O) Emissions

Direct N_2O emissions were calculated using a Tier 1 approach that estimated nitrogen (N) inputs from the following sources: synthetic N fertilizers, crop residues, urine deposited in pasture, and animal manure (IPCC 2006). In Yolo County, 16 crop categories accounted for approximately 90 percent of irrigated cropland. The harvested area of each crop was taken from the county crop reports for 1990 and 2008 (YCAC 1990, 2008). To calculate the total amount of synthetic N applied in Yolo County, the recommended N rate for each crop was multiplied by its cropping area and then summed across all crop categories. For a given inventory year, the recommended N rate for each crop was obtained from archived cost and return studies published by the University of California Cooperative Extension (UCCE, various years). Nitrogen inputs from crop residues for alfalfa, corn, rice, wheat, and miscellaneous grains were calculated using crop production data taken from the county crop reports (IPCC 2006). Nitrogen excreted by livestock in the form of urine or manure was calculated for the six main livestock groups (dairy cattle, beef cattle, horses, sheep, goats, and swine) assuming year-round production. Emissions from poultry were not calculated, since no large-scale poultry operations exist in the county (YCAC 1990, 2008). Dairy cattle numbers for both inventory years were taken from the National Agricultural Statistics Service database (NASS 1990, 2008), while all other livestock numbers were obtained from the county records (YCAC 1990, 2008). Dairy cattle and swine manure were assumed to be stored temporarily in anaerobic lagoons and then spread on fields. All other livestock categories were assumed to deposit their urine in pastures. Indirect N_2O emissions were estimated based on the total amounts of N added as synthetic N fertilizer, urine, and manure; and calculated using standard values for the volatilization and leaching rates, and default emission factors (IPCC 2006).

Mobile Farm Equipment and Irrigation Pumping

A Tier 1 approach was developed to calculate fuel consumption from mobile farm equipment. Each crop's annual harvested area was multiplied by its average diesel fuel use per hectare from archived cost and return studies and then summed across all crop categories to determine the total amount of diesel fuel used each year (YCAC 1990, 2008; UCCE, various years). The amount of CO_2, N_2O, and methane (CH_4) emitted was determined by multiplying the total amount of diesel fuel consumed by mobile farm

Table 4.1. Summary of Data Sources Used in Inventory of Yolo County Agricultural GHG Emissions

Source	Data Types	Description of Reference
Yolo County Agricultural Crop Reports (YCAC)	Harvested area by crop (hectare, ha) Crop production by crop (tons) Livestock numbers by group (head) *excluding dairy cattle	Annual Crop Reports for 1990 and 2008
U.S. Department of Agriculture (USDA)	Dairy cattle numbers (h)	National Agriculture Statistical Service Online Database
University of California Cooperative Extension (UCCE)	Synthetic N application rate (kilograms ([kg] of N ha^{-1}) Diesel fuel use (Liters ha^{-1})	Archived Cost and Return Studies (various years)
California Air Resources Board (CARB)	Number of diesel irrigation pumps and activity data Emission factor for rice production (kg CH_4 ha^{-1}) Fraction of crop acreage burned (%) Emission factors for residue burning (by crop)	Survey of irrigation pump engines Inventory technical support document
California Department of Agriculture (CDFA)	County lime and urea sales (t)	Fertilizer Materials Tonnage Reports (1990, 2008)
International Panel on Climate Change (IPCC)	Default Emissions Factors	2006 IPCC Guidelines for National Greenhouse Gas Inventories

equipment by emission factors for each gas (EIA 2010; U.S. EPA 2007). The Tier 1 estimate of emissions from mobile farm equipment was then compared with results generated by the Yolo County Planning Division who used Tier 3 OFFROAD emissions model (CARB 2007b). The OFFROAD model estimates end-use fuel consumption based on detailed information collected on equipment population, activity patterns, and emissions factors (Yolo County 2010). A detailed summary of the OFFROAD model framework and activity data specifications is available from CARB (CARB 2007b).

Fuel use for irrigation pumping was calculated as the product of the number of diesel-powered irrigation pumps in the county, the estimated annual activity of each pump (hrs yr^{-1}), the average brake horsepower of pump engines in the Yolo/Solano Air Quality Management District, and the brake specific fuel consumption per hour (CARB 2003a, 2010; Yolo County 2010). As of 2003, an estimated 643 diesel-powered irrigation pumps were operated in Yolo County (Yolo County 2010). Statewide, the number of diesel irrigation pumps was projected to increase by 3.5 percent between 1990 and 2010 (CARB 2000). In this inventory we estimated the 1990 and 2008 pump populations based on an assumption that the statewide trend was proportional to the increase in the number of pumps in the county. Input values for engine activity (hr yr^{-1}) and average engine horsepower were taken from recent government reports which inventory statewide emissions from diesel irrigation pumps (CARB 2006). The amount of CO_2, N_2O, and CH_4 emitted was the product of the total amount of diesel fuel consumed by pumps operated in the county and the emission factor for each gas (EIA 2010; U.S. EPA 2007).

CH_4 Emissions from Livestock and Rice Cultivation

Methane emissions from livestock were calculated using county records for the six livestock groups mentioned above (NASS 1990, 2008; YCAC 1990, 2008). To calculate the CH_4 emissions for each livestock group (and its type of storage or deposition in pasture), the animal population was multiplied by a group-specific emissions factor for both enteric fermentation and manure management (IPCC 2006). Total emissions from enteric fermentation and manure management were determined by summing the CH_4 emissions across all livestock categories.

Methane emissions from rice cultivation were estimated by multiplying the area of rice harvested in a given year by a California-specific emission factor (CARB 2009b; Cicerone, et al. 1992). This Tier 1 estimate of CH_4 emissions was then compared to a Tier 3 estimate generated using the DeNitrification-DeComposition (DNDC) model, which was modified for paddy-rice through the addition of anaerobic soil biogeochemical processes (Li et al. 2004, 2005). Due to the passage of the Rice Straw Burning Act of 1991, the burning of rice residue in California has been gradually phased out (Hill et al. 2006). As an alternative to burning residue, most rice farmers now practice a combination of residue incorporation and winter flooding. To characterize how differences in cultivation practice effect CH_4 emissions, three residue and water management scenarios were modeled as follows:

- Scenario A: residue burned and no winter flooding
- Scenario B: 12.5 percent residue burned, 87.5 percent incorporated and 0 percent winter flooding
- Scenario C: 12.5 percent residue burned, 87.5 percent incorporated and 100 percent winter flooding.

A GIS database of rice field locations, area-weighted SSURGO[14] soil data (sand, silt, clay, pH, and soil organic matter) and daily weather data from CIMIS[15] was compiled for 66 rice fields in Yolo County. The DNDC model was validated against field results from two California-based field experiments which assessed the affects of residue and water management on CH_4 emissions (Fitzgerald et al. 2000; Assa and Horwath, unpublished). Results from the model runs allowed us to generate an emissions factor specific to each management scenario by averaging the simulated CH_4 emissions rates across all 66 fields. To account for changes in practice over time, we assumed that 100 percent of the harvested rice area in 1990 was managed according to Scenario A, while in 2008 rice area was divided equally between Scenarios B and C. The percentage of the county's rice area attributed to each scenario is roughly consistent with statewide estimates for residue burning, residue incorporation, and winter flooding (CARB 2007a; U.S. EPA 2010; Salas personal communication). Finally, the management-specific emissions factors were multiplied by the area under each management scenario and then summed across each management category to give the total CH_4 emissions from rice cultivation for a given year. Further details on residue inputs, fertilizer rates, water management, and model calibration can be found in Sumner et al. (2010) and Holst and Buttner (2011).

Residue Burning, Liming, and Urea Application

A California-specific method developed by the CARB (2009b) was used to estimate emissions from residue burning. This approach is based on studies conducted by the University of California at Davis, which established emissions factors for CO_2, N_2O, and CH_4 for the most commonly burned residues in California (almond, corn, rice, walnut, and wheat residues; Jenkins et al. 1992, 1996). For each gas, the harvested area was multiplied by the fraction of area burned, the crop mass burned per unit area, one minus the residue moisture content, and the corresponding emissions factor for each crop (see Appendix 3). For all crops other than rice the fraction of area burned each year was held constant over the study period. In the case of rice, the fraction burned was assumed to have declined from 99 to 11 percent between 1990 and 2008, which is consistent with statewide trends (CARB 2007a; U.S. EPA 2010). Carbon dioxide emissions from the addition of limestone and urea were determined by multiplying the amount of each material applied in Yolo County by its default emission factor (IPCC 2006). The amount of each material was based on county sales records (CDFA 1990, 2008).

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[14] The Natural Resources Conservation Service's Soil Survey Geographic (SSURGO) Database.

[15] The California Irrigation Management Information System (CIMIS) is a program in the Office of Water Use Efficiency at the California DWR.

4.3 Results

Inventory of Agricultural Emissions in 1990 and 2008

In Yolo County, total agricultural emissions declined by 10.4 percent between 1990 and 2008 (Table 4.2). The primary reason for this generalized decline was a notable reduction in both direct and indirect N_2O emissions (Table 4.2). Direct N_2O emissions were the largest source of emissions during both inventory years, but decreased by 23.1 percent over the study period due to a countywide reduction in the amount of synthetic N fertilizer applied (Figure 4.1). This reduction in fertilizer use was driven by two important land use trends: (1) a 6 percent reduction in the county's irrigated cropland (Table 4.3; Figure 4.2); and (2) a general shift away from crops that have high N rates (e.g., corn, tomatoes) coupled with an expansion in alfalfa and grape area which require less fertilizer (Table 4.4). The large expansion of alfalfa acreage resulted in a moderate increase in the direct N_2O emissions from crop residues (Figure 4.1), but this increase was not enough to offset the overall savings achieved by the displacement of corn and tomatoes. The direct N_2O emissions from urine in pasture and manure application ranged between 5 percent and 15 percent of the total direct emissions and showed a small rise over the study period due to a proportional increase in livestock population. Estimates of nitrate lost through leaching and runoff accounted for approximately two-thirds of the indirect N_2O emissions countywide, with ammonia (NH_3) volatilization responsible for the remaining one-third (Figure 4.1). More than 90 percent of indirect emissions originated from synthetic N fertilizers, while urine and manure from livestock were relatively minor sources. Consequently, the notable decline in indirect N_2O emissions was also due to a decrease in the amount of synthetic N applied countywide.

In both years, emissions of CO_2, N_2O, and CH_4 from diesel-powered mobile farm equipment were responsible for 20.0 to 23.0 percent of total agricultural emissions in Yolo County (Table 4.2). This category showed little change in emissions over time (69.1 kilotons carbon dioxide equivalent (CO_2e) in 1990 and 69.0 kt CO_2e in 2008). This was because an increase in fuel consumption per unit area for several important crops (e.g., rice, corn, tomatoes, melons, and miscellaneous vegetables) offset the small decline in irrigated cropland (Table 4. 4; Figure 4.2). Total emissions from mobile farm equipment were 4 percent lower using the Tier 1 method as compared to estimates generated using the OFFROAD model (Yolo County 2010). However, since the OFFROAD model uses equipment population and hourly usage data to estimate emissions, results from this Tier 3 method could not be used to disaggregate emissions by specific crop category.

In both years, emissions of CO_2, N_2O, and CH_4 from diesel-powered mobile farm equipment were responsible for 20.0 to 23.0 percent of total agricultural emissions in Yolo County (Table 4.2). While a reduction in county's irrigated cropland may have been expected to save fuel and reduce associated emissions, this category showed little change in emissions over time (69.1 kt CO_2e in 1990 and 69.0 kt CO_2e in 2008). This was because an increase in fuel consumption per unit area for several important crops (e.g., rice, corn, tomatoes, melons, and miscellaneous vegetables) offset the small decline in irrigated cropland (Table4. 4; Figure 4.2). Total emissions from mobile farm equipment were 4 percent lower using the Tier 1 method as compared to estimates generated using the OFFROAD model (Yolo County, 2010). However, since the OFFROAD model uses equipment population and hourly usage data to estimate emissions, results from this Tier 3 method could not be used to disaggregate emissions by specific crop category.

Diesel-powered irrigation pumps emitted approximately 39.6 kt of CO_2e in 1990 and 41.0 kt of CO_2e in 2008 (Table 4.2). This was equal to 11.7 to 13.5 percent of the total agricultural emissions. While irrigated cropland in the county has decreased overall, the amount of land with access to groundwater has continued to expand as new wells are drilled. The small increase in the number of wells operating in the county, therefore accounts for the proportional rise in emissions from irrigation pumping.

Table 4.2. Summary of Yolo County Agricultural CO_2, N_2O, and CH_4 Emissions (kt CO_2e) for 1990 and 2008, by Source Category. Estimates were made using Tier 1 methods, activity data based on local agricultural practices, and default emission factors. For detailed methods see supplementary material.

	1990 Emissions					2008 Emissions					Change since 1990
Source Category	CO_2	N_2O	CH_4	Total	Annual	CO_2	N_2O	CH_4	Total	Annual	
	--------------- kt CO_2e ----------------				%	--------------- kt CO_2e ---------------				%	%
Direct N_2O from soil	---	126.55	---	126.55	37.0	---	97.27	---	97.27	31.8	- 23.1
Indirect N_2O	---	36.43	---	36.43	10.7	---	26.68	---	26.68	8.7	- 26.8
Mobile farm equipment	71.00	0.57	0.21	71.78	21.0	69.43	0.55	0.21	70.19	23.0	- 2.2
Irrigation pumping	39.16	0.31	0.12	39.59	11.7	40.54	0.32	0.12	40.98	13.5	3.5
Livestock[1]	---	*10.64*	26.53	26.53	7.8	---	*12.39*	31.84	31.84	10.5	20.0
Rice cultivation	---	---	25.92	25.92	7.7	---	---	31.16	31.16	10.2	20.2
Residue burning[2]	---	4.86	1.76	6.61	2.0	---	1.59	0.83	2.42	0.8	- 63.4
Lime	4.35	---	---	4.35	1.3	2.32	---	---	2.32	0.8	- 46.7
Urea	4.15	---	---	4.15	1.2	3.46	---	---	3.46	1.1	- 16.7
Total	118.66	168.71	54.54	341.92		115.74	126.41	64.16	306.31		- 10.4

[1] N_2O from N excreted by livestock (in italics) is assumed to be applied to soil as manure or urine, thus it is only included in the totals for direct and indirect N_2O.

[2] CO_2 emissions from residue burning (104.92 kt in 1990 and 42.69 kt in 2008) is considered a biogenic emission, thus was not included in the total.

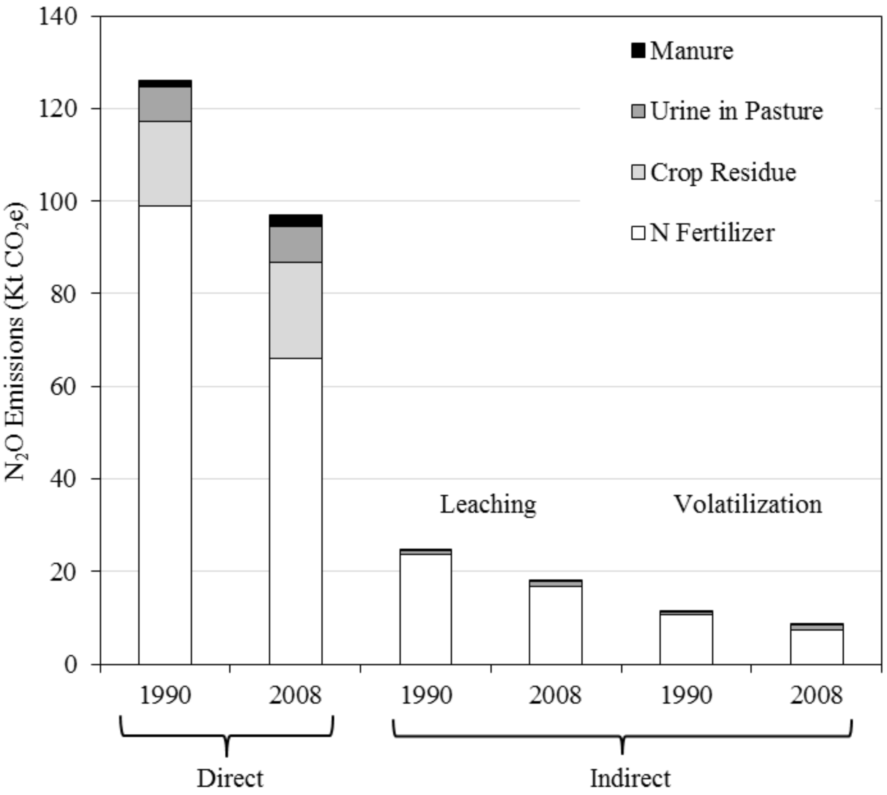

Figure 4.1. Direct and Indirect N_2O Emissions (kt CO_2e) in Yolo County during 1990 and 2008 as a Function of N Source (N Fertilizers, Crop Residues, Urine in Pasture, Manure), Leaching and Volatilization. Emissions were estimated using Tier 1 methods, activity data that reflects local crop management practices and default emission factors.

Table 4.3. Land Area and Average Emissions Rates (t CO_2e ha^{-1} yr^{-1}) for Rangeland and Irrigated Cropland and in Yolo County during 1990 and 2008, Estimated Using Tier 1 Methods, Activity Data Based on Local Agricultural Practices, and Default Emission Factors

	Land Area		Average Emissions Rate	
Land-use Category	1990	2008	1990	2008
	----- ha -----		--- t CO_2e ha^{-1} yr^{-1} ---	
Rangeland[1]	53,419	54,946	0.70	0.80
Irrigated Cropland[2]	139,407	131,439	2.19	1.99

[1] Emissions from rangeland include all emissions from livestock.

[2] Emissions from irrigated cropland include emissions from all other source categories.

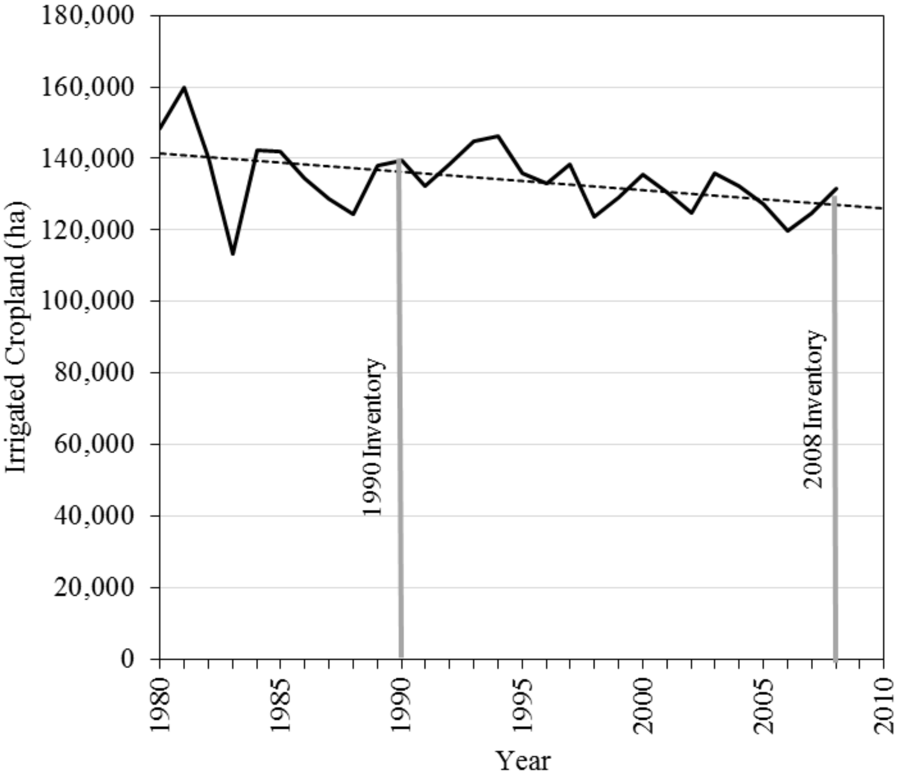

Figure 4.2. Change in Yolo County Irrigated Cropland (ha) between 1980 and 2008. Vertical lines indicate when the 1990 (AB 32 base-year) and 2008 inventories were conducted.

In Yolo County, CH_4 emissions from livestock contributed between 7.8 and 10.5 percent of the total agricultural emissions depending on the inventory year (Table 4.2). This is lower than the proportion attributed to livestock statewide, which was more than 50 percent of all agricultural emissions in 2008 (CARB 2010). The lower figure for the county essentially reflects the small number of dairy farms operated locally. By contrast, enteric fermentation from pasture-raised beef cattle (and to a lesser degree sheep) was the largest source of CH_4 emissions from livestock in both inventory years (Figure 4.3). Since beef cattle and sheep populations have changed little since 1990, emissions from these livestock types were also relatively stable. While dairy cattle represented only 5 to 12 percent of the county's cattle in any given year, an increase in the number of dairy cattle from approximately 800 to 2300 animals over the study period resulted in a 20.0 percent increase in total CH_4 emissions from livestock (Table 4.3).

Using the Tier 1 method prescribed by CARB, emissions of CH_4 from rice cultivation were estimated to increase from 25.9 to 31.2 kt CO_2e between 1990 and 2008 (Table 4.2). This increase was entirely due to a 20.3 percent expansion in the area under rice cultivation (Table 4.6). Estimates generated using the DNDC model showed a larger increase in emissions over the study period (32.2 to 57.9 kt CO_2e); this Tier 3 method accounted for changes in residue and water management in addition to the increase in cultivated area (Table 4.6). Emissions of N_2O and CH_4 from residue burning contributed 2.0 percent to the total agricultural emissions in 1990 and declined to less than 1.0 percent in 2008, due to the phasing out of rice straw burning in accordance with State regulations (Table 4.2). Emissions of N_2O and CH_4 were relatively small compared to the amount of CO_2 emitted during combustion (104.9 kt CO_2e in 1990 and 42.7 kt CO_2e in 2008). Most inventory guidelines consider CO_2 from residue burning to be a "biogenic" emission, arguing that it is theoretically equivalent to the CO_2 generated during the decomposition of the same crop residue in the soil over the course of the year (CARB 2009b; IPCC 2006). Consequently, CO_2 from residue burning has been excluded from our inventory total. Emissions of CO_2 from lime and urea application each contributed approximately 1 percent to the overall agricultural emissions, and both declined over the study period (Table 4.2).

4.4 Discussion

One of the main findings of this study is that emissions from agriculture in Yolo County were already on the decline long before the implementation of recent mitigation policies. This trend is largely market-driven, arising from broad economic factors that are prompting local farmers to shift more of their land to crops which happen to require less N fertilizer and diesel fuel. For instance, many local farmers point to the strong markets for wine grapes and alfalfa, which require fewer inputs as the main factor behind their recent local expansion (Merenlender 2000). These Tier 1 methods do not fully capture the extent to which some growers are reducing fertilizer and fuel use in response to the rising cost and market volatility of inputs, rather than mitigation *per se* (see Section 5). It should be noted that interviews with Yolo County growers have documented numerous strategies to decrease energy use in cost-effective ways, but they are often not yet integrated into the cost and return studies for Yolo County crop production (see Section 5).

Land Use Change and Its Effects on Emissions

Another important factor contributing to the overall reduction in agricultural emissions was the 8,000 hectare (ha) decline in irrigated cropland. This loss of irrigated cropland raises two important questions. First, what type of land use is the cropland being displaced by? And second, how does the carbon footprint of other land uses compare to that of agriculture? Four countywide land-use trends may explain the decline. Cropland could either be: (1) left fallow, (2) converted to non-irrigated rangeland, (3) restored to natural habitat, or (4) developed for urban and industrial use. Shifting land use from irrigated cropland to fallow, rangeland, or natural habitat will generally reduce anthropogenic GHG emissions. The same cannot be said for cropland that is developed for urban uses. Urbanization accounted for the loss of about 6,500 acres (2,631 hectares)

Table 4.4. Cultivated Area, Production Input Rates and Estimated Emissions for Yolo County Crop Categories in 1990 and 2008. Estimated emissions for direct N_2O, indirect N_2O, and mobile farm equipment are based on Tier 1 inventory methods, local activity data, and default emission factors.

			Production Input Rates[2]						Estimated Emissions					
	Cultivated Area[1]		N Fertilizer		Crop Residue		Agricultural Fuel		Direct N_2O		Indirect N_2O		Mobile Farm Equipment	
Crop Category	1990	2008	1990	2008	1990	2008	1990	2008	1990	2008	1990	2008	1990	2008
	----- ha -----		------- kg N ha^{-1} yr^{-1} --------				-- L ha^{-1} yr^{-1} --		--------------- kg CO_2e ha^{-1} yr^{-1}----------------					
Alfalfa	14,569	22,950	12	12	57	68	85	33	338	389	20	20	228	88
Almond	3,054	4,639	224	247	---	---	269	103	1092	1201	355	390	727	278
Corn	6,070	3,285	392	269	99	112	137	262	2394	1857	621	426	369	706
Grain Hay	5,099	6,804	112	90	51	77	56	56	794	811	177	142	151	151
Grapes	640	4,857	56	45	---	---	215	215	273	218	89	71	580	580
Irrigated Pasture	5,261	5,261	50	50	---	---	2	2	246	246	80	80	6	6
Melons	2,145	578	146	196	---	---	306	1169	710	955	231	310	826	3154
Prunes	880	851	168	168	---	---	168	168	819	819	266	266	454	454
Rice	10,117	12,164	191	207	12	48	186	253	337	535	302	328	502	681
Safflower	11,214	5,469	112	112	---	---	122	122	546	546	177	177	328	328
Tomato	24,079	15,204	224	235	---	---	514	730	1092	1146	355	373	1387	1968
Walnuts	2,739	3,606	224	224	---	---	106	56	1092	1092	355	355	287	151
Wheat	28,428	17,158	224	135	68	73	115	123	1424	1008	355	213	311	333
Misc. Field Crops	12,100	12,309	125	125	---	---	240	227	607	607	197	197	648	613
Misc. Fruit & Nut	590	619	110	140	---	---	221	190	534	682	174	222	596	512
Misc. Vegetables	307	1,449	232	198	---	---	816	1110	1130	966	367	314	2200	2995
Other Non-specified[3]	12,115	14,236	---	---	---	---	---	---	---	---	---	---	---	---

[1] Cultivated area for all crop categories was taken from Yolo County Agricultural Crop Reports.

[2] Inputs of Synthetic N and Agricultural Fuel (diesel) are taken from University of California Cooperative Extension cost and return studies.

[3] Inputs and emissions from the "Other Non-specified" crop category were not included in the inventory, since data on input rates were unavailable.

Table 4.5. Emissions from Mobile Farm Equipment in Yolo County during 2008, Estimated Using the Tier 1 Method as Compared to the OFFROAD Model

	Mobile Farm Equipment Emissions	
Year	Tier 1 Method[1]	OFFROAD Model[2]
	----------- kt CO_2e yr^{-1} -----------	
1990	69.1	72.2
2008	69.0	71.7

[1] The Tier 1 method was based on estimated diesel fuel consumption for each crop category reported in the cost and return studies.

[2] The Tier 3 OFFROAD emissions model estimates end-use fuel consumption based on detailed information collected on equipment population, activity data, and emissions factors.

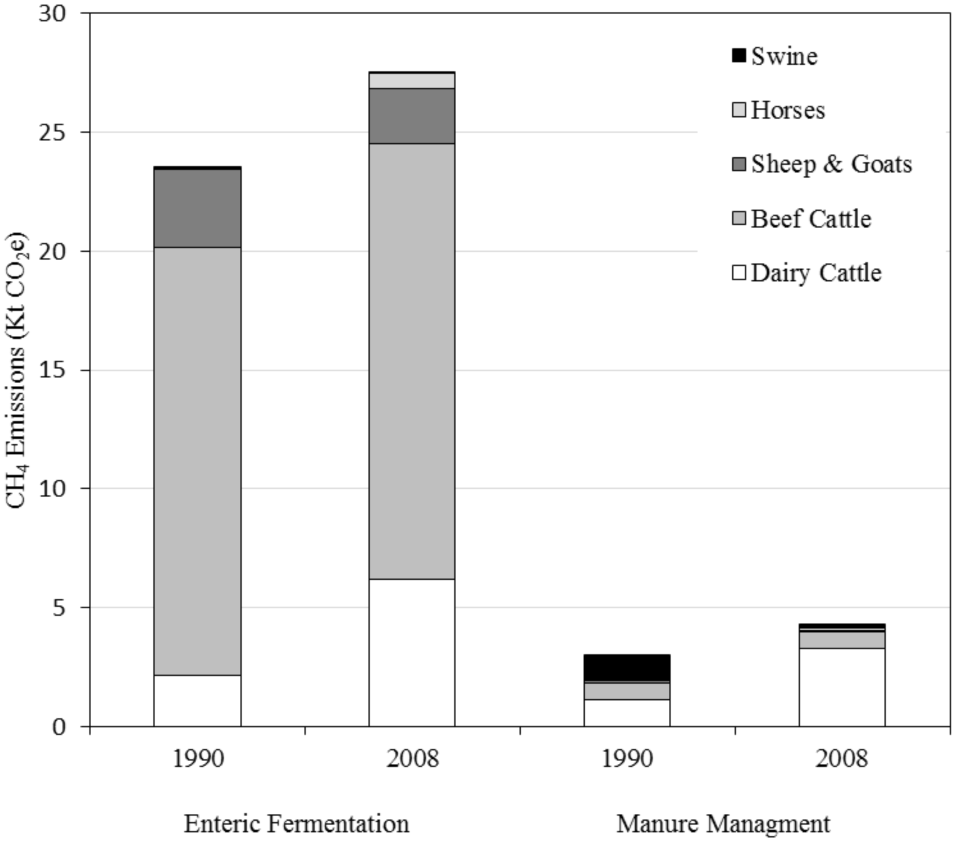

Figure 4.3. Livestock CH_4 Emissions from Enteric Fermentation and Manure Management as a Function of Livestock Category. Emissions were estimated using Tier 1 methods, local livestock population data, and default emission factors.

Table 4.6. Methane Emissions from Rice Cultivation in Yolo County for 1990 and 2008, Estimated Using the Tier 1 Method and the DNDC Model

Method	Year	DNDC Scenario	Harvested Area	Residue Burned	Residue Incorporated	Winter Flooded	Emissions Factor	Total CH_4 Emissions
			ha	% of ha	% of ha	% of ha	kg CH_4 ha^{-1} yr^{-1}	kt CO_2e
Tier 1 Method[1]	1990	---	10,117	---	---	---	122.0	25.9
	2008	---	12,164	---	---	---	122.0	31.2
DNDC Model[2]	1990	A	10,117	100.0	0.0	0.0	151.4	32.2
	2008	B	12,164	12.5	87.5	0.0	196.0	50.0
	2008	C	12,164	12.5	87.5	100.0	257.4	65.8
	2008	Ave. B & C	12,164	12.5	87.5	50.0	226.7	57.9

[1] For the Tier 1 method developed by CARB, no differences in residue and water management among growers are explicitly defined.

[2] For the DNDC model, scenario A is assumed to reflect farmer practice before the 1991 passage of the Rice Straw Burning Act, while an average of scenarios B & C best approximates the range in residue and water management as of 2008.

of agricultural land (including grazing land) between 1992 and 2008 (FMMP 1992 and 2008). In 1990, emissions sources associated with Yolo County's urban areas (West Sacramento, Davis, Woodland, and Winters) accounted for approximately 86 percent of the total GHG emissions countywide, while unincorporated areas supporting agriculture were responsible for the remaining 14 percent (Yolo County 2010). If calculated on an area-wide basis the county's urban areas emitted approximately 152.0 t CO_2e ha^{-1} yr^{-1} (Yolo County 2010). By contrast, our inventory results indicate that in 1990 Yolo County's irrigated cropland averaged 2.16 t CO_2e ha^{-1} yr^{-1} and that livestock in rangelands emitted only 0.70 t CO_2e ha^{-1} yr^{-1} (Table 3). This 70-fold difference in the annual rate of emissions between urbanized land and irrigated cropland suggests that land-use policies, which protect existing farmland from urban development, are likely to help stabilize and or reduce future emissions, particularly if they are coupled with "smart growth" policies that prioritize urban infill over expansion (Liu et al. 2003; Norman et al. 2006; Beardsley et al. 2009).

Potential for voluntary mitigation in a local agricultural policy framework

While avoided conversion of farmland will help curb emissions from urban sprawl, keeping farmland intact also affords numerous opportunities to mitigate emissions through changes in agricultural practice or by sequestering carbon in soils, perennial crops, or woody vegetation. In considering mitigation options, strategies should not hinder adaptation to climate change, as this could lead to loss of agricultural viability and potential urbanization, a much greater source of GHG emissions per acre. To explore the potential for voluntary mitigation of agricultural emissions in Yolo County, local officials held a series of stakeholder meetings in 2010 and 2011 where members of the agricultural community provided input on proposed mitigation strategies and policies outlined in the county's climate action plan. Table 7 and the paragraphs below highlight many of the tradeoffs and co-benefits identified by local stakeholders.

Since N_2O emissions originating from the use of N fertilizers were the largest source of agricultural emissions, strategies to further optimize N management are a high priority (Table 7). Local field and modeling studies suggest that reducing N applications, organic production, and cover cropping all have potential to reduce N_2O emissions with minimal affects on crop yield (Krusekopf et al. 2002; De Gryze et al. 2009; De Gryze et al. 2010; Smukler et al. 2010). An examination of local archived cost and return studies indicates that recommended N rates have already decreased somewhat for corn, wheat, hay, and grapes over the past 20 years, but have increased slightly for tomatoes, melons, rice, and almonds (UCCE, various years). Thus, while some growers have already improved N management, further reductions in N inputs are possible for some crops (Cavero et al. 2000; Smukler et al. 2010). County records indicate that organic production has expanded from approximately 250 to 2500 ha over the study period, but is still less than 2 percent of the total irrigated cropland. Cover cropping has become more common in recent years (based on conversations with farmers), but is less viable in rotations that require early planting dates. Local outreach programs conducted in partnership with agricultural organizations and local UCCE cooperative extension are underway to share information on practices, technologies, and incentives that will help growers optimize N rates while maintaining yields, cover cropping, and other organic-based practices. Policy makers should seek opportunities to align future mitigation initiatives with these nascent efforts.

Local strategies to minimize emissions from mobile farm equipment and diesel irrigation pumps were also considered (Table 4.7). As a first step, local officials have proposed a series of workshops and information bulletins that would focus on possible fuel savings achieved through routine engine and pump bowl assembly maintenance or more efficient field operations (e.g., optimizing drawbar load, fewer tillage passes) (Yolo County 2010). These workshops could also be used to encourage participation in California's Carl Moyer Off-Road Equipment Replacement Program, which provides financial assistance for new equipment or engine upgrades that meet or exceed state air quality standards (CARB 2008a).

The benefits and tradeoffs of policies to reduce CH_4 emissions from livestock were also explored. For livestock raised primarily on pasture, practical options to reduce CH_4 emissions from enteric fermentation and manure management are limited. This is because livestock managers cannot intensively manage the diet and manure of animals raised in an extensive rangeland setting. Furthermore, manure deposited in pasture undergoes aerobic decomposition and thus has a lower rate of CH_4 emissions than manure stored in the anaerobic lagoons used by confined livestock operations (e.g., feedlots or dairies) (IPCC 2006). For the small number of animals in confined facilities, policies to help livestock managers fund biogas control systems (e.g., for electricity or heat) could reduce countywide CH_4 emissions from livestock by as much as 10 percent. In addition to the expense of installation, strict air quality standards can sometimes pose a disincentive for adoption since they require engines that burn methane to emit less than 50 parts per million (ppm) of nitrogen oxides (NOx) (CARB 2001). A reevaluation of state and local air quality regulations in light of the possible climate change benefits associated with biogas control technologies could help strike a balance between air quality and climate change objectives.

Emissions of CH_4 from rice cultivation in Yolo County provide another example of how differing air quality and climate change priorities can sometimes lead to policies that run contrary to one another. Prior to 1991, virtually all rice straw in California was burned in the field after harvest; a practice that led to protracted public debate about local air pollution and culminated with the passing of the Rice Straw Burning Act (Jenkins et al. 1992; Hill et al. 2006; Assembly Bill 1378, 1991). As an alternative to burning, most rice farmers shifted their post-harvest practices to a combination of residue incorporation and winter flooding, which has led to lower yields and higher production costs (Hill et al. 2006). These policy-driven changes in residue and water management have improved air quality in the Sacramento Valley and enhanced winter habitat for migratory waterfowl. However, field studies testing the effects of residue incorporation and winter flooding now estimate that this policy has led to a two- to three-fold increase in the amount of CH_4 emitted from California rice fields (Bossio et al. 1999; Fitzgerald et al. 2000). The increase in countywide CH_4 emissions arising from this regulatory measure, as estimated in this study using the DNDC model, is consistent with these findings. Management options that can help reduce CH_4 emissions include baling straw for off-farm uses (e.g., bedding, energy generation, low-quality feed), mid-season drainage, and reduced winter flooding. However, before promoting such practices policy makers should carefully consider how they might affect grower livelihoods and the other ecosystem services provided by local rice fields.

Estimates presented in this study indicate that emissions from burning crop residues and the application of lime and urea are a very small fraction of agricultural emissions in Yolo County, and have already been declining over the past two decades. This suggests that additional policies targeting residue burning, lime, and urea will have little impact on overall emissions. By contrast, recent landscape studies conducted in Yolo County suggest that programs to sequester carbon in agricultural soils and plant biomass through various reforestation projects (e.g., in rangelands, riparian zones, and hedgerows) have considerable potential to offset the county's GHG emissions (Smukler et al. 2010; Young-Mathews et al. 2010). Carbon can also be sequestered in the biomass of perennial orchard crops, however at present offset protocols for these systems do not exist. At present, the lack of high-resolution data on the diverse range of agricultural practices used here in Yolo and the shift in practices over the past 20 years makes it very difficult to estimate changes in soil and woody biomass carbon with any degree of accuracy. Future research could investigate how restoration efforts might be able to increase carbon sequestration in soil and wood using spatially explicit modeling, with special focus on management of marginal lands. The sale of carbon offset credits in California's new carbon market is also a potential opportunity to raise funds for reforestation and farmscaping projects, assuming that future protocols to quantify and monitor local carbon storage can meet the criteria of being real, permanent, quantifiable, verifiable, enforceable, and additional (Niemeier and Rowan 2009).

4.5 Conclusions

As California begins to implement the mitigation policies of AB 32, the present study offers several insights that will be relevant to other local governments and agricultural communities. First, since emissions from cropland and rangeland were several orders of magnitude lower than urbanized land (per unit area), local measures to protect farmland may themselves be viewed as mitigation strategies, or at the very least a means of stabilizing emissions. Perhaps more important, the idea of "GHG mitigation via farmland preservation" is likely to win support among rural stakeholders with long-term intentions to remain in farming, ranching, and associated industries. Aligning farmland preservation policies with legislation to reduce GHG emissions (i.e., SB 375 for regional planning and AB 32 for reducing global warming) might also generate further backing within rural communities if it helps to justify and safeguard agriculture's unique "voluntary" mitigation status among California's major economic sectors (Niemeier and Rowan 2009). This bit of common ground may also bear fruit in other ways by helping to engage both stakeholders and regional planners in the broader discussion of how agriculture can adapt to the risks posed by climate change. Since farmland preservation also requires coping with climate change, more attention needs to be placed on the tradeoffs that sometimes arise between managing for mitigation of GHG emissions versus adaptation.

While some have characterized voluntary mitigation strategies as inherently weak policy instruments (Lyon 2003), others have begun to highlight examples of how partnerships between local governments and various stakeholders can lead to substantive climate action planning and noteworthy reductions in GHG emissions (Flatt 2006; Adger 2003). In this context, bottom-up local initiatives may be more attractive to farmers in that promoting more efficient use of agricultural inputs (e.g., fertilizer, fuel and water) while maintaining or enhancing crop productivity. While some initiatives by stakeholders will seek transformative change of local agroecolgical systems (e.g., organic agriculture), others will chose to mitigate and adapt using an incremental and market-driven approach (Reganold et al. 2011). No matter the approach, local knowledge on co-benefits and tradeoffs of GHG mitigation must be shared among farmers, extension workers, researchers, and policy makers so as to further empower rural communities to develop sustainable solutions and avoid urbanization (Warner 2005; Cohen and Neale 2006; Reganold et al. 2011).

Table 4.7. Trade-offs and Co-benefits of Potential Agricultural Strategies to Mitigate GHG Emissions in Yolo County

Emissions Category	Strategy	Trade-offs	Co-benefits
Direct and Indirect N_2O from Agricultural Soil	N rate reduction	-yield loss for some crops -already optimized for some crops	-lower input costs -water quality
	organic methods	-organic fertilizer costs -labor costs -limited fertilizer options -limited pest control options -yield loss for some crops	-price premium -local or direct marketing -environmental quality -agrobiodiversity
	cover cropping	-cost of crop establishment -additional fuel use -not compatible with all crop rotations -spring incorporation constraints	-soil quality -erosion and runoff control -water quality -agrobiodiversity
Mobile Farm Equipment	equipment maintenance	-maintenance cost -generally done already	-lower fuel costs
	optimize draw-bar load	-generally done already	-lower fuel costs
	conservation tillage	-not compatible with all crop rotations	-lower fuel costs -less labor -less wear on tractors -soil carbon sequestration -water conservation
	engine upgrades or retrofits	-cost of new equipment	-lower fuel costs -conservation of soil organic matter
Irrigation Pumping	Maintain pump bowl assembly	-maintenance cost -generally done already	-lower fuel or electricity costs
	solar-powered pumps	-cost of photovoltaic cell -limited to low-horsepower engines -limited to daytime use	-lower fuel or electricity costs

Table 4.7 (continued)

Emissions Category	Strategy	Trade-offs	Co-benefits
Livestock CH_4	biogas control systems	-cost of building the system -engines subject to air quality regs.	-energy generation (gas or electricity) -sale of carbon credits
Rice Cultivation CH_4	baling and removal of straw	-baling costs -limited market for rice straw -impacts quality of waterfowl habitat	-sale of rice straw -feed and bedding for livestock -feedstock for biomass power generation
	reduce winter flooding	-poor decomposition of straw -impacts quality of waterfowl habitat	-lower pumping costs, fuel savings -water conservation
	mid-season drainage	-crop water stress -yield loss	-control of aquatic weeds -water conservation
Residue Burning	minimize burning	-low overall mitigation potential -already regulated	-air quality
Urea Use	substitute non urea-based N fertilizers	-low mitigation potential	--
Lime Use	none proposed	-low mitigation potential	--
Carbon Sequestration	reforest rangelands, riparian zones and hedgerows	-cost of establishment -access to irrigation during early years	-water quality -erosion control -biodiversity

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4.7 Glossary

AB 32	California Assembly Bill 32, California Global Warming Solutions Act of 2006
CAGO	California Attorney General's Office
CARB	California Air Resources Board
CDFA	California Department of Agriculture
CH_4	methane
CMIS	California Irrigation Management Information System
$CO2_e$	carbon dioxide equivalent
DNDC	DeNitrification-DeComposition
EIA	Energy Information Administration
FMMP	Farmland Mapping and Monitoring Program
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
N	nitrogen
N_2O	nitrous oxide
NASS	National Agricultural Statistics Service database
NH_3	ammonia
NO_x	nitrogen oxide
OFFROAD	Tier 3 OFFROAD emissions model
ppm	parts per million
SB 375	California Senate Bill 375
SSURGO	Natural Resources Conservation Service's Soil Survey Geographic
UCCE	University of California Cooperative Extension
USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency
YCAC	Yolo County Agricultural Crop Reports

Section 5: Farmer Perceptions of Climate Change in Yolo County: What Drives Their Inclination to Adopt Various Adaptation and Mitigation Practices?

V. R. Haden, M. Niles, M. Lubell, J. Perlman, and L.E. Jackson

5.1 Introduction

Given agriculture's direct reliance on natural resources, people who make their living from agriculture are highly vulnerable to climate change (Leary et al. 2006; Adger et al. 2007; Bryan et al. 2009). While climate change is a complex global phenomenon, localized impacts with significance to agriculture are already being observed in California. Noteworthy examples based on empirical records include; rising mean temperatures, declining snowpack in the Sierra Nevada, temporal changes in stream flows, and a reduction the in winter chill hours required for many fruit and nut crops (Barnett et al. 2008; Baldocchi and Wong 2008). Since these climatic trends are expected to continue in the decades ahead, strategies which integrate innovative agricultural practices with effective local outreach programs and policies are needed to support California's agricultural stakeholders in their efforts to adapt to climate change and mitigate the emissions that contribute to it (Adger 2000; Cayan et al. 2008; Jackson et al. 2009).

To better inform climate change programs and policies, a sound understanding is needed about what influences farmers' perception of climate change and their subsequent adaptation and mitigation responses. A number of studies have indicated that characteristics of the individual farmer and their farm can influence their perception of and response to climate change (Bryant et al. 2000; Bryan et al. 2009). Other studies have demonstrated that farmers' views on the occurrence of climate change, as well as their response, is more often related to recent climate trends or weather events as opposed to long-term changes in mean temperatures or precipitation (Thomas et al. 2007; Bryan et al. 2009). Levels of concern about the future impacts of climate change can also be a strong motivator to adapt or mitigate, though very few studies have explored this explicitly among farmers (Mertz et al. 2009; Leiserowitz et al. 2011). Social networks and involvement in programs run by local institutions, agricultural organizations, and extension services have also been shown to play a key role in facilitating (or hindering) farmers' ability to respond (Adger 2000; Tompkins and Adger 2004; Agarwal 2008; Maddison 2007; Nhemachena et al. 2007). Likewise, farmers' views on government programs and environmental policies can also influence their perceptions of climate change and what adaptation and mitigation practices they are inclined to adopt (Adger 2001).

Adaptation practices are meant to help farmers cope with potential future impacts, while mitigation practices are intended to minimized GHG emissions and/or sequester carbon in the agricultural landscape. Some agricultural practices may facilitate adaptation and mitigation simultaneously; however, most changes in practice require farmers to consider a mix of tradeoffs and co-benefits (see Section 4). Whether or not a new practice is desirable to a farmer may also depend on the time frame of the benefit, and if the benefits of adopting are public or private (Berkhout 2005). For example, adaptation and/or mitigation practices with direct short term benefits to the farmer are likely to be preferred over practices that yield only long-term public benefits to society. As such, different factors can influence the practicality and profitability of certain adaptation and mitigation practices, and thus result in non-uniform patterns of adoption.

Against this brief conceptual backdrop, the goal of this study is to: (1) examine farmers' perceptions of climate change and its risks to agriculture; and (2) develop a better understanding of how the various factors mentioned above influence farmers' adoption of proposed adaptation and mitigation practices.

5.2 Methods

Study Area

The study was conducted in Yolo County, California from 2010–2011. Yolo County is among the first rural counties in California to specifically address climate change mitigation and adaptation in their recently passed "climate action plan" (Yolo County 2010). The county's climate action plan consists of three main components: (1) an inventory of GHG emissions for 1990 and the current period; (2) a set of local policies to mitigate future emissions; and (3) a section examining possible adaptation strategies to help county stakeholders cope with the local impacts of climate change. Consequently, concerns about the impact of climate change, as well as new state and local environmental policies, have brought a diverse range of stakeholders into the discussion about climate change adaptation and GHG mitigation.

Semi-structured Interviews and Mail Survey

To develop an ethnographic understanding of local farmers' livelihoods, their perceptions of climate change, and their views regarding climate risks we conducted semi-structured interviews with eleven farmers and two agricultural extension workers in the fall of 2010. A purposive sampling strategy was used to recruit respondents from a cross section of farm sizes, local cropping systems (e.g., row crops, fruit and nut orchards, livestock) and market orientations (e.g., commodity, direct market, certified organic) (Kemper et al. 2003; Pearce et al. 2010). Interviewers followed a set of open-ended questions to minimize prompting and interviewer bias, but allow respondents to share personal experiences from their career in agriculture and their perspectives on various economic, regulatory and climate-related issues. The interviews were voluntary and respondents were given the opportunity to remain anonymous.

Audio recordings of the interviews were transcribed and used to develop a quantitative survey which was mailed to farmers in Yolo County during February and March of 2011. Prior to mailing, the survey was further refined based on detailed comments provided by members of the Yolo County Farm Bureau. A copy of the final survey is available upon request. The survey sample was drawn from a mail and phone list of 572 individuals in Yolo County who have submitted pesticide use permits to the Yolo County Agriculture Commissioner's office. The State of California requires all farms and businesses that apply conventional or certified organic pesticides to request a permit through the local agricultural commissioner, who then maintains this database as a part of the public record. The mail survey was conducted using the tailored design method (Dillman 2009). An alert postcard was mailed in mid-February and followed a week later by a survey packet containing a cover letter, survey booklet, and return envelope. A second round of postcards and survey packets were mailed two weeks later. A final round of follow-up postcards and phone calls were made to those on the mail list that did not respond.

The follow-up phone calls indicated that approximately 82 percent of unknown non-respondents were the owner or principle operator of a farm, and thus eligible for the study, while the remaining 18 percent were outside its intended scope (e.g., managers of golf courses, grain storage facilities, university research stations). Of the 572 surveys mailed out, 162 were returned with sufficiently complete answers to be used in the study. This amounts to a raw response rate of 28.3 percent (as a proportion of the total surveys mailed out) and a final response rate of 34.0 percent (as a proportion of the estimated number of eligible surveys excluding those which were returned undeliverable). An analysis of descriptive statistics and bivariate regressions was conducted using STATA 11 (StataCorp LP, College Station, Texas).

5.3 Results and Discussion

Farmer's Perceptions of Climate Change and Its Impacts on Global and Local Agriculture

Results of the survey indicated that 54.4 percent of farmers in Yolo County agreed to some extent with the statement "the global climate is changing" (Table 5.1). A plurality also agreed that global temperatures were increasing (38.5 percent) and that human activities were an important cause of climate change (35.2 percent). Those who were skeptical of the role of human activities, however, tended to disagree strongly. Most respondents agreed that climate change poses risks to agriculture globally (53.4 percent), though many felt it also offered opportunities (44.5 percent). As such, when asked if the overall impacts (both global and local) would be positive or negative, a larger fraction of farmers expressed uncertainty regarding the outcome (Table 5.1).

The survey also asked farmers to indicate any local trends in temperature, rainfall, water availability, drought, and flooding that they may have observed over the course of their farming career. In most cases a strong majority (> 61 percent) of respondents indicated that temperatures have stayed the same over time (Table 5.2). However, a close examination of which way farmers (as a whole) tended to lean in their response, also yielded some important observations. For instance, a large minority (21.3 percent) indicated that local summer temperatures had decreased over time, while only 5.6 percent observed an increase. While contrary to statewide and global mean temperatures, this actually corresponds with local climate records that show a slight downward trend in maximum summer temperature over the course of the last 100 years (Figure 5.1a; see Section 2 above). This trend in microclimate is only visible if summer maximum and minimum temperatures are examined independently, and has been linked in previous studies to a gradual expansion of irrigation throughout the Central Valley (Christy et al. 2006; LaDochy et al. 2007). The rationale is that higher rates of evapotranspiration in irrigated farmland can reduce maximum temperatures during the day, but higher soil moisture also increases summer minimum temperatures by reducing radiation cooling at night (Figure 5.1b). This particular observation and explanation was also alluded to during a pre-survey interview with a local extension agent.

Table 5.1. Level of Agreement with Global and Local Climate Change Statements Among Respondents

	Level of agreement with the statement					
Statement	Strongly agree	Agree somewhat	Neutral	Disagree somewhat	Strongly disagree	I don't know
	-------------------- % of respondents --------------------					
The global climate is changing. (n = 160)	23.8	30.6	19.4	14.4	10	1.9
Average global temperatures are increasing.(n = 161)	16.1	22.4	24.8	16.1	14.9	5.6
Human activities such as fossil fuel combustion are an important cause of climate change. (n = 162)	15.4	19.8	26.0	16.0	18.5	4.3
Climate change poses risks to agriculture globally. (n = 161)	26.7	26.7	23.0	8.7	11.1	3.7
Climate change presents opportunities for agriculture globally. (n = 162)	13.0	31.5	31.0	11.1	7.4	6.2
Climate change presents more risks than benefits to agriculture globally. (n = 161)	14.3	23.0	32.9	9.3	9.3	11.1
Climate change presents more risks than benefits to agriculture in Yolo County. (n = 161)	11.8	17.4	34.2	14.3	11.8	10.6

n=number of respondents

Table 5.2. Perception of Past Trends in Local Summer Temperatures, Winter Temperatures, Annual Rainfall, Water Availability, Frequency of Drought, and Frequency of Flooding

	Perception of past trends in local climate, weather and water			
Parameter	Has increased over time	Has stayed the same over time	Has decreased over time	I don't know
	------------------- % of respondents -------------------			
Summer temperature (n = 160)	5.6	61.9	21.3	11.3
Winter temperature (n = 158)	7.6	70.3	8.9	13.3
Annual rainfall (n = 156)	3.2	69.2	15.4	12.2
Water availability (n = 158)	0.7	46.8	43.0	9.5
Frequency of drought (n = 157)	14.6	62	5.1	17.8
Frequency of flooding (n = 157)	3.2	65	14.6	17.2

n=number of respondents

Respondents who reported a decrease in local temperatures over time were also: (1) more likely than average to think global climate is changing; (2) less likely than average to think global temperatures are increasing; (3) less likely to think humans are an important cause, and (4) more likely to think that climate change presents more risks than opportunities (Table 5.3). Thus, the tendency for some farmers to report a decrease in summer temperatures may reflect a nuanced understanding of their local microclimate, which could influence their overall views on global climate change.

While a majority of farmers indicated that rainfall, drought, and flooding had not changed over the course of their career, a sizable minority (43.0 percent) reported that water availability had decreased, and less than 1 percent said it had increased. Interestingly, records from the Yolo County Flood Control and Water Conservation District do not fully corroborate farmers' perceptions. In 1976, the newly constructed Indian Valley Reservoir began supplementing the District's surface water supplies to local growers. This increased storage capacity has improved the ability of the District to deliver water to local farmers and also facilitated groundwater recharge, as demonstrated by a notable recovery in local ground water levels since the reservoir began operating (Borcalli and Associates Inc. 2000). However, a recent drought in 2009 and 2010 reduced water releases in those years to less than 40 percent of the average for the preceding decade (1999–2008) (Yolo County Flood Control and Water Conservation District (YCFCWCD) data, unpublished). The memory of this recent a drought may occupy a central place in farmers' perception of water-related trends. Variations on this rationale have been offered elsewhere (Meze-Hausken 2004; Bryan et al. 2009) to explain farmers' tendency to report declining precipitation and/or water availability even when the empirical record cannot support such claims.

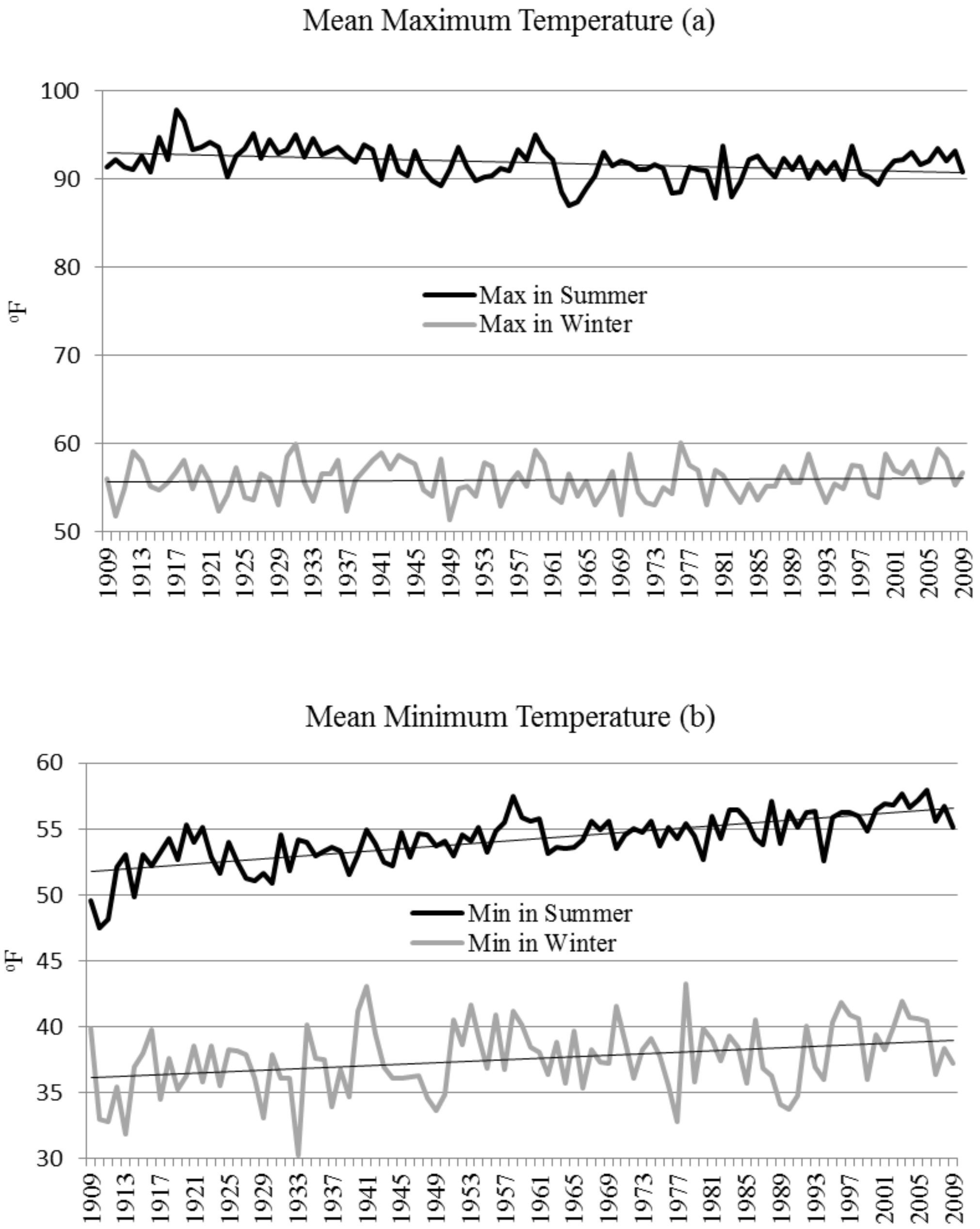

Figure 5.1. Historical Trends (1909–2009) in Mean Maximum (a) and Minimum (b) Temperatures during the Summer (June, July, and August) and Winter (December, January, and February) Months in Davis, California. Temperature records are from the Davis weather station

Source: Lee et al. See Section 2 of this paper.

Table 5.3. Mean Response of Farmers Who Reported a Decrease in Summer Temperatures over Career to Climate Change Statements as Compared to All Farmers

	Mean response to statement	
Statement	All farmers	Farmers reporting a decrease in summer temperature
	(1 = strongly agree, 5 = strongly disagree)	
The global climate is changing	2.55 (n = 157)	2.31 (n = 32)
Average global temperatures are increasing	2.92 (n = 152)	3.13 (n = 30)
Human activities are an important cause of climate change	3.03 (n = 155)	3.27 (n = 33)
Climate change poses risks to agriculture globally	2.49 (n = 55)	2.39 (n = 33)
Climate change presents opportunities to agriculture globally	2.66 (n = 152)	2.58 (n = 33)
Climate change presents more risks than benefits to agriculture globally	2.73 (n = 143)	2.67 (n = 33)
Climate change presents more risks than benefits to agriculture in Yolo County	2.97 (n = 144)	2.88 (n = 33)

n= number of respondents

What Climate Related Impacts Concern Farmers the Most?

When asked to indicate their level of concern for various climate-related impacts, farmers consistently showed greater concern for more regulations and higher energy prices followed by more volatile markets, new pests and diseases, changes in the availability of surface and groundwater resources, and more severe droughts (Table 5.4). Risks associated with changes in summer temperatures were a more moderate concern to growers, while impacts such as spring flooding, freezing temperatures, and fewer winter chill hours (all associated with winter climate) tended to be of lesser concern. While this trend was generally consistent for all farmers, respondents with certain product types did show differences in the level of concern for impacts that were relevant to their farming operations (Table 5.4). For instance, rice farmers tended to be more concerned about government regulations (e.g., rice straw burning and pesticides), the availability of surface water, and increased flooding; while fruit and nut tree growers expressed greater concern for groundwater supplies and winter chill hours. For most climate impact categories, those who grazed livestock were less concerned than other farmers. Concerns about future impacts were also related to respondents’ perceptions of past climate trends (Table 5.5). For example, growers who reported a decline in local water availability tended to show greater concern for most future impacts, with winter chill hours and government regulations being the only exceptions to this pattern. Likewise, farmers who reported a decrease in local rainfall over time were much more concerned about future severe droughts. Observations of past temperature change also resulted in corresponding concerns for future impact (Table 5.5). Consequently, those who felt that summer temperatures have decreased showed less concern for future heat waves, while those who reported a decrease in winter temperatures were more concerned about winter freezes.

Does Concern for Specific Climate Impacts Influence What Adaptation Practices Farmers Will Adopt?

Results of the survey indicated significant relationships between farmers' concern for future climate impacts and their inclination to adopt water-related adaptation practices. Respondents with greater concern for drought and less reliable water (i.e., both surface and groundwater) were more likely to pump groundwater, drill new wells, and adopt drip irrigation (Table 5.6). Those concerned about severe drought (and to a lesser extent surface water) were more willing to adopt drought tolerant varieties of the crops that they already cultivate. Concerns for higher summer temperatures and heat waves were also linked with the intention to use drought tolerant crops. Adopting drip irrigation also tended to be linked with concern for fewer winter chill hours and more frequent winter freezes, a result likely driven by the widespread use of drip and micro-sprinkler irrigation in perennial orchards and vineyards which are more sensitive to changes in winter temperature. Well drilling also followed the same pattern, albeit at a weaker level of significance. Respondents who indicated that they were likely to drill more wells, seek alternative water sources, or adopt drip irrigation were also more concerned about volatile markets, higher energy prices, and more government regulations in the future.

What GHG Mitigation Practices Are Farmers More Inclined to Adopt?

The study was also interested in understanding what practices farmers are willing to adopt on a voluntary basis to reduce energy use and mitigate GHG emissions (Figure 5.2). The majority of farmers in the survey were either likely or very likely to adopt energy-saving measures such as reducing on-farm energy consumption (63.7 percent), investing in fuel-efficient farm equipment (66.4 percent) and installing solar panels or wind turbines (56.7 percent) (data not shown). Approximately 49.3 percent were also inclined to adopt conservation tillage. While a large majority of famers were willing to improve nitrogen use efficiency through improved timing and placement of fertilizers (65.6 percent), only 22.8 percent said they were inclined to reduce their N application rate. Of the rice farmers surveyed, more than half said they were likely to modify their water and residue management to save energy and reduce emissions. Less than 7.0 percent of all respondents said they were likely to shift more of their land to organic production. Likewise, there was very little interest among the few livestock managers surveyed in mitigating emissions through changes to livestock diet or building methane digesters. The notable lack of interest in these livestock-related practices is likely because intensive management of diet and manure is impractical for extensively grazed livestock on annual grasslands, which is the dominant livestock system in Yolo County. Overall, these results indicate that farmers favor voluntary mitigation practices that have direct economic co-benefits to the individual, particularly those that help keep their energy costs low.

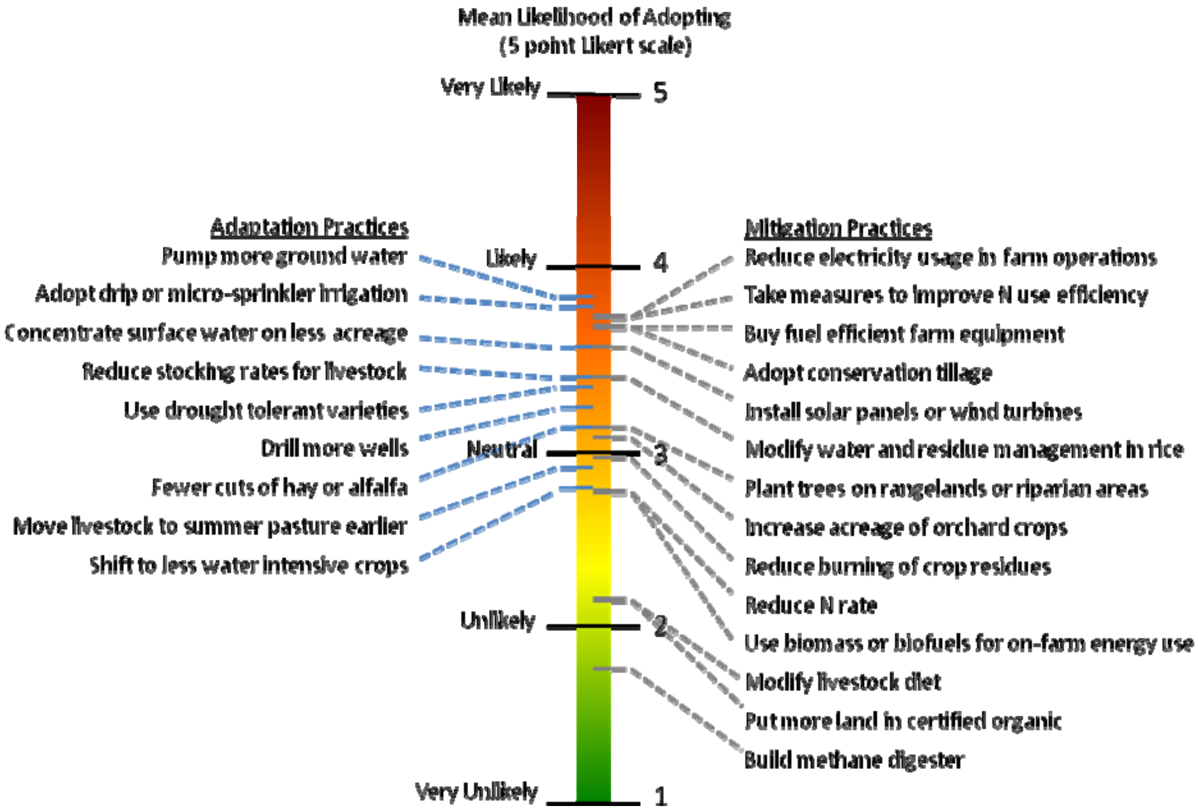

Figure 5.2. Mean Likelihood of Farmers Adopting Various Mitigation and Adaptation Practices (5-point Likert scale)

Table 5.4. Mean Level of Concern (1 = very concerned, 4 = not concerned) for Future Climate-related Impacts as a Function of Crop Type

	Mean level of concern by product type (1 = very concerned, 4 = not concerned)								
Future Impact	Row crops and vegetables (n = 49)	Hay and alfalfa (n = 53)	Rice (n = 26)	Grain (n = 47)	Grapes (n = 19)	Fruit and nut trees n = 70	Dairy (n = 1)	Grazed livestock (n = 20)	All product types
More government regulations (n = 160)	1.29	1.30	1.08	1.3	1.74	1.50	1.00	1.75	1.57
Higher fuel and energy prices (n = 160)	1.55	1.43	1.46	1.62	1.79	1.41	1.00	1.8	1.64
More volatile markets (n = 159)	2.31	2.38	2.27	2.36	2.26	2.19	2.00	2.65	2.34
New pests and diseases (n = 161)	2.27	2.42	2.58	2.43	2.26	2.16	3.00	2.70	2.36
Less reliable groundwater (n = 159)	2.39	2.35	2.50	2.61	2.66	2.11	3.00	2.40	2.41
Less reliable surface Water (n = 156)	2.31	2.49	2.19	2.51	2.37	2.34	3.00	2.55	2.47
More severe droughts (n = 156)	2.55	2.72	2.77	2.89	2.79	2.40	3.00	2.95	2.62
More heat waves (n = 159)	3.16	3.15	3.23	3.32	3.16	3.03	4.00	3.30	3.09
Warmer summer temperatures (n = 159)	3.18	3.19	3.19	3.43	3.11	3.03	4.00	3.45	3.14
Increased flooding (n = 161)	3.12	3.11	2.62	3.04	3.00	3.11	4.00	3.40	3.16
More winter freezes (n = 159)	3.16	3.26	3.61	3.45	3.32	2.87	3.00	3.45	3.20
Fewer winter chill hours (n = 160)	3.53	3.53	3.77	3.64	3.26	2.94	4.00	3.85	3.34

n = number of respondents

Table 5.5. Regression Coefficients for Past Climate Perceptions (1= increased over time, 2 = stayed the same, 3= decreased over time) and Future Impact Concerns (1=very concerned, 4 = not concerned)

	Past trends in local climate, weather and water					
Future impact	Summer temperatures	Winter temperatures	Annual rainfall	Water availability	Frequency of drought	Frequency of flooding
More severe droughts	0.10	-0.21	-0.73**	-1.02**	0.56**	-0.04
Less reliable surface water	-0.18	0.14	-0.39	-0.69**	0.04	0.06
Less reliable groundwater	-0.10	0.08	-0.28	-0.88**	0.25	-0.09
Increased flooding	-0.11	0.06	0.02	-0.49**	-0.10	-0.04
Fewer winter chill hours	-0.16	-0.07	0.09	-0.16	-0.01	-0.57**
Warmer summer temperatures	0.22	-0.28	-0.23	-0.41**	0.21	-0.30
More heat waves	0.38*	-0.28	-0.29	-0.44**	0.40*	-0.18
More winter freezes	-0.17	-0.52**	-0.36†	-.47**	0.41*	-0.56**
New crop pests/diseases	0.10	0.17	-0.15	-.51**	0.20	-0.08
More volatile markets	-0.17	0.36†	-0.12	-.39*	0.24	0.30
Higher fuel and energy prices	0.04	-0.05	-0.25	-.54**	0.09	-0.04
More government regulations	-0.27	0.31	-0.18	-.08	0.13	-0.08

*significant at *P*<0.05
**significant at *P*<0.01

Table 5.6. Regression Coefficients for Future Climate Impact Concerns (1=very concerned, 4 = not concerned) and the Inclination to Use Various Practices to Adapt to Water Scarcity (1= very likely to adopt, 5= very unlikely to adopt)

	Climate impact concerns									
	Changing water resources			Changing temperatures				Changing markets and regulations		
Adaptation practices	Severe droughts	Less reliable surface water	Less reliable ground-water	Warmer summer temps.	More heat waves	Fewer winter chill hours	More winter freezes	More volatile markets	Higher energy prices	More government regulations
Surface water on less acreage	0.01	0.11	0.07	-0.03	0.07	-0.09	-0.06	0.03	0.23*	0.19*
Pump more groundwater	0.15	0.27*	0.35*	0.13	0.10	0.07	0.13	0.11	0.24*	0.06
Drill wells or seek alternative water sources	0.19*	0.31*	0.19*	0.10	0.06	0.14	0.14	0.27*	0.21*	0.16*
Adopt drip irrigation	0.16	0.23*	0.23*	0.15	0.11	0.21*	0.24*	0.24*	0.19*	-0.05
Use drought tolerant varieties of my current crops	0.27*	0.16	0.14	0.18*	0.19*	-0.01	0.13	0.17*	0.19*	0.13
Change to less water intensive crops	0.07	0.13	0.06	-0.01	0.04	0.01	0.09	0.01	0.09	0.10
Make fewer cuts of hay or alfalfa	0.06	0.17	-0.02	0.16	0.08	0.14	0.19	0.04	-0.01	0.14
Move livestock to irrigated summer pasture earlier	-0.11	-0.01	0.04	-0.15	-0.08	-0.18	-0.18	-0.10	-0.05	-0.01
Reduce stocking rate for livestock	-0.06	-0.13	-0.10	-0.30†	-0.23	-0.30	-0.23	0.05	0.02	-0.05

*significant at *P*<0.05
**significant at *P*<0.01

What Influences Farmers’ Likelihood to Adopt Voluntary Strategies to Mitigate GHG Emissions?

Our study also found significant relationships between a farmer’s views on climate change and their inclination to implement voluntary mitigation practices (Table 5.7). More specifically, farmers who disagreed with the statement “The global climate is changing” were less likely to adopt 9 out of 14 mitigation practices than those who agreed with the statement. Likewise, those who were skeptical that human activities are an important cause of climate change were also less likely to adopt most mitigation practices (e.g., 8 out of 14 practices). Those who disagreed with the statements that climate change presented more risks than benefits to global and local agriculture also tended to be less willing to adopt most of the mitigation practices included in the survey.

Influence of Farmer Contact with Local Agricultural Organizations

Farmers obtain information about agriculture and climate change from a variety of sources. These sources of information are likely to inform farmers’ views on climate change and thus influence their willingness to adopt voluntary mitigation practices. In general, farmers who had frequent contact with local agricultural organizations were more likely to implement mitigation strategies (Table 5.8). Notably, contact with the Yolo County Resource Conservation District had the most significant effect, with more frequent contact resulting in greater likelihood to adopt 9 of the 14 proposed mitigation practices. More frequent contact with the Center for Land-Based Learning resulted in willingness to adopt 6 out of the 14 practices, while contact with the local irrigation district resulted in greater willingness to adopt 5 out of the 14 practices. Contact with the Yolo County Farm Bureau, the University of California (UC) Cooperative Extension, and all other agricultural organizations (with the exception of the California Farm Bureau) resulted in greater likelihood of adoption for two to four mitigation practices. Stronger statistical relationships between certain organizations and the specific mitigation practices they regularly promote suggests that these programs are likely having a positive impact on the people they reach. For example, the willingness to plant trees increases with frequent contact with the Yolo County Resource Conservation District. This is likely an outcome of this organization’s sustained efforts to help local farmers restore riparian areas. Likewise, the strong link between on-farm energy conservation (e.g., lower electricity use, investment in fuel efficient equipment, and conservation tillage) and frequent contact with both the Yolo County Agricultural Commissioner and UC Cooperative Extension, suggests that local outreach programs related to these practices are having a beneficial effect. It also implies that further mitigation (and adaptation) benefits may be possible if personnel and resources are made available to expand participation among farmers who rarely interact with these groups. However, resources for agricultural technical advisors and funding sources have declined in recent years, as summarized in a report by the California Climate and Agriculture Network (CalCAN 2011).

Table 5.7. Regression Coefficients for Climate Change Views (1= strongly agree, 5= strongly disagree) and Farmers Inclination to Adopt Mitigation Practices (1= very likely to adopt, 5= very unlikely to adopt)

	Response to climate change statement			
Mitigation practice	Global climate is changing	Humans activities contribute to climate change	Presents more risks that benefits to agriculture globally	Presents more risks that benefits to agriculture locally
Reduce on-farm electricity use	0.26**	0.32**	0.29**	0.29**
Invest in fuel efficient farm equipment	0.156*	0.22**	0.25**	0.24**
Use conservation tillage	0.11	0.20**	0.08	0.08
Install solar panels or wind turbines	0.34**	0.41**	0.36**	0.32**
Use biofuels or biomass for energy needs	.21**	0.26**	0.16	0.16
Reduce nitrogen fertilizer rate	0.13*	0.23**	0.18*	0.19**
Improve nitrogen use efficiency	0.01	0.09	0.08	0.05
Increase certified organic acreage	0.18**	0.20**	0.11	0.08
Increase orchard crop acreage	0.11	0.14	0.28**	0.21*
Modify water and residue management in	0.23	0.09	0.40**	0.28*
Build methane digester	0.06	-0.06	-0.01	0.07
Modify livestock diet	0.35*	0.18	0.41**	0.29†
Reduce burning of crop residues	0.41**	0.33**	0.33**	0.31**
Plant trees	0.37**	0.32**	0.36**	0.25*

*significant at *P*<0.05
**significant at *P*<0.01

Table 5.8. Regression Coefficients for Frequency of Contact with Local Agriculture Organizations (1= weekly, 2= monthly, 3= annually, 4= never) and Farmers' Willingness to Adopt Mitigation Practices (1= very likely to adopt, 5= very unlikely)

	Frequency of communication with local agricultural organizations								
Mitigation practice	Commodity organization	County Farm Bureau	California Farm Bureau	County Agricultural Commissioner	Local Irrigation District	UC Cooperative Extension	County Resource Conservation District	Community Alliance with Family Farmers	Center for Land-Based Learning
Reduce on-farm electricity use	0.06	0.23*	0.16	0.25*	0.07	0.25*	0.30*	0.18	0.63**
Invest in fuel-efficient farm equipment	0.30**	0.22*	0.24*	0.43**	0.33**	0.49**	0.45**	0.33*	0.38*
Use conservation tillage	0.11	0.17	0.05	0.38**	0.11	0.36**	0.33**	0.16	0.32
Install solar panels or wind turbines	0.02	0.07	0.14	0.13	0.12	0.17	0.31*	0.30	0.42*
Use biofuels or biomass for energy	0.10	0.21	0.05	0.24	0.18*	0.16	0.21	0.28	0.33
Reduce nitrogen fertilizer rate	0.08	0.17*	0.16	0.17	0.14*	0.16	0.22*	0.13	0.35*
Improve nitrogen use efficiency	-0.01	0.08	0.04	0.13	0.08	0.15	0.19*	0.10	0.05
Increase certified organic acreage	-0.11	-0.05	0.05	0.22	-0.02	0.12	0.07	-0.12	0.45*
Increase orchard crop acreage	0.04	0.16	0.15	0.31	0.14	0.25	0.32*	0.36*	0.33
Modify water and residue management in rice	0.11	0.11	-0.04	0.46	0.30*	0.309	0.12	-0.06	0.05
Build methane digester	0.07	0.08	-0.07	0.01	0.03	-0.13	0.01	0.10	0.32
Modify livestock diet	0.22	-0.02	-0.40	0.20	0.028	0.19	-0.05	0.28	0.02
Reduce burning of crop residues	0.46**	0.26	0.16	0.38*	0.32**	0.50**	0.53**	0.21	0.43
Plant trees	-0.03	0.17	0.26	0.1	-0.06	0.23	0.46**	0.49*	0.77**

*significant at *P*<0.05
**significant at *P*<0.01

Links Between Government Program Participation and the Adoption of Mitigation Practices

Table 5.9 shows the number of farmers that participate in organic certification, Williamson Act, Natural Resources Conservation Service-Environmental Quality Incentives Program (NRCS-EQIP), and Land Trust programs. Participation in such government programs, which often focus on agricultural sustainability, may affect a farmer's willingness to adopt mitigation practices. Our results support this hypothesis, and show that farmers who do not participate in these programs are also less likely to adopt various mitigation practices (Table 5.10). While no practices consistently result in significant relationships for all four programs, many practices were significant in three out of these four programs, including planting trees, increasing orchard crop acreage, installing solar panels or wind turbines, and using conservation tillage. Participation in organic certification and EQIP each had significant results for 9 of the 14 practices and a number of high regression coefficients. In many cases, some of the mitigation practices suggested here are also encouraged or rewarded in the government programs listed above. For example, NRCS-EQIP provides funding for farmers to replace their farm equipment and transition to organic agriculture (NRCS 2011). The findings also suggest that expanding the support for, and reach of, these government programs may help additional farmers implement mitigation practices on their farms.

Table 5.9. Percent of Respondents Participating in Conservation Programs

Conservation Program	Participant	Non-participant
	--------------- % of respondents	---------------
Organic certification (n = 148)	15.6	84.5
Williamson Act (n = 159)	65.4	34.6
NRCS – EQIP (n = 148)	36.5	63.5
Land Trust (n = 149)	18.1	81.9

How Farmers View Environmental Regulations and their Influence on Mitigation

Results presented in Table 5.4 indicated that farmers are often more concerned about the future impact of government regulations than they are about the direct impacts of climate change. This ranking of concern is not surprising, given the gradual nature of climate change. However, it does underscore the importance of understanding how farmers view environmental regulations and government policies and whether or not these views influence their likelihood to adopt various mitigation practices. Our findings indicate that farmers who disagree with the statement, "environmental regulations are effective at protecting natural resources" were also less likely to adopt 9 out of 14 mitigation practices (Table 5.11). Not surprisingly, farmers who were less inclined to participate in a government programs for climate change mitigation or adaptation were also less likely to adopt a large number of mitigation practices. These results

Table 5.10. Regression Coefficients for Participation in Conservation Programs and Inclination to Adopt Mitigation Practices (1= very likely to adopt, 5= very unlikely)

Mitigation practice	Participation in conservation programs			
	Organic	Williamson Act	EQIP	Land Trust
Reduce on-farm electricity use	-0.71**	-0.12	-0.55**	-0.28
Invest in fuel-efficient farm equipment	-0.52*	-0.31	-.081**	-0.43
Use conservation tillage	-0.59*	-0.44*	-0.47*	-0.32
Install solar panels or wind turbines	-0.80*	-0.19	-0.86**	-0.58*
Use biofuels or biomass for energy needs	-0.11**	-0.06	-0.41	-0.35
Reduce nitrogen fertilizer rate	-0.29	-0.04	-0.43**	-0.06
Improve nitrogen use efficiency	-0.15	-0.05	-0.10	-0.22
Increase certified organic acreage	-1.37**	0.27	-0.37*	0.04
Increase orchard crop acreage	-0.80**	-0.81**	-0.49*	-0.36
Modify water and residue management in	0.10	0.18	-0.36	0.07
Build methane digester	0.09	-0.01	-0.24	-0.29
Modify livestock diet	-0.56	-0.14	0.40	0.35
Reduce burning of crop residues	-0.84*	0.11	1.02**	-0.59
Plant trees	-1.33**	-0.31	-0.93**	-0.75*

*significant at *P*<0.05
**significant at *P*<0.01

indicate that farmers’ general views on the efficacy of environmental regulations has a strong impact on their inclination to adopt mitigation practices and participate in government programs related to climate change adaptation and mitigation. A detailed analysis of the external and psychological factors which influence the formation of farmers’ views on government programs and environmental regulations is beyond the scope of this study. However, our results do suggest that future studies should be designed with these objectives in mind.

5.4 Conclusions

The primary aims of this study were to examine farmers’ perceptions of climate change and its risks to agriculture, and to develop a better understanding of how various factors influence farmers’ adoption of proposed adaptation and mitigation practices. From this study we can draw the following broad conclusions:

- Farmers in Yolo County, hold a diverse range of views regarding whether or not climate change is happening, its causes, and the risks it presents for agriculture.
- These views on climate change are related to farmers’ perceptions of past trends in local temperatures, water availability, and drought, as well as their subsequent concern for future local impacts.
- Specific concerns about future impact, particularly those having to do with water availability, are positively linked with farmers’ inclination to use certain practices that may help them adapt to water scarcity in the future.
- Farmers generally favor voluntary mitigation practices that have direct economic co-benefits to the individual, particularly those that help keep their energy costs low.
- Stronger beliefs that climate change is occurring, and that it is caused by human activities, increase farmers’ inclination to adopt voluntary mitigation practices
- When farmers do not have frequent contact with local agricultural organizations, do not participate in government conservation programs, and do not hold favorable views on the efficacy of environmental regulations, they are generally less willing to implement voluntary mitigation practices and participate in future government programs supporting adaptation and mitigation.
- Strategies to expand the reach of local agricultural organizations and government conservation programs by improving farmer participation in their activities are thus seen as an important way to strengthen adaptation and mitigation efforts.

Table 5.11. Regressions Coefficients for Views on Government Policy Statements (1= strongly agree, 5= strongly disagree) and the Inclination to Adopt Mitigation Practices (1= very likely to adopt, 5= very unlikely)

	Government policy statements			
Mitigation practice	Environmental regulations are effective at protecting natural resources.	Environmental regulations make it harder to operate my farm.	Government regulations will make it harder to adapt to climate change.	I would participate in a government program for climate change adaptation and mitigation.
Reduce on-farm electricity use	0.36**	-0.14	-0.08	0.29**
Invest in fuel-efficient farm equipment	0.17*	-0.01	0.09	0.25**
Use conservation tillage	0.18*	-0.07	0.06	0.24**
Install solar panels or wind turbines	0.29**	-0.23*	-0.12	0.41**
Use biofuels or biomass for energy needs	0.27**	-0.07	-0.06	0.34**
Reduce nitrogen fertilizer rate	0.16*	-0.06	-0.12	0.19**
Improve nitrogen use efficiency	0.13*	-0.01	0.08	0.08
Increase certified organic acreage	0.19*	-0.01	-0.08	0.26**
Increase orchard crop acreage	0.11	0.09	0.08	0.20*
Modify water and residue management	0.06	-0.11	0.13	0.30**
Build methane digester	0.06	0.05	0.03	-0.05
Modify livestock diet	0.32	-0.38	0.21	0.18
Reduce burning of crop residues	0.19	-0.37**	-0.27*	0.40**
Plant trees	0.33**	-0.29*	-0.14	0.39**

*significant at $P<0.05$
**significant at $P<0.01$

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Section 6: Land Use Change, GHG Mitigation, Alternative Urban Growth Potential in Yolo County

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6.1. Introduction

California’s Central Valley is one of the most productive agricultural regions in the world, yet it is facing some of the most rapid population growth in the state. A midrange projection forecasts up to 59 million residents statewide by 2050, with massive conversion of agricultural to urban land in the Central Valley, and cities such as Fresno doubling in population (Sanstad et al. 2009). Urbanization in California tends to consume lands with high quality soils and relatively abundant water supply due to their proximity to existing towns and cities in the valleys (American Farmland Trust 2010). Given such prospects of population growth, the purpose of this task was to develop future urbanization scenarios for Yolo County, and assess implications for agriculture, greenhouse gas (GHG) emissions, and other issues related to land use change.

Urbanization presents both opportunities and challenges for agriculture. In some regions, it does generate markets for agricultural products, such that farm production increases locally (Lockeretz 1986; 1988; Wu et al. 2010). But urbanization is more typically accompanied by challenges: the loss of agricultural land due to subdivision and development; vandalism at the urban edge (Lisansky 1986); and conflicts with new suburban residents about noise, odor, and potential spray drift associated with farming operations. If development takes place in a dispersed pattern that fragments agricultural land, farming may become difficult on some remaining agricultural parcels due to difficulties in moving farm machinery from field to field. Also, fragmentation and loss of farmland causes farmers to lose benefits associated with being part of a large farming community, such as sourcing inputs, accessing information, sharing equipment, and supporting processing and shipping operations (Porter 1998). Impacts on agriculture from urbanization will then be disproportionate to the land area covered.

Suburban or exurban development increases GHG emissions per land area substantially when compared with agricultural land uses (see Section 4; Norman et al. 2006). It is useful to know the extent of these increases, especially since California counties will need to demonstrate ongoing commitment towards reducing GHG emissions in response to state mandates, such as the Climate Action Plan that was adopted in 2011 for the unincorporated areas in Yolo County (Yolo County 2010). In addition, land use planning for climate change can potentially set the stage for greater provision of other ecosystem services at the rural-urban interface, such as regulation of environmental resources, biodiversity conservation, livelihood options, and business opportunities that build social capital (Gutman 2007).

The A2 and B1 scenarios of the International Panel on Climate Change (IPCC) are based on storylines for higher and lower GHG emissions, respectively, which can be conceptually downscaled at local scales to explore how future local land use patterns will respond to climate change (Rounsevell et al. 2006; Hallegatte et al. 2011). A2 has higher economic and population growth, and less emphasis on environmental, social, and sustainability priorities than B1. The downscaled storylines can form the basis for spatial modeling of land use change and the challenges that would occur at the rural-urban interface. In California, UPlan is a simple rule-based urban growth model used for regional or county level modeling (Walker et al. 2007). The spatial configuration of each land use type is based on demographics, land use designations of the General Plan (although in this case we chose not to include this, as described further below), and on a set of attractors and detractors for land use change that can be informed by the storylines of climate change scenarios.

To investigate interactions between agriculture, urbanization, and GHG emissions we performed the following tasks:

- Developed scenarios for future urban growth that correspond to the IPCC's A2 and B1 storylines (a relatively pro-growth scenario and a moderate environmental protection scenario), as well as an AB32+ storyline that assumes continued, stronger state action in California to reduce GHG emissions. (Much of this scenario development was done during a previous phase of this study [Jackson et al. 2009]).
- Modeled urban growth between 2010 and 2050 for these scenarios using UPlan GIS-based software.
- Examined effects of this modeled growth on the farmland that is now used to grow particular crops in recent years, as well as on irrigated farmland in general.
- Calculated transportation-related and residential building-related GHG emissions from this new development for each scenario.

6.2. Background on Land Use in Yolo County

The majority of California's new residents will settle in urban areas in coastal counties and in the Central Valley. The Sacramento metropolitan region, where Yolo County is located, will house a significant portion of this growth. Projections prepared for the Sacramento Area Council of Governments (SACOG) Blueprint project in 2005 estimated a population increase from 1,948,700 persons in 2000 to 3,952,098 persons in 2050, i.e., >100 percent increase (Levy and Doche-Boulos 2005). The conversion of the region's undeveloped land into urban, suburban, and exurban development often occurs at the expense of agriculturally productive land.

Yolo County includes 653,452 acres (264,443 hectares) according to the 2008 California Department of Conservation Farmland Mapping and Monitoring Program (FMMP 2008). Agricultural land occupied 538,043 acres (217,738 hectares) in 2008. About 87 percent of the acreage was in agricultural use (Yolo County, 2011). Land use was classified as 4.6 percent urban in the incorporated cities of Davis, West Sacramento, Woodland, and Winters. Important farmland (defined as several categories of cultivated land for grains, row crops, orchards, and vineyards) was 57 percent, and livestock grazing land was 24 percent of the county's acreage. In 1998, Yolo County alone contained about 43 percent of the prime farmland that existed within the Sacramento region (including El Dorado, Placer, Sacramento, Sutter, Yuba, and Yolo Counties), and it yielded the highest farm market values out of all the counties (Kuminoff et al. 2000). Thus Yolo County is an important reservoir of productive farmland within the Sacramento metropolitan region.

A net loss of about 30,000 acres (12,141 hectares) of agricultural land occurred between 1992 and 2008, and this includes a net gain of about 16,000 acres (6,475 hectares) of grazing land (FMMP 1992 and 2008). New grazing lands were formed by draining parts of the Yolo Bypass along the Sacramento River and by transitioning dry-farmed grain fields to grassland, such as near the Dunnigan Hills. Overall, only 1 percent of Yolo County's total prime farmland was lost up until 2000 (Kuminoff et al. 2000). Between 1998 and 2008, the rate of agricultural conversion to wetlands, especially along the Sacramento River for wildlife conservation, has increased to approximately 2,000 acres yr^{-1} (826 hectares yr^{-1}) (Landon 2009).

Urbanization accounted for the loss of about 6,500 acres (2,631 hectares) of agricultural land (including grazing land) between 1992 and 2008 (FMMP 1992 and 2008), i.e., approximately 406 acres yr^{-1} (168 hectares yr^{-1}). Most of this was prime farmland and farmland of local importance.

Yolo County has been relatively successful at protecting agricultural land from urban conversion through land preservation programs, incentives for farmers, and land use policies that make it difficult to develop land zoned for agriculture. Yolo County's population grew an average of 2.2 percent per year from 1985 to 2007, from 120,300 to 197,530 residents (Sandstad et al. 2009; Johnson 2008). But by 2050 the county's population may reach 320,000 to 394,000 (SACOG, 2007; Sandstad et al. 2009; Johnson 2008), depending on assumptions used in scenarios for either regional or statewide planning. This would result in an increased urban population and pressures to expand the current urban footprint. Given the county's geography, urban expansion will almost certainly occur at the expense of farmland and open space if growth is not restricted to infill development within existing boundaries.

With respect to California's climate change policies aimed at reducing GHG emissions (e.g., California Assembly Bill 32 (AB 32, the Global Warming Solutions Act of 2006)[16] and Senate Bill 375 (SB 375)[17] which connects land use planning with implementation of AB 32), urbanization onto agricultural land raises two important issues for the 2050 time frame: (1) magnitude of the loss of agriculturally productive land that provides ecosystem services such as meeting the food needs of an expanding state and global population, wildlife habitat, and open space for residents; and (2) an increase in GHG emissions from decentralized urbanization when compared with more compact, centralized forms of urban development that leave agricultural lands undeveloped. There is a need to better understand the relationships between

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[16] Assembly Bill 32 (Nuñez), Chapter 488, Statutes of 2006.

[17] Senate Bill 375, Steinberg, Chapter 728, Statutes of 2008.

urbanization, agriculture, and climate change, and their interrelated effects on ecosystem services.

6.3 Methods

In order to understand the type, extent, and likely locations of urbanization in the county, we used UPlan GIS-based software, a rule-based, land use allocation model developed by the Information Center for the Environment at the University of California, Davis (Walker et al. 2007). UPlan is an open-source, relatively simple model that can be run on a sub-county area, a county, or a group of counties. It is a suitable model for broad-brush urbanization modeling of large land areas using multiple development scenarios, and has been used by more than 20 counties in California, including a group of rural Blueprint counties in the San Joaquin Valley (Johnston et al. 2009). In the past it has been employed to assess the impacts of urbanization policies and growth on natural resources (Beardsley et al. 2009), to understand the risk of wildfires in rural woodlands from urban growth (Byrd et al. 2009), and to evaluate the effect of land use policies on natural land conversion (Merenlander et al. 2005).

UPlan relies on a number of demographic inputs (current and future population, household size, employees per household, proportion of population by land use type, density of residential land use types, and floor-area per employee) to create scenarios reflecting possible urban growth trends. Households are divided into four residential land-use types (High, Medium, Low, and Very Low) based on density parameters, while employees are assigned to nonresidential land use types (Commercial High, Commercial Low, and Industrial), also by density. New development is divided by land use type (e.g., different residential densities; commercial; industrial) and allocated across the landscape based on the geographic cells with the highest combined attraction weights and the user-defined land use order. The model uses a cell size of 50 meters, roughly about half an acre. The final output is a map displaying the location, by land use type, of future urbanization.

UPlan is designed based on the following main assumptions (adapted from ESP 2007):

1. Population growth is converted into demand for land based on employment and household factors.
2. New urbanization will generally adhere to current city and county planning contexts.
3. County land and features are converted into grid cells with different attraction weights based on proximity to urban infrastructure.
4. Some feature cells, such as parkland and lakes, will not be developed, while other feature cells, like wetlands and floodplains, will discourage development.

Attractors (variables that would tend to attract urban growth) are given a positive value. Discouragements (variables that would tend to discourage urban growth) are given a negative value. A weighting system is used to rank the attractive or discouraging property of each variable. Masks are geographic variables where growth is prohibited because of logistical or ownership considerations. Table 6.1 gives an example of possible geographic layers used in UPlan.

Table 6.1 Examples of UPlan Geographic Variables

Attractors	Discouragements	Masks
Census Blocks with Growth	Floodplains	Public Lands
Freeway Ramps	Low Infill Areas	Lakes
Major and Minor Arterials	Prime Agricultural Soils	Vernal Pools
High Infill Areas	Steep Slopes	Wetlands
Commercial Strips	Endangered Species Habitats	Streams

Modifications to UPlan

For the purposes of this project, we modified UPlan in several ways when compared to previous usages. Since our time frame is longer than in many previous applications, we no longer required that the model place growth in areas conforming to the current county General Plan. Land use politics and regulation can change greatly over 40 years, which is equal to at least two General Plan cycles in most California counties. Furthermore, the County Board of Supervisors by majority vote can approve zoning variances four times a year, allowing development that does not conform to a current General Plan and zoning code. Thus, the planning documents and zoning codes that are a short-term deterrent to development may no longer be relevant in the longer term. The purpose of this project was also to model three significantly different scenarios, and restricting development to the current policy framework would make this difficult. For these reasons we did not include the countywide General Plan land use designations.

We also modified UPlan to allow development within existing urban areas, on the assumption that a significant amount of urban redevelopment is likely within the 2010–2050 timeframe. Lack of an infill development option was a significant drawback with previous versions of UPlan. Sharply increased levels of infill are likely within more environmentally oriented future scenarios. Indeed, our AB32+ scenario assumes that 100 percent of development takes place within existing urban areas. This approach is likely to rapidly decrease GHG emissions because lifestyles of urban area dwellers tend to have smaller carbon footprints, such as less energy expenditure for transportation (Ewing et al. 2008), as long as their economic actions do not increase to the point of significantly outweighing that benefit (O'Neill et al. 2010). Urban development is already increasingly taking the form of infill within the state's largest urban areas, including Los Angeles and the San Francisco Bay Area, and infill development is a leading goal of the Sacramento region's 2004 Blueprint vision for the future (SACOG 2007).

Lastly, we established density categories that are relatively high by historical California standards, but fairly close to the density levels of recent development in the more urban portions of the state. Our categories were "Very Low Density Residential," with an average lot size of one acre; "Low Density Residential," with an average density of 8 units per acre (approximately 5,000 square foot lots); "Medium Density Residential", with an average density of 20 units per acre; and “High Density Residential,” with an average of 50 units per acre. The latter two categories are similar to densities currently being achieved within many of California’s more urban communities (e.g., SCANH, n.d.). Within each scenario, we also apportioned development differently between these types. The A2 scenario focuses primarily on Low Density Residential development, while B1 is relatively evenly split between High, Medium, and Low Density types, and AB32+ favors High and Medium densities.

In terms of building types, the Medium Density category might consist of two- to three-story apartment or condominium buildings with significant green space around them, while the High Density category might include three- to five-story buildings in a more urban format. It is important to emphasize that none of these categories require high-rise apartment living, although this development type is not forbidden, and might in fact be desirable for limited locations within the county during the study period.

Additional Urban Attractor Variables

Several types of urbanization attractors are typically used in UPlan, including blocks with growth in the previous census period (in our case 1990–2000), freeway ramps, arterial streets, collector streets (“minor arterials”), and urban spheres of influence. To predict infill development more accurately, we added additional attractors such as existing commercial strips, shopping centers, freeway retail zones (all of which can potentially be redeveloped into dense housing), existing neighborhood centers, and rail transit stations. In most cases adding these factors meant creating new GIS data layers with information from publicly available sources or visual analysis of Google aerial imagery.

We took into account existing land uses within cities by creating a data layer of current zoning districts, and consolidating these districts into high and low infill potential layers. The first of these includes existing commercial and industrial land, which typically consists of relatively large parcels of land being used for relatively short-lived purposes (parking lots, shopping malls, industrial parks), owned by landowners who are likely to be open to profitable redevelopment over a 40-year timeframe. The second of these layers includes existing residential neighborhoods, which typically consist of small parcels of land owned by residents who are highly resistant to redevelopment, unless in the context of adding second units to existing houses. Even the process of creating secondary units tends to be slow and to produce relatively few units, despite some municipal programs to encourage it.

Different types of development are likely to be attracted to different factors. Commercial and industrial land uses and apartment buildings are likely to be located near major and minor arterials and freeway ramps. Low-density residential development is more likely to occur at a distance from these roads due to noise and traffic concerns. Mid- to high-density residential development is likely to be attracted to downtown locations, neighborhood centers, and shopping centers; especially in the low-GHG emissions scenarios in which public policy focuses on redeveloping and building up existing urban centers. Mid- to high-density residential development is also likely to be attracted to railroad stations in these scenarios as new passenger service is added and public policy emphasizes “transit-oriented development.” Some industrial development is likely to locate near railroad lines in these scenarios, since rail offers more energy-efficient transportation of many goods.

We assumed that locations currently slated for development that are distant from existing cities County, such as the Dunnigan area along Interstate 5 in the north of the county, will serve as urbanization attractors only in the scenario(s) with higher GHG emissions.

Census blocks with recent development are distributed fairly evenly between rural and urban areas of the county. We assumed that these blocks with recent growth would attract more urbanization in the future. This is in part because these areas are likely to possess infrastructure such as roads, water lines, sewer mains, and power lines which make development easier and cheaper. It is also because these areas are likely to contain previously subdivided parcels of land that are not yet built upon, and land owners that are more interested in subdividing, selling, or building on the land. In scenario(s) with higher GHG emissions, in which planning controls are weaker, census blocks with growth will be a stronger attractor, particularly in exurban locations. In the lower GHG emissions scenarios they will play a weaker role in attracting urbanization, since public policy is more likely to protect non-urban land, and less left-over land is likely within urban areas.

Previously, our larger research team developed a set of storylines for scenarios reflecting different climate change and urbanization policies for Yolo County in 2050 (Jackson et al. 2009). These were intended to emulate for the county storylines developed in 2000 by the IPCC (2000), with the addition of a scenario with very low GHG emissions corresponding to an even more stringent policy direction than established by California's AB 32 legislation. Each scenario corresponds to a broad-brush storyline, which is built upon a set of political, economic, institutional, and demographic assumptions. Each storyline is a possible future for urban growth and emissions for the county.

A2 - Regional Enterprise Storyline

As in IPCC scenario A2 (Regional Enterprise), our A2 scenario assumes that population growth would remain high, with an approximate doubling of the current county population to 394,000 (Johnson 2008; Sanstad et al. 2009). With an increase in population, continued economic growth and technological innovation, the county would see urbanized areas increase by 50 percent. Current preservation and land use policies would remain in place and although new suburban subdivisions would be built, there would be some focus on improving land use through greater land use mix, higher densities, and more infill, and limiting sprawl. Agricultural land would be lost to urbanization while less participation in farmland preservation programs, such as the Williamson Act, would result in less farm acreage and fewer farmers. Even with an increase in population, vehicle miles traveled would remain stable through land use and pricing changes, increased use of alternative modes, and greater fuel efficiencies. Still, the A2 storyline would be fossil fuel intensive as a result of more drivers and the dominance of automobiles as the main transportation mode. In terms of climate, under A2, average temperatures are predicted to increase between 1°C and 3°C (1.8°F to 5.4°F) for 2050. Changes in cropping systems and technological support for agriculture would continue in about the same way as present, without major societal investment in alternative options to deal with the impacts of global warming. The A2 storyline is a near continuation of current demographic, economic, technological, and environmental developments with some improvements and responses to current issues being addressed and implemented.

We should emphasize that in terms of suburban sprawl, the A2 storyline is by no means a worst-case scenario. Rather, it should be seen as a continuation of practices in the 1990 to 2010 period. If this storyline had been based on prevailing development patterns from 1950 to 1990, suburban densities would be in the range of 4–6 units per acre instead of 8, less development would occur in medium- and high-density forms, and a higher percentage of larger 1–10 acre ranchettes would be created. Suburban sprawl would cover a much larger percentage of the county in that case, taking far more agricultural land out of production.

B1 - Global Sustainability Storyline

In IPCC scenario B1 (Global Sustainability), societies become more conscious of environmental problems and climate change, and sustainable development efforts are implemented. Under our Yolo County B1 storyline, population would growslowly, reaching a mid-range population size of 335,000 by 2050 (Sanstad et al. 2009). Economic development would be moderate, with a shift from the production of goods to a more service-based economy that is connected to the larger global economy. Technological innovation remains high in the Sacramento region, with an emphasis on small-scale, green technologies. B1 is a relatively low GHG emissions scenario in which the urban area extends only 20 percent as a result of compact growth through higher densities, increased infill, and a focus on small, locally owned retail stores rather than big box developments that require more driving. As current transportation and emission policies become more stringent and the use of high-efficiency vehicles and alternative modes increases, vehicle miles traveled would be significantly reduced and transportation emissions with them.

Agricultural land conversion would be lower in this storyline as a result of less urban expansion and the use of farming easements and other incentives to maintain land in farming. Though long-term temperatures may be lower than in the A2 storyline, average temperatures in 2050 do not differ (see Sections 2 and 3). Consistent with AB 32, voluntary actions in agriculture would place more emphasis on increasing carbon sequestration and decreasing N_2O emissions through multiple crops per year, more ecologically intensive practices, reduction of fertilizer use, and efforts to capture methane emissions from livestock. Moreover, there would be greater societal investment in preparing ahead for climate change adaptation options, such as crop breeding, pest management, and resilience to intermittent droughts. Under B1, Yolo County experiences the benefits of slower population growth and improved urban land use practices, resulting in preservation of agricultural land and reduced GHG emissions.

AB32+ Precautionary Change Storyline

To the two IPCC-based storylines, we add a third scenario with more stringent GHG emissions regulation than AB 32. Under our AB32+ (Precautionary Change) storyline, Yolo County experiences slower population growth reaching only 235,000 in 2050, which would have to occur through policies or voluntary actions that affect family planning and migration (Lee 2011). In this storyline, moderate economic growth focuses on value-added production economic viability of the local rural sector, and support for ecosystem services generated by closer alignment between the rural and urban sectors (Gutman 2007). A less resource-intensive lifestyle would dominate, coupled with an increase in the quality of life through an increase in ecosystem services in both sectors. Priorities would be placed on both regulating services (e.g. for improved environmental quality) and cultural services (e.g., for education, health care, and sustainable livelihoods). The urban boundary remains at the current extent through strict land use planning policies and development emphasizing efficient use of land, mixed use, intense infill, increased densities, and growth in the urban core. More compact development patterns and the promotion of local development and payment for ecosystem services, coupled with many alternative modes of transportation and increased use of zero emission vehicles, would result in a reduction of vehicle miles traveled and GHG emissions from transportation.

Although long-term temperatures may be lowest under this scenario, 2050 temperatures are essentially the same as in the other storylines. In order to both mitigate and adapt to the changing climate, agricultural producers would make major changes in management practices, focusing on ecological intensification rather than on non-renewable inputs. This would require substantial societal investment in development of new renewable technologies and for diversification of cropping systems to fit site-specific situations. Practices such as farmscaping and revegetation of riparian buffer zones to mitigate and reduce GHG emissions would also be promoted for their co-benefits, such as improved water quality (Young-Mathews et al. 2010). Markets for products may become more locally based, and efforts would be made to reduce GHG emissions from processing and transport of agricultural products. Overall emissions would be the lowest under AB32+ with a reduction from urban areas due to denser, more balanced land development, less resource-intensive lifestyles, and improved transportation options. Changes in crop choice and management practices would likewise reduce GHG emissions from agriculture.

In addition to modeling these three scenarios using UPlan, we modeled additional versions of A2 and AB32+ in which population was held constant at the B1 level. This step allows us a more analogous comparison of the three storylines.

Greenhouse Gas Emissions from New Urbanization

After using UPlan to produce urban growth footprints for the above scenarios, we calculated two main categories of GHG emissions for the new urbanization produced by each. These calculations are very approximate, but help to give a sense of the magnitude of variations that can result from different policy approaches.

One category of GHG emissions was from transportation. Household travel surveys done by SACOG show that household vehicle miles travelled (VMT) vary by a factor of six between households in low-density (< 4 dwelling units (du) per acre) and high-density (> 40 du per acre) locations (SACOG 2007). Some of this difference may be due to household size and composition, but much is likely due to proximity to jobs, shopping, schools, and alternative transportation modes. In addition, many other policy steps in the lower GHG emissions scenarios are likely to reduce driving in the 2050 time frame. These other factors include rising gas or carbon taxes; improved balance of jobs, housing, and shopping within communities; improved bicycle, pedestrian, and public transit options; and other economic incentives such as higher parking charges and tolls.

Transportation emissions are also of course dependent on the fuel efficiency of motor vehicles. Average fuel efficiency of American vehicles remained more-or-less unchanged from the mid-1980s through 2010, and so for purposes of illustration, this was assumed in the A2 scenario until 2050. In the B1 scenario, we assumed modest efficiency increases of 2 percent a year (for an average of 61 mpg in 2050), and for the AB32+ scenario we assumed improvements of 4 percent a year (for an average of 136 mpg in 2050). Rather than continually improve conventional gasoline engines, these scenarios would most likely see increasing percentages of the motor vehicle fleet converting to hybrid or all-electric propulsion, with an increasing proportion of the electricity produced by renewable sources. We thus derived the motor vehicle fuel consumption of new households for each dwelling type through the formula:

> (# HH of each dwelling type x VMT/HH for that type) / average miles per gallon x GHG emissions per gallon

Household energy use was a second category of calculated GHG emissions. In Yolo County domestic energy comes almost entirely from electricity or natural gas, as oil heating is rare in California and use of wood stoves is also low and increasingly discouraged due to local air pollution concerns. Here again we can expect substantial differences in GHG emissions between infill urbanization and new residential development on agricultural land, due to larger unit sizes and a much higher percentage of stand-alone single family homes in the former case.

To calculate household energy use for the three scenarios, we used data from the 2009 California Residential Appliance Saturation Study (CEC 2010), a collaboration of the state's five largest utility companies that surveyed detailed consumption habits of nearly 26,000 households. This study breaks households down by climate zone, and compares energy consumption for single-family homes, townhomes, small multifamily buildings, large multifamily buildings, and mobile homes by California Energy Commission climate zone. Both electricity and gas use for the middle three categories were approximately half that of single family homes, probably in large part because average unit sizes were smaller, and perhaps also because shared-wall construction tends to be more energy efficient than stand-alone single-family homes. Since we can estimate the relative percentages of these unit types across our three scenarios, we could then calculate approximate energy use for the new households in each scenario. We adjusted for assumed trends in household energy use and efficiency within each scenario, using the 1985 to 2005 statewide reduction of approximately 15 percent per household as a baseline for the A2 scenario (Harper et al. 2011). The calculation for each land use type can be represented as follows:

Households of a given dwelling type x average energy consumption for that type x assumed 2050 trends in household energy use and efficiency improvement x GHG emissions/unit of energy = total GHG emissions for that dwelling type in the scenario.

6.4. Results of UPlan Modeling

Distribution and Amount of New Urban Development

The distribution of new development in 2050 varies under each storyline (Table 6.2). Under the A2 storyline development is dispersed in and around existing urban areas (Figure 6.1 and 6.2). The new development footprint is highest at over 14,000 acres. The urbanization pattern reflects an urban sprawl pattern of growth that is typical today and likely to continue into the future unless there are changes to planning policies and a reduction in population growth. Dunnigan, an area of the county where growth is currently being proposed, receives new development under A2.

The B1 storyline has urbanization that is more attracted to existing urban features. Under B1, growth is less dispersed and more concentrated in and around the urban sphere of influence; new development takes up over six thousand acres (Figure 6.2 and 6.3).

Due to the AB32+ storyline's strict infill planning policy and mask on non-urban lands, almost all new development occurs within existing city boundaries (Figure 6.2 and 6.4). No development occurs in West Sacramento, which is within the one-hundred-year floodplain and was thus masked from development within this scenario. The urbanization policy reflected in the UPlan variables and the amount of population growth under each storyline creates a unique pattern and footprint of development. AB32+ is by far the most compact, has the smallest urban footprint, and consumes the least amount of crop- and irrigated land, as well as non-irrigated grazed lands.

The storylines vary in the amount and type of new land uses (Table 6.2). Under the A2 storyline, for example, residential low, commercial low, and residential very low categories take up 9,081 (21,976 hectares), 2,687 (6,502 hectares), and 1,441 acres (3,487 hectares), respectively, by 2050. In this storyline, residential medium-density development takes up a larger percentage of newly developed land area, and in the AB32+ storyline, most development is either residential medium or residential high density. One of the most striking findings is just how little land is required to house future populations at these higher densities. The B1 and AB32+ scenarios require 44 percent and 7 percent of the urbanized land of the A2 scenario respectively. Even holding population increase constant at B1 levels, these scenarios use 63 percent and 38 percent of the land of the A2 scenario; most or all of it within existing urban areas.

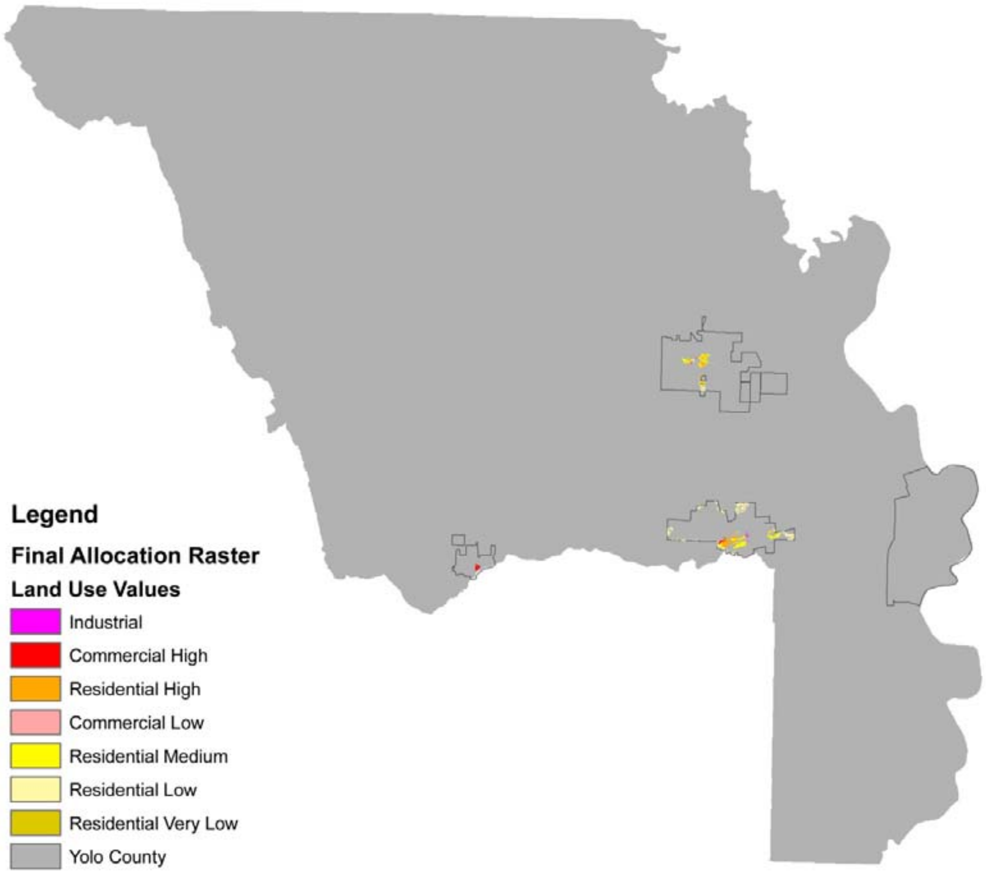

Figure 6.1. Urban Growth in Yolo County, 2010–2050, A2 Scenario. Dark grey lines represent municipal boundaries as of 2010. See Figure 6.2 for more detail on urbanization.

Table 6.2. Summary of New Development by Land Use Type under Each Storyline. Values in parentheses indicate population held constant at B1 levels.

Land Use Type	2050 Development		
	A2 (population constant at B1 level)	B1	AB32+ (population constant at B1 level)
	------------------------------ acres	------------------------------	
Industrial	554 (386)	55	14 (54)
Commercial High	172 (120)	200	68 (259)
Residential High	288 (201)	402	188 (717)
Commercial Low	2,687 (1,872)	100	0 (0)
Residential Medium	541 (377)	614	377 (1,435)
Residential Low	9,081 (6,328)	4,576	377 (1,435)
Residential Very Low	1,441 (1,004)	558	0 (0)
TOTAL	14,764 (10,288)	6,505	1,024 (3,900)

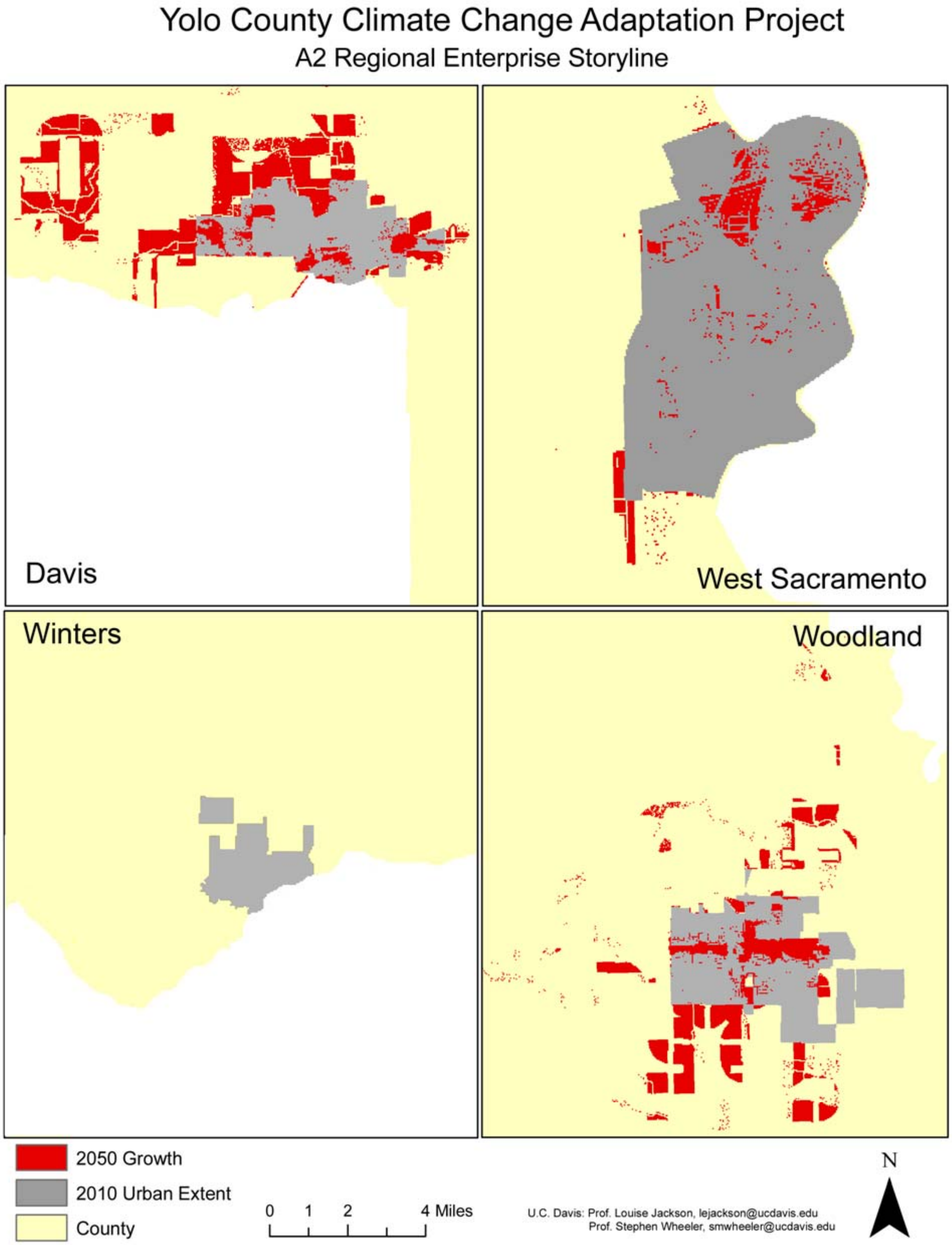

Figure 6.2. Urban Growth in Yolo County, 2010–2050, A2 Scenario, Detail of Cities

Under A2, urbanization on agricultural land makes up 72 percent of new development (Table 6.3). Under B1 it makes up 52 percent, and under AB32+ it makes up 2 percent. (Even though the AB32+ storyline calls for all development to occur within existing urban areas, current municipal boundaries include some farmland).

Urbanization Effects on Agricultural Cropland

A detailed GIS map of cropland in Yolo County for 2008 (Richter 2009) was overlaid onto UPlan results to show the crop acreage lost to urban growth under each scenario. The acreages of crops lost to development varied greatly among the three storylines, ranging from 10,562 in A2 (16.5 square miles or 4,274 hectares) to 3,363 in B1 (5.3 square miles or 1,373 hectares) to 23 in AB32+ (0.04 square miles or 9.31 hectares) (Table 6.3). These results reflect the lower total population growth and stricter urbanization policies in the B1 and AB32+ storylines.

Alfalfa, processing tomatoes, and pasture lands had the highest acreage loss under the A2 storyline. The same three crops were most affected under the B1 storyline but impacts were higher on processing tomatoes than alfalfa. In the A2 storyline, the new development footprint resulted in about 3 percent of irrigated crop land being lost in the county, while in the B1 storyline 1 percent was lost, and for AB32+, only 0.04 percent was lost.

Impact on Use of Soils, Land Forms, and Farmland Protection

The Storie Index Soil Rating classifies the potential productive capacity of land based on soil and landscape properties (Storie 1978). The excellent and good Storie grades for Yolo County would represent soils with Storie Index ratings as follows:

- **Grade 1 (excellent):** Soils with Store Index Ratings between 80 percent and 100 percent and which are suitable for most crops, including alfalfa, orchard, vegetable, and field crops.

- **Grade 2 (good):** Soils with Store Index Ratings between 60 percent and 79 percent and which are also suitable for a wide range of crops, but require more careful management or inputs.

The A2 scenario lost twice as much highly productive acreage to urbanization compared to B1, i.e., 3926 vs. 1916 acres (1622 vs. 792 hectares) (Table 6.5). Approximately 40 percent and 55 percent of the urbanized acreage was on soils with excellent and good Storie Index ratings in the two scenarios, respectively.

Table 6.3. Total Acres of Development on Agricultural Land Under Each Storyline. Values in parentheses indicate population held constant at B1 levels.

2050 Yolo County Urban Development on Farmland		
A2 (population constant at B1 level)	B1	AB32+ (population constant at B1 level)
	------------------- acres -------------------	
10,562 (7,165)	3,363	23 (114)

Floodplains were more likely to support urbanization under the A2 storyline (1226 acres or 496 hectares) compared to B1 (20 acres) (Table 6.5). The B1 storyline assumed much more discouragement to wetland and floodplain urbanization, both for protection of constructed units, and for environmental benefits. Urbanization on wetlands under frequent inundation was unlikely in either scenario, partly because flooding risk discourages building construction. Vernal pools, a landform that supports many endemic species, were more vulnerable to urbanization under the A2 storyline (Table 6.5). The wetland area is currently increasing in Yolo County due to creation of freshwater wetlands for flood conveyance for the high flows from several northern California waterways to the Sacramento-San Joaquin River Delta, and for wildlife habitat (Yolo County 2011). Wetland conversion can indeed be a "Best Management Practice" in some circumstances, and there can be additional ecosystem services provided by specific management of wetlands. But the loss of agricultural land is still a significant concern for the viability of agricultural operations, markets, and related industries in the county.

The Williamson Act (the California Land Conservation Act of 1965) is a California law that reduces property taxes to owners of farmland and open-space land in exchange for a ten-year agreement that the land will not be developed. Under the A2 storyline, farmers would be more likely release their holdings in the Williamson Act. The A2 outcome was nearly four times greater losses compared to B1, whereas AB32+ assumed no change in Williamson Act (Table 6.5).

Table 6.4. Summary of Specific Crops and Acres Lost to Urbanization Under Each Storyline. Note that pasture refers to upland, non-irrigated grazing lands and savanna. Only forest, grassland, and pastures are typically non-irrigated.

2050 Agricultural Acreage Consumed by Urban Development			
Type of Crop or Agroecosystem	A2	B1	AB32+
	---------- acres ----------		
Alfalfa	2,329	621	2
Almond and Pistachio	81	2	-
Barren	28	3	-
Corn	505	167	-
Cucurbits	13	-	-
Dry Beans	85	54	1
Fallow	170	25	-
Forest	-	-	-
Grain	1,422	471	-
Grassland	67	48	1
Onions and Garlic	68	2	-
Other Deciduous Trees	107	83	-
Other Field Crops	1,358	366	-
Other Subtropical Crops	2	-	-
Other Truck Crops	23	3	-
Pasture	1,629	514	15
Processing Tomato	1,958	704	4
Rice	-	-	-
Safflower	515	258	-
Vine	203	40	-
TOTAL	10,562	3,363	23

Table 6.5. Acreage of Floodplain, Storie Grades Excellent and Good Soils, Vernal Pools, and Williamson Act Lands Consumed by Urban Development under the A2, B1, and AB32+ Storylines According to Landform, Soil Quality (Storie Index), and Current Enrollment in the Williamson Act, which Provides Tax Advantages for Avoided Urbanization

	Acreage Consumed by Urban Development		
	A2	B1	AB32+
	-------------------------- acres --------------------------		
Storie Grade Excellent	2037.5	1085.8	359.8
Storie Grade Good	1889.0	830.3	45.5
Floodplains	1225.8	20.5	9.5
Vernal Pools	22.0	0.0	0.0
Williamson Act Lands	2042.0	586.8	0.0

Impact of Urbanization on Transportation-Related GHG Emissions

Not surprisingly, transportation-related GHG emissions from new development vary greatly across the three storylines (Table 6.6). As noted above, this difference is a function of assumptions about reduced driving by residents of infill development compared with development on previously unbuilt lands at the urban fringe, about improved vehicle fuel efficiency under the lower GHG emission scenarios, and about different rates of population growth in the three scenarios. Under the A2 scenario, transportation emissions related to new development are approximately 789,229 metric tons (MT) CO_2e annually. The B1 scenario produces similar emissions of 254,243 MT CO_2e, compared to 63,244 MT CO_2e in the AB 32 scenario. (Small amounts of emissions would take place in each scenario from public transit vehicles, but since these would be a small fraction of those from private motor vehicles they are not considered here. A full accounting of emissions related to transportation might also consider embodied emissions within the materials that make up vehicles, but again such factors are beyond the scope of this analysis).

Table 6.6. New Residential Transportation Greenhouse Gas Emissions by Storyline

Storyline	A2	B1	AB32+
	---------- MT CO_2e ----------		
With population varying according to scenario	789,229	254,243	63,244
With constant population at B1 level	671,047	254,243	90,128
With constant population, mpg, and residential occupancy at B1 levels	331,031	254,243	155,396

Even holding population constant at B1 levels (or population, vehicle efficiency, and household size all constant), the emissions differences between the three scenarios are profound. These results suggest that the most important climate change mitigation policy that Yolo County could adopt would be to restrict urban development to infill locations within existing cities, and to keep existing farmland in agriculture.

Residential GHG Emissions from Electricity and Gas

Residential energy-related greenhouse gas emissions also show strong differences among the three scenarios, due to the lower energy usage of multifamily units compared with single-family homes, as well as other assumptions about different efficiency improvements and electric portfolio composition between the scenarios. Annual electricity-related emissions from new development built in the 2010 to 2050 time period range from 132,104 MT CO_2e in the A2 scenario to 60,548 MT CO_2e in the B1 scenario, and just 11,536 MT CO_2e in the AB32+ scenario. Holding population constant across the three scenarios diminishes differences only slightly; holding assumptions constant about efficiency improvements and changes to utility portfolio mix still yields substantial differences solely due to the different mix of dwellings between infill-heavy scenarios and the greater urban sprawl in the A2 scenario.

Greenhouse gas emissions from residential gas consumption are slightly higher than for electricity consumption, in part because electricity will become cleaner over time as utilities develop renewable production sources; GHG emissions from gas will remain the same per unit of energy. (Almost all homes in Yolo County use gas for heating). Annual gas-related GHG emissions from new development built in the 2010–2050 time period range from 196,414 MT CO_2e in the A2 scenario to 84,384 MT CO_2e in the B1 scenario to 15,259 MT CO_2e in the AB32+ scenario (Table 6.7). Many of these reductions result from different assumptions about improved energy efficiency; if those assumptions are held constant at the A2 level, emissions still decline from 196,414 to 147,673 and 106,813 MT CO_2e because of different mixes of dwelling types. Thus, GHG emissions from residential energy use, as from transportation, will be much greater if urban development sprawls onto agricultural land in the countryside.

Overall, our three scenarios vary dramatically in their GHG emissions from new urbanization (Table 6.8). AB32+ produces much lower GHG emissions from residential development—approximately 8 percent of the emissions in A2, or about 14 percent with population held constant. The B1 scenario also produces substantial GHG savings—about 36 percent and 50 percent of those in A2 under the two different population levels. The strong implication is that preserving agricultural land from development is essential if the county is to stabilize and reduce its GHG emissions.

6.5. Mitigation and Adaptation Implications

Vision for a New Rural-urban Framework

The preceding analysis shows that a strong growth management framework for Yolo County, by channeling much or all future development into existing urban areas rather than onto agricultural lands, would have significant value in terms of preserving agricultural land, and extraordinary value in terms of reducing the county’s GHG emissions. Agriculture plays a modest role in Yolo County’s GHG emissions; farming occupies approximately 87 percent of the land area, but is estimated to produce only 14 percent of total county-wide GHG emissions in 1990 (Yolo County 2010). Detailed analysis of all urban GHG emissions in the county are not yet available, yet preliminary estimates suggest that the MT of CO_2e per hectare of agricultural lands are >70 times less than cities and towns (see Section 4).

A growth management framework to limit urban development would most likely combine a number of the following strategies, many already contained within the County's General Plan, municipal General Plans within Yolo County, and the Sacramento Region's Blueprint, and also modeled by jurisdictions elsewhere in California:

- Strong agricultural zoning; for example, requiring minimum 80-acre or 160-acre parcel sizes in much of the county (the current status).
- Farmland protection measures such as mitigation fee requirements on developers, purchase of development rights, transfer of development rights along with conservation easements, and funding of the Williamson Act
- Urban growth boundaries, urban service boundaries, or similar policies establishing sharp edges between urban and agricultural lands and locking in farmland protection more securely than through zoning
- Acquisition of conservation easements on agricultural lands by local agencies or nonprofit organizations, especially on farmland in likely-to-develop locations such as near freeway interchanges
- Adoption of municipal policies to facilitate and encourage infill development near town and neighborhood centers, major employers, and transit-accessible locations
- Adoption of municipal policies for urban greening; that is, to increase urban tree canopy, create coordinated greenspaces networks, decrease hardscapes, and reduce runoff, thus enhancing a range of environmental benefits for both urban residents and nearby farmers
- Expanded county and regional planning to coordinate infrastructure with these strategies, and to develop large-scale land use plans identifying, for example, desirable habitat conservation corridors through both urban and agricultural lands, and strategies to promote long-term agricultural viability and improved farm-to-table connections within the region

Table 6.7. Annual 2050 Greenhouse Gas Emissions from Residential Energy Usage in New 2010–2050 Development by Storyline

Scenario	A2			B1			AB32+		
	Electricity	Gas	Total	Electricity	Gas	Total	Electricity	Gas	Total
					---------- MT of CO$_2$e ----------				
With population varying according to scenario	132,104	196,414	328,518	60,548	84,384	144,932	11,536	15,259	26,795
With constant population at the B1 level	124,803	185,558	310,361	60,548	84,384	144,932	12,791	16,918	29,709
With constant population and constant assumptions about efficiency and utility portfolio improvements at the A2 level	124,803	185,558	310,361	105,959	147,673	253,632	89,536	118,428	207,964

Table 6.8. Overall (Transportation Plus Residential) Greenhouse Gas Emissions from New 2010–2050 Residential Development

Scenario	A2			B1			AB32+		
	Transportation	Residential	Total	Transportation	Residential	Total	Transportation	Residential	Total
					---------- MT of CO$_2$e ----------				
With population varying according to scenario	789,229	328,518	1,117,747	254,243	144,932	399,175	63,244	26,795	90,039
With constant population at the B1 level	671,047	185,558	856,605	254,243	144,932	399,175	90,128	29,709	119,837
With constant population and constant assumptions about improved energy efficiency, etc.	331,031	185,558	516,589	254,243	253,632	507,875	155,396	207,428	362,824

Given that Yolo County currently has unusually strong support for agricultural preservation (Landis and Reilly 2003), many of these strategies may potentially be implemented in the future. In Yolo County, an agricultural conservation ordinance already requires a one-to-one acreage mitigation requirement from conversion of agricultural land to another use (Kuminoff et al. 2000; Yolo County 2002). It has one of the state's highest percentages of land protected by the Williamson Act. Yolo County's climate action plan takes these issues a step further, as explained on its website (http://www.yolocounty.org/Index.aspx?page=2004):

> "The Climate Action Plan represents a significant milestone for Yolo County, which has a long history of being in the forefront of the green movement with land use policies that emphasize growth management, open space preservation and agricultural protection."

Whether other Central Valley counties will choose to follow this approach remains to be seen.

Land Use Under Different Climate Change Scenarios

The A2 scenario produces a relatively dispersed pattern of growth that consumes more farmland, although it is still a small percentage of the county's agricultural acreage. This would be likely to occur in a pattern often referred to as "leapfrog development," in which developers build on separated parcels across the agricultural landscape. Such development would occur primarily between and around the towns of Davis and Woodland. Also, to the extent that urbanization generally makes agriculture more difficult (by making it harder to move equipment between fields, support agricultural supply and processing industries, and by creating public opposition to aerial spraying, noise, odor, and other typical agricultural operations), the A2 scenario could amplify operational or economic hardships due to climate change.

Higher-quality soils are present in the floodplain region near the towns of Davis and Woodland, and support the crops with the highest income per acre (Jackson et al. 2011). This helps explains why leapfrog development in the A2 scenario resulted in the greatest loss of land classified as either excellent or good soils with the Storie Index. Previous UPlan modeling showed, however, that protecting only prime agricultural land in California's San Joaquin Valley resulted in greater use of less desirable land, and more urban sprawl than prioritizing compact growth (Roth et al. in review). Beardsley et al. (2009) also used UPlan to show that compact growth was the most effective way to preserve biologically valuable land in the Central Valley.

Such effects would be somewhat less pronounced in the B1 scenario, although our model shows leapfrog development was still widespread in the same locations, just at lower intensities. The AB32+ scenario prohibits most urbanization of current agricultural land, and so these effects would be essentially nonexistent. In a previous survey, growers with land in the Williamson Act tax relief program were more likely to be concerned about climate change (Jackson et al. 2011). Individuals who are most committed to agricultural preservation are more likely to recognize the need for options to adapt to climate change, especially to decreased water availability (see Section 5).

By fragmenting the landscape in the vernal pools and floodplain, urbanization in the A2 scenario could work against the provision of ecosystem services related to water quality, biodiversity conservation, open space, and its aesthetic and recreational value. By adopting a more “business as usual” storyline than B1, the A2 scenario would also be less conducive to investment in new programs to restore wetlands waterways, riparian vegetation, and hedgerows in agricultural landscapes, a strategy that could increase these types of ecosystem services as well as carbon sequestration (Young-Mathews et al. 2010; Smukler et al. 2010).

Potential Impact of Urbanization on Microenvironmental Conditions

Urbanized areas with a large percentage of their land covered by asphalt and other hard surfaces absorb solar radiation and reach ambient temperatures well above the surrounding areas (US EPA 2009). Road, roof, and parking surfaces within urban areas have been shown to lead to increased speed and volume of stormwater runoff and lower groundwater recharge (Erickson and Stefan 2009). In a nationwide assessment, the large increase in population and assumption of dispersed development under the A2 scenario results in about 10 percent increase in the surface area of impervious surfaces compared to the B1 storyline, and at least one-third of the nation’s wetlands will be affected by 2050 in both scenarios (Bierwagen et al. 2010). Urban planning to date has done relatively little to try to mitigate these effects, and by extension our A2 scenario might continue to produce them, especially since the urban footprint would expand under a “business as usual” storyline. However, the storylines of the B1 and AB32+ scenarios might well reduce these effects through extensive tree-planting in urban areas, reduced amounts of paved surfaces, green roofs, lighter-colored paving and roofing materials, and other steps.

The extent to which urban heat island effects would actually undermine agricultural adaptation in Yolo County, however, is highly uncertain. Towns such as Davis and Woodland are relatively small, and would likely produce much smaller warming effects on surrounding farmland than a larger city like Sacramento. Prevailing winds, particularly on summer evenings, are from the west, and would tend to carry the Sacramento region’s heat toward the Sierra Nevada foothills rather than Yolo County. A defined urban boundary that reduces the area of interaction between urban and agricultural landscapes, however, could reduce any potential heat island and runoff effects on agriculture. By leaving larger tracts of agricultural landscapes intact, the interface problems are, to a degree, mitigated.

Opportunities and Challenges of Urbanization in Response to Climate Change

Population expansion in Yolo County, the Sacramento Region, and northern California in general can be expected to expand customer base for agriculture (Wu et al., 2011). These potential increases are quite significant, on the order of two million additional residents in the Sacramento region and many more in northern California, and so might lead to expanded opportunities for locally- or regionally-oriented agriculture. Expanded urban populations might also provide a financial base with which to pay rural communities for ecosystem services (Gutman 2007), and a prime market for ecotourism within agricultural areas.

Strengthening the urban community's interest and support of farmland preservation is a key challenge for mitigation of GHG emissions, and the long-term viability of agriculture in Yolo County. During the past several decades California communities have come to accept increasingly higher densities within their borders, and there is no reason not to expect this trend to continue in the future. Awareness of the value of local food production and other associated ecosystem services of sustainable agriculture is one of the motivations that will likely move people's attitudes toward support of land use policies for infill and compact growth in the B1 and AB32+ scenarios.

Cities and towns in Yolo County are experiencing a surge of interest in local food (SACOG 2010). Several indicators demonstrate this change (Ellsworth 2011), although most of the agricultural sales in Yolo County are through large-scale food distribution chains to wholesale or retail markets. Organically produced commodities are largely consumed locally, and acreage has increased from 1,556 to 5,774 acres (Yolo County, 1997–2009). The number of organic farm operations has nearly tripled. Davis has adopted a Farm-to-School lunch program, and University of California Davis depends on >20 percent of its cafeteria food from local and regional growers. In the greater Sacramento region, farm gate value is $1.66 billion, but only 2 percent is consumed locally. Diversification of crops, more local processing, and increases in local markets could substantially increase the local consumption of Yolo County's products (SACOG 2010)

California's recent stakeholder-driven AgVision project produced several outcomes that are consistent with both the improvement of the rural-urban connections, and the support for developing greater awareness for mitigation of GHG emissions and adaptation to climate change in agricultural landscapes (American Farmland Trust 2010). Specific objectives included:

- Improving food access through urban agriculture, food preservation, and farmers markets
- Assuring supplies of land and water resources to sustain all sectors in an economically viable fashion
- Establishing clear state policy for measurable goals for conserving California's agricultural land and water resources
- Developing markets that economically reward and promote good environmental stewardship
- Supporting adequate public financing of stewardship practices and ecosystem benefits that do not necessarily result in economic returns in the marketplace

With direct respect to climate change AgVision takes a fairly narrow view of the most necessary tasks ahead, i.e., "Assure that all sectors of California agriculture can adapt to the most likely climate-related changes in seasonal weather, water supply, pests and diseases, and other factors affecting agricultural production." In this study, we have broadened the scope of the climate change challenges for agricultural sustainability in California, and have developed a strong case for strengthening the rural-urban interface as a means to mitigating and adapting to climate change in agricultural landscapes.

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6.7 Glossary

ESP	Department of Environmental Science and Policy , University of California at Davis
FMMP	Farmland Mapping and Monitoring Program
GHG	greenhouse gas
HH	household
IPCC	International Panel on Climate Change
MT	metric tons
SACOG	Sacramento Area Council of Governments
SCANH	Southern California Association of Non-Profit Housing
U.S. EPA	U.S. Environmental Protection Agency
VMT	vehicle miles traveled

Section 7: Integration and Conclusions

The following bullets outline the conclusions of this paper's authors based on the study results discussed in the preceding sections.

1. Growers are capable of adapting to climate change as they currently do when faced with changing markets, prices, emerging pests/disease, and meteorological variations. As at present, adaptation would be facilitated by information delivery for decision and negotiation support. In the future, climate change is likely to become more important in their decisions about choice of specific crops, crop diversification, water use efficiency, and management for mitigation of GHG emissions.
2. Historical relationships show a minor increase in summer temperatures relative to winter temperatures during the past 100 years in Yolo County. This has meant that climate has had more influence on acreage decisions for crops affected by winter/early spring conditions (wheat, alfalfa, tomato, prunes, walnuts, and other miscellaneous fruits). Future projections based on these historical relationships indicate that warmer winter temperatures would favor vegetable crops (e.g., tomatoes) over field crops (e.g., wheat).
3. In developing recommendations for GHG mitigation in Yolo County agriculture, attention must be given to the tradeoffs that might be incurred in terms of adaptation to uncertain changes in temperature and precipitation. At present, careful N management (within both organic and conventional systems) can reduce input costs and decrease N_2O emissions, which are the largest source of agricultural GHG emissions in the county. In the future, N management may be affected by the increase in CO_2. Policies that reward and protect farmers for such management decisions for climate change mitigation should be encouraged.
4. Agriculture plays a modest role in Yolo County's GHG emissions; farming occupies approximately 87 percent of the land area, but is estimated to produce only 14 percent of total county-wide GHG emissions (based on data available for 1990). Farmland protection would mitigate climate change; therefore, channeling much or all future development into existing urban areas, rather than onto agricultural lands, would have significant value in terms of preserving agricultural land, and would have immense value in terms of reducing the county's GHG emissions.
5. Water is arguably the most important agricultural resource in California. The uncertainty associated with California's water supply now, and in the midst of climate change, must be addressed. There is a great deal of uncertainty surrounding modeling efforts of precipitation patterns in response to climate change in California. Thus, the most sustainable mechanism to ensure an adequate water supply for the future is to encourage growers to plan for uncertainty by (1) adopting more diverse cropping systems and investing in water-saving technologies during dry years, and (2) implementing groundwater replenishment strategies in wet years.

6. The most appropriate way to address climate change (both mitigation and adaptation) for growers’ decision-making is continued investment in information delivery mechanisms and applied research to ensure that tools and options are available to address adaptation to climate change and its broad impacts in growers’ long-range planning efforts. Some types of information would be relevant across California, but there is also a need for place-based, regional problem-solving that is supported within rural communities.
7. Strengthening connections at the rural-urban interface would generate greater awareness among urban dwellers for the ecosystem services provided on agricultural lands (food and fiber, environmental resources, biodiversity conservation, livelihood options, and business opportunities that build social capital), and their vulnerability to climate change. Stronger rural-urban connections are necessary for achieving consensus for farmland protection via zoning, urban growth boundaries, and infill development.

Appendix 1

Missing Observations for Weather Data (Section 2)

The Davis weather station had the least number of unreported days. The Davis station had 356 unreported days out of 36,865 days spanning the period of 1909–2009 (<1 percent), while the Woodland station had 7,511 unreported days (20 percent), and Winters had12,570 days (34 percent).

To maintain the consistency of the data that may be sensitive to location, we chose Davis as the primary source to represent Yolo County climate (the Davis station is at latitude 38:32, longitude -121:46, and elevation is 60 feet [NOAA]). To complete the time series, data was generated for missing observations using secondary information. For Davis, we estimated values using information from the Woodland station. Any systematic differences (e.g., differences in the observation time or the geographical and surrounding conditions of the station) between the Davis and Woodland stations had to be eliminated. We ran regressions for the daily minimum temperature and the daily maximum temperature at both Davis and Woodland station, for different seasons, as well as for two exceptionally cold winters (1911 and 1912) to capture the abnormality of the weather. The equations with the estimated coefficients ($P<0.01$) all have $R^2 > 0.9$. These equations were used to compute the missing values for the Davis station. The estimated regressions equations are as follows:

MaxDavis = 3.196 + 0.935*MaxWoodland + 0.583*Dsummer + 1.236*Dfall - 0.09*Dwinter - 2.629*Dyear

MinDavis = 1.724 + 0.924*MinWoodland + 0.325*Dsummer + 0.015* Dfall + 0.336*Dwinter - 7.881*Dyear

where MaxDavis = Predicted daily maximum temperature in Davis

MaxWoodland = Daily maximum temperature observed in Woodland

MinDavis = Predicted daily minimum temperature in Davis

MinWoodland = Daily minimum temperature observed in Woodland

Dsummer = 1, if month = June, July, or August, otherwise 0

Dfall = 1, if month = September, October, or November, otherwise 0

Dwinter = 1, if month = December, January or February, otherwise 0

Dyear = 1 if Dwinter = 1 and year = 1911 or 1912, otherwise 0

This approach filled in all but 78 unreported days for the Davis station, which were from October 1910 to October 1923. For these days, interpolation of the average of the day before and the day after was used, except for December 1910, for which the entire month was interpolated from monthly averages from November 1910 and January 1911. However, when our climate index generation required daily temperature data, we omitted this year and our sample started from 1911.

Appendix 2

Stationarity of Time Series for Econometric Analysis (Section 2)

One basic assumption of time series analysis is that of stationarity. That is, the mean and variance of a time series are constant over time. When they are constant over time, the series is stationary, and when they change over time, the series is nonstationary. In most time series data and models, this stationary assumption is unlikely met, and violation of this assumption complicates statistical analysis of time series. The major consequence of nonstationarity for regression analysis is spurious correlation that leads to incorrect model specification.

To avoid spurious regressions, it is important to test for nonstationarity of the time series. A quick glance at the data indicates that the key variables in our analysis are not stationary (i.e., the mean and/or variance are not constant over time). The first step is to conduct a formal test whether the data are "trend stationary" or not. In particular we test if the series have a unit root (i.e., they are nonstationary). If a unit root is found, the data are nonstationary.

However, if the data are trend stationary, then analysis can proceed by regressing levels on levels with some function of a trend included in the regression to detrend the data. The presence of a unit root is often tested using the augmented Dickey-Fuller method. The test is carried out for each variable by regressing the first-difference ($Y_t – Y_{t-1}$) on a constant, a time trend, once-lagged level (Y_{t-1}), and *p* lagged differences, where *p* is chosen by the analyst (an initial statistical investigation led us to choose *p* to be two, but the results of the tests described next were not sensitive to numbers of lags).

For the unit root test, the t-statistic on the lagged level is the relevant test statistic. The usual t critical values, however, are not applicable. Appropriate critical values are given in Enders (2004, p. 439). Results from the augmented Dickey-Fuller tests are reported in Table 4.1. Among the climate related variables, the presence of a unit root can only be rejected for the precipitation variable, meaning that all climate variables but the precipitation variable are nonstationary. For acreage variables, none rejected the presence of a unit root, indicating all acreage variables are nonstationary. Test on most price variables cannot reject the presence of a unit root. A few price variables, mostly the prices of orchard crops, narrowly reject a unit root. But, overall, most price variables are nonstationary.

Given the failure to reject unit roots by most variables, the next step is to test for cointegration.[18] If the left-hand side and right-hand side variables are cointegrated, then analysis can proceed with an error correction model even though data are nonstationary. However, if there is not

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[18] One simple way to deal with nonstationarity of the data may be to take the first differences in data and use them in the regression equation. However, a more rigorous approach would be to use first differences after the residuals are tested for cointegration. Even though individual variables may be nonstationary, it is possible for linear combinations of nonstationary variables to be stationary (i.e., cointegrated). If the variables are cointegrated, one can avoid spurious regressions in the presence of nonstationarity.

strong evidence of cointegration then regressing levels on levels will lead to spurious regression results and reliable estimates are only obtained by regressing first-differences on first-differences.

The variables are tested for cointegration by two separate methods. The Engle and Granger (1987) method regresses levels on levels and tests the residuals for a unit root. If the residuals do not have a unit root, then they are cointegrated. Thus, the null hypothesis of the test is that the variables are not cointegrated. The Dickey-Fuller critical values are not applicable in this case, but appropriate critical values are found in Enders (2004, p. 441). As a robustness check, cointegration is also tested using the Johansen test with critical values found in Enders (2004, p. 443).

Table Appendix 2.1. Augmented Dickey-Fuller Unit Root Test Results

Variable	Test-statistic
Climate	
Summer GDD	-1.950
Winter GDD	-1.529
Chill Hours	-2.161
Precipitation	-4.338*
Acres & Prices	
Rice Acres	-3.395
Rice Prices	-1.791
Alfalfa Acres	-1.544
Alfalfa Prices	-2.565
Wheat Acres	-1.227
Wheat Prices	-2.589
Corn Acres	-1.947
Corn Prices	-2.429
Safflower Acres	-2.374
Safflower Prices	-3.738*
Pasture Acres	-3.498
Pasture Prices	-3.891*
Barley Acres	-2.724
Barley Prices	-2.205
Tomato Acres	-1.562
Tomato Prices	-2.415
Other Vegetables Acres	-1.999
Other Vegetables Prices	-1.862
Grapes Acres	-0.659
Grapes Prices	-3.768*
Prunes Acres	-2.168
Prunes Prices	-4.028*
Almonds Acres	-0.900
Almonds Prices	-4.727*
Walnuts Acres	-2.112
Walnuts Prices	-4.975*
Misc. Fruit Acres	-1.641
Misc. Fruit Prices	-2.770

5% Critical value=-3.50

* denotes significance at the 5% level.

Engle-Granger cointegration test results are given in Table 4.2. There was very little sensitivity of the results to the method used, so the Johansen test results are not reported. For each crop, the cointegration test was performed by regressing acres on its own lagged price and the relevant climate variable for that crop, and then testing the residual for a unit root with the augmented Dickey-Fuller test. Precipitation was not included in the regression, since a unit root is rejected for precipitation. The relevant climate variable for all field and vegetable crops, except wheat, is summer growing degree days; wheat acres were regressed on winter growing degree days instead. The relevant variable for tree crops is chill hours.

There is only evidence of cointegration for 4 out of the 13, and for 2 of these crops the null hypothesis is very narrowly rejected. Given the results from the unit root and cointegration tests, estimates from regressing levels on levels could simply be spurious correlations. While it may be acceptable to specify an error correction model for a few crops (those with cointegration), we prefer that all acreage equations be estimated with the same methodology. Given the strong evidence in the data of unit roots with no cointegration between the variables, we regress differences on differences for every crop equation.

Table Appendix 2.2. Engle-Granger Cointegration Test Results

Crop	Test-statistic
Tomatoes	-2.386
Rice	-5.989*
Alfalfa	-2.199
Wheat	-2.352
Corn	-3.372
Safflower	-3.361
Pasture	-2.654
Other Vegetables	-6.338*
Grapes	-3.972*
Prunes	-1.894
Misc. Fruit	-3.193
Almonds	-2.917
Walnuts	-4.089*
Barley	-1.560

5% Critical value=-3.915

* denotes significance at the 5% level.

We also investigate whether autoregressive and/or moving average terms should be included in the analysis. Autocorrelation and partial autocorrelation functions were plotted for the first difference of acres for each crop. After first-differencing, we see little evidence that other time series properties need modeling. The fact that first-differenced acreage appears stationary without autoregressive or moving average components gives us further assurance of the reliability of our regression results.

Appendix 3

Calculations for Tier 1 Inventory Methods for Agricultural Greenhouse Gas Emissions in Yolo County (Section 4)

1. Direct N_2O Emissions

Current agricultural practices rely on relatively large inputs of nitrogen (N) to support crop growth. The majority of N in California is applied in the form of synthetic fertilizers. Organic sources of N from crop residues, animal urine, and animal manure also contribute a significant amount of N to agricultural soils. Emissions of N_2O are a natural by-product of the nitrification and denitrification processes carried out by soil microbes. Nitrous oxide emissions are only a small fraction of the total N applied and essentially represent inefficiencies in the microbial nitrification and denitrification processes. Direct N_2O emissions are defined as those arising directly from farm fields following N application, while indirect emissions are the result of volatilization, leaching, and runoff which carry N off the farm and into the surrounding environment. The equations used to calculate direct N_2O emissions from synthetic N fertilizers, crop residues, urine deposited in pasture, and animal manure are listed below.

Equations for Direct N_2O Emissions

Equation 1.

N_2O from synthetic N fertilizer:

$$NE_{SF} = \sum_{crop} NR_{crop} \times HA_{crop} \times EF_1 \times 1.5711 \times 310$$

Calculated for alfalfa, almonds, corn, grain hay, tomatoes, wheat, rice, walnuts, prunes, safflower, grapes, misc. field crops, misc. fruit and nut, and misc. vegetables.

Where:

NE_{SF} = Amount of N_2O emitted from synthetic fertilizer application (kg CO_2e yr^{-1})
NR_{crop} = N application rate for each crop (kg N ha^{-1} yr^{-1})
HA_{crop} = Harvested area for each crop (ha yr^{-1})
EF_1 = Fraction of N applied to agricultural soils emitted as N_2O (Default $EF_1 = 0.01$ for all crops other than rice)
EF_{1rice} = Fraction of N applied to rice emitted as N_2O (Default $EF_{1rice} = 0.003$)
crop = Crop type
1.5711 = Molecular weight ratio of N_2O to N_2
310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)

Source: U.S. EPA, 2004; IPCC, 2006

Equation 2.

Amount of N in crop residues:

$$N_{CR} = \sum_{crop} \{HM_{crop} \times (HA_{crop} - AB_{crop} \times CF) \times F_{renew,crop} \times [R_{AG,crop} \times N_{AG,crop} \times (1 - F_{remove,crop}) + R_{BG,crop} \times N_{BG,crop}]\}$$

Equation 3.

N_2O emissions from crop residues:

$$NE_{CR} = N_{CR} \times EF_1 \times 1.5711 \times 310$$

Calculated for alfalfa, corn, rice, wheat, and misc. grains (where misc. grains consisted of the averaged input values for barley, sorghum, oats, and rye).

Where:

N_{CR} = Amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually (kg yr^{-1})

HM_{crop} = Harvested dry matter yield for given crop (kg ha^{-1} yr^{-1})

$HA_{T,crop}$ = Total area harvested of crop (ha yr^{-1})

AB_{crop} = Area of crop burnt (ha yr^{-1})

CF_{crop} = Combustion factor (crop-specific, see IPCC, 2006)

$F_{renew,crop}$ = Fraction of total area under crop that is renewed annually. Where pastures are renewed on average every X years, $F_{renew,crop}$ = 1/X. For annual crops $F_{renew,crop}$ = 1

$R_{AG,crop}$ = Ratio of above-ground residues dry matter ($AG_{DM,crop}$) to harvested yield for crop (HM_{crop}), where

= $AG_{DM,crop}$ ● 1000 / HM_{crop} (Table 1)

$N_{AG,crop}$ = N content of above-ground residues for crop (kg) (Table 1)

$F_{remove,crop}$ = Fraction of above-ground residues of crop removed annually for purposes such as feed, bedding and construction. Survey of experts in country is required to obtain data. If data for $F_{remove,crop}$ is not available, assume no removal.

$R_{BG,crop}$ = Ratio of below-ground residues to harvested yield for crop. If alternative data are not available, $R_{BG,crop}$ may be calculated by multiplying R_{BG-BIO} in Table 1 by the ratio of total above-ground biomass to crop yield (= [($AG_{DM(crop)}$ ● 1000 + HM_{crop}) / HM_{crop}]

$N_{BG,crop}$ = N content of below-ground residues for crop, kg N $(kg)^{-1}$, (Table 1)

crop = Crop type

NE_{CR} = Amount of N_2O emitted from crop residues (kg CO_2e yr^{-1})

EF_1 = Fraction of N in soil that is emitted as N_2O (Default EF_1 = 0.01 for all crops other than rice)

1.5711 = Molecular weight ratio of N_2O to N_2

310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)

Source: IPCC, 2006

Table Appendix 3.1. Values of AG_{DM}, N_{AG}, $R_{BG\text{-}BIO}$, and N_{BG} for Equation 2

Crop Type (crop)	$AG_{DM} = HM_{crop} * Slope_{crop} + Intercept_{crop}$		N_{AG} (kg)	$R_{BG\text{-}BIO}$	N_{BG} (kg)
	Slope	Intercept			
Alfalfa	0.29	0.00	0.027	0.40	0.019
Corn	1.03	0.61	0.006	0.22	0.007
Rice	0.95	2.46	0.007	0.16	N/A
Wheat	1.51	0.52	0.006	0.24	0.009
Misc. Grains	0.965	0.9225	0.006	0.22	0.009

Source: IPCC 2006

Equation 4.

N_2O from Dairy and Swine Manure:

$$NE_{AM} = \sum_{group}^{1} N_{group} \times TAM_{group} \times NER_{group} \times 365.2465 \times EF_2 \times 1.5711 \times 310$$

(Sum includes only dairy cattle and swine groups where manure is assumed to be spread daily)

Equation 5.

N_2O from Urine Deposited in Pasture:

$$NE_{AU} = \sum_{group}^{1} N_{group} \times TAM_{group} \times NER_{group} \times 365.2465 \times EF_2 \times 1.5711 \times 310$$

(Calculated for beef cattle, horses, sheep, and goats raised in pasture and then summed across these livestock groups)

Where:

NE_{AM} = Amount of N_2O emitted from manure of a given livestock group (g CO_2e yr^{-1})
NE_{AU} = Amount of N_2O emitted from urine of a given livestock group (g CO_2e yr^{-1})
A_{group} = Number of animals in a given livestock group (head)
TAM_{group} = Typical animal mass of animals in the livestock group (kg live weight $head^{-1}$)
NER_{group} = Nitrogen excretion rate of animals in the livestock group (g N kg^{-1} live weight day^{-1})
365.2425 = Average number of days in a year (days yr^{-1})
EF_2 = Fraction of N in manure or urine deposited on pastures, rangelands, or paddocks emitted as N_2O (Default $EF_2 = 0.02$)
group = Livestock group (Table 2)
1.5711 = Molecular weight ratio of N_2O to N_2
310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)

Source: CARB 2009; IPCC 2006

Table Appendix 3.2. Values for TAM_{group}, NER_{group} and Manure Management System (MMS) for Each Livestock Group

Livestock group	NER_{group}	TAM_{group}	MMS
(group)	(g N kg^{-1} day^{-1})	(kg)	
Dairy Cattle	0.44	604	Stored in lagoon and spread daily
Beef Cattle	0.31	389	Deposited in pasture
Sheep	0.42	27	Deposited in pasture
Goats	0.45	64	Deposited in pasture
Horses	0.30	450	Deposited in pasture
Swine	0.24	198	Stored in lagoon and spread daily

Source: IPCC 2006; U.S. EPA 2007

2. Indirect N_2O Emissions

Indirect N_2O emissions arise from applied N that is lost from farm fields either as gaseous ammonia (NH_3) and aqueous nitrate (NO_3^-) in runoff or leachate. The first pathway is due to the volatilization of NH_3 from synthetic N fertilizers, urine deposited in pasture, and manure. Volatilized N is returned to the soil through atmospheric deposition, where it is subject to loss as N_2O during nitrification and denitrification. Nitrate in runoff and leachate collects in streams and water bodies where it is undergoes denitrification. Indirect emissions are estimated based on the amount of N added as synthetic N fertilizer, urine and manure, default values for the volatilization and leaching, and emission factors established by the IPCC (Equations 6 and 7).

Equations for Indirect N_2O Emissions

Equation 6.

N_2O from Volatilization:

$$NE_V = [N_{SF} \times V_1 + (N_U + N_M) \times V_2] \times EF_4 \times 1.5711 \times 310$$

Equation 7.

N_2O from Leaching and Runoff:

$$NE_{LR} = [N_{SF} \times (1 - V_1) + (N_U + N_M) \times (1 - V_2)] \times L \times EF_5 \times 1.5711 \times 310$$

Where:

NE_V = Amount of N_2O emitted from volatilization (kg CO_2e yr^{-1})
NE_{LR} = Amount of N_2O emitted from leaching and runoff (kg CO_2e yr^{-1})
N_{SF} = Total N applied in synthetic fertilizers from all crop categories (kg yr^{-1})
N_M = Total N applied in manure from dairy and swine categories (kg yr^{-1})
N_U = Total N applied in urine deposited in pasture from other livestock categories (kg yr^{-1})
V_1 = Fraction of N applied as synthetic N that volatilizes (Default $V_1 = 0.1$)
V_2 = Fraction of N applied as urine or manure that volatilizes (Default $V_2 = 0.2$)
L = Fraction of applied N lost by leaching (Default L = 0.3)
EF_4 = Fraction of N that is volatilized, redeposited on soil, and then emitted as N_2O (Default $EF_4 = 0.01$)
EF_5 = Fraction of applied N that is leached and then emitted as N_2O (Default $EF_5 = 0.0075$)
1.5711 = Molecular weight ratio of N_2O to N_2
310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)

Source: CARB 2009; IPCC 2006

3. Mobile Farm Equipment

The combustion of fossil fuels to run agricultural machinery produces CO2 and smaller amounts of nitrous oxide (N2O) and methane (CH4). To calculate emissions from mobile farm equipment for a given crop, data on diesel fuel use per unit area was obtained from the University of California Cooperative Extension's cost and return studies (UCCE, various years). The fuel use data was then multiplied by each crop's annual cultivated acreage and then summed across all crops to estimate Yolo County's aggregate fuel consumption. The amount of CO_2, N_2O, and CH_4 produced from the combustion of diesel fuel was determined using emission factors for each gas published by the U.S. EPA (2007) and EIA (2010). The advantage of this method is that it captures changes in fuel consumption related to annual trends in acreage for specific crops. However, since the approach assumes a fixed set of management practices for a given crop it, will not reflect the adoption of alternative practices such as reduced tillage or the use of alternative fuel sources (biodiesel, etc.).

Equations for Emissions from Agricultural Fuel Use

Equation 8.

CO_2 emissions from fuel use:

$$CE_F = \sum_{crop} D_{crop} \times HA_{crop} \times EF_{CO2}$$

Equation 9.

N_2O emissions from fuel use:

$$NE_F = \sum_{crop} D_{crop} \times HA_{crop} \times EF_{N2O} \times 310$$

Equation 10.

CH_4 emissions from fuel use:

$$ME_F = \sum_{crop} D_{crop} \times HA_{crop} \times EF_{CH4} \times 21$$

(Emissions of each gas were calculated for alfalfa, almonds, corn, grain hay, tomatoes, wheat, rice, walnuts, prunes, safflower, grapes, misc. field crops, misc. fruit and nut, and misc. vegetables, and then summed across crop categories for each gas.)

Where:

CE_F = Amount of CO_2 emitted from agricultural fuel use (kg CO_2e yr^{-1})

NE_F = Amount of N_2O emitted from agricultural fuel use (kg CO_2e yr^{-1})

ME_F = Amount of CH_4 emitted from agricultural fuel use (kg CO_2e yr^{-1})

D_{crop} = Amount of diesel fuel used per ha of a crop (L/ha)

HA = Harvested area of a crop (ha yr^{-1})

EF_{CO2} = CO_2 emission factor for diesel combustion (2.668 kg L^{-1})

EF_{N2O} = N_2O emission factor for diesel combustion (0.000069 kg L^{-1})

EF_{CH4} = N_2O emission factor for diesel combustion (0.00038 kg L^{-1})

crop = Crop type

310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)

21 = Global warming potential of CH_4 expressed in carbon dioxide equivalents (CO_2e)

Source: U.S. EPA 2007; EIA 2010

4. Irrigation Pumping

Irrigation pump engines can run on diesel, natural gas, liquefied petroleum gas, butane, gasoline, or electricity from the grid or solar PV. Diesel-fueled irrigation pumps are known to be a significant source of both gaseous emissions and particulate matter, thus they are monitored periodically by the California Air Resources Board. Since detailed data at the county/air district level are available only on diesel pumps, we have only included this pump type in our inventory. Emissions from other fossil fuel-powered pumps are not included because adequate local data were not available. As of 2003, an estimated 643 diesel-powered irrigation pumps were operated in Yolo County (Yolo County 2010). Statewide, the number of diesel irrigation pumps was projected to increase by 3.5 percent between 1990 and 2010 (CARB, 2000). We estimated the 1990 and 2008 pump populations based on an assumption that the statewide trend was proportional to the increase in the number of pumps in the county. Input values for engine activity (hr yr^{-1}) and average engine horsepower were taken from statewide survey data (CARB 2006; CARB 2000). Diesel fuel emission factors for CO_2, N_2O, and CH_4 were taken from the U.S. EPA (2007) and the EIA (2010).

Equation 11.

CO_2 emissions from diesel powered irrigation pumps:

$$CE_P = P \times EA \times FC \times HP \times 0.85 \times EF_{CO2}$$

Equation 12.

N_2O emissions from diesel powered irrigation pumps:

$$NE_P = P \times EA \times FC \times HP \times 0.85 \times EF_{N2O} \times 310$$

Equation 13.

CH4 emissions from diesel powered irrigation pumps:

$$ME_P = P \times EA \times FC \times HP \times 0.85 \times EF_{CH4} \times 21$$

Where:

CE_P = Amount of CO_2 emitted from diesel irrigation pumps (kg CO_2e yr^{-1})
NE_P = Amount of N_2O emitted from diesel irrigation pumps (kg CO_2e yr^{-1})
ME_P = Amount of CH_4 emitted from diesel irrigation pumps (kg CO_2e yr^{-1})
P = Number of diesel irrigation pumps in Yolo County (pumps)
EA = Average engine activity (hr yr^{-1})
FC = Brake specific fuel consumption (0.245 kg hp^{-1} hr^{-1})
HP = Average horsepower for pump engines in Yolo County (hp)
0.85 = Diesel fuel kg to L conversion (kg L^{-1})
EF_{CO2} = CO_2 emission factor (2.668 kg L^{-1})
EF_{N2O} = N_2O emission factor (0.000069 kg L^{-1})
EF_{CH4} = CH_4 emission factor (0.00038 kg L^{-1})
310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)
21 = Global warming potential of CH_4 expressed in carbon dioxide equivalents (CO_2e)

Table Appendix 3.3. Irrigation Pump Population and Activity Data for Given Years in Yolo County

Pump Population		Engine Activity (hr yr^{-1})	Average Horsepower (hp)
1990	2008		
626	648	750	149

Source: Yolo County 2010; CARB 2006

5. Livestock Emissions

Livestock are an important source of both CH_4 and N_2O emissions in Yolo County. The main mechanism of CH_4 production is enteric fermentation, which involves microbial breakdown of carbohydrates in the digestive system of ruminant livestock (e.g., cattle, sheep, and goats). Several non-ruminant livestock (e.g., horses, mules, and swine) also depend on enteric fermentation to help break down poor quality plant material in their caecum and large intestine, but produce less methane than ruminants. A secondary source of CH_4 from livestock is the manure they produce, and more important, how it is stored. Manure deposited in the field or paddock decomposes under aerobic conditions and thus produces little or no CH_4. However, when manure is stored in lagoons, as is common in dairy and swine operations, large amounts of CH_4 can be produced via anaerobic decomposition. Nitrogen in livestock urine and manure is also subject to loss as N_2O during nitrification and denitrification. In this inventory, we assume that all N excreted by livestock is applied to soils either as urine or manure, and thus the emissions are included in the direct and indirect N_2O emissions categories. This approach is justified given that the vast majority of livestock in Yolo County are grazed on pasture or rangelands and the manure management methods used by the small number of local dairy and swine operations are well-known. Methane emissions from enteric fermentation and manure management were calculated for each livestock category using a Tier 1 approach (IPCC 2006) and records of livestock numbers reported by the National Agricultural Statistics Service database (NASS 1990, 2008) or the Yolo County Agricultural Commissioner's reports (YCAC 1990, 2008). The equations and tables below summarize the method used to estimate CH_4 emissions from livestock.

Equations for CH_4 Emissions from Livestock

Equation 12.

CH_4 from Enteric Fermentation:

$$ME_E = \sum_{group} A_{group} \times EF_{ent,group} \times 21$$

Equation 13.

CH_4 from Manure Management:

$$ME_M = \sum_{group} A_{group} \times EF_{man,group} \times 21$$

(Calculated for dairy cattle, beef cattle, sheep, goats, horses, and swine, and then summed across all livestock groups)

Where:

ME_E = Amount of CH_4 emitted from enteric fermentation (kg CO_2e yr^{-1})
ME_M = Amount of CH_4 emitted from manure management (kg CO_2e yr^{-1})
A_{group} = Number of animals for a given livestock group (head)
$EF_{ent,group}$ = CH_4 emissions from enteric fermentation per head for a livestock group (kg hd^{-1} yr^{-1})
$EF_{man,group}$ = CH_4 emissions from manure management per head for a livestock group (kg hd^{-1} yr^{-1})
group = Livestock group (Table 4)
21 = Global warming potential of CH_4 expressed in carbon dioxide equivalents (CO_2e)

Table Appendix 3.4. Emission Factors for Enteric Fermentation and Manure Management for Various Livestock Groups

Livestock group	EF_{ent}	EF_{man}	Manure Management
(group)	(kg hd^{-1} yr^{-1})	(kg hd^{-1} yr^{-1})	
Dairy Cattle	128.0	68.00	Stored in lagoon
Beef Cattle	53.0	2.00	Deposited in pasture
Sheep	8.0	0.28	Deposited in pasture
Goats	5.0	0.20	Deposited in pasture
Horses	18.0	2.34	Deposited in pasture
Swine	1.5	14.00	Stored in lagoon

Source: IPCC, 2006

6. Rice Cultivation

Flooded rice fields produce CH_4 from the anaerobic decomposition of organic matter present in the soil. In California, the amount of methane emitted per unit area can vary widely depending on the rice cultivar, season, temperature, soil type, amount of crop residue incorporated, and both the in-season and winter flooding regimes. To estimate the total CH_4 emissions from rice cultivation in Yolo County, we multiplied a California-specific emission factor developed by the CARB (2009) by the amount of rice harvested in a given year reported by the county agriculture commissioner.

Equation for CH_4 Emissions from Rice Cultivation

Equation 14.

CH_4 from Rice Cultivation:

$$ME_R = HA_{rice} \times EF_{rice} \times 21$$

Where:

ME_R = CH_4 emitted from rice cultivation (kg CO_2e yr^{-1})

HA_{rice} = Harvested area of rice in Yolo County (ha yr^{-1})

EF_{rice} = CH_4 emission factor for rice (122 kg ha^{-1})

21 = Global warming potential of CH_4 expressed in carbon dioxide equivalents (CO_2e)

7. Lime and Urea Application

Certain agricultural materials such as lime and urea can also produce CO_2 emissions when they are added to soil. The addition of limestone or dolomite releases bicarbonate (HCO_3^-) as it dissolves. By contrast, urea ($CO(NH_2)_2$) is broken down by soil urease enzymes to form ammonium (NH_4^+), bicarbonate (HCO_3^-), and a hydroxyl ion (OH^-). The bicarbonate produced in both cases further dissociates into CO_2 and H_2O. To estimate CO_2 emissions from the addition of limestone, dolomite, and urea, we multiplied the default IPCC emission factor for each material by the amount of material applied in Yolo County. The amount of each material applied was estimated from county sales records maintained by the California Department of Food and Agriculture (CDFA 1990, 2008). No sales of dolomite were recorded in 1990 and 2008, therefore this material was not included in our analysis.

Equations for CO_2 Emissions from Lime and Urea

Equation 15.

CO_2 from Lime:

$$CE_L = AR_{lime} \times EF_{lime} \times 3.6642$$

Equation 16.

CO_2 from Urea:

$$CE_U = AR_{urea} \times EF_{urea} \times 3.6642$$

Where:

CE_L = Amount of CO_2 emitted from lime application (t CO_2e yr^{-1})
CE_U = Amount of CO_2 emitted from urea application (t CO_2e yr^{-1})
AR_{lime} = Amount of limestone applied (t yr^{-1})
AR_{urea} = Amount of urea applied (t yr^{-1})
EF_{lime} = Fraction of lime applied emitted as CO_2 (Default EF = 0.12)
EF_{urea} = Fraction of urea applied emitted as CO_2 (Default EF = 0.2)
3.6642 = Molecular weight ratio of CO_2 to C

Source: IPCC 2006

8. Residue Burning

For a number of crops grown in California, it is common to burn residues as a means of disposal and disease control. The burning of crop residues produces emissions of CO_2, N_2O, and CH_4. Since the carbon contained in the crop residue is assumed to have been recently absorbed from atmospheric CO_2, the CO_2 released during burning is a "biogenic" emission and not considered a net source of emissions. In this inventory the CO_2 emissions were calculated but not added to the inventory total. In contrast, the N_2O and CH_4 released during burning are not considered biogenic emissions, and therefore are included in the inventory total.

To estimate emissions from residue burning, a California-specific method developed by CARB (2009) was used. This approach is based on studies conducted at the University of California, Davis that established emissions factors for the most commonly burned residues in California:

almond, corn, rice, walnut, and wheat residues (Jenkins et al. 1996). For each of these crops, data on harvested area was obtained from the Yolo County commissioner's crop reports. Survey data from California was used to determine the fraction of area burned, the crop mass burned per unit area, and the residue moisture content for each crop (Jenkins et al. 1992; Jenkins et al. 1996). Due to the passage of the Rice Straw Burning Act of 1991, the burning of rice residue has been gradually phased out (Assembly Bill 1378). To account for this, we assumed that the fraction of rice area burned in Yolo County declined from .99 in 1990 to 0.11 in 2008, consistent with the rate of decline reported for all of California (CARB 2007; U.S. EPA 2010). For all other crops, the fraction of area burned was held constant.

Equations for Emissions from Residue Burning

Equation 17.

C_2O from Residue Burning:

$$CE_{RB} = \sum_{crop} HA_{crop} \times FB_{crop} \times MR_{crop} \times (1 - RMC_{crop}) \times EF_{CO2,crop} \times 907184.7$$

Equation 16.

N_2O from Residue Burning:

$$NE_{RB} = \sum_{crop} HA_{crop} \times FB_{crop} \times MR_{crop} \times (1 - RMC_{crop}) \times EF_{N2O,crop} \times 907184.7 \times 310$$

Equation 17.

CH_4 from Residue Burning:

$$ME_{RB} = \sum_{crop} HA_{crop} \times FB_{crop} \times MR_{crop} \times (1 - RMC_{crop}) \times EF_{CH4,crop} \times 907184.7 \times 21$$

(Calculated for almond, barley, corn, rice, walnut, and wheat)

Where:

CE_{RB} = Amount of CO_2 emitted from agricultural residue burning (g CO_2e yr^{-1})
NE_{RB} = Amount of N_2O emitted from agricultural residue burning (g CO_2e yr^{-1})
ME_{RB} = Amount of CH_4 emitted from agricultural residue burning (g CO_2e yr^{-1})
HA_{crop} = Harvested area of a given crop (ha yr^{-1})
FB_{crop} = Fraction of area burned for a given crop
MR_{crop} = Mass of crop residue that is burned for a given crop (t ha^{-1} yr^{-1})
RMC_{crop} = Residue moisture content for a given crop
$EF_{GHG,crop}$ = Emission factor for a given GHG for each crop (Table 5)
907184.7 = Short ton to gram conversion factor (g t^{-1})
310 = Global warming potential of N_2O expressed in carbon dioxide equivalents (CO_2e)
21 = Global warming potential of CH_4 expressed in carbon dioxide equivalents (CO_2e)

Table Appendix 3.5. Input Values for Calculating Emissions from Crop Residue Burning

Crop	FB_{crop}	MR_{crop} (t ha^{-1} yr^{-1})	RMC_{crop}	EF_{CO2}	EF_{N2O}	EF_{CH4}
Almond	0.84	2.24	0.183	1.83	0.00117	0.0002
Corn	0.03	9.41	0.086	1.31	0.00175	0.0001
Rice	0.99 or .11	6.72	0.086	1.16	0.00072	0.0002
Walnut	0.95	2.69	0.331	1.64	0.00164	0.0002
Wheat	0.11	4.26	0.073	1.19	0.00182	0.0001

Sources: CARB 2007; U.S. EPA 2010

9. Miscellaneous Crop Categories

Additional crops farmed in Yolo County were categorized into three miscellaneous categories: field crops, fruit and nut crops, and vegetable crops. Several crops were chosen to represent each miscellaneous category based on their presence in Yolo County. Crop acreage for the individual crops was provided in the Yolo County Agricultural Commissioner's reports (YCAC 1990; YCAC 2008). Nitrogen application rate and diesel fuel consumption rates were gathered for each crop using the University of California Cooperative Extension's cost and return studies for years 1990 and 2008 (http://coststudies.ucdavis.edu/archived.php). If a given year was not available, the closest available year was used to gather data. The N rates and diesel consumption rates were then averaged across all crops in each miscellaneous category. Crops used to represent each category are presented below.

Table Appendix 3.6. Miscellaneous Crop Category Crop Types

Misc. Crop Category	Crops Included
Field Crops	Dry beans, sorghum, sugar beet, sunflower
Fruit and Nut Crops	Apricot, citrus (lemons and oranges), fig, olive, pistachio
Vegetable Crops	Asparagus, onion, strawberry, summer squash, winter squash

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