POTENTIAL FOR ADAPTATION TO CLIMATE CHANGE IN AN AGRICULTURAL LANDSCAPE IN THE CENTRAL VALLEY OF CALIFORNIA

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DRAFT PAPER

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Preface

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

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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

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

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

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

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

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Abstract

This interdisciplinary document is intended to build awareness about the urgent need to develop mitigation and adaptation strategies to climate change for specific agricultural regions. It is neither a handbook, nor a set of predictions, but instead addresses planning issues at both the farm and landscape levels, using a process that has engaged stakeholders. Three storylines for potential responses in Yolo County, California, to climate change during the period 2010–2050 differ mainly in decision-making approaches rather than climate regimes: (high growth (Intergovernmental Panel for Climate Change A2 – high greenhouse gas emission scenario); more sustainable (Intergovernmental Panel for Climate Change B1 - lower greenhouse gas emission scenario); and most precautionary (AB 32-Plus scenario). Crop shifts are expected, such as replacement of warm-season horticultural crops (for example, tomatoes) to hot-season crops (for example, melon and sweet potato). Without explicit breeding programs, grains, walnuts, and almonds will decline or at very best, slightly increase. Greater crop diversification is possible in Yolo County and will likely increase adaptation to climate change. Promising management options for mitigating greenhouse gas emissions are using less nitrogen fertilizer and farmscaping with woody perennials; both options require research and development. Yolo County's water supply may see little change under the B1 and AB 32-Plus scenarios, based on current models for 2010–2050, but agricultural water will decrease with urban demand in the A2 scenario. Reduced Sierra snowpack will increase flooding along the Sacramento River, presenting serious economic and ecological tradeoffs for ecosystem restoration versus farming. Not all California counties will experience the same agricultural vulnerabilities to climate change as Yolo County, but this approach to assessing mitigation and adaptation potential could be useful elsewhere. Vigorous planning strategies are immediately needed to reduce vulnerabilities and to increase mitigation and adaptation, so that preservation of California's agricultural lands will continue.

Keywords: Agricultural water, crop diversity, farmscaping, IPCC scenario, greenhouse gas emissions, nitrogen fertilizer, participatory planning, Yolo County

Executive Summary

The Central Valley of California, the United States' main source of fruits and vegetables, is highly vulnerable to climate change impacts during the next 50 years, based on this case study in Yolo County. Using an interdisciplinary approach that involved researchers from the biophysical and social sciences, the study shows the urgency for building mitigation and adaptation strategies to climate change for specific agricultural regions. Several types of methods were used to assemble information relevant to Yolo County's agriculture, such as literature reviews, models, geographic information system analysis, interviews with agency personnel, and a survey of farmers. Throughout the course of the study, various types of stakeholders were engaged in developing scenarios, reviewing information, and editing the paper.

Climate change within agricultural landscapes of California's Central Valley focused on Yolo County, a jurisdiction just west of Sacramento. Modeling done by the Scripps Institution for the California Energy Commission's Public Interest Energy Research (PIER) Program shows that temperatures in this region are likely to be 1.3°C–2°C (2.3°F–3.6°F) hotter in 2050 regardless of the extent of greenhouse gas mitigation efforts, and between 2.3°C–5.8°C (4.1°F–10.4°F) hotter in 2100 depending on the emissions reduction scenario. Warming effects are likely to be more severe in summer than winter, and precipitation is likely to remain the same through 2050 and to decline slightly toward the end of the century.

This study examined three storylines summarizing potential responses in Yolo County to climate change during the period 2010–2050, and showed that vigorous planning for change is necessary to maintain agricultural preservation. The three storylines differ mainly in decision-making approaches rather than climate regimes: (high growth (Intergovernmental Panel for Climate Change A2 – high greenhouse gas emission scenario); more sustainable (Intergovernmental Panel for Climate Change B1 - lower greenhouse gas emission scenario); and most precautionary (AB 32-Plus scenario). The third scenario (AB 32-Plus) considers potential Yolo County responses if California enhances the climate change policy framework being established under AB 32.

Many changes in the crop mix are needed to adapt to climate change during the next 50 years, and research will smooth these transitions for farmers and other agricultural industries. Warm-season horticultural crops (tomatoes, cucumbers, sweet corn, and peppers) will be less viable in Yolo County by 2050, prompting a shift to hot-season crops such as melon and sweet potato. Grain growth will benefit only very slightly from elevated carbon dioxide concentrations, and wheat, barley, corn, and rice will be vulnerable to heat waves during their reproductive phase, resulting in lower yields. Higher temperatures will likely decrease yields of walnuts and table grapes, but almonds may be less sensitive. Almonds and walnuts will benefit from a decline in winter freezes, as will citrus. By the end of the century, yields from some orchard crops will decline due to insufficient hours of winter chill, but there may be more citrus and olive production. A switch is expected to higher cash value crops with greater income per amount of applied water.

Crop breeding is immediately needed to cope with climate change adaptation (e.g., traits that adapt crops to intermittent heat waves). In addition, research is needed on responses to simultaneous increases in temperature and carbon dioxide levels, and implications for stomatal closure, growth declines, and effects on water use efficiency, so that crop breeding stays one step ahead to cope accurately with environmental change

Climate change will lead to a northern migration of weeds, and disease and pest pressure will increase with earlier spring arrival and warmer winters, allowing greater proliferation and survival of pathogens and parasites. Higher temperatures during the summer season will likely reduce rangeland livestock production and the supply of irrigated forage crops. It should be noted that these projections have not adequately considered adaptation potential. Investment in technology, plant breeding and cropping system research will result in less yield loss, higher yield reliability, and greater agricultural sustainability.

Different regions of Yolo County will experience different vulnerabilities to water supply, indicating that attention to complex planning strategies should begin now. Eastern Yolo County relies on water resources from the Sacramento River that are supplied by the Sierra Nevada snowpack. It is less vulnerable to water shortages than agricultural locations further south in California that are dependent on deliveries of water from the Delta pumping stations. In western Yolo County, agriculture relies on local rainfall and Coast Range water supplies, and will be more vulnerable to water shortages, although groundwater supplies are plentiful at present. Higher temperatures and increasing population and urbanization will place greater demands on water resources and lead to a more uncertain water supply for agriculture.

The menu of potential adaptation and mitigation responses to climate change by growers includes changes in crop mix, irrigation methods, fertilization practices, tillage practices, and land management:

- **Crop mix.** Growers will shift toward hot-season species, with greater winter potential for cool-season crops such as lettuce and broccoli. Additional crops or varieties may become more prevalent in Yolo County by mid-century, especially if advances are made in second-generation biofuels, such as those producing cellulose useful as fuel. A shift to greater crop diversity will offset some of the risks from weather variation due to climate change.

- **Irrigation.** If water supply becomes threatened, shifts toward drip irrigation and crops that provide higher income per amount of applied water are potential adaptive responses. In addition to reducing water use, drip irrigation has been shown to reduce both carbon dioxide and nitrous oxide emissions compared to furrow irrigation, with no difference in yields (for tomatoes, a major crop in the county). However, it is not useful for all crops and entails substantial investment, labor, and energy for pressurization. Rice, pasture, and hay are the county's crops with the highest water use and evapotranspiration, and are therefore the most vulnerable to water shortages and most likely to be reduced.

- **Fertilizer use.** Reducing inputs of nitrogen-based fertilizers is a strategy to reduce emissions of nitrous oxide, a potent greenhouse gas. Current application of nitrogen fertilizers is often 25%–50% higher than needed.

- **Cover cropping**. Cover cropping with legumes is a strategy to improve soil fertility and decrease fertilizer use, but may lead to additional nitrous oxide emissions and prevents the possibility of cool weather cash crops.

- **Tillage.** Low-till or no-till methods hold the potential for increasing the carbon sequestration in soils, decreasing evaporative water loss, and lowering fossil fuel inputs to agriculture. For many of Yolo County's crops, however, tillage reduction presents production constraints, such as seed establishment or efficient movement of irrigation water. Also, alternative tillage practices can increase nitrous oxide emissions due to higher moisture content and increased activity of anaerobic microorganisms. Net greenhouse gas reduction is likely only after many years of low-till practice, which is often not feasible.
- **Manure management.** Manure management activities are important for achieving reduction in greenhouse gases (principally methane) and local air pollutants. Methane digesters are useful for dairy production, but most livestock in Yolo County is beef cattle.
- **Farmscaping.** Use of perennial vegetation in marginal lands on farms, such as farm margins and riparian corridors, can increase carbon storage, reduce carbon dioxide and nitrous oxide emissions, and benefit water quality, habitat, and biodiversity.
- **Carbon sequestration in tree crops and vines.** Perennial woody crops offer a potential opportunity for growers to receive greenhouse gas mitigation credits, although such a mechanism does not yet exist, and may be difficult to justify in terms of permanence of carbon storage.
- **Organic production.** Yolo County currently contains more than 50 organic farms, most producing a diverse mix of crops for local markets. Organic production may hold adaptive advantages in that its diversity of crops can better respond to a changed climate. Net greenhouse emissions also may be lower. New and increased pests and disease pressure may be an even greater problem for organic than conventional farms. However, tradeoffs exist in terms of yields for many organic crops, and new markets would need to be developed to support expanded organic production.

Mitigation and adaptation strategies to climate change will differ among the four main regions in the county, and each region has research priorities that require unique attention. Using geographic information system approach, we identified some of these issues.

In low-lying Region 1 near the Sacramento River, marginal farmlands are at risk of flooding, due to less snowpack and earlier snowmelt in the Sierra Nevada. Research is needed to understand different priorities of habitats and biota by stakeholder groups, and the tradeoffs for multiple ecosystem services, such as water quality, greenhouse gas mitigation, food production, and conservation of endangered species. Although restoration to wetlands would increase carbon sequestration and wildlife habitat, benefits might be offset by increased nitrous oxide and methane emissions. The means and outcomes for ecosystem restoration are controversial and need to be carefully planned to maximize biodiversity and to maintain farmer livelihoods.

Landscapes of Region 2, including much of the county's prime farmland, have the greatest potential for agricultural resilience to the effects of climate change, and for enhanced carbon storage in soils. Region 3, an area of terraces and low hillslopes, can benefit from practices to increase crop diversification with practices that increase carbon storage, while Region 4, a large area of uplands in the west of the county, currently has large aboveground and belowground carbon stocks that should be carefully maintained through best rangeland management practices, such as oak regeneration and avoidance of overgrazing.

We conducted a survey of growers, which found that 67% of respondents considered climate change “very important” or “somewhat important” to their investment decisions. Forty-three percent of growers reported that they “always” or “frequently” considered climate change in their production decisions. Growers with land in Williamson Act set-asides were more likely to be concerned about climate change.

Based on the research summarized previously, we developed the three storylines for future county climate change responses as follows:

A2. “Regional Enterprise.” In this scenario, county population expands rapidly from 197,000 residents currently to approximately 400,000 in 2050. Urban land would nearly double, resulting in the loss of 27,775 acres of farmland, and substantial additional areas of the county might be affected by rural sprawl. Agriculture would remain in a monoculture model with some changes in crop mix emphasizing higher value monocultures. Soil and land management and water usage would remain little changed, at the risk of large variation in production from year to year due to climate change-induced water shortages and flooding risks.

B1. “Global Sustainability.” In this scenario, county population expands more slowly to around 320,000 in 2050, and urban and rural residential encroachments on agricultural land are proportionally less. Growers diversify their crop mix for resilience, and reduce intensity of nitrogen-based fertilizer use and tillage. Conservation practices create wetlands in low-lying areas and vegetated corridors along waterways and farm margins. Cover cropping adds to soil fertility but reduces potential for income from cool-weather crops. Efficient water management practices are used extensively, organic-based practices increase carbon sequestration in soils, and farming practices greatly reduce greenhouse gas emissions.

AB 32-Plus. “Precautionary Change.” In this greenest scenario, county population stabilizes at about 210,000 and the urban footprint remains constant, enabling maximum farmland protection and helping reduce greenhouse gas emissions from motor vehicle travel. Growers further diversity their crop mix, substantially increase orchard crops, and eliminate fossil fuel inputs to agriculture, both through fertilizers and motor vehicle fuels. Water use is reduced through crop mixes that reduce evapotranspiration, and by alternative irrigation methods. Extensive conservation practices sequester carbon in wetlands and woodlands along waterways, using practices that minimize nitrous oxide and methane emissions. Biodiversity increases in cropped and non-cropped areas of the landscape. Novel food systems encourage reduction of greenhouse gas emissions, as well as new markets and greater resilience, creating the greatest long-term agricultural sustainability of all of the three scenarios.

1.0 Introduction

1.1. California in a Global Climate Change Context

Climate change will cause agricultural and land use change in California, and the extent and direction of these changes will depend on the global capacity for mitigation of greenhouse gas (GHG) emissions and the strategies that are developed to cope with uncertainties in temperature and precipitation (Cayan et al. 2006). This paper describes a case study that examines climate change scenarios using a variety of information sources, agricultural modeling, and geographic information system (GIS) analysis of natural resource indicators in an agricultural landscape. These scenarios, based on storylines from the International Panel on Climate Change (IPCC) for high and low GHG emissions (IPCC scenarios A2 and B1, respectively), form the basis for projections of changes in agricultural production, land use, the provision of ecosystem services, and factors affecting farmer's planning horizons and decision-making relevant to climate change.

Scenarios are possible pictures of the future that depend on many assumptions, rather than predictions. They are instructive in thinking about the vulnerabilities and responses associated with climate change, both in terms of costs and opportunities. Given the complexity of agricultural landscapes, a disclaimer is necessary: results of this study are highly stylized and depend on sets of assumptions that are undoubtedly simplistic. Since there are very few studies on adaptation to climate change, this paper at least sets the stage for some of the major issues in thinking ahead for future planning.

Agriculture in California is complex, diverse, and has shown the capacity for resilience to change in the past (Johnston and McCalla 2004; Jackson et al. 2007). California has a history of mobilizing natural, financial, human, social, and physical capital to adapt to new challenges. California leads the nation in agricultural production, in legislation for the protection of water and air quality in agricultural landscapes, and most recently, in policies to mitigate to climate change. Using a case-study approach, this paper discusses some of the broad mechanisms by which California agriculture may react to climate change, and suggests approaches for thinking about adaptation pathways for both high and low GHG emission scenarios.

In planning for climate change, Californians will likely choose options that favor agricultural sustainability, defined as supporting agricultural productivity and profitability, environmental quality, and social well-being. This requires that scientists, farmers, policymakers, and the general public better understand the complexity of costs and responses to climate change. To achieve significant mitigation of GHG emissions, substantial adaptation will be necessary within the agricultural sector, and would be most effective if combined with adaptations that cope with variable and hotter climate. Thus, options that both reduce GHG and deal with climate impacts are explored here to enhance the transition to more sustainable agriculture. Overall, mitigation and adaptations to climate change will be most likely to occur when they achieve other benefits, i.e., provide other ecosystem services (Daily 1997), such as higher productivity, or air and water quality. Aiming for multiple benefits should increase the provision of ecosystem services in agricultural landscapes over the long term.

1.2. AB 32 as a Driver of Change

The California Global Warming Solutions Act of 2006 (AB 32)[1] directs the California Air Resources Board (ARB) to develop plans in conjunction with other agencies to lower emissions to 1990 levels by 2020. Executive Order S-3-05 sets the even more ambitious target of reducing emissions 80% below 1990 levels by 2050. The 2020 target of 427 MMTCO$_2$E (million metric tons of carbon dioxide (CO_2) equivalents) requires reductions of 169 MMTCO$_2$E, or approximately 30%, from the state's projected 2020 emissions of 596 MMTCO$_2$E (business-as-usual). This will mean reductions of 42 MMTCO$_2$E, or almost 10%, from the average total emissions for the years 2002-2004 (ARB 2008). With this commitment, California will play a pioneering role for the United States and potentially for the world. At this time, ARB is directing the development of appropriate regulations to establish a mandatory reporting system to track and monitor GHG emission levels in the year 2020 (ARB 2008). The target levels still are under discussion. Targeted changes will be inventoried from all sectors in year 2020, but this inventory is not a reflection of accumulated change in GHG emissions. Instead it uses net annual potentials of GHG reduction over the years assuming that certain changes will be reached in the year 2020. This reduction will be accomplished through an enforceable statewide cap on global warming emissions that will be phased in starting in 2012.

Agriculture is unlikely to be regulated in terms of its GHG emissions, as it accounts for only 6% of the state's emissions (ARB 2008) (Figure 1). Farming is about 1% of the state's economy, measured by share of employment or gross state product. Therefore, by that measure agriculture contributes more than other sectors to GHG emissions relative to its contribution to the economy (UCAIC 2006). We note, however, that electricity and transport are major inputs to industrial and consumer activities, including food and agriculture, so regulations of those industries will affect food consumers and farm production costs. Agricultural GHG contributions of CO_2 are largely considered to be from farm management—for example, electricity used by a farm pump, or fossil fuel used by a farm truck (ARB 2008). Food processing and transport CO_2 emissions are assigned to other sectors, such as electricity or transportation. There are likely to be opportunities for agriculture to benefit, however, from climate change mitigation benefits, by sequestering carbon (C) or reducing methane (CH_4) or nitrous oxide (N_2O) emissions (ARB 2008).

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

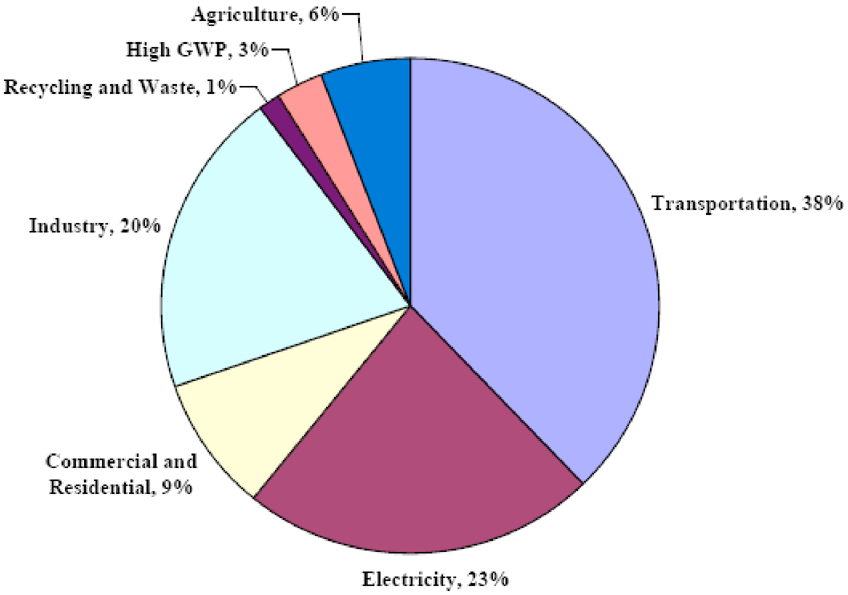

Figure 1. California's GHG emissions by sector. Agriculture accounts for only 6% of the state's total emissions.

Source: ARB 2008.

1.3. California Agricultural Landscapes: Distribution and Diversity

California is the world's fifth largest supplier of food and other agriculture commodities (UCAIC 2006). California's agricultural sector generated $31.4 billion in farm receipts in 2006, which was 13.1% of the U.S. total (CDFA 2006b). Agriculture occupies nearly 28 million acres (11 million hectares), of which about half is pasture and rangeland, and 40% is cropland (UCAIC 2006).

In California, farming, forestry, fishing, and hunting account for about 1.5% of the gross state product, at $21 billion. The share rises to 6.5% when activity closely related to farming and indirect effects, is included. California agriculture currently accounts for approximately 13% of the United States agricultural cash receipts, leading the nation as it has done every year since 1948.

California is characterized by high crop diversity, intensively managed cropping systems, and high nutrient and agrochemical input levels, which have potentially harmful environmental impacts (CDFA 2006a). With over 250 different commodities produced, California is the most diverse agricultural producer within the United States. High value horticultural commodities (nuts and fresh fruits and vegetables) account for greater than 50% of the cash receipts and dairy is the single largest commodity in terms of income in the state (Table 1). On a national scale, California produces half of the nation's total fruits and vegetables and 19% of dairy.

California is vital for domestic consumption, with 80% of production bound for national markets and 20% for export.

Table 1. California's ten most important crops in 2006 in terms of area cultivated and revenue generated. High value horticultural commodities (fresh fruits, vegetables, and nuts) account for more than half of all cash receipts. Dairy is the single most valuable commodity in the state

Area rank	Crop	Area (ha)	Revenue generated ($million)	Economic rank
1	Hay (primarily alfalfa)	627,000	1,141	6
2	Nuts (almonds, walnuts, and pistachios)	364,000	3,454	1
3	Grapes	324,000	3,166	2
4	Cotton	266,000	625	11
5	Rice	213,000	408	13
6	Intensely cropped vegetables (lettuce, broccoli, carrots)	201,000	2,920	3
7	Wheat	149,000	104	>15
8	Fruit trees (oranges, plums, lemon, and peaches)	145,000	1,292	5
9	Tomatoes	124,000	942	9
10	Corn	45,000	52	>15

Source: CDFA 2006a.

Agricultural land in California covers about 9.9 million acres (4 million hectares [ha]). Of this area, 74% is non-woody crops (e.g., annual crops such as grains, vegetable, cotton) and 26% are woody crops (e.g., orchards, vineyards) (CDFA 2006a) (Figure 2). Land area in pasture and rangeland for livestock grazing is typically in the uplands, while irrigated crop production is in the valley lowlands.

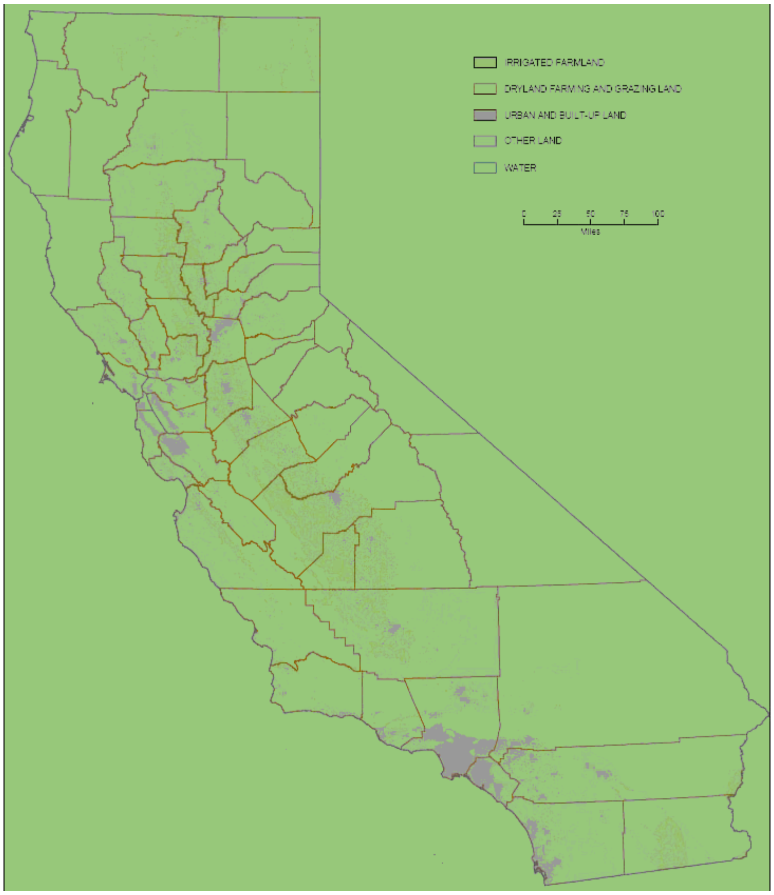

Figure 2. Major land uses in California: Agricultural land covers about 9.9 million acres. Of this area, 74% was non-woody crops (e.g., annual crops such as grains, vegetable, cotton) and 26% was woody crops (e.g., orchards, vineyards)

Source: Division of Land Resource Protection 2002.

In many of California's lowland agricultural landscapes, riparian areas and other natural ecosystems have been greatly reduced and biodiversity has been lost due to agricultural intensification. There is a strong commitment to ecosystem restoration, floodplain and floodplain management, e.g., by the California Department of Water Resources (DWR 2005), and wildlife conservation, e.g., by the California Department of Fish and Game in the remaining areas. There are also regional programs directed towards habitat restoration by the Yolo County Resource Conservation District, and the Habitat Conservation Plan/Natural Community Conservation Plan (NCCP/HCP 2006).

The diversity of topography, the latitudinal range, and seasonality of weather patterns play an important role in the success of California agriculture (CEC 2006b). Although a Mediterranean-type climate is present in most of California's agricultural regions, there are milder temperatures in the coastal valleys, mountain ranges which serve as rain catchments, and hotter summers and wetter winters in the Central Valley, which lies between the Coast Range and the Sierra Nevada

(Barbour et al. 1993). Few other states or agricultural regions exhibit such a unique confluence of climatic conditions, availability, and seasonality of water resources; well-established water supply infrastructure; and appropriate temperature regimes to support a similarly diverse and productive agricultural landscape. However, the regional and climatic diversity of California also predisposes the state to potentially significant impacts with climate change, since the large set of commodities produced may be affected differentially. Nevertheless, with topographic diversity may come the potential for enhanced adaptive capacity in response to climate change (CEC 2006b).

If GHG emissions proceed at a medium to high rate, temperatures in California are expected to rise 4.7°F to 10.5°F (2.5°C to 5.8°C) by the end of the century, compared to 3°F to 5.6°F (1.7°C to 3.1°C) at a lower emissions rate (CEC 2007a). These temperature increases would have widespread consequences for agriculture including substantial loss of snowpack, changes in the timing of the agricultural water supply, increased probability of large wildfires that would affect livestock grazing lands, and either reductions or increases in the quality and quantity of certain agricultural products. The state's natural resources and landscapes are already under stress due to California's rapidly growing population, which is expected to grow from 38 million today to 60 million by 2050 (CDF 2007). The effects of global climate change may be dramatic in some regions (low-lying flood plains, islands, and coastal regions), while far less severe in others, or in some situations potentially beneficial in terms of increased agricultural productivity.

1.4. Framework for Addressing Adaptation to Climate Change

Adaptation to climate change is set within a much larger context of changing landscapes in California. Besides climate change, several factors will drive major changes in California agriculture during the next 50 years, including population growth, water availability, regulations that favor agricultural sustainability, and changes in local and world agricultural markets. Dissecting the impact of climate change alone is impossible, as it is only one aspect of an uncertain future (Figure 3). The time frame of this study is from 2010–2050, as this period is within the planning horizons of many farmers and natural resource managers. Climate change during this period is fairly well understood compared to later in the century, and is relatively similar for high and low emissions scenarios (see below). Thus, different mitigation and adaptation strategies are based to a large extent on goals and projections for social decisions and economic futures.

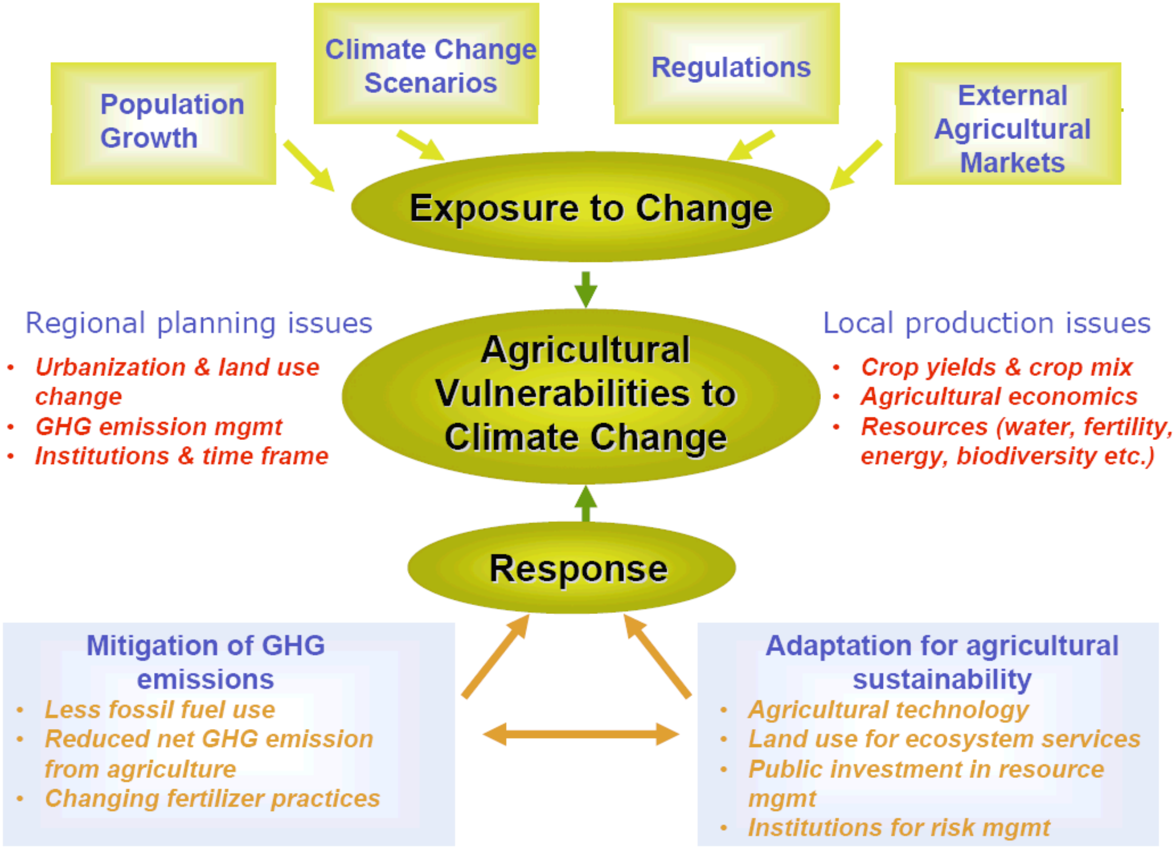

Figure 3. Potential agricultural vulnerabilities from exposure to climate change and the response in terms of mitigation and adaptation options. Climate is one of several factors that will concurrently change in the next 50 years.

Source: Jackson and Tomich, unpubl. 2008.

Exposure to climate change will cause vulnerabilities for different sectors within the agricultural landscape in different ways. *Vulnerability* can be defined as the degree to which a system or system component is likely to experience harm due to exposure to a hazard. For example, agricultural crops may be more vulnerable to environmental stress (e.g., water supply, water quality, salinity, or heat) for crop production that leads to lower economic viability. There may be greater vulnerability to land use change due to flooding near the Sacramento River, for example. Both mitigation and adaptation are response options to decrease vulnerability, and they can actually have synergistic effects, under some circumstances. For example, reduction in fossil fuel use for groundwater pumping can be coupled with irrigation strategies that reduce the impacts of water shortages.

The expected temperature change during the time frame of the study (2050) is 2°C to 3°C (3.6°F to 5.4°F, see below), with minor differences for the high-emission (A2) and low-emission (B1) scenarios (Cayan et al. 2006), due to the time lag in observing earth responses to elevated GHG emissions. This is within the temperature range of expected “autonomous” adaptations by the

IPCC (2007), in which individuals choose options that fit their own livelihoods and operations without the direct involvement of government agencies and non-governmental organizations. Three of the main pathways are important in this initial phase of individual, ”autonomous” adaptation by the Food and Agriculture Organization of the United Nations (FAO 2007): *agrobiodiversity* such as use of different crops and livestock, their genetic diversity, rotations, and integrated pest management; *soil and land management* such as lower fossil-fuel based inputs of fertilizers, pesticides and tillage, which may become very expensive, and use of marginal lands to increase C sequestration; and *water management* such as water use efficiency and decreased energy for water transport. Ultimately these adaptation strategies should be coupled with mitigation strategies.

In planning for future increases in temperature and extreme events, collective adaptations are needed such as developing infrastructure, research and development for new production methods and changing institutions and policy (IPCC 2007). This kind of adaptation is concerned with *capacity-building and technology transfer*, *knowledge management*, and *new legislation and policy* (FAO 2007). Some of these adaptation strategies will be considered in this study, mainly for considering factors that will influence farmers' decisions about how to mitigate and adapt to climate change.

The goals of this paper are to:

1. Understand the vulnerabilities of a representative California agricultural landscape to climate change (exposure, sensitivity, and resilience).
2. Determine the key biophysical and socioeconomic uncertainties (local and regional) that will affect mitigation and adaptation to climate change in this landscape.
3. Develop a template for exploring sustainable regional responses to climate change for California's agricultural counties.

Approach:

- Create a set of potential storylines for different climate change scenarios that show how the future might unfold, using information about baseline conditions and uncertainty of outcomes, and assumptions about behavior
- Identify environmental factors that might restrict the productivity of a specific crop at high spatial and temporal resolution using modeling tools
- Consider changes in crops and livestock that may occur under different climate change scenarios
- Assess the effects of changes in regional and world agricultural markets that may affect the economic resilience of farm operations and conservation of agricultural resources
- Explore plausible vulnerability and adaptive capacity of the current agricultural land uses and landscape types, set within the regional context of the Central Valley
- Explain relationships between land use change and water use and quality in irrigated agriculture
- Examine options for ecosystem restoration and its effects on biodiversity
- Show how urbanization may affect the multiple benefits derived from ecosystem services in agricultural landscapes under different climate change scenarios

- Survey planning horizons of farmers, and how decision-making support tools may increase the capacity to cope with mitigation and adaptation to climate change

Thus, three main categories in this paper consider mitigation and adaptation options to climate change from different perspectives: (1) a commodity production viewpoint that examines options based on potential productivity, management, and economics; (2) a landscape viewpoint that explores patterns of land use change; and (3) mechanisms to increase the interest and capacity of farmers to respond successfully. These categories in reality are interwoven, and the distinction is somewhat artificial, but the intent is to group agricultural versus natural resource issues versus building capacity to adapt in these separate sections.

The project involves a team of interdisciplinary faculty from the University of California (UC) Davis[2] and a steering committee composed of industry and agency representatives. It has benefited from discussions with the people from the following offices and agencies: Yolo County Administrator, Yolo County Agricultural Commissioner, Yolo County Flood Control and Water Management District, Yolo County Planning Department, Yolo County Habitat Conservation Program, California Farm Bureau, California Department of Food and Agriculture, California Department of Water Resources, and UC Cooperative Extension. There has been a great deal of interest and involvement on the part of the Yolo County agencies in terms of providing interviews and information. Yolo County is taking a proactive role with regard to climate change. The Yolo County Board of Supervisors established a working group charged with determining a course of action for Yolo County on the issue of climate change in January 2007. A list of actions and activities the county has already taken to reduce energy usage and greenhouse gas production is now underway. This paper is intended to contribute to the next planning stages.

1.5. Yolo County in California's Central Valley

Yolo County represents many of the attributes of agricultural landscapes throughout California's Central Valley: irrigated row crops on alluvial plains; upland grazed grasslands; small towns and cities; and a changing mixture of urban, suburban, and farming-based livelihoods through the past few decades. Located on the Sacramento River in the Sacramento Valley in the north-central region of the Central Valley, Yolo County encompasses the floodplain of the Yolo Bypass, an intensive cropland of diverse horticultural and field crops, upland grasslands, and savanna of the Coast Range. The choice of crops has been influenced by a climate that is slightly cooler and wetter than the more productive agricultural counties further south. The most important crops are tomatoes, alfalfa hay, wine grapes, and almonds, but a diversity of crops can be produced which ultimately may increase resilience for future environmental changes, extreme events, and market competition. Yolo County has strong local interest in agricultural preservation, but there is regional pressure for urban and suburban growth, due to its proximity to the city of Sacramento.

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[2] The project has been supported by the Agricultural Sustainability Institute at UC Davis.

1.6. Yolo County under Different Climate Change Scenarios, 2010 to 2050

For Yolo County, the widely adopted approach of using more than one GCM model and GHG emissions scenario has been used. Data on downscaled climate data has been provided by the Scripps modeling group. Following the IPCC's *Special Report on Emissions Scenarios* (SRES) (Nakicenovic et al. 2000), scenarios emphasize either high growth (A2 - high emission) and or more sustainable (B1 - lower emission) storylines. However, a storyline was also included for an "AB 32-Plus" scenario, which we have designed to be more stringent than the current AB 32 law. This is not an IPCC scenario, but was created specifically for this project.

Rather than forecasting change, these scenarios are each a description of a possible future state of the world that shows a range of uncertainty (www.ipcc-data.org/ddc_definitions.html). These storylines are narrative descriptions of scenarios that show effects and relationships between key driving forces (Figure 4). Through AB 32, California has chosen to adopt a B1-type scenario in terms of mitigation of GHG emissions. The IPCC A2 scenario still serves as a vantage point for viewing alternative futures, as does the AB 32-Plus scenario (raised only for the purpose of this paper), which assumes that even greater GHG emissions restrictions are necessary to prevent severe climate change impacts.

IPCC SCENARIOS

Scenario	**A2**	**B1**
Population growth	high	low
GDP growth	very high	high
Energy use	high	low
Land-use changes	medium/high	high
Resource availability	low	low
Technological change favoring regional efficiency and dematerialization	slow	medium

Figure 4. Main characteristics of emissions scenarios families outlined in the *Special Report on Emissions Scenarios* (SRES) emphasize either high growth (A2 - high emission) or more sustainable (B1 - lower emission) storylines

Source: Nakicenovic et al. 2000.

We use the word "scenario" in the same sense as the IPCC, which includes the following definition of "scenario" in the glossary that accompanies the Assessment Reports: "a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a 'narrative storyline'." This report considers three scenarios, which do not cover all possible future pathways, but they advance understanding of climate change by indicating different plausible pathways. In this way, they indicate the range of possible futures, and indicate the relationships among components that could lead one or another future to come to reality.

Since gasses mix rapidly in the world's atmosphere, the concentration of GHG (other than water vapor) does not vary greatly in different regions. Many models, and thus many scenarios, are global in scale. Nonetheless, the study of human response to climate change is often conducted at smaller scales, since many key human institutions and organizations that manage and govern resources are at national, regional, or local scales. It is therefore crucial to downscale scenarios from global scales to smaller scales. The various projects funded by the California Energy Commission (Energy Commission), taken as a whole, accomplish such downscaling to the level of California, and largely focus on biophysical criteria. In this report, we downscale further, to a single county, one that represents the key industry of agriculture in California and that, through its environmental and agronomic diversity, illustrates many forms of agriculture in the state.

To accomplish this downscaling, we have developed "narrative storylines," as the IPCC envisaged, to account for a number of crucial elements, such as population, land use and policy. To select the corresponding elements for each storyline (Table 2), we have reviewed studies of economic, political and social development in California and other regions and interviewed key stakeholders. We held a series of meetings in which individuals familiar with each element participated; we reviewed successive drafts of the storylines until we reached consensus on all three of them. The following descriptions are taken from the IPCC's global vantage point (IPCC 2007):

IPCC A2-high emissions scenario for Yolo County. The *Regional Enterprise* scenario represents a socioeconomic future which imposes a high level of stress upon natural resources. This is the most economically competitive of the scenarios, and it suggests a greater degree of economic and political autonomy than at present. The environment is seen as a commodity which can be traded. This does not necessarily imply degradation or loss of resources, but rather assets will be improved and be given a market value. Certain sectors, such as agriculture, would be much more exposed to the market and could decline as a result, although there would be economic support where this promotes regional benefits. For example, agricultural subsidies would be reduced, which will expose some agricultural commodities to more global markets. A strong regional government will encourage more political control and involvement in planning, development, investment, and resource management than is currently the case.

IPCC B1-low emissions scenario for Yolo County. In the *Global Sustainability* scenario, the global approaches to achieving sustainable development take precedence over regional responses. The world is seen as an interconnected whole, both functionally and morally, with a concentration on the wider impacts of individual actions. Subsidy payments and environmental taxation are used to move agriculture away from the negative aspects of intensification, to reduce fossil fuel use and to increase agricultural sustainability. Equity considerations are likely to be increasingly important in general. Biodiversity and water resources are seen and managed in a broad spatial context, at different national and global scales.

AB 32-Plus scenario for Yolo County. In the *Precautionary Change* scenario, we have assumed a faster implementation rate and more stringent efforts to reduce GHG emissions worldwide than in the B1 scenario. This scenario assumes that more drastic change may be needed to reduce GHG emissions in California to actually achieve AB 32's intended emissions levels, and that to achieve worldwide reductions in emissions, countries may be required to further reduce emissions levels below that of AB 32 in order to abate the potential dangers of climate change.

The storylines for Yolo County under different CC scenarios (A2, B1, AB 32-Plus) are based on the following assumptions that were developed from expert opinion and consensus (Table 2):

Table 2. Storylines for the three climate change scenarios for Yolo County agriculture. Two of the scenarios (A2 and B1) used the storylines for IPCC scenarios, as interpreted for the local rather than global level. The storylines were developed as an exploratory tool, rather than as future projections for the region. The projections for temperature and precipitation are general values from Hayhoe et al. (2004), as run by the Parallel Climate Model (PCM) and the Hadley Centre Coupled Model, version 3 (HadCM3) global circulation models (GCM).

Scenario	**Regional Enterprise**	**Global Sustainability**	**Precautionary Change**
	A2	**B1**	**AB 32-Plus**
PHYSICAL CONDITIONS			
2050 CO_2 LEVEL	approx. 550 ppm	approx. 500 ppm	<=450 ppm
2100 CO_2 LEVEL	850 ppm	550 ppm	<=450 ppm
2050 TEMPERATURE	+1.3ºC to +2ºC (+2.3ºF to +3.6ºF)	+1.3ºC to +1.6ºC (+2.3ºF to +2.9ºF)	not modeled yet
2100 TEMPERATURE	+3.8ºC to +5.8ºC (+6.8ºF to +10.4ºF)	+2.3ºC to +3.3ºC (+4.1ºF to +5.9ºF	not modeled yet
2050 PRECIPITATION	-51 mm to -70 mm (-2.0 in to -2.8 in)	-37 mm to +6 mm (-1.5 in to +0.2 in)	not modeled yet
2100 PRECIPITATION	-91 mm to -157 mm (-3.6 in to -6.2 in)	-117 mm to +38 mm (-4.6 in to +1.5 in)	not modeled yet
2050 STORYLINES			
Population growth	High population growth with a doubling from 180K to 394K (H. Johnson's high growth projection) and the SACOG "Scenario B" for job and household projections for 2050	Mid-range population reaching 335K (H. Johnson's mid-range growth projection) and the SACOG "Scenario C" for job and household projections for 2050	Low population growth reaching only 235K (H. Johnson's low growth projection which is close to the SACOG mid-range projection of 263K) and the SACOG "Scenario D" for job and household projections

Scenario	**Regional Enterprise**	**Global Sustainability**	**Precautionary Change**
	A2	**B1**	**AB 32-Plus**
Economic growth	Continued high growth in northern CA; market-driven growth; heterogeneous growth worldwide (greater inequities)	Moderate growth; shift in emphasis from quantitative production of goods to qualitative growth in quality of life (in line with global shift to a more interwoven service economy); value-added, less efficient production; ordinances to benefit small industries, rural sector, open space, agritourism and recreation; more even growth worldwide with reduced inequities	Moderate growth; decrease in quantitative production and use of resources but strong growth in quality of life; greatest emphasis on value-added production; ordinances to benefit small industries, rural sector, open space, agritourism and recreation; more even growth worldwide with reduced inequities
Agriculture	~3ºF to 4ºF hotter climate changes crop mix; summer climate now closer to that of in Merced County; yield variability; longer growing season; less irrigation applied per crop than at present to save water (CO_2 effects on water use efficiency are difficult to predict); more groundwater recharge; fewer farmers and less farmland	~3ºF to 4ºF hotter climate changes crop mix; multicropping; summer climate now closer to Merced County; practices encouraged to increase C sequestration and reduce N_2O emissions; methane recapture required for livestock operations; gradual planning to adapt to high temperatures in 2100	~3ºF to 4ºF hotter climate changes crop mix; summer climate now closer to Merced County; multicropping; agrobiodiversity-based practices; strong incentives for immediate adoption of practices encouraged to increase C sequestration and reduce N_2O emissions; methane recapture required for some livestock operations; early planning to adapt to high temperatures in 2100
Land use	Current trends plus somewhat higher densities and greater infill (Yolo County has been pretty good to date at preserving farmland and limiting sprawl); urbanized area increases 50% with 100% population increase; new communities built but gradually improving land use mix; SACOG ”Scenario B”	More compact growth countywide, higher densities and intensified infill; urbanized area expands 20% with 50% population increase; much better land use mix and emphasis on local retail rather than big box help reduce driving; SACOG ”Scenario C-P”	With stable population and strong land use planning the urban footprint does not expand; existing urban areas are used more efficiently and the land use mix improves greatly; emphasis on small-scale local retail, services, and employment helps reduce driving; SACOG ”Scenario D” with highest housing densities and most urban growth in core areas
Water supply	Greatly diminished Sierra snowpack means quick spring runoff with flooding and summer shortages; hotter and possibly marginally drier climate increases crop and residential needs; passive water use (significant demands on groundwater resources during drought and surface water during wet years).	Same as in A2, but greater allocation of water to the agricultural sector; moderate conjunctive use of surface and groundwater supplies.	Same as in A2, but greater allocation of water to the agricultural sector; active conjunctive use (development of artificial groundwater recharge areas).

Scenario	**Regional Enterprise**	**Global Sustainability**	**Precautionary Change**
	A2	**B1**	**AB 32-Plus**
Water allocation	Scenario with the highest allocation of water to urban sector (similar to “Current Trends” scenario of DWR); lowest investment in technologies and subsidies to improve agricultural water delivery; greatest shift to groundwater use responses depend on wet vs. dry scenarios.	”Less Resource Intensive” scenario of DWR. Shift to drip irrigation, high value crops (organic) for high water use efficiency; use of deficit irrigation management on tree and vine crops, subsidies to improve irrigation systems for uniform and efficient delivery; more environmental water dedication; responses depend on wet vs. dry scenarios.	Full implementation of cost-effective conservation measures; Widespread use of deficit irrigation techniques; Water use for restoration of perennial vegetation in lands with marginal soils or flooding and for farmscaping (water use to increase C sequestration); high value crops for high water use efficiency; subsidies to improve irrigation systems for uniform and efficient delivery; responses depend on wet vs. dry scenarios.
Water management	Increasing sprinklers and drip irrigation, less flooding and furrow irrigation. More “crop per drop” through changes in irrigation methods, although more improvement is possible. Multicropping area increases significantly from the 2000 level.	Increased multicropping compared to A2, also more improvement in water management to increase water use efficiency. Greater production per acre and decreased applied water per irrigated crop acre.	Greatest water use efficiency and multicropping, relying mainly on drip irrigation.
Carbon sequestration	Some sequestration (forest planting and constructed and/or restored wetlands) takes place under market-based systems. Soil loss tolerances in tons per acre per year have a 25% to 50% excess of T factors (i.e., maximum amount of erosion for a given soil type that maintains soil quality for plant growth).	Substantial sequestration under market-based systems and conversion of public land; tax incentives to increase soil and plant C sequestration. Soil loss tolerances (T factors in tons per acre per year) are achieved resulting in little excess of T factors. Greater adoption of residue management practices (mulch, compost, conservation tillage).	Substantial sequestration under market-based systems and conversion of public and private land; tax incentives to increase soil and plant C sequestration. Soil loss tolerances (T factors in tons per acre per year) are achieved resulting in little excess of T factors. Greater adoption of residue management practices (mulch, compost, conservation tillage).
Technology	Continued high innovation in northern CA; very uneven application worldwide; less emphasis on irrigation technology due to lower agricultural water use	Continued high innovation in northern CA; emphasis on green, small-scale, distributed, and appropriate technologies; irrigation technology developed to reduce energy for pumping groundwater	Continued high innovation in northern CA; greatest emphasis on green, small-scale, distributed, and appropriate technologies; irrigation technology developed to reduce energy for pumping groundwater
Agricultural land tenure	Little incentive to preserve farming lands and low participation in the Williamson Act	Farming easements and other incentives become more prevalent so that land stays in farming	Farming easements and other incentives become more prevalent so that land stays in farmings
Transportation	Vehicle miles traveled (VMT)/capita is stabilized at 2008 levels through changes in pricing, land use, and availability of alternative modes; efficiencies improve and there is some shift towards electric vehicles or use of hydrogen fuel	VMT/capita is reduced substantially (30% below 2008 levels) through stronger versions of these same means; low-carbon vehicles become the norm after a period of transition; alternative modes are strengthened	VMT/capita is reduced dramatically (60+% below 2008 levels); many alternative modes are used; zero emission vehicles (using hydrogen or electricity created from renewable sources) become universal after a period of transition

Scenario	Regional Enterprise	Global Sustainability	Precautionary Change
	A2	**B1**	**AB 32-Plus**
Electricity source	Renewable share increased from 12% now to 25%, no coal (only 1% now), continued reliance on gas, large hydro, and nuclear	Higher renewable share (50% primarily from solar, wind, and geothermal) with various storage solutions; gas still used with some C sequestration	No fossil fuels; very high percentage of renewables with various storage solutions (pumped storage, vehicle batteries, fuel cells, etc.)
Energy pricing	Increases in fossil fuel prices due to world demand outstripping supply; renewables become more cost-effective; present rate of increase in prices may be a spike rather than a long-term trend	Even greater increases in fossil fuel prices beyond A2 because of C taxes and/or price increases due to cap-and-trade systems	Large increases in fossil fuel prices beyond A2 because of incentives such as steep C taxes and/or cap-and-trade systems; renewables very cost-effective
Landfills	All landfills capped and methane burned or sequestered	All landfills capped and methane burned or sequestered	All landfills capped and methane burned or sequestered; greatest efforts to reduce inputs into landfills
Consumption	Improved recycling and reuse of products (~70%) with stabilized per capita material consumption at 2008 levels; substantially greener product mix through consumer choice and state/federal/local regulation	High recycling and reuse rates; balance shifted toward reuse; reduction in per capita consumption of material products (not services); green product mix through state/federal/local regulation	Very high recycling reuse rates; mandatory reuse of many components and packaging; deep reduction in per capita consumption of material products (not services); highly green product mix through state/federal/local regulation

*Sacramento Area Council of Governments (SACOG) Scenarios (www.sacog.org/forum2004/home.cfm)

Scenario A: Future development the same as today's (fairly low density). The scenario has an outward growth pattern, with jobs-housing imbalances in sub-areas.

Scenario B: More housing choice, some growth through re-investment, mix of land uses, "edge" cities get their most growth.

Scenario C: Slightly higher housing densities and re-investment than B, mix of land uses, "inner ring" areas get their most growth.

Scenario D: Highest housing densities and re-investment levels, mix of land uses, "core" areas get their most growth.

The storylines for the three scenarios are used in various parts of the paper, particularly when modeling has been conducted. At the end of the paper (Section 5.0), outcomes are attributed to each scenario, emphasizing the tradeoffs that may occur between production agriculture, urbanization, and the provision of a range of ecosystem services.

1.7. Climate and Climate Projections for the A2 and B1 Scenarios

Yolo County has a Mediterranean climate with warm, dry summers and cool, moist winters. Average monthly temperatures range from about 42°F to 84°F (5.6°C to 29°C) (Figure 5). The southern area of the county is generally cooler than the northern areas because cool ocean air flows from the San Francisco Bay Delta into the Sacramento Valley in the summer (USDA 1972). Precipitation mainly occurs as rainfall. Snow occasionally occurs on the Coast Range mountain ridges in the western part of the county. Average annual rainfall decreases slightly from the western toward the eastern part of the county (Water Resources Association 2007), since rain storms generally move eastward from the Pacific Coast, and higher elevations increase the condensation of water vapor as precipitation. Historic data suggests that the first part of the twentieth century was generally drier in Yolo County than the latter part (Yolo County 2007b). About 80% of precipitation in Yolo County occurs during the non-growing season, while only 20% occurs during the growing season (Yolo County 2006b). Therefore, the ability to meet water demands during the growing season is carried out by surface water deliveries and ground water pumping.

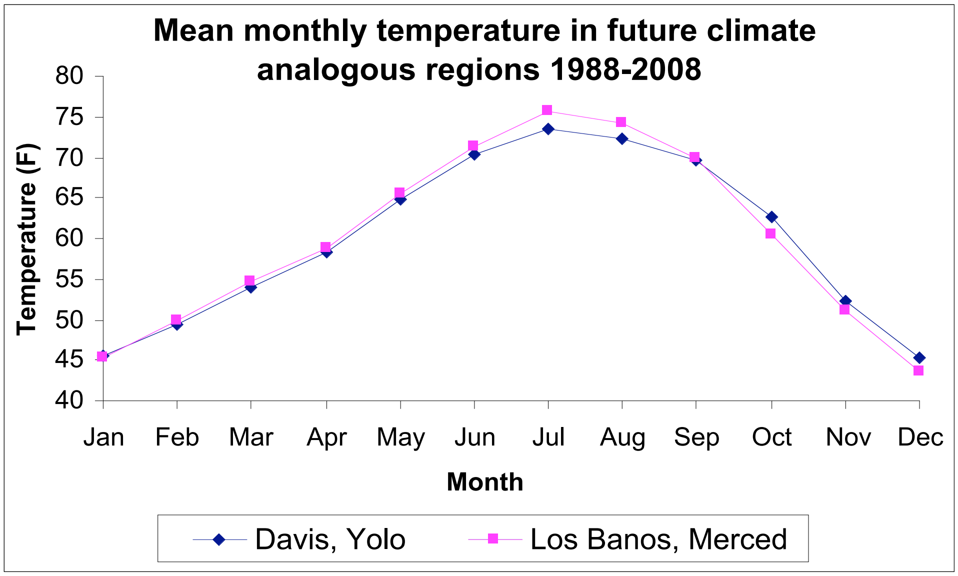


Figure 5. Daily temperature averages and extremes for Davis, Yolo County and Los Banos, Merced County. Merced County is used as an analog for projected temperatures in the mid-point period of the timeframe of this study, approx. 2030.

Source: Weather data from Davis and Los Banos California Irrigation Management Information System (CIMIS) stations.

In 30 years, CO_2 concentrations are expected to increase about 60 parts per million (ppm) (from today's 380 ppm to about 440 ppm), and temperatures will increase by about 1.2°C (2.1°F) over the contiguous United States (Hatfield et al. 2008). The western United States is already experiencing reduced snowpack and earlier peaks in spring runoff, and will likely become drier (Hayhoe et al. 2004; Hatfield et al. 2008). From 1951–2000, the growing season has increased by about a day per decade, and the area has experienced an increase of 30 to 70 growing degree days per decade, mainly occurring in the spring (Feng and Hu 2004).

Two main themes are expected in terms of projections of temperature and precipitation for Yolo County from 2010–2050 (Cayan and Tyree, pers. comm.): (1) A2 and B1 scenarios are likely quite similar, due to the long-term effects of GHG emissions (mean annual temperatures of approx. 1°C to 3°C (1.8°F to 5.4°F) (Figure 6); and (2) precipitation patterns are highly uncertain, except for the expectation of a general drying trend, which becomes more pronounced at the end of the century (Figure 7). Imposed upon global trends is the impact of the change of vegetation and irrigation in the Central Valley (Kueppers et al. 2008). Daily maximum temperatures have decreased by 3°C to 6°C (5.4°F to 10.8°F), most likely due to greater conductivity of irrigated soils Kanamaru and Kanamitsu (2008).

Closer examination of temperature projections shows that greater temperature increases are expected in summer (June, July, August, or *JJA*) than in winter (December, January, February, or *DJF*), even by 2054–2050 for the 12 square kilometer (km^2) downscaled zone around Sacramento (Figure 6). (Much data analysis is available for Sacramento by the Scripps Institution of Oceanography for the Energy Commission Scenarios Analysis program, and GCM modeling of temperature in Woodland (the Yolo County county seat) was typically <0.1°C (<0.2°F) different). Nighttime temperatures are expected to increase more than daytime temperatures (Dan Cayan, pers. comm.).

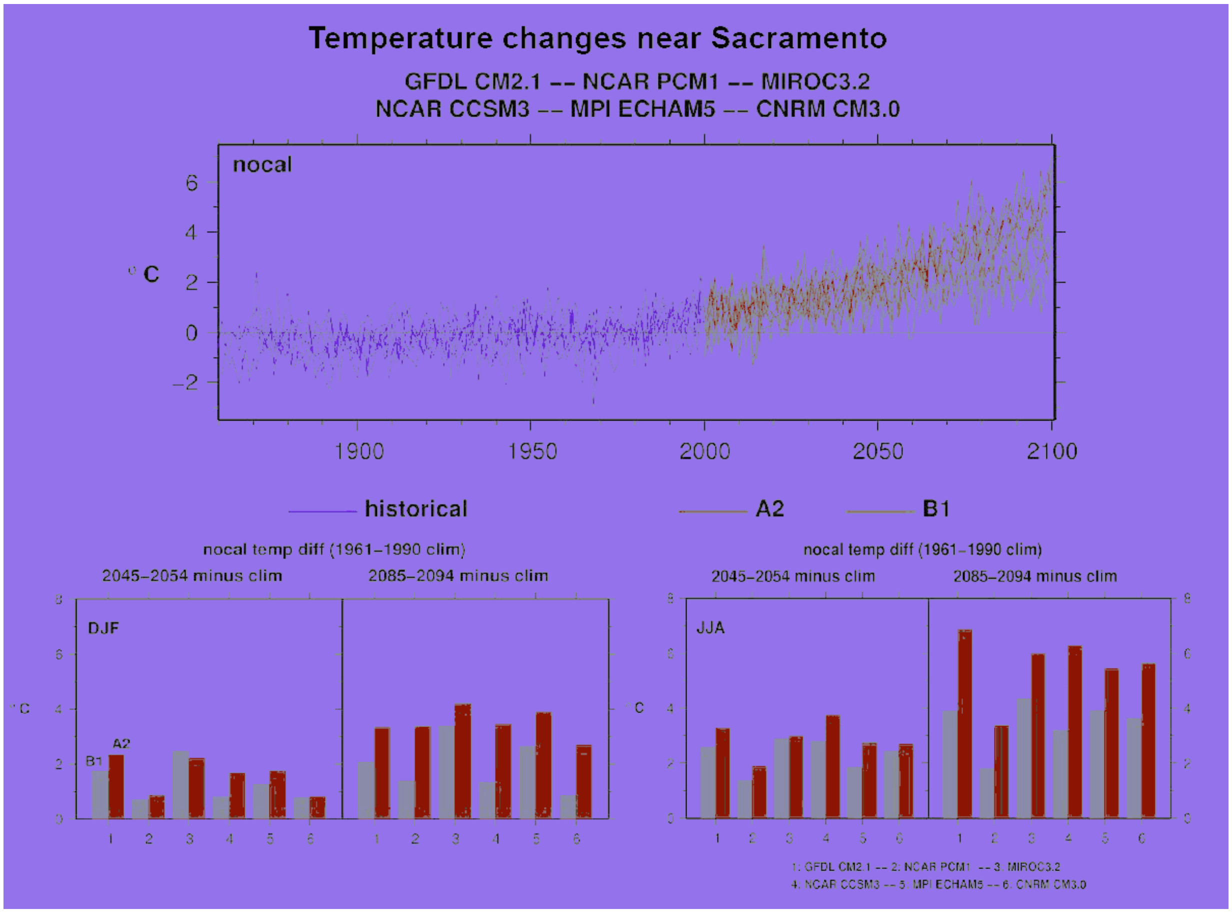


Figure 6. Projected temperature changes near Sacramento for 6 GCM models. The line chart shows mean annual changes in temperatures relative to the mean of a historical period of 1961-1990. Blue lines indicates a historical period, red lines show the projected A2 scenario and yellow lines show the projected B1 scenario until 2100. The bar charts compare June, July and August (JJA) and December, January, and February (DJF) temperature differences for 6 GCM models for two time periods (2045-2054 and 2090-2099). Note that running the same models for Woodland in Yolo County resulted

in <0.2°C (.36°F) difference in temperature compared to Sacramento, <20 miles (32 km) away.

Source: Dan Cayan and Mary Tyree, Scripps Institute of Oceanography, November, 2007.

Precipitation for Sacramento at mid-century varies widely among the six GCM models, but with no consistent difference compared to the present, nor between A2 and B1 scenarios. In contrast, precipitation decreases in both scenarios by the end of the century, as much as -25 centimeters (cm), depending on the GCM model.

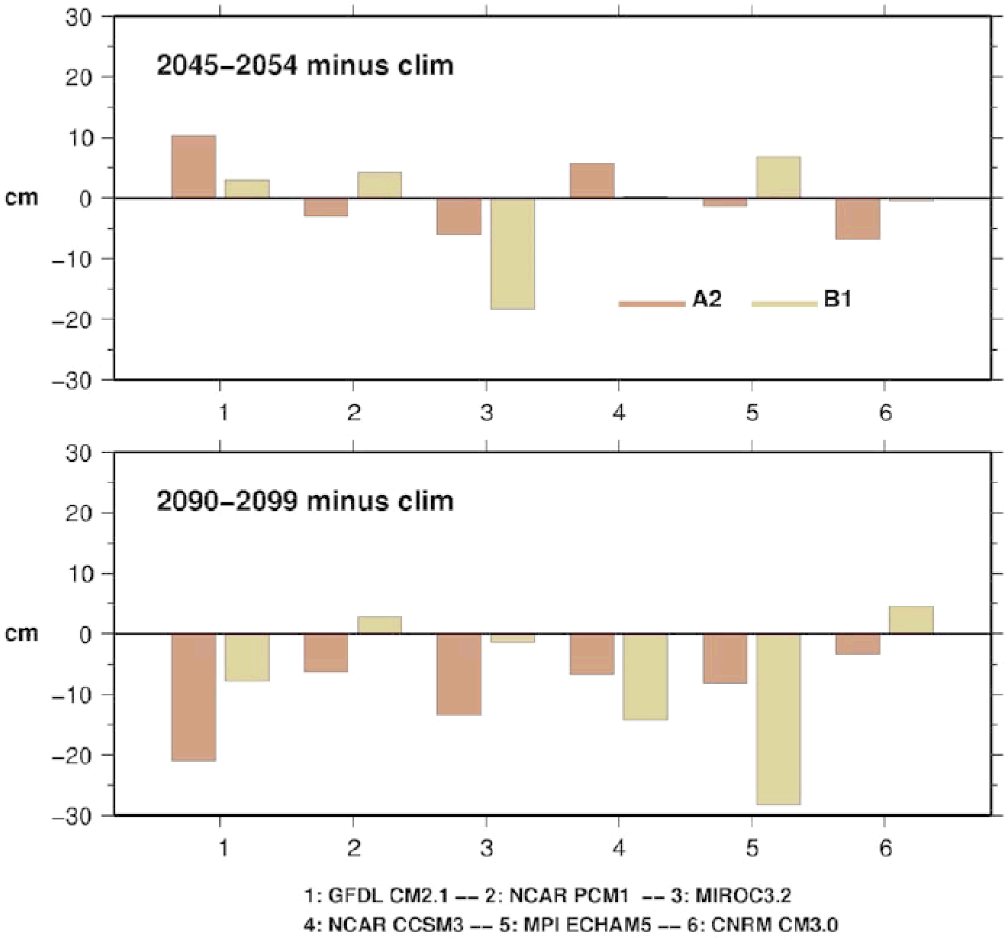


Figure 7. Projected changes in precipitation near Sacramento for six GCM models, showing the difference in mean annual precipitation compared to a historical mean (1961–1990), referred to as *clim*, for two time periods (2045–2054 and 2090–2099) for the A2 and B1 scenarios.

Source: Dan Cayan and Mary Tyree, Scripps Institute, November, 2007.

Heatwaves will occur more frequently, last longer, experience higher temperatures, and begin earlier in the summer than historically (Hayhoe et al. 2004; Miller et al. 2007). This can be illustrated by the increase in the number of days that exceed T90 threshold values (90% probability of exceeding the warmest summer days under the current climate). In nearby Sacramento, for the period 2005–2034, the A2 scenario is expected to have 16 to 24 days that exceed this value; for the B1 scenario, the exceedance is expected to be 19 to 24 days, which again shows the predicted similarity of the two scenarios in this time period. Thresholds consider that an average of 12 days per year exceed the T90 threshold during the period 1961–1990 (Miller et al. 2007). This increases to 22 to 49 and 26 to 42 days in the 2035–2064 period, respectively for A2 and B1. The projections are based on the range from downscaled HadCM3, Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1, and PCM model simulations for A2 and B1 scenarios. Cooling degree days are projected to decrease in Sacramento from a high of 690 over the 1961 to 1990 time frame, to a lower range of 270 to 360 for the A2 scenario, and to 220 to 280 in the BI scenario, in the 2035 to 2065 time frame.

2.0 Agricultural Commodities: How Productivity, Management, and Market Opportunities Influence Mitigation and Adaptation to Climate Change

2.1. Crop Responses to Climate Change: A Generalized Overview

Crop productivity will increase with temperature in more northern latitudes of the United States, but will decrease with increased temperatures in some of the southern regions of the country, based on the recent report of the Climate Change Science Program (CCSP) Synthesis and Assessment Product (SAP) (Hatfield et al. 2008). While the responses of California specific crops to predicted regional changes remains largely unknown, anticipated climate changes will likely have both positive and negative effects on the yield and quality of currently produced commodities (Cavagnaro et al. 2006). For example, increased temperatures may adversely affect yields of tomato (Sato et al. 2000), rice (Ziska et al. 1997; Moya et al. 1998), stone fruits (deJong 2005), and grapes (Hayhoe et al. 2004), but allow for more crops of lettuce outside of the coastal regions (Wheeler et al. 1993) and expansion of citrus production (Reilly and Graham 2001), as well as heat and drought-tolerant trees, such as olives. Concurrent increases in CO_2 levels may also have positive or negative influences on yield and quality depending on the crop. For example, elevated CO_2 decreases protein contents of cereals which lowers product quality (Pleijel et al. 2000; Kimball et al. 2001), while strawberries become more flavorful (Wang and Bunce 2004).

Major physiological impacts of these anticipated temperature changes include diminished yields from increased temperatures during key stages of crop development (Sato et al. 2000; West 2003; Peng et al. 2004), shorter periods of crop development (Wheeler et al. 1993; Moya et al. 1998; deJong 2005), reduced product quality from unseasonal precipitation or adverse temperatures during fruit development (Southwick and Uyemoto 1999), and shifts in growing regions suitable for specialty crops (Reilly and Graham 2001).

Horticultural crops are more sensitive to short-term environmental stresses that affect reproductive biology, water content, visual appearance, and flavor quality, compared to field crops, and are thus likely to be more impacted by climate change and extreme events. For crops such as stone fruits and grapes, water stress, temperature, and the timing of precipitation can be extremely important for yields and maximizing fruit quality (Bazzaz and Sombroek 1996). Phenological, i.e., life cycle, phases are affected by temperature, and can be adversely affected in specific ways, e.g., tomato pollen release and pollen germination are severely reduced at temperatures of 96.8°F/ 78.8°F (36°C/26°C) (day/night) (Sato et al. 2000), resulting in a loss of 90% of fruit production, compared to 82.4°F/ 71.6°F (28°C /22°C) (Peet et al. 1998). The survival, productivity and quality of perennial fruit and nut crops is very sensitive to winter temperatures, due to fruit physiological requirements for chilling, as well as to water shortages (USDA 2002).

Turning from temperature to the sole effects of elevated CO_2, crops are likely to increase biomass production by roughly 10%–20% under field conditions, based on reviews of the literature (Bloom 2006; Long et al. 2006). Although larger increases often occur in greenhouse and environmental chamber studies, FACE (Free-Air CO_2 Enrichment) plot studies, which more closely simulate field conditions, and also have well-mixed CO_2 concentrations show lower values. One explanation for the lower response is CO_2 acclimation, whereby plants exposed to elevated CO_2 for longer periods of time are unable to consume all the carbohydrates that they generate. Carbohydrates accumulate, downregulating photosynthetic activity and growth (Ainsworth and Rogers 2007).

Genetic constraints, high temperature limitations, nitrogen limitations, and development changes all play a role in the complex response of crops to elevated CO_2. Some of these complexities are summarized by Hatfield et al. (2008) in the CSSP-SAP report. For example, vegetative growth usually has higher temperature optima than reproductive development processes. Also, while vegetative growth increases up to an optimum temperature, the response is not linear, and will vary, for example, with water supply depending on the crop. Higher temperatures and higher CO_2 do not act synergistically. Despite the known beneficial effects of higher CO_2 on crop growth, there are no reported increases in grain yield caused by the combined effects of higher CO_2 and temperature (Hatfield et al. 2008). In fact, yields of C_3 plants can decrease when both CO_2 concentrations and canopy temperatures increase, due to the lower stomatal conductance of water vapor that results in less transpirational cooling (Prasad et al. 2002; Prasad et al. 2006).

For horticultural crops, there is a general lack of simulation models for use in climate change assessments, compared to the major grain and oilseed crops (Hatfield et al. 2008). An exception is tomato, which is used in the DAYCENT modeling in this project (see Section 2.4). Also, little information exists on response of horticultural crops to CO_2. Even for field crops, with more information available, responses to climate change are inherently difficult to model to the reasons explained above.

For a given crop taxa, evapotranspiration (ET) and water use is not likely to increase during the next 30 years, according to the integrated conclusions formed from several meta-analysis and review papers summarized in the CSSP-SAP report (Hatfield et al. 2008). An increase in CO_2 concentration from 380 to 440 ppm will probably cause reductions in stomatal conductance of approximately 10% compared to today. During the next 30 years, expected increases in ET due to higher temperature and decreases in stomatal conductance will likely balance out, resulting in insignificant changes in ET. If the growing seasons of certain crops shorten, however, it is possible that some crops, e.g., horticultural crops harvested in the vegetative phase such as lettuce and spinach, or determinate crops such modern tomato varieties, then ET per crop may decrease slightly. Of course, choosing alternative crop mixes and rotations will affect ET due to different inherent water use patterns.

For non-irrigated rangelands that are limited by cool temperatures in winter and spring, higher temperature and CO_2 enrichment could potentially stimulate productivity on winter/spring rangelands, but this depends on precipitation and soil water availability. The impact on livestock is difficult to predict, as concomitant summer temperatures, e.g., above 35°C (95°F) cause physiological stress and low consumption of feed (Conrad 1985). Dairy cows with high body temperatures also have lower milk yield (West 2003).

Agricultural weeds, pests, and diseases will be impacted by climate change in uncertain ways within California (Field et al. 1999; Wilkinson 2002; Hayhoe et al. 2004) and globally (Scherm 2000; IPCC 2001). For insect ecology, epidemiology, and distribution, temperature is the single most important factor, while plant pathogens will be highly responsive to humidity and rainfall, as well as temperature (Coakley et al. 1999). Predicting these changes requires better understanding of ecophysiology, and the complexity of the multi-trophic and multi-factor interactions in which they are involved.

2.2. Current Status of Agricultural Commodities in Yolo County

Current crop and livestock production. Yolo County had 1,060 farms in 2002, averaging 519 acres (210 hectares), with about 12% of the farms >1,000 acres (>400 hectares) (USDA-NASS 2002). (The 2007 census is currently underway and will be released in 2009). Total agricultural revenues in Yolo County in 2006 were $370.2 million. Agricultural revenues have generally increased each year, except due to losses from natural disasters, such as the 17% decrease from 1997–1998 from the adverse, late spring rainfall El Niño weather (USDA-NASS 1999–2006).

Yolo County ranks in the mid-range of gross agricultural sales of California's 58 counties; in 2005 it ranked twenty-fourth (USDA-NASS 1999–2006). Some southern and central Californian agricultural counties have higher gross agricultural production than the counties in the Sacramento region, due to their larger size, and a higher proportion of high cash value specialty crops.

Processing tomatoes became the most important crop both revenue and acreage grown in Yolo County (Table 3), after a mechanical tomato harvester became commercially available in 1962 (Thompson and Blank 2000). Tomato processing nearly doubled between 1963 and 2000 (Yolo County 2002), and processing tomatoes remain the leading commodity despite a sharp decline after closure of two large canneries in the county in 2000, with a slight increase upon re-opening of a plant in 2002 (USDA-NASS 1999–2006). Rice and alfalfa hay have been among the top 10 commodities for the last 10 years, with slight value shifts from year-to-year depending on acreages and prices. Rice in Yolo County is generally grown on poor soils, e.g., high clay content, unfavorable for other crops (Kuminoff et al. 2000). In 2003, the value of almonds has increased nearly 80%, replacing tomato and field crops (Lamb 2007). Wine grape revenues have risen from $6.2 million in 1994 to $38 million in 2006 (Yolo County Department of Agriculture 1998–2006, Yolo County 2002). Yolo County produced 8% of California's total value for melons in 2005 (USDA-NASS 1999–2006).

Cattle and calves are among the top 10 most valuable commodities in Yolo County (Table 3). Livestock production encompasses nearly 30% of the total agricultural acreage, mainly located in the western non-irrigated grasslands the foothills of the Coast Range. Lambs, poultry, hogs, slaughter sheep, milk products, eggs, wool, honey, pollination, package bees, queens, colonies, and wax are all other animal products produced in the county, but play a much smaller role than cattle/calf operations.

Historically, wheat was the most important crop in Yolo County in the early twentieth century. By 1942, over half of the agricultural acreage was small grains, alfalfa, sugar beets, and corn, and <15% of the acreage was producing asparagus, processing tomatoes, almonds, and apricots. Vegetables, fruits and nuts have gradually become more important as both water supplies and markets have developed (Thompson 1902; Sumner and Howitt 1997).

Current projections for agricultural production. Without considering climate change, future crop patterns in Yolo County are expected to continue to increase agricultural revenues, by replacing lower value crops, such as alfalfa and processing tomatoes, with higher value commodities and products (Yolo County 2002). Prices for canning tomatoes declined until 2007 and if that trend is reestablished alternative crops are likely (Water Resources Association of Yolo County 2007). Concerns for the scarcity of water resource in the San Joaquin Valley, another important tomato-producing area in California, are speculated to continue to indirectly support the tomato industry in Yolo County, where water resources are more abundant (Water Resources Association of Yolo County 2007). In contrast, crops with very high water consumption, such as alfalfa, rice, and corn are likely to become less prevalent if water availability declines, and would be likely to be replaced with higher cash value crops per unit of water such as vegetables, fruits and nuts (Yolo County 2002, Water Resources Association of Yolo County 2007). Typically, high value/specialty crops, including processing tomatoes, are require more infrastructure and technology for processing than agronomic crops.

Organic crop acreage and income increased by 94 and 67%, respectively, between 1996 and 2000 (Yolo County 2002), and although organic acreage decreased by 20% between 2000 and 2005, income still increased by 89% (Klonsky and Richter 2007). It is also one of the leading heirloom tomato growing regions in California (Downing 2007), which although small in economic value at present, could indicate future directions to increase diversification.

Table 3. Yolo County's top 10 crop commodities (value and rank) 1998–2006. Processing tomatoes remain the leading commodity over the last decade. Rice and alfalfa hay remain among the top 5 commodities, with slight value shifts from year-to-year.

	Million $ (rank of crop per year)								
Commodity	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Processing tomatoes	87.9 (1)	132.7 (1)	76.5 (1)	68.8 (1)	74.1 (1)	61.2 (1)	86.1 (1)	68.3 (1)	77.1 (1)
Hay, alfalfa	24.4 (3)	23.8 (5)	21.4 (4)	31.8 (3)	32.8 (3)	31.1 (4)	36.8 (3)	36.2 (3)	39.4 (2)
Grapes, wine	46.8 (2)	35.4 (2)	40.9 (2)	33.2 (2)	44.7 (2)	37.4 (3)	33.3 (4)	42.0 (2)	38.0 (3)
Almonds	7.4 (8)	–	–	–	–	12.2 (8)	19.3 (6)	31.0 (4)	28.8 (4)
Seed crops (all)	20.6 (4)	26.6 (3)	20.0 (5)	17.1 (5)	15.0 (5)	17.9 (5)	21.3 (5)	21.4 (7)	28.8 (5)
Rice	11.7 (5)	24.3 (4)	34.6 (3)	28.3 (4)	27.7 (4)	39.9 (2)	40.8 (2)	28.2 (5)	23.9 (6)
Walnuts (all)	7.6 (7)	9.7 (7)	9.9 (8)	12.6 (6)	11.5 (6)	12.3 (7)	11.4 (9)	21.7 (6)	18.5 (7)
Organic crops	–	–	–	8.3 (9)	9.1 (7)	10.6 (9)	13.7 (7)	13.9 (8)	14.5 (8)
Cattle and calves	7.4 (9)	–	10.0 (7)	9.5 (8)	7.7 (9)	10.19 (10)	10.6 (10)	12.4 (9)	11.6 (9)
Apiary, livestock and poultry	–	–	–	–	–	–	–	–	9.1 (10)
Wheat	7.1 (10)	7.4 (9)	8.4 (9)	9.6 (7)	8.5 (8)	16.4 (6)	12.9 (8)	7.7 (10)	–
Safflower	–	9.9 (6)	–	–	6.7 (10)	–	–	–	–
Field corn	8.6 (6)	–	13.7 (6)	7.6 (10)	–	–	–	–	–
Honeydew melons	–	9.3 (8)	7.5 (10)	–	–	–	–	–	–
Prunes, dried	–	7.1 (10)	–	–	–	–	–	–	–
– = not ranked that year in the top 10 highest crop values.									

Source: Yolo County Agricultural Crop Reports.

2.3. Vulnerabilities of Agricultural Commodity Production to Climate Change

The recently released CSSP-SAP report on climate change for U.S. agriculture indicates several vulnerabilities of specific crops to climate change (Hatfield et al. 2008). As described above, with increased CO_2 and temperature, the life cycles of grain and oilseed crops are very likely to progress more rapidly, but only small yield increases are expected, with the highest vulnerabilities due to heat waves during flowering, and to negative effects on growth due to higher canopy temperatures. If precipitation decreases, then yields would suffer more failures due to climate variability and less precipitation. Yields of many horticultural crops are very likely to be more sensitive to climate change than grain and oilseed crops.

Many of Yolo County's row crops are warm-season horticultural crops (e.g., tomato, cucumber, sweet corn, and pepper) with a temperature optimum of 68°F to 77°F (20°C to 25°C) for yield, and an acceptable range of 53.6°F to 86°F (12°C to 30°C), with a maximum tolerance of 95°F (35°C) (Hatfield et al. 2008). Mean mid-summer maximum temperatures already slightly exceed this threshold (Figure 5), suggesting that 2°C to 3°C (3.6°F to 5.4°F) increase by mid-century may force a shift to hot-season crops such as melon and sweet potato, which have a higher acceptable temperature ranges (18°C to 35°C, or 64°F to 95°F). Warmer winter temperatures, however, would favor cool-season crops, such as lettuce and broccoli, that are now grown in winter/early spring further south, and which have an acceptable range of 5°C to 25°C (41°F to 77°F).

For field crops such as corn and rice, temperature maxima >25°C and 35°C (>41°F and 95°F), respectively, decrease pollen viability and pollen production, reducing yields (Hatfield et al. 2008). For corn, kernel development is reduced at temperatures >30°C (86°F). Corn, as a C4 plant, thus will benefit less from elevated CO_2 concentrations compared to other grains, but is less vulnerable to heatwaves during the reproductive phase than grains such as wheat, barley and rice.

For perennial crops, Lobell et al. (2006) found that climate change in California will likely decrease the yields of almonds, walnuts, avocados, and table grapes by 2050, using statistical models developed from 1980–2003 records of statewide yield and monthly average temperatures (minimum and maximum) and rainfall variations. Projected losses range from 0 to >40% depending on the crop and the climate change scenario, but these results do not consider CO2 fertilization or adaptation measures, and therefore are not likely to occur (see below).

Although increased CO_2 and temperatures may balance ET at current rates for irrigated crops, water storage in California's snowpack is predicted to decrease, which will alter the amount and timing of water available to agriculture for irrigation, although this may be less pronounced in Yolo County as compared to counties further south. As a result, California will need to cope more effectively with the constraints of its Mediterranean-type climate than it has done in the past.

Fruit trees require 200 to 1200 hours of winter chill to flower (Hatfield et al. 2008). Chill hours are computed on a daily basis relative to a reference temperature. In Contra Costa County, a significant decrease in accumulated chill degree hours occurred between 1986 to 2005 (Baldocchi and Wong 2006). Using climate predictions for the Central Valley using GCM data, winter chill hours will decrease from a baseline of 1000 hours, as observed in 1950, to about 500 hours by 2100. With both A2 and B1 climate scenarios, the local winter climate will approach the critical thresholds for yield for many fruit tree species by the end of the century.

Ozone (O_3) is a particular concern for crop yields. It is estimated that more fuel combustion worldwide will increase the global average ozone up 50% by 2100 (Reilly et al. 2007). Crops are particularly sensitive to ozone damage. Ozone enters plants through stomata and disrupts biochemical functioning, leading to decreased productivity, lowered fertility, and accelerated senescence (Mauzerall and Wang 2001), all of which already cause significant economic losses within California croplands (Murphy et al. 1999). Increased GHG concentrations, such as CO_2 and CH_4, could accelerate O_3 formation through radiative forcing, and the ratio of nitrogen oxides (NOx) to volatile organic compounds (VOCs), which is important in determining O_3 precursors. The ozone yield is a complex function of this ratio, the concentrations of different VOC constituents, temperature, sunlight, and other factors.

In upland grasslands, elevated CO_2 decreased grassland productivity in field studies that also increased temperature, precipitation and soil nitrate (NO_3-) compared to current ambient levels (Shaw et al. 2002). One concern is that soil nitrogen (N) availability in grasslands will actually decrease, due to deposition of plant residues with lower nutrient content (de Graaff et al. 2006), as well as greater demand for N under elevated CO_2 (Hatfield et al. 2008), and lower capacity for nitrate (NO_3-) assimilation (Rachmilevitch et al. 2004). Several long-term Free Air CO_2 Enrichment (FACE) experiments in grasslands with and without N additions have shown a declining stimulation of plant biomass production with time when no N was added (Schneider et al. 2004; Dukes et al. 2005; Reich et al. 2006), suggesting that over the long-term, growth stimulation by higher levels of CO_2 cannot be sustained without N additions. This will require management alternatives to limit the production of the GHG, N_2O, and also to avoid higher input costs.

Alternatively, N-fixing legumes may become more abundant in annual grasslands, partly due to warmer winter temperatures, contributing more N supply to these ecosystems. Overall, current evidence suggests that livestock forage may decrease, especially in dry years, leading to lower livestock stocking rates, and shifts in animal removal dates may occur earlier as a result of climate change. Higher temperatures are likely to cause more difficulty for livestock during hotter summers, especially for animals left on rangelands, compared to those transported to permanent pasture in the lowland valleys.

Climate change is likely to lead to a northern migration of weeds, and disease and pest pressure will increase with earlier spring arrival and warmer winters, allowing greater proliferation and survival of pathogens and parasites. Higher temperatures will very likely reduce livestock production and dairy production during the summer season. Dairy cows with elevated body temperatures produce less milk (West 2003).

Historical weather vulnerabilities in Yolo County. To determine the feasibility of using weather records as past indicators of vulnerability to heatwaves and freezing periods in Yolo County, the countywide yields of a representative crop, processing tomato, were related to extreme weather events. Tomato was chosen because it is planted in several of the county’s growing regions and has consistently been one of the most important crops in the county. Also, California is the major producer of processing tomatoes in the United States, with over 93% of total production, and an average area of about 277, 000 acres (112,100 hectares) per year (USDA 2006), so this analysis pertains to a larger statewide context.

Any changes in production due to weather may be confounded by the trends in planted acreage and in price per ton of tomatoes. In the 1990s tomato production peaked in Yolo County, but in the 2000s, it suffered a drop in production and acreage (Figure 8). The long-term trend is a decrease in total acreage during the last 25 years, with an increase in total acres and $ value of production. This inverse effect between total production and acreage can be attributed to increases in the efficiency of tomato production (Thompson and Blank 2000). The high tomato acreage in the 1990s has subsequently been converted to a variety of other crops.

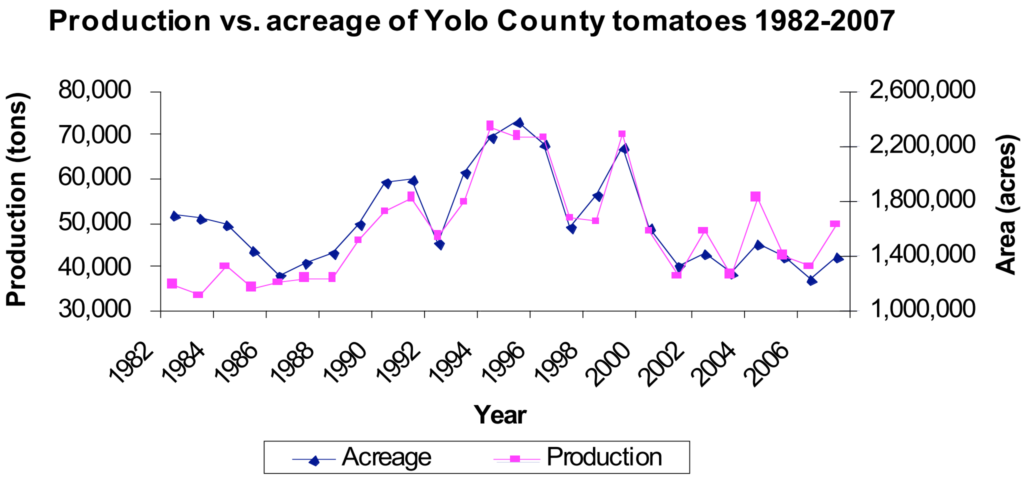


Figure 8. Yolo County tomato production and acreage, 1982-2007. The long-term trend displays that while total acreage decreased during the last 25 years, total production has increased. This inverse effect between total production and acreage can be attributed to increases in the efficiency of tomato production.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos and Joel Kramer, UC Davis.

Another way to evaluate the efficiency of tomato production over time is to compare the market price to harvested tons per acre or productivity through time. While productivity experiences a strong and steady positive trend, the price trend is relatively flat (Figure 9). Higher production in the previous year triggers lower prices the next year (Western Farm Press, Feb 2006). A more detailed economic analysis than is possible here would be required to determine how much of the price variation in the tomato industry can be attributed to local environmental conditions versus global market conditions.

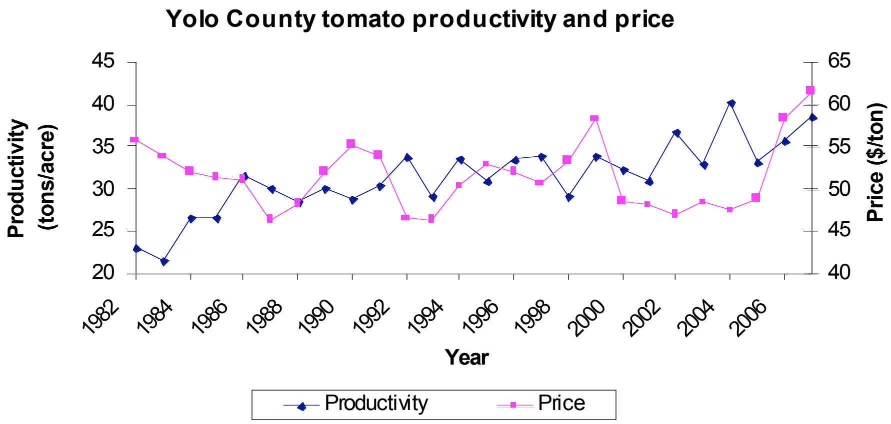


Figure 9. Yolo County tomato productivity (tons/acre) and price, 1982–2007. While productivity shows a strong and steady positive trend, the price trend is relatively flat. The increases in productivity can be attributed to technological improvements.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos and Joel Kramer, UC Davis.

If climate events, however, affect productivity, the total countywide production may decrease. For example, tomatoes are susceptible to late frosts or heat waves that last for several days. By reviewing the daily temperature record for the last 25 years, we identified extreme temperature events that may have had an effect on tomato yield. Heat waves were defined for this purpose as >39°C (>102°F) that were sustained for three days. This high value was chosen to exaggerate any potential effect on tomato yields. This temperature was based on the tolerance levels for tomato fruit maturation outlined by the UC Davis Vegetable Research and Information Center. For late frosts we identified years in which the temperature dropped below 0°C (32°F) for at least one day during the months of March to May (Table 4).

Table 4. Estimated tomato exposure to extreme weather events (1982–2007). For heat waves we focused on those above 39°C (102°F) that were sustained for three days, or more in order to exaggerate their potential effect on tomato yields. For late frosts we identified years in which the temperature had dropped below 0°C (32°F) during the months of March to May.

	Late Frost Occurrence	**Sustained Heat Waves** (3 days or more)
Months Analyzed	March–May	June–Sept
Temperature Range	0 and below	>39
Dates	1987	1983, 7/11–13
	1989	1988, 7/17–19
	1990	1990, 7/10–13
	1998	1990, 8/6–10
	1999	1991, 7/2–7/4
	2001	1996, 8/10–8/13

	2002 2006	1997, 8/5–8/7 2006, 7/20–25

Source: Weather data from California Irrigation Management Information System (CIMIS), Davis station.

Figure 10 illustrates years in which environmental and market forces may have combined to cause changes in the value of tomato production in Yolo County. For example, 1990 was a growing season with both a frost and multiple heat waves lasting four days and five days. The combination of frost and heat probably caused the decrease in the tomato yields during the 1990 growing season. The decrease in yields from the frost and heat may have played a role in the increased tomato production during 1991 and 1992.

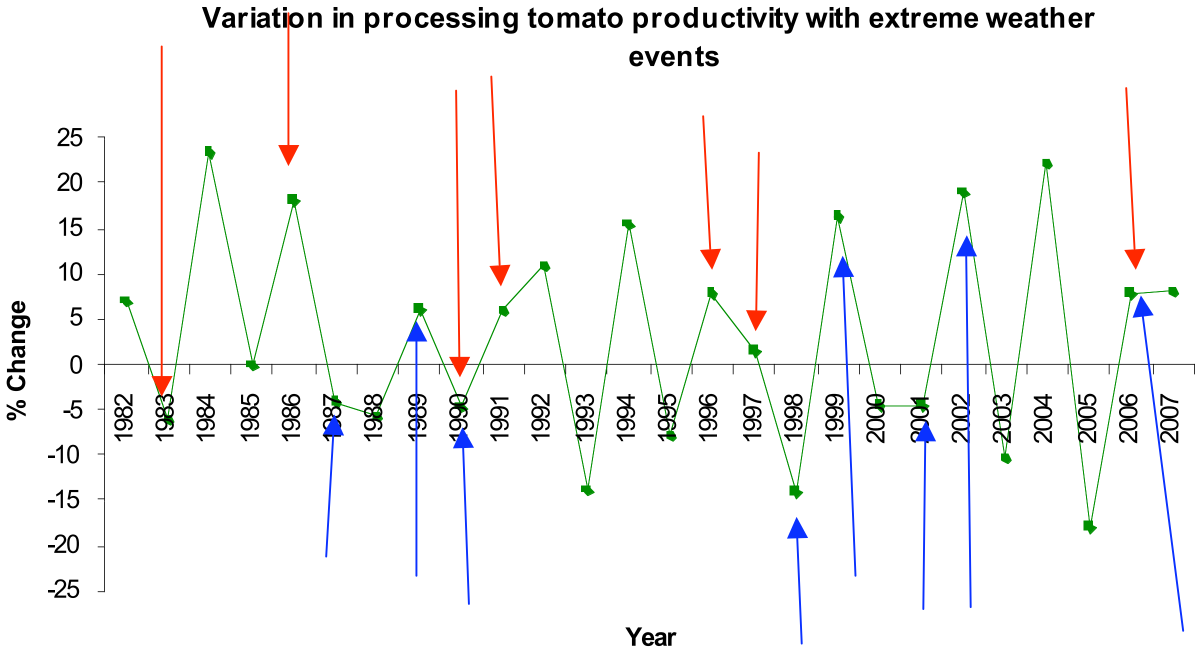


Figure 10. Annual % change in tomato productivity (tons/acre) in Yolo County, based on comparison to the preceding year. For definition of late frosts (blue from below) and sustained heat waves (red from above) depicted as arrows, 1982–2006, see Table 3. Years in which environmental and market forces may have combined to cause changes in the value of tomato production in Yolo County.

Source: Weather data from CIMIS, Davis station. Figure created by Fernando Santos and Joel Kramer, UC Davis.

A detailed economic analysis could provide important insight into the role that environmental changes have in determining the increase in tomato production. The year 1990 is unique because it underwent two environmental impacts. Most years with only one event of shorter duration did not result in a significant impact on yield. For example, in 1986, 1999, and 2002, despite late frosts or heat waves, productivity improved dramatically, compared to the previous year. Other environmental factors such as pest and diseases which were not analyzed as part of this study, and these could be important factors in explaining this variation. However, it is important to emphasize that larger-scale market forces have a much greater and more immediate effect than weather effects on determining the overall quantity of tomatoes produced. Even so, Yolo County has consistently demonstrated the ability to adapt to such harsh economic transitions on the crop market.

The increases in productivity in terms of tons of tomatoes per acre can be attributed to technological improvements (Thompson and Blank 2000). The technology used to increase production on fewer acres has been developed slowly over time and producers have adopted the technology to fit their specific needs. Climate change will require new technological advances in productivity, e.g., less susceptibility of pollen viability to heatwaves, and even so, weather variability may decrease yields. For example, tomato production is based on contracts that include rigid schedules for specific tonnages of tomatoes to be delivered to canneries. Some of the biggest unknowns about climate change are precipitation patterns, but if a longer rainy season extends into May and June, tomato producers will not be able to plant in time to achieve their delivery date because the fields will be too wet. If fall rains start earlier during the harvest season, then yields would decrease through increased proportions of mold, and this would further complicate growers' abilities to physically harvest the crop. On the other hand, frosts would be expected to decrease in early spring, possibly allowing an earlier planting date, at least in dry years.

Thus, technology advances for tomato production can be thought of as a form of insurance that helps guarantee profitability to producers. Examples are selection for disease resistance or pollen viability at high temperatures, or higher productivity per amount of water applied (Hanson and May 2006). Climate change could nullify the benefits of certain technologies (e.g., current varieties that have been selected to be highly determinate may no longer be as predictably high-yielding as indeterminate varieties). Alternately, the high rate of environmental change may make it difficult for research advances to maintain their historical upward trend of increasing productivity.

Yolo County crop water needs. Farmers rely on groundwater for almost 40% of their supply in a normal water supply year, and this is expected to increase under possible future drought and population growth conditions (Yolo County 2007a). The California Department of Water Resources (2007) has been collecting and computing irrigated crop area and crop water use data for Yolo County since 1998, including crop ET, effective rainfall, amount of applied water, and the consumed fraction (California Department of Water Resources 2007). Rice, pasture, and hay have the highest applied water, and ET of applied water, and are therefore the most vulnerable to water shortages (Table 5).

Water supply is probably the most uncertain effect of climate change for California agriculture. Both groundwater overdraft and water transfers contribute to uncertainty in the quantity and sometimes the quality of irrigation water for agriculture (California Department of Water Resources 2006). Intermittent periods of dry years may not permit an easy rebound for irrigated crops, especially if groundwater is not available and affordable. Perennial crops are particularly vulnerable, but even growers of annual crops are also vulnerable, and may need to shift crops or set aside land. The prognosis of a drier Western United States (Barnett et al. 2008) suggests high vulnerability for crops that are abundant water users, especially if their cash value is low.

Table 5. Yolo County 2003 crop water use (sorted highest to lowest by water applied). Rice, pasture, and hay have the highest water requirements and are therefore the most vulnerable to potential water shortages.

Commodity	**Irrigated crop area (1,000s of acres)**	**Applied water (acre ft/acre)**	**Evapotranspiration (acre ft/acre)**	**Evapotranspiration of applied water (acre ft/acre)**	**Effective precipitation (acre ft/acre)**	**Consumed fraction***
Rice	37.1	5.47	3.25	3.06	0.19	0.56
Pasture	6.9	5.40	4.20	3.46	0.75	0.64
Hay, alfalfa	52.8	4.97	4.33	3038 (sic)	0.95	0.68
Almonds/pistachios	9.1	3.9	3.39	2.69	0.7	0.69
Other deciduous	15.3	3.82	3.47	2.67	0.80	0.70
Onions & garlic	0.2	3.70	3.20	2.55	0.65	0.69
Subtropical crops	0.3	3.37	3.13	2.30	0.83	0.68
Processing tomatoes	38.2	2.79	2.4	1.92	0.48	0.69
Fresh tomatoes	3.8	2.61	2.20	1.80	0.40	0.69
Other field crops	14.3	2.41	2.00	1.64	0.37	0.68
Dry beans	2.4	2.32	1.88	1.58	0.30	0.68
Other truck crops	2.2	2.03	1.97	1.37	0.60	0.67
Cucurbits	5.2	1.69	1.34	1.14	0.20	0.67
Grapes, wine	13.6	1.26	1.61	1.01	0.6	0.8
Grain	57.8	0.86	1.46	0.57	0.89	0.67
Safflower	23.6	0.81	1.22	0.63	0.59	0.78

*Consumed fraction is a decimal representation of the proportion of applied water that is used to meet crop evapotranspiration over the growing season.

Source: Dept of Water Resources (DWR), Planning and local assistance, online annual land and water use data by county.

Insect pests and disease. Pest and disease problems are difficult to project, and agriculture impact assessments often do not account for potential yield losses due to changes in pest dynamics and density under climate change (Scherm 2004).

Even a 2°C (3.6°F) temperature rise can result in 1–5 additional generations/ yr for a range of invertebrates such as insects, mites and nematodes (Yamamura and Kiritani 1998). Many insect species will expand their geographical range in a warmer climate (Pollard et al. 1995; Hill et al. 1999; Parmesan and Yohe 2003).

Pierce's Disease on grapes has caused severe damage in southern California on grapevines, and is likely to become more prevalent northwards as the temperature warms, unless new solutions are found (Wine Institute 2002). Pierce's Disease is a bacterial disease of California grapes, caused by *Xyllela fastidiosa*, and vectored by the glassy-winged sharpshooter, a native to the southeastern U.S. that is more mobile than leafhoppers already present, and is limited to climates with mild winters such as southern California (Purcell and Hopkins 1996). Under climate change, these northern and central California may face vulnerability to significant loss.

Some of the possible effects of higher temperature that were identified in discussions with the Yolo County UC Cooperative Extension farm advisors were: stripe rust on wheat (especially under wetter conditions), insect pests on nuts, medfly, corn earworm on tomato, and earlier activity of perennial weeds such as bindweed.

2.4. Commodity Production: Agrobiodiversity as a Source of Innovation for Responding to Climate Change

Agrobiodiversity refers to the variety of living organisms that contribute to agriculture in the broadest sense, e.g., crop and animal breeds, species that interact with these species such as pollinators and pests (FAO 2007; Jackson et al. 2007). Not only croplands and pastures, but also habitats outside of farming systems are included, since they affect agroecosystems in an agricultural landscape, e.g., through effects on pollinators, predators of insect pests, and provision of water quality. In the context of commodity responses to climate change, agrobiodiversity mainly refers here to how crop species and genotypes, and their mixtures, can be used in adaptation strategies.

Additional crops or varieties will become more prevalent in Yolo County by mid-century. The western part of Merced County provides an analogy to the summer climate that Yolo County will face in the coming years; the mean temperature in Merced County is 2°F (1.1°C) warmer (Figure 5). The winter climate, however, is 2°F (1.1°C) cooler. The topography and soils are generally similar (U.S. Department of Agriculture-Natural Resources Conservation Service-Soil Survey Geographic [USDA-NRCS-SSURGO]), and the approximate zonation of crops can be imposed in Yolo County to show possible changes. Overall, a definitive analogous region that matches Yolo County in the future will be nearly impossible to find.

Perennial crops. Using statistical models of yields and temperature across California, perennial crops (wine grapes, almonds, table grapes, oranges, walnuts, and avocados) were found to have an optimum temperature above and below which yields decline (Lobell et al. 2006). The optimal temperature for yield of a specific crop was approximately equal to the average temperature value from 1980–2003 across statewide locations for each crop, indicating that the current varieties are well-suited to the current California climate where they are grown. As described above (see Section 2.3), projections by Lobell et al. (2006) found that climate change in California will likely decrease the yields of almonds and walnuts by 2050. In recent simulations, however, using county rather than statewide data, almonds were found to be relatively insensitive to temperature increases (Lobell and Field 2008).

Any predictions for crop yields, however, must consider potential adaptation, which is likely to partially override such declines, even for perennial crops, at least for an initial period before crops exceed typical tolerance limits. For all of the perennial crops above, except avocados, there is a positive yield trend period in California, ranging from 9% to 57% over the past 24 years (Lobell et al. 2006). Technological advances and/or higher atmospheric CO_2 concentrations, have the potential to maintain or increase yields based on current trends as long as there is support for developing adaptive technologies (Brunke et al. 2004).

In Yolo County, some tree crops may become more prevalent as the climate warms, due to less damage from winter freezes. Almonds, for example, are especially sensitive to frost due to their early bloom periods from mid-February through March (Reil 2001), and would be expected to increase. Boron toxicity, derived from water emanating from the Coast Range, deters tree production in Yolo County. For almonds, however, peach-almond rootstocks help to overcome the toxicity problem. Like almonds, citrus and walnuts in Yolo County are now affected by winter freezes. In a severe freeze in January, 2007, citrus growers in Yolo County experienced a loss of approximately 60% of the year's crop (Yolo County Board of Supervisors 2007). In walnuts, damage can occur as high as 28°F, if trees are very dry, and management must currently harden off trees early in the fall to prevent winter kill (Reil 2002).

Tree crops require a minimum number of winter chill hours for flowering and fruit production. For Davis, winter chill hours in mid-century (2040–2060) will average approximately 2000 chilling degree hours <45°F between November 1 and February 29, based on projections from GCM models conducted by Baldocchi and Wong (2006). This average exceeds the requirements for almond (400–700 hours) and walnut (400–1500 hours), and most stonefruit (300–1700 hours). But the modeled range of values during this time frame indicate that there will be at least a few years with inadequate chilling for these crops.

Because orchards and vineyards remain productive for 25 to 30 years, it is likely that current varieties will become less well-adapted as their life span progresses, e.g., due to decreased winter chill hours (Baldocchi and Wong 2006). There is likely to be a shift in wine grape varieties and adoption of new crops, such as blueberries, based on conversations with Yolo County UC Cooperative Extension farm advisors. In the future, the more reliable water supply in Yolo County, as compared to southern counties, may allow greater investment in perennial crops. In this drought year (2008), for example, tree crops are vulnerable to significant loss south of the Delta due to water cutbacks of 40% of the contract amount (Campbell 2008).

Decisions for directions in perennial crop breeding programs, and for shifts in geographic distributions, will require more planning as well as financial investment than for annual crops. Climate change is likely to pose new issues that may require additional effort and management, such as more expense for fossil fuel-based inputs, and new pest pressures (see below), so the investment in adaptation strategies may need to be substantially higher than at present.

Annual crops. It is likely that much potential exists for adapting annual cropping systems to climate change through choices of different crops and varieties, and altering rotations to include more winter crops. Higher cash value crops would be expected to replace grain crops, especially if there are water shortages. For example, both safflower and cereals require irrigation if there is inadequate fall/winter rain (Kent Brittan, UC Cooperative Extension, pers. comm.). Rather than irrigate these crops, growers are likely to choose specialty crops that will generate more income per amount of water applied (Lee et al. 2001a).

By analogy to Merced County, warmer season crops such as sweet potatoes, melons, peppers and lima beans may increase. Also, cool season vegetables for winter production may come more prevalent with an increase in temperature (Gene Miyao, UC Cooperative Extension, pers. comm.), such as broccoli, lettuce and spinach that are now harvested in March/April in the West Side of the Central Valley (extending more than 200 miles from Los Banos in Merced County in the north to Bakersfield in Kern County). Again, Yolo County may benefit because its relatively reliable water supply will favor it for these crops in comparison to other regions, if there continue to be water shortages or reductions in Delta deliveries to the southern areas.

With increases in winter temperatures, legume cover crops may become more important than at present, because their winter growth is currently temperature limited (Steve Temple, UC Cooperative Extension, pers. comm.). With the increase in fertilizer prices, and incentives to reduce N_2O emissions, use of legumes may be viewed as more viable economic management practice. Nitrogen fixation increases under elevated CO_2 although this response is also dependent on the availability of other nutrients (de Graaff et al. 2006).

Diversified production, i.e., one aspect of agrobiodiversity, is more common among vegetable growers in California (only 26% produce one sole commodity) than orchard producers (70% produce only one commodity), who are more likely to rely on crop insurance as a risk management tool (Lee and Blank 2004). A planned shift to greater diversity may offset some of the risks from weather variation due to climate change.

Crop diversification. Crops in Yolo County fluctuate in acreage by year, and the general categories of crops have been changing during the past 25 years. Grazing, grain and field crops are the major uses of agricultural land, while orchard, seed and truck (which refers to horticultural row crops such as vegetables, melons, strawberries etc.) crops are less important despite their higher cash value (Figure 11). Since 1984, however, grain acreage was the largest category, it is now the least. The acreage cropped with orchards/vineyards has increased by two thirds while seed crop acreage has doubled. Field crops increased in acreage during the 1990s, but then declined, coincident with the increase in tomato production (Figure 8). Grazing land remains the largest component and is the most constant.

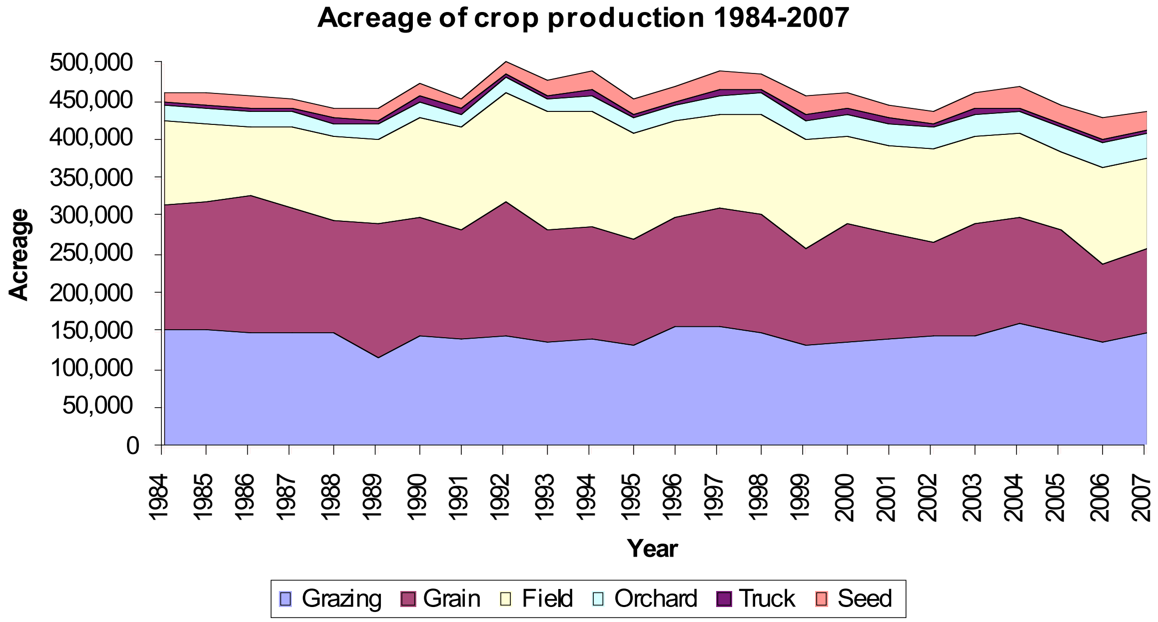


Figure 11. Acres planted within major categories in Yolo County 1984-2007. Grazing remains most constant while grain acreage has halved and orchard and seed crop acreages have increased by two-thirds and doubled, respectively.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos and Joel Kramer, UC Davis.

Seven major county crops, including almonds, grapes, walnuts, alfalfa, rice, tomatoes and wheat, can be chosen to represent three of these categories (orchard/vineyard, field, and grain crops). As will be described in more detail, individual crop commodities appear to experience greater flux than these general categories, indicating opposing fluctuations by different crops within the same categories.

Almonds and walnuts were initially the dominant orchard type crops. Wine grapes, once an insignificant crop for Yolo, began a rapid increase in 1995 (Figure 12). During that initial period, almond acreage was declining in turn. However, by 2005, almond acreage had increased by 50% so that the orchard/vineyard crop category was increasing with a total of roughly 10,000 acres, (4,050 hectares) per year by 2007. Effectively these orchard/vineyard crops were replacing part of the acreage normally reserved for field and grain crops in the county.

Meanwhile, within the major crop acreage, wheat lost nearly the majority of its acreage since 1984, and alfalfa more than doubled its acreage.

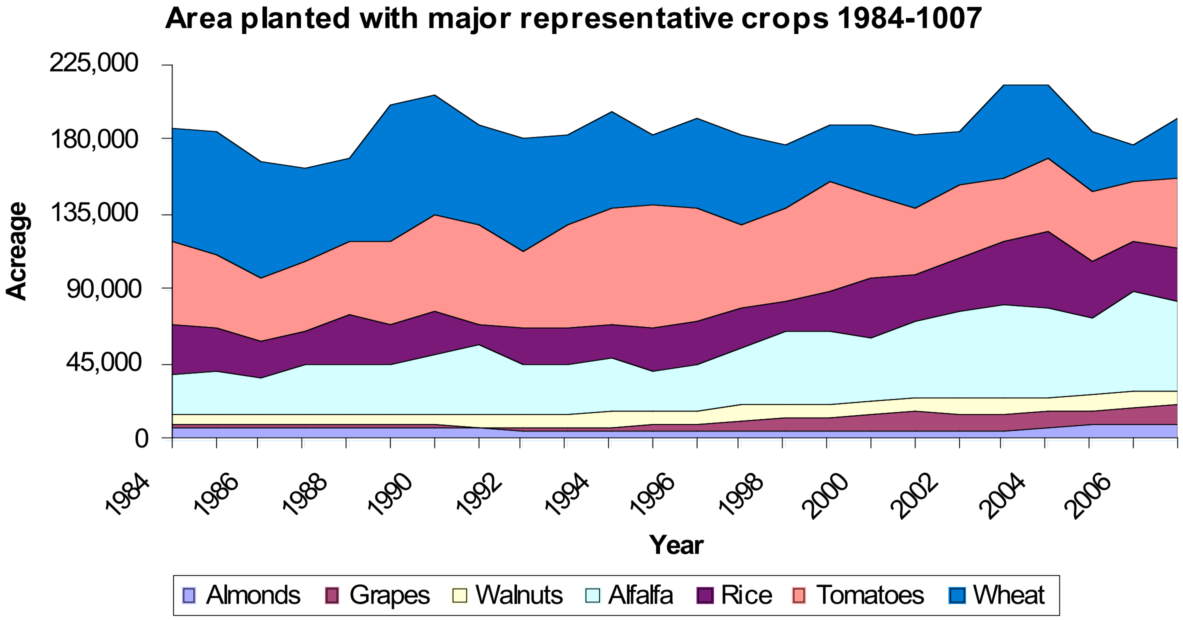


Figure 12. Acreage of seven major crops in Yolo County 1984–2007. Fluctuations of individual crops are more rapid than categorical groupings. During the past 25 years, tree crops became more important and irrigated alfalfa replaced some of the wheat acreage.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos, and Joel Kramer, UC Davis.

To assess the effect of these fluctuations in crop acreage on crop diversity, we applied the Shannon-Weaver Index, using 45 different crops found in the Yolo County Agricultural Crop reports. The index measures species richness (H) and evenness (E) and is usually applied to assessments of biodiversity. It essentially assesses the proportion (*p*) of each crop with respect to its category's total, and then exaggerates that relationship (Figure 13).

$$H = -\sum_{i=1}^{s} p_i \ln p_i$$

$$E = \mathrm{H} / \ln(\text{number of species})$$

According to the Shannon-Weaver Index, orchard / vineyard crops and grain crops share a higher average richness than do the other crops. The index for orchard-cropped area rose to a two year peak in 1992–1993 and has declined thereafter, as a consequence of increased acreage in grapes and almonds with respect to other woody crops. But, grain crops appear to be more sporadic than orchard crops in terms of the annual proportions that farmers choose to plant (Figure 13). This may be due to the fact that grain crops are annuals, occupy a much larger amount of land overall, and more prone to crop changes.

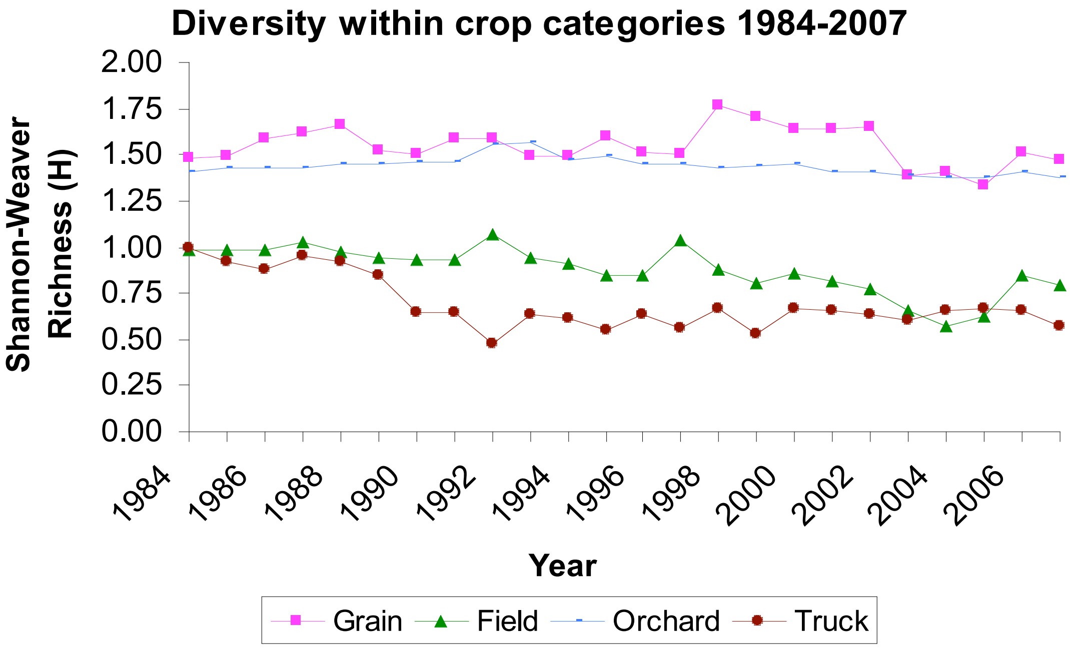


Figure 13. Shannon-Weaver Diversity Index richness within crop categories based on acreage 1984–2007 in Yolo County. Orchard and grain crops maintain a higher level of species richness than other categories. The number of commodities in use continues to decline overall for grain, field and truck crops.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos and Joel Kramer, UC Davis.

While the diversity index for truck (i.e., vegetable) and field crops were both initially higher, they have been reduced over the last 25 years to a species-poorer crop mix. Both have undergone rapid ups and downs (e.g., field crops as recently as 2006). Essentially, there have been no important changes in diversity within each of the categories during this period.

Figure 14 shows evenness of crop diversity (*E*), to show how evenly acreage was distributed among all of the crops in a given category. A value of 1 indicates that all crops were occupying the same area of land. This can be interpreted as an annual measure of the relative acreage of dominant crops versus acreage in minor crops in that category. It should be noted that the "miscellaneous" classification in the Yolo County annual crop reports obscures these differences. Also organic production is not reported by commodity, and there is very high diversity of crops in Yolo County's organic sector. Field and grain crop share the highest evenness, with orchard crops nearly as high. Conversely, truck crops are far less even than all of the other three. Truck crops plummeted in evenness from 1989, indicating the increased dominance of tomatoes. Orchard/vineyard crops were fairly even in terms of crop mix during the period 1989–1997, then grapes and almonds began to increase, decreasing evenness from 1998 onwards until the present.

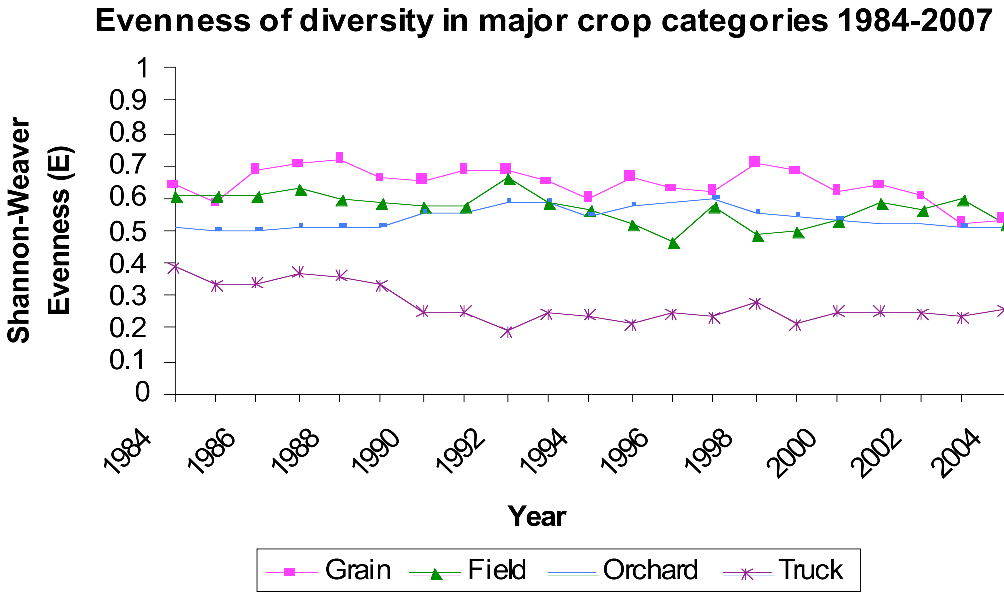


Figure 14. Shannon-Weaver Diversity Index evenness of acreage cropped within crop categories 1984-2007. All crop categories in decline of crop evenness, indicating that a few of the commodities in each category occupy most of the acreage.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos and Joel Kramer, UC Davis.

Evenness as a whole across the entire county is generally decreasing, indicating that dominant crops occupy more of the acreage with time (Figure 15). Most increases in crop diversity have been followed by immediate extreme decline, as an example, see the last few years since 2003. Overall, Yolo County has shown its capacity to grow crops in many different types of categories, and to make changes in and within these categories, but the current trend is for less diversity in the last 25 years.

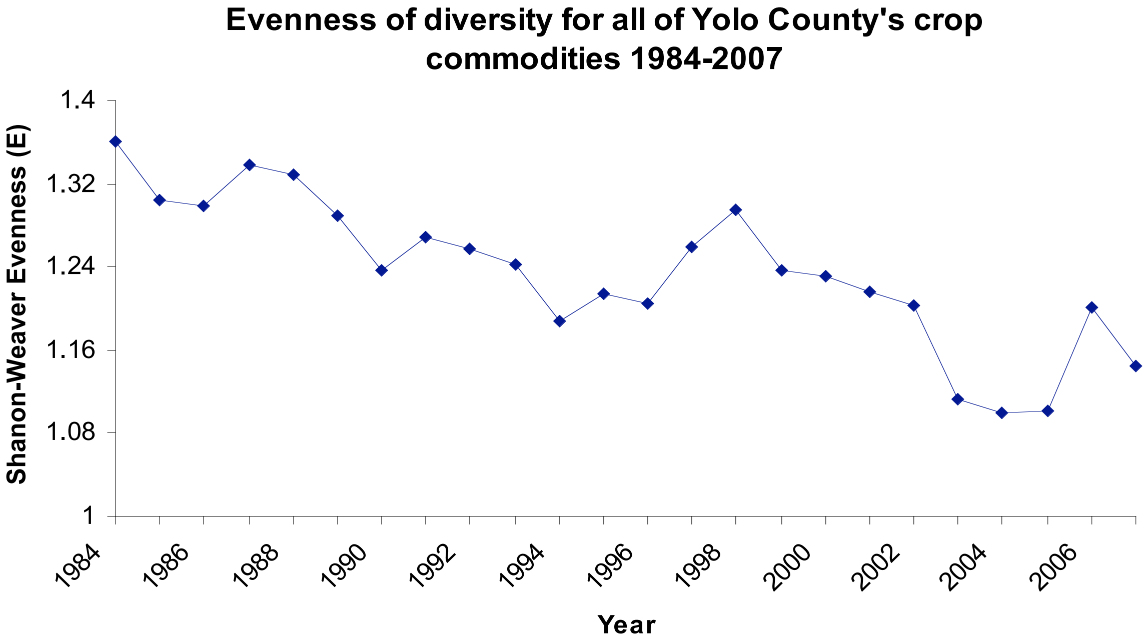


Figure 15. Shannon-Weaver Diversity Index evenness of acreage for total crop species evenness for Yolo County, 1984–2007. Consistent total decline in the evenness between the acres of each species cropped indicates that a few commodities increasingly occupy more of the acreage with time.

Source: Data from Yolo County Agricultural Crop Reports. Figure created by Fernando Santos and Joel Kramer, UC Davis.

One example of diversification in Yolo County is on organic farms. Many of the organic farms in Yolo County produce more than 20 crops or crop varieties. Organic production was valued at $19.5 million in 2007, up from $15 million in 2006 (Yolo County Agricultural Commissioner 2008). There are >50 organic farms in Yolo County, both small and large. The Yolo County Agricultural Commissioner's office is one of the few counties in California to offer an organic certification program to qualified agricultural producers and handlers. Yolo County is the number one county, nationwide, in direct sales (Hardesty 2005), largely due to the proximity of urban Sacramento and San Francisco Bay Area restaurants and grocery stores. In addition, Yolo County farmers supply thousands of community supported agriculture (CSA) boxes each week, and participate in more than a dozen farmer’s markets locally and in these metropolitan areas. There is growing interest in diversification for direct marketing opportunities in Yolo County, such as Taste of Yolo and the Buy Fresh, Buy Local project of the California Association for Family Farmers.

The historical record, and the current growth in diverse organic production, indicate that Yolo County has the potential to further diversify its commodity production, although new marketing avenues must be developed. An increase in crop agrobiodiversity (e.g., with more minor crops) may confer an advantage given the uncertainty of climate change effects on agriculture.

Modeling for annual field crops. In order to assess the effect of climate change on crop productivity, we integrated detailed databases on soils, land use, and climate within Yolo County. The crop productivity of alfalfa, maize, rice, sunflower, tomato, and wheat in Yolo County was modeled using DAYCENT to establish a baseline yield from 2000 to 2004. Once the baseline was established, the model was used to predict the effects of climate change on field crop yields. In this study, climate change predictions for A2 (medium-high) and B1 (low) emission scenarios from the CNRM-CM3 model (Randall et al. 2007) were considered for modeling the effect of climate change on crop yield. The original climate data were downscaled to a 1/8 degree grid resolution (approximately 12 km) by a constructed analogues method (Maurer and Hidalgo 2008). We assumed current management practices (conventional management, fixed management schedules and a typical set of crop rotations) for the period 2000 to 2050. Under both A2 and B1, average modeled maize, sunflower, and wheat yields decreased by approximately 2% to 8% by 2050 relative to the 2000–2004 average yields (Table 6). For these crops, the yields tend to decline slightly more under A2 than B1. In general, alfalfa, rice, and tomato were predicted to increase under climate change in the same period.

Additional model runs were conducted to examine how extreme weather events may affect crop production. Specifically, the effects of an extreme weather event were tested using a daily time step, such as heat waves or drought-like conditions that could happen over the next 50 years. For our heat waves simulations, we found the 99.9th percentile (i.e., 46˚C, or 115°F) for the summer months from June through September in the period 2000 to 2050. We then set daily maximum temperatures to 46˚C for the last 10 days of the month of May, June, July, or all three months each year from 2000. Heat waves are often accompanied by drought over a broad range of time scales. Particularly in the Sacramento Valley, water scarcity in agriculture was currently approximately 2%. It is expected to further increase by 20% by the year 2050 under A2 unless adaptations for water management are made (Medellín-Azuara et al. 2008). As a result, climate change likely decreases annual water deliveries and increases water supply variability in agriculture (Anderson et al. 2008). Therefore, in addition to heat waves, water available for irrigation under climate change was assumed to have 75% soil water holding capacity at the time of irrigation (baseline = 95% soil water holding capacity). Effects of precipitation changes on irrigation water supply are not considered because their trends were still uncertain. Early heat waves seem to have a profound effect on crop growth except for alfalfa and winter wheat (Table 6). Heat waves in May resulted in yield loss of 1%–10% for maize, rice, sunflower, and tomato, whereas heat waves in June affected only maize and sunflower yields. The effects of heat waves in July on crop yields were relatively small. Heat waves in May-July had the most profound effects on crop production by decreasing 3%–19% of the 2050 baseline yields. However, drought did not have much effect on crop yields.

Table 6. Effects of heat waves[1] and drought[2] on field crop yields in Yolo County under A2 and B1 emission scenarios, as determined by the DAYCENT model

		2000–2004	2046–2050						
					Heat waves only				Heat waves & drought
Commodity	**Emission scenario**		**Baseline climate change**		**May**	**June**	**July**	**May-July**	**May-July**
		ton ha^{-1}	ton ha^{-1}	% change from 2002	Additional % change from baseline				
Alfalfa	A2	16.4	17.0	3.5	1.2	0.0	-0.4	1.0	1.2
	B1	16.5	17.8	7.3	1.1	0.4	-0.5	1.1	1.4
Maize	A2	13.9	13.5	-2.4	-4.4	-5.4	-0.2	-11.2	-11.2
	B1	13.6	13.4	-1.6	-3.5	-6.4	-0.9	-7.3	-7.3
Rice	A2	9.3	9.5	1.7	-3.8	0.0	-0.1	-6.1	-6.9
	B1	9.3	9.4	1.7	-4.1	-0.7	-1.1	-6.9	-8.0
Sunflower	A2	1.4	1.3	-7.9	-9.5	-5.2	-1.9	-18.5	-20.3
	B1	1.4	1.3	-5.4	-6.5	-7.1	-2.9	-18.7	-20.3
Tomato	A2	94.5	97.4	3.0	-1.5	-0.6	-0.8	-3.2	-4.8
	B1	95.9	97.2	1.4	-1.4	-0.3	-0.7	-2.9	-4.8
Wheat	A2	6.0	5.8	-2.4	-0.1	0.0	0.0	-0.1	-0.1
	B1	5.7	5.6	-2.6	0.0	0.0	0.0	-0.1	-0.1

[1] Temperature for heat waves (= 46°C) is the 99.9th percentile in the period 2000 to 2050. Heat waves are simulated for the last 10 days of the month of May, June, July, or all the months each year from 2000.

[2] Under drought conditions, water available for irrigation is assumed to have only 75% soil water holding capacity at the time of irrigation. The baseline irrigation has 95% water holding capacity.

Source: Juhwan Lee and Johan Six, UC Davis.

2.5. Commodity Production: Soil and Land Management Options for Responding to Climate Change

Changes in soil and land management will be needed to maintain soil quality with less dependence on fossil fuel-based inputs, as the cost of these inputs is rapidly increasing, and also contribute to GHG emissions. One example is nitrogen fertilization. Elevated CO_2 is likely to increase the nitrogen demand of crop plants (de Graaff et al. 2006), and excessive N is a major reason for high emissions of the N_2O, the most potent GHG in terms of warming potential. Improved management options, such as precision agriculture, drip irrigation with fertigation, and increased soil N cycling, such as legume inputs and turnover, offer some potential solutions, but any implementation of changes in N delivery and management poses tradeoffs. For example, the use of legume cover crops requires additional fossil fuel to plant and manage for optimal N availability, and if rapid decomposition of legume residues occurs before crop N demand is high, then N_2O emissions may increase (Kallenbach 2008). The management options to mitigate GHG emissions are not completely understood and therefore their efficacy to address climate change has uncertainty.

California's agricultural and forestry sectors contribute 8.3% of all anthropogenic GHG emissions (Figure 16) according to the California Energy Commission (CEC 2006a), which can be converted into a rough estimation of 37.5 $MMTCO_2E$, based on the fact that over 450 $MMTCO_2E$ annually is attributed to human activity in California (IPCC 2001). If California's agricultural and forestry sectors want to proportionately (8.3%) mitigate GHG emissions to maintain emissions at the 1990 level, it would be necessary to reduce emissions by 14.5 $MMTCO_2E$ by the year 2020.

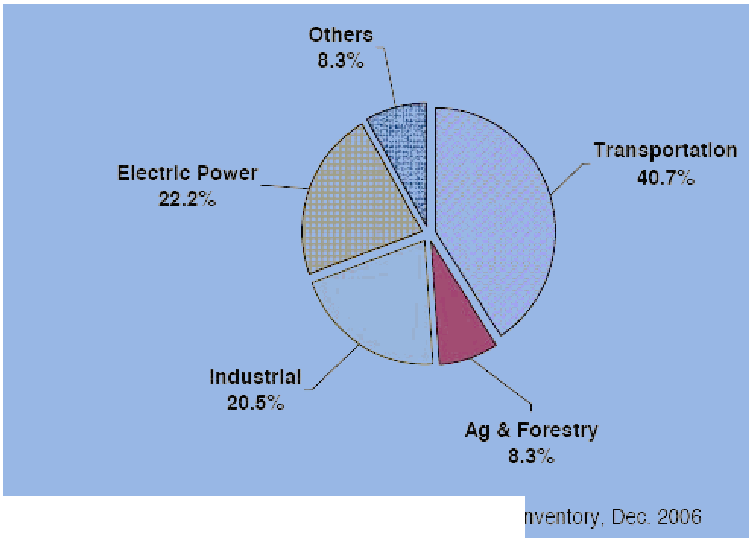


Figure 16. Sources of California's 2004 GHG emissions by end-use sector (includes electricity imports and excludes international bunker fuels). If agricultural and forestry sectors want to proportionately (8.3%) mitigate GHG emission to maintain emissions at the 1990 level, it would be necessary to reduce emissions by 14.5 $MMTCO_2E$ by the year 2020.

Source: California Energy Commission, Greenhouse Gas Inventory. December 2006.

Half of the California agricultural emissions is emitted as N_2O (CEC 2005) mainly due to microbial nitrification and denitrification of fertilizer and available soil N that is mineralized from soil organic matter, breakdown of crop residues, and manure management. Methane emissions are also substantial at 37.5%, which mainly comes from crop residue decomposition in anaerobic soils, e.g., rice, or from enteric fermentation of livestock. In the United States, rice accounts for approximately 1% of total CH_4 agriculture emissions, while enteric fermentation and manure management account for 71% and 28%, respectively (USEPA 2007). The remainder is CO_2 (12.5%) from combustion of fossil fuels which are used to power field equipment or processing systems (Figure 17). In these assessments, biogenic CO_2 is considered to have no net effect on GHG emissions. As a GHG, CO_2 is much less potent than N_2O (298 times more potent for a 100-year period) and CH_4, (12 times more potent for a 100-year period).

Agriculture accounts for only 3% of CO_2 emissions statewide from all sectors. Agriculture-related emissions of CH_4 and N_2O, however, are relatively much larger, and account for a total of 5% of California's statewide emissions (Figure 17). Most of the agricultural GHG emissions are from non-CO_2 sources such as N_2O (44%) and CH_4 (16%). The intensive management of California agroecosystems with high rates of N fertilizer, flooding or flood irrigation, and typically relatively low inputs of organic matter contributes to these high non-CO_2 GHG emissions. Net emissions through the decomposition of plant residues are assumed to be negligible, since it is assumed that most soils are in equilibrium, unless there is a major switch to frequent high organic matter inputs, e.g. organic production. For this reason, priority areas for further research to improve California's GHG inventory for agriculture will likely be focused on CH_4 and N_2O emitted from soils, wastewater, manure and enteric fermentation.

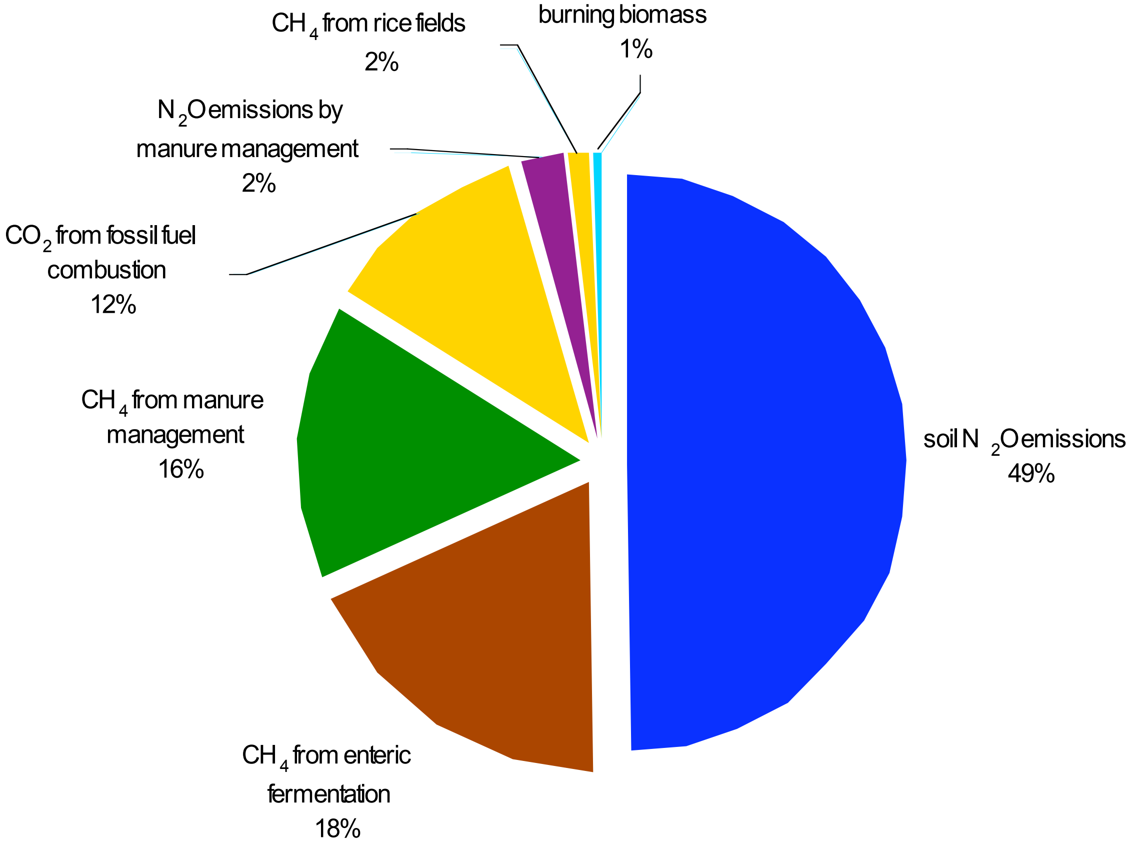


Figure 17. Relative sources of anthropogenic GHG emissions in California agriculture and forestry. Half of total emissions are emitted as N_2O mainly due to microbial activity. One-third is methane (CH_4) emissions which mainly comes from manure management and enteric fermentation, which are probably less important in Yolo County than statewide due to few dairies and feedlots, and to a lesser extent, crop residue decomposition in anaerobic soils, e.g., rice.

Source: CEC 2006.

The management for soil C sequestration can have significant short-term effects, however, this will not continue indefinitely as long-term sequestration is limited. Long-term research at UC Davis suggests that the use of cover crops and manure can contribute to up to 300 kilograms (kg) of soil C sequestration per year under consistent management (Horwath et al. 2002).

However, after five years the rate of soil carbon sequestration diminished significantly. The only specific practice for agriculture mentioned in the recent ARB Scoping Plan (ARB 2008), however, is the reduction of CH_4 emissions from large dairies, probably because this is a highly concentrated point source GHG emissions that is more consistent spatially and temporally than the rates of CO_2 and N_2O emissions across the broad range of commodities and management practices on agricultural fields in California.

It is envisioned that agricultural GHG emission reduction strategies can result in both emission reductions and increased sequestration without compromising product yields or income. Many agriculture strategies to reduce GHG emissions provide co-benefits which support existing regulations, policies and programs. Other agricultural management strategies such as water and fertilizer use efficiency and soil carbon sequestration through conservation tillage, riparian restoration and rangeland management, offer further opportunities to reduce agricultural GHG emissions (ETTAC 2007). The most sustainable options include other aspects of environmental stewardship to increase the overall quality of natural resources and achieve multiple benefits in working landscapes (Jordan et al. 2007).

Reducing tillage intensity. Alternative tillage practices based on reduced tillage intensity are often thought to increase soil organic C and hence C sequestration (Horwath et al. 2002). Alternative tillage systems have many benefits apart from sequestering C in the soil, including the reduction of soil erosion by water and wind, the conservation of soil organic matter and soil structure, the prevention of evaporative water loss, and less fossil fuel use (Jackson et al. 2005). However, alternative tillage practices can actually increase the emission of other GHGs, outweighing the beneficial effects of increases in soil C. For example, Six et al. (2004) showed that no-tillage can initially result in increased global warming potential (GWP) due to higher N_2O emissions relative to conventional practices. One of the main reasons for these higher initial rates is slightly higher moisture content and increased compaction (from lack of tillage and aeration) that favors the activity of anaerobic microorganisms such as denitrifiers.

It is only after longer-term adoption (>10 years) of reduced tillage that a significant reduction in GWP can be observed, especially in humid climates. Emissions of N_2O are the driving force behind much of the trend in net GWP in reduced tillage systems. Estimates of C sequestration for reduced tillage range from 200 to 600 kilograms of carbon per hectare per year ($kg\ C\ ha^{-1}\ yr^{-1}$) (Lal et al. 1999), the U.S. Department of Energy estimates a sequestration rate of about 300 $kg\ C\ ha^{-1}\ yr^{-1}$. Another issue is that recent literature is questioning the true capacity for even no-tillage to increase C, since most data is taken for only the surface layer, rather than the deep soil profile (Venterea et al. 2006: Veenstra et al. 2007; Blanco-Canqui and Lal 2008), which receives proportionately less C inputs in reduced tillage systems.

Direct reduction in fossil fuel use via reduced or no-tillage also contributes to mitigation of GHG emissions. For Sacramento Valley field crops, De Gryze et al. (in press) estimated that this accounts for a reduction in GHG emissions of 0.25 to 0.50 megagrams of carbon dioxide equivalent per hectare per year ($Mg\ CO_2E\ ha^{-1}\ yr^{-1}$).

In reality, it is difficult for most farmers to reduce tillage for the several years that is needed for effective C sequestration in California (Mitchell et al. 2007; Mitchell et al. 2008). For example, tillage increases the evenness of both water movement via irrigation, and microsites for germination of small seeded crops (Minoshima et al. 2007). In some situations, however, reduced tillage has increased C sequestration substantially, e.g., pasture production by dairy farmers (Mitchell, pers. comm.), which is also related to manure additions.

Cover cropping. In California, cover crops in row crop systems are usually grown during the winter when sufficient rainfall is available. Perennial systems including vineyards and orchards can maintain year round cover crops. A cover crop is typically not harvested, but is mowed and/or incorporated into the soil at the end of its growing period. Other benefits of cover crops include reduced soil erosion, weed growth suppression, attraction of beneficial insects, microbial nutrient cycling, C sequestration, enhanced productivity of subsequently cultivated cash crops. In California, legumes are not commonly chosen as cover crops, despite their nitrogen fixation, because cool winter temperatures often limit stand establishment and growth.

Small grains such as oat, winter wheat, barley, triticale, hairy vetch or winter rye are often used as winter cover crop species. For many conventional horticultural production systems in California, these cover crops are often incorporated when plants are small, and is at a low C:N ratio, to avoid competition between microbes and plants for nutrients, and is only done sporadically, and this tends to create only no or very slight increases in soil C sequestration as managed on farm (Jackson et al. 1993; Wyland et al. 1996; Jackson 2000). Moreover, if cover cropping does not occur every year, the long-term stabilization of soil organic matter is less likely to occur (Voroney et al. 1989). As mentioned above, as temperatures and CO_2 rise, legumes are likely to become more productive in winter. Research on N release after incorporation into soil is needed to find optimal methods to store N during the crop growth period, and avoid N_2O emissions. Summer cover crops are another possibility, especially heat and water-stress tolerant species such as cowpea, which are now being selected under summer conditions for horticultural production in the California desert (Wang et al. 2006).

Organic agriculture. Organic farming systems promote the use of renewable resources and enhance the ecological processes of nutrient cycling and retention. Organic residues (mostly cover crops, manure and compost) are used as nutrient inputs, along with soluble fertilizers from organic sources, and no synthetic pesticides are used. Alternative weed control, often hand weeding, is used in place of chemical herbicides, which increases labor costs. Often, high soil disturbance through tillage is used to suppress weed growth, which increases fuel use. The application of composts, manure, and cover crops are frequently used together, and this generally increases soil organic C contents. Also, addition of cover crops, compost and manure increase the emissions of CO_2, due to higher microbial activity, but C storage also occurs, resulting in a net sequestration of soil C (Kong et al. 2005). The transportation of manures and other bulky organic fertilizers from source to farms requires fossil fuel negating some of the benefits of organic management. In one successful California transition study, however, NO_3^- concentrations decreased markedly, with no apparent crop nutrient deficiency, as a result of lower N inputs in organic versus conventional production (Smukler et al. 2008), implying that N_2O emissions were probably also much lower.

Reducing N fertilization. According to IPCC (2001), the most effective way to reduce GHG emissions in intensive agricultural systems is through minimizing N-surpluses. This is relevant in California where high N fertilizer inputs and intensive irrigation are the norm. Although N deficiency is a concern, many examples exist in California crop production in which fertilizer N application often exceeds the needs of the crop by 25%–50%, especially for vegetables and tree crops, and this extra N is applied as cheap insurance against N deficiency. There are many examples of high N_2O emissions in California annual cropping systems (Ryden and Lund 1980; Burger et al. 2005). For perennial crops, either small amounts of N are added to maintain quality (e.g., wine grapes) or growers feel that they are already fairly efficient in meeting critical values for N application (e.g., almonds), although critical values may need to be updated (G. Ludwig, California Almond Board, pers. comm.) With the increase in fertilizer prices, high applications may not be so commonplace; however, N fertilizer inputs are a still a small proportion of the total costs of producing many specialty crops. With the new emphasis on N_2O-related research by the PIER and ARB programs, there will be more opportunities to learn how to mitigate GHG emissions without reducing crop yield.

Manure management in feedlots, dairies and rangelands. Manure management activities are important for achieving reduction in both GHGs and pollutants such as VOCs, ammonia (NH_3), and particulate matter (PM). For CH_4 emissions, as an example, a report on GHG emissions for Sacramento County, calculated manure enteric fermentation and manure management losses, based on IPCC and USDA guidelines (Stokes 2008). Dairy cattle (17,400 head) were greater CH_4 emitters (186 kilograms per head per year [kg head^{-1} yr^{-1}]) than beef cattle (43,600 head at 55 kg head^{-1} yr^{-1}). In Yolo County, no dairy cattle are listed in the 2007 Agricultural Commissioner's Crop Report, but there are 35,000 cattle and calves, which are assumed to be beef cattle. Methane digesters are intended for dairy production, so this technology to reduce GHG emissions and generate electricity apparently is not applicable in Yolo County, at least at a commercial scale.

Increasing carbon stocks in tree crops and vines. Carbon stocks in agricultural crops increase by planting of tree crops such as orchards and vineyards, at least temporarily, but as yet, there is no mechanism for farmers to receive GHG mitigation credit through C sequestration in wood of agricultural species, despite the interest in native forest species in the California Forest Sector Protocol (CCAR 2007). Perennial crops often have much deeper root depth distributions than annuals which increases the potential to store C (Smart et al. 2006). There are few numbers available on root allocation in almonds or grapevines, so that calculating C in belowground wood is difficult. Estimates for grapes, however, indicate that a 50:50 trunk:woody root ratio (E. Carlisle, pers. comm.). Carbon sequestration in wood provides an example of how a C credit system may eventually presents an opportunity for growers to mitigate GHG emissions, as well as provide additional gross income to ease the management transition to perennials. The additional gross income can serve as an insurance against the increased vulnerability of transition and/or could be an increase in net income. A perverse incentive could be created, however, by removing existing woody crops and vegetation in order to accrue C in new plantings, since payments on the C market are not currently designed to support C storage that currently exists.

Farmscaping by using perennial vegetation in marginal lands on farms. Farmscaping refers to non-production plantings along farm margins, riparian corridors, or tailwater ponds. Hedgerows of trees and shrubs have been shown to increase C storage in woody trunks, branches and roots (Follain et al. 2007) and reduce CO_2 and nitrous N_2O emissions (Robertson et al. 2000; Falloon et al. 2004), increase C storage. There are also benefits for water regulation and quality (Caubel-Forget et al. 2001; Caubel et al. 2003), biodiversity (Le Coeur et al. 2002), and habitat for insects that regulate pests or increase pollination (Olson and Wackers 2007). In a recent study on a 100-acre organic farm in Yolo County, the riparian corridor along one side of the farm contributed 16% of the C storage on the farm (140 Mg C ha^{-1}) (Smukler et al., ms. in prep.). The annual emissions of CO_2 and N_2O were similar between riparian, hedgerow, and crop field habitats, but C storage was highest by far in the riparian corridor, largely due to wood: twice that found in hedgerows, and more than three times that of the crop production fields.

Biomass utilization for energy and fuel production. Yolo County is a dynamic agricultural production area that exhibits changes in cropping patterns based on market demand and technological improvements as discussed in Section 2.2.

Over the forty-year time horizon assumed for this study, a potential higher value market for agricultural commodities may be energy. High energy costs may erode some if not much of California's (therefore Yolo County's) competitive advantage for the production of certain crops during specific times of the year. Therefore the production of dedicated energy crops needs careful consideration as a potential strategy for farmers to adapt to climate change. Such crops may also provide multiple benefits when considered in an agroecosystem context, e.g., habitat values, biodiversity, soil conservation/building benefits, pest management benefits, and market diversification opportunities.

Over a forty-year time frame, it is likely that bioenergy/biofuels production technology will advance well past first generation sugar/starch/vegetable oil conversion to ethanol and biodiesel. Second and third generation biofuels based on ligno-cellulose (biomass) and microbial systems in both terrestrial and aquatic systems are already the subject of much publicly and privately funded research and development. Such crops may produce not only liquid transportation fuels, but also provide feedstock for biomethane, electricity and hydrogen.

Just as the tomato harvester and associated tomato breeding program revolutionized processing tomato production in the 1960s, advanced biomass crops, algae systems and conversions processes are expected to improve greatly over the next forty years, providing new economic opportunities for agriculture.

Potential conventional crops may include but not be limited to corn, sugar/fodder beets, oil seeds crops including canola/mustard, and safflower. These crops all have the potential to provide ancillary benefits and may fit well into crop rotations with food crops. Crops that may achieve commercial viability within the next forty years, admittedly only with a concerted, sustained development effort, include sweet sorghum, perennial grasses, algae, cattails, miscanthus, hybrid poplar, and willow, just to name a few.

It should also be noted that utilization of existing crop residues such as orchard and vineyard prunings, rice straw, animal manures for bioenergy production can provide additional revenue to farming operations, or at least fix energy costs if produced and used onsite, while also potentially mitigating other environmental liabilities and disposal or management costs.

There is no denying that higher value food crops will always be the foundation of California and Yolo County agriculture. However, as the security, cost and environmental footprint of energy continue to increase in importance as national priorities, new market opportunities will present themselves.

Estimating GHG emissions reductions from agriculture. Scaling up from field scale, several approaches have examined the potential GHG emissions from California agriculture in 2020, each coming up with somewhat different estimate of emissions reductions. These differences, along with the spatial and temporal variability encountered in field studies, make it difficult to arrive at a consensus view on the actual role of agriculture in GHG mitigation.

Using the Carnegie-Ames-Stanford Approach (CASA) model, along with data on harvest indices and yields, Kroodsma and Field (2006) calculated net primary production, woody production in orchard and vineyard crops, and soil C. The model found that annual agriculture sequestered an average of 120 kg C ha^{-1} yr^{-1} in soil, while perennial crops sequestered more carbon, with orchards sequestering 1070 kg C ha^{-1} yr^{-1} (900 kg C m^{-2} yr^{-1} in woody material and 170 kg C ha^{-1} yr^{-1} in soil) and vineyards sequestering 240 kg C ha^{-1} yr^{-1} (40 kg C ha^{-1} yr^{-1} in woody material and 200 kg C ha^{-1} yr^{-1} in soil).

Using the DAYCENT model, De Gryze et al. (in press) found that there was biophysical potential to sequester 0.7 to 3.3 Mg CO_2E ha^{-1} yr^{-1} (carbon dioxide equivalent) in agricultural soils in the Sacramento Valley. Of these values, 60–80% of the mitigation potential was attributable to soil C sequestration, and the remainder was mainly due to reduction of N_2O emissions. The DAYCENT model tended to overpredict soil organic C by about 10% compared to measured soil C at two long-term field trials. The total mitigation potential of alternative practices was smallest for conservation tillage (0.57–0.68 Mg CO_2E ha^{-1} yr^{-1}), followed by cover cropping (1.35 Mg CO_2E ha^{-1} yr^{-1}) and the use of organic inputs (1.87–2.60 Mg CO_2E ha^{-1} yr^{-1}). Respectively, the soil C storage amounted to 103 kg C ha^{-1} yr^{-1}, 310 kg C ha^{-1} yr^{-1}, and 395–405 kg C ha^{-1} yr^{-1}, with a typical standard error (SE) or coefficient of variation of 30%–200% (Table 7). Kroodsma and Field (2006) estimated that conservation tillage alone would double C sequestration from a mean of 150 to 240 kg C ha^{-1} yr^{-1} compared to current practices, based on statewide averages across cropping systems.

Table 7. Modeled changes in the Global Warming Potential (GWP), Soil organic carbon (SOC), and nitrous oxide (N_2O) emissions for the Sacramento Valley. Averages were taken for each crop over 10 years (1997-2006), over all fields and crop rotations within multiple counties of the Sacramento Valley. Values are biophysical potentials that do not reflect practical limitations of combining practices. Note that reductions in CO_2 emissions due to decreased fuel use in conservation tillage systems are not included in these values. These account for an additional reduction in GHG emissions of 0.25 to 0.50 Mg CO_2E ha^{-1} yr^{-1}. convent. = conventional tillage; conserv. = conservation tillage.

Variable	Tillage	Fertilizer	Cover crop	Alfalfa	Corn	Rice	Safflower	Sunflower	Tomato	Wheat
GWP	convent.	mineral, 75%	no	-0.04	-0.70	-0.93	-0.02	-0.62	-0.79	-0.16
(Mg ha^{-1} yr^{-1})	conserv.	mineral	no	-0.01	-0.42	-0.83	-0.08	-1.44	-1.13	0.09
	convent.	mineral	yes	0.02	-0.93	-2.25	-0.44	-2.36	-1.79	0.19
	conserv.	mineral	yes	0.02	-0.95	-2.25	-0.48	-2.47	-1.80	0.16
	convent.	organic	no	0.03	-2.91	-1.26	-0.71	-0.54	-1.27	-0.75
	conserv.	organic	no	0.01	-3.17	-2.16	-1.46	-2.20	-2.70	-0.80
	convent.	organic	yes	0.08	-4.97	-3.54	-0.29	-1.44	-2.16	-0.66
	conserv.	organic	yes	0.06	-4.95	-4.46	-1.10	-3.03	-3.43	-0.59
ΔSOC	convent.	mineral, 75%	no	4.23	16.1	7.85	-105	19	-4.0	-6.9
(kg C ha^{-1} yr^{-1})	conserv.	mineral	no	2.72	56	123	56.8	316	213	-28
	convent.	mineral	yes	-4.01	193	580	144	557	410	-49
	conserv.	mineral	yes	-4.17	196	579	157	585	413	-41
	convent.	organic	no	-10.13	600	227	108	144	227	86
	conserv.	organic	no	-5.59	623	372	267	491	514	108
	convent.	organic	yes	-21.03	1171	665	53.7	361	411	79
	conserv.	organic	yes	-17.17	1132	832	230	705	675	50
N_2O flux	convent.	mineral, 75%	no	-0.06	-1.37	-1.92	-0.88	-1.18	-1.71	-0.40
(kg N ha^{-1} yr^{-1})	conserv.	mineral	no	0.00	-0.46	-0.80	0.27	-0.60	-0.74	-0.02
	convent.	mineral	yes	0.01	-0.48	-0.27	0.20	-0.67	-0.61	0.02
	conserv.	mineral	yes	0.01	-0.49	-0.27	0.21	-0.69	-0.61	0.02
	convent.	organic	no	-0.02	-1.51	-0.90	-0.68	-0.03	-0.94	-0.92
	conserv.	organic	no	-0.03	-1.89	-1.71	-1.02	-0.84	-1.74	-0.86
	convent.	organic	yes	0.00	-1.44	-2.35	-0.19	-0.26	-1.40	-0.79
	conserv.	organic	yes	0.00	-1.70	-3.01	-0.54	-0.96	-2.04	-0.86

Source: De Gryze et al., in press.

Unlike soil C sequestration, which can be lost upon tillage, N_2O emissions are permanent. Modeling a 25% N fertilizer reduction reduced GHG emissions by -0.9 ± -0.8 Mg CO_2E ha^{-1} yr^{-1} in the Sacramento Valley (De Gryze et al., in press). The IPCC guidelines estimate direct emissions of N_2O from agricultural soils using a fixed percentage, 1.25%, and up to 2.25%, of added N inputs (Mosier and Kroeze 1998). Assuming an average application of 150 kg N ha^{-1} yr^{-1}, and this simple approach shows an approximate reduction of -0.22 to -0.40 Mg CO_2E ha^{-1} yr^{-1} from a 25% decrease in N fertilizer. These generic values are much lower than the mean N_2O emissions of California's croplands, since high-value specialty crops are typically overfertilized with N, and rates of N_2O emissions increase at an exponential rate in relation to N inputs.

Reconciling some of the modeled GHG emission and soil C sequestration with on-farm potential is difficult. One reason is that the modeled results are based on field station trials that use less tillage, more cover crop biomass, and more compost or manure than farmers, and thus may accumulate more C than is typical on-farm. There are few on-farm long-term trials to test this. A two-year field study in the Salinas Valley on a vegetable farm showed that a minimum tillage, winter cover crop + compost treatment increased soil C by 175 kg ha^{-1} yr^{-1} (Jackson et al. 2004), lower than the average by the DAYCENT model, for conservation tillage, cover cropping, and organic fertilizer (532 ± 246 kg C ha^{-1} yr^{-1}) which was conducted for a range of crops grown in the Central Valley (Table 8) (De Gryze et al., in press). In another on-farm study in the Salinas Valley, soil C did not change significantly during the 2.75 year transition to organic production, which used cover crops, manure and compost (Smukler et al. 2008). By contrast, at one of the UC Davis long-term agricultural experiments (SAFS), winter cover cropping and the combination of winter cover cropping + manure increased soil C by 3–5 Mg C over 10 years, respectively, i.e., 300–500 kg C ha^{-1} yr^{-1} (Poudel et al. 2001), which is similar to the DAYCENT modeled output (405 ± 212 kg C ha^{-1} yr^{-1}). These examples indicate that it is difficult to make clear predictions for effects of changing management practices on farmers' fields, especially given the diversity of soils and cropping systems in California.

A statewide estimate of GHG emission reduction potential from the agricultural sector was done for the report of the Economic and Technology Advancement Advisory Committee (ETAAC 2008). On February 14, 2008, the Economic and Technology Advancement Advisory Committee (ETAAC) presented its final report to the California Air Resources Board. The report, "Technologies and Policies to Consider for Decreasing Greenhouse Gas Emissions in California", describes 7 agriculture-related strategies to reduce GHG emissions: (1) manure to energy facilities, (2) enteric fermentation mitigation, (3) biomass utilization, (4) biofuels, (5) soil C sequestration (6) farmscape sequestration, and (7) increased fertilizer and water use efficiency. The estimates are focused on the reductions that are feasible in 2020, the year in which voluntary reductions will be evaluated. The report considers the biophysical potential as well as the likely adoption of different practices in $MMTCO_2E$ yr^{-1} across the entire state. The net annual California reduction potential is given in $MMTCO_2E$ yr^{-1} across the entire state as: Manure-to-energy facilities (3.1), enteric fermentation (0.8), agricultural biomass utilization (4.1), dedicated biofuel crops (1.0), soil C sequestration (3.1), farmscape sequestration, e.g., planting of trees and hedgerows (2.9), and fertilizer use efficiency (1.8). The overall result (16.7 $MMTCO_2E$ yr^{-1}) exceeds agriculture's proportional contribution to statewide GHG, and shows the potential for agriculture to contribute significantly to GHG emission reduction and mitigation. This outcome of the ETAAC report may be somewhat optimistic since it assumes rather high rates of sequestration (e.g., soil C sequestration at the rate of 0.61 MTCO$_2$E acre^{-1} yr^{-1}, which corresponds to 1500 kg C ha^{-1} yr^{-1}) and high rates of adoption by farmers. More in-depth research is needed to understand the processes, assumptions and conversions, e.g., soil C as described above, across the wide range of commodities, management, and soils across the state.

Table 8. Weighed averages of changes in the GWP, SOC, and nitrous oxide (N_2O) emissions (see Table 7). Averages are taken for each crop over 10 years (1997-2006) over all fields and crop rotations within multiple counties of the Sacramento Valley versus the San Joaquin Valley. Standard deviations represent the uncertainty around GHG emissions for one single field if this field was under the specific management for 10 years. Note that reductions in CO_2 emissions due to decreased fuel use in conservation tillage systems are not included in these values. These account for an additional reduction in GHG emissions of 0.25 to 0.50 Mg CO_2E ha^{-1} yr^{-1}.
Convent. = conventional tillage; conserv. = conservation tillage.

Tillage	Fertilizer	Cover crop	GWP (Mg CO_2-eq ha^{-1} yr^{-1})	ΔSOC (kg C ha^{-1} yr^{-1})	N_2O (kg N ha^{-1} yr^{-1})
			Sacramento Valley		
convent.	mineral, 75%	no	-0.89 ± 0.76	-2 ± 16	-1.92 ± 1.59
conserv.	mineral	no	-0.68 ± 0.36	103 ± 34	-0.64 ± 0.56
convent.	mineral	yes	-1.36 ± 0.89	310 ± 180	-0.48 ± 0.94
conserv.	mineral	yes	-1.37 ± 0.88	312 ± 178	-0.48 ± 0.94
convent.	Organic	no	-1.16 ± 0.78	158 ± 63	-1.23 ± 1.51
conserv.	Organic	no	-1.94 ± 1.03	288 ± 88	-1.89 ± 1.86
convent.	Organic	yes	-2.60 ± 1.87	405 ± 212	-2.38 ± 2.81
conserv.	Organic	yes	-3.29 ± 2.07	532 ± 246	-2.86 ± 2.98
			San Joaquin Valley		
convent.	mineral, 75%	no	-0.61 ± 0.58	-4 ± 14	-1.33 ± 1.24
conserv.	mineral	no	-0.57 ± 0.33	81 ± 35	-0.59 ± 0.55
convent.	mineral	yes	-1.35 ± 1.07	284 ± 170	-0.66 ± 1.36
conserv.	mineral	yes	-1.38 ± 1.08	287 ± 169	-0.68 ± 1.39
convent.	Organic	no	-0.49 ± 0.89	154 ± 54	0.16 ± 1.96
conserv.	Organic	no	-1.14 ± 0.90	255 ± 79	-0.43 ± 1.82
convent.	Organic	yes	-1.87 ± 1.41	395 ± 203	-0.89 ± 2.41
conserv.	Organic	yes	-2.45 ± 1.52	498 ± 235	-1.32 ± 2.41

Source: De Gryze et al., in press.

Two important issues emerge from this analysis: (1) there is uncertainty and a wide range of variability for GHG emissions estimates from agriculture in California depending on crops, management systems, and soils; and (2) it is difficult to validate these estimates at landscape and larger scales. Thus, continuing research is an important component of achieving the maximum emission reductions from the agricultural sector in order to clarify technical issues and projections. In the meantime, estimates should be taken with care, and that management to reduce GHG emissions should be combined with the capacity to increase other ecosystem services, e.g., productivity, water quality, air quality, and erosion prevention.

2.6. Commodity Production: Water Resources and Responses to Climate Change

Water resources will be an essential theme in California to accommodate trends in population growth, climate change, and vulnerability to drought and flooding. As described in Section 1.6 and 2.2, California's Mediterranean climate presents a management challenge that requires the flexibility to be able to shift water from wet years or locations to drier events and locations. In Yolo County, joint use of surface water for groundwater is an example of shifting water supplies to maintain its supply. In western Yolo County, the major water supplies from rainfall come from the Coast Range, while eastern Yolo County relies more strongly on water originating from snowmelt from the north and east Sierra Nevada (Sections 3.6 and 3.7). Water supply in both areas are likely to be affected by climate change, but in different ways. Since a significant amount of Yolo County's surface water supply is primarily from rainfall, an annual decrease in the amount of precipitation would have the most negative consequences on water supply.

California precipitation history over the last century shows an very slight increasing trend. There were fewer periods of extended drought in the latter part of the last century as compared to the period of 1915 to 1935, when severe drought occurred, although the early 1990s also brought a serious drought. The historical runs of the GCM models (e.g., Figure 6) are in agreement with these records (Cayan and Tyree, Scripps Institute 2008). Present climate models do not predict any prolonged drought occurrence until the end of this century (Joyce et al. 2006). However, drought typically remains unpredictable and therefore planning agencies should always include extended drought events in their planning horizons. Competition for surface water supplies under drought conditions can be fierce and likely would impact the amount and timing of water deliveries. Since agricultural enterprises rely on the concept of "use as needed," an interruption in water delivery would impact the industry negatively.

Adaptation to a more uncertain water supply will require that crops be planned and managed with methods that reduce water use per acre: applying alternative technologies, such as using drip irrigation rather than furrow irrigation; finding ways to reduce evaporation in relation to transpiration, such as crop breeding for greater canopy cover; switching to crops that use less water; and/or reducing overall irrigated crop acreage.

Subsurface drip irrigation has been shown to reduce both CO_2 and N_2O emissions, compared to furrow irrigation, with no differences in tomato yields on a recent research station study at UC Davis (Kallenbach 2008). The GHG emissions following a winter legume cover crop were also lower. With subsurface drip irrigation, across different tillage and cover crop treatments, water use efficiency was 40% to 50% higher than with furrow irrigation. Adoption of pressurized, micro-irrigation systems, however, requires higher energy inputs, plastics, and labor. As a result, the overall advantages of drip irrigation may not be as high as simply indicated by water use.

Based on projections with the WEAP model, using climate outputs from Global Circulation Models (GCMs), only small changes in management, water deliveries and pumping are expected to occur in the Sacramento area up to 2050 (Joyce et al. 2006). Under dry climate change scenarios (PCM A1fi and GFDL A2), the intensity, frequency and duration of droughts will increase, but larger droughts, i.e., similar to those in 1976–1977 and the early 1990s droughts, may occur only late in the century (Figure 18). Since Yolo County relies on surface water from the Sacramento River it is expected to experience less impact than elsewhere in California, since much of the Sacramento watershed above Lake Shasta lies below the snow line and is therefore less dependent on snow melt runoff than the American and Feather Rivers.

Nevertheless, the adverse effects of drought in the County should be considered since drought has been a recurrent theme for California agriculture. Lee et al. (2001b) examined the impacts of hypothetical surface water irrigation cutbacks (25% less during a normal, non-drought year with no supplemental groundwater) on agricultural patterns and the local economies of Sacramento Valley's counties. Projected crop supply and input use responses were analyzed, including changes in crop acreage, per-acre water use, irrigation system costs and resulting water costs. Changes in farm revenue were also calculated (Table 9). All evaluations included potential farmer actions to mitigate for water cutbacks, including reducing water use per acre (alternative technologies), switching to crops that use less water, and reducing acreage that is irrigated. The negative effects in Yolo County are more dramatic for high water-demanding crops including alfalfa, some small grain crops, vegetable crops such as tomatoes, and most importantly rice. In total, they found only a 0.31% loss in personal income in Yolo County. Across all counties, crops with more return per acre and per unit of water showed less acreage reductions.

Table 9. Farm revenue changes from a hypothetical 25% surface water cutback in Sacramento Valley. The negative effects are more dramatic for more water-demanding crops, most importantly rice, alfalfa, and vegetable crops such as tomatoes.

	Farm revenue changes (1,000 dollars)								
Commodity	**Tehama**	**Glenn**	**Butte**	**Sutter**	**Colusa**	**Yuba**	**Yolo**	**Sacramento**	**Total**
Pasture	-299	-337	-418	-483	-40	-139	-249	-349	-2,314
Alfalfa hay	46	-86	-8	-14	-124	-4	-243	105	-328
Sugarbeets	-5	-105	-13	-60	-171	-3	-158	-26	-541
Field crops	-155	-348	-102	-1,000	-934	-41	-899	-152	-3,631
Rice	-26	-4,132	-2,575	-2,744	-6,584	-1,405	-929	-211	-18,606
Vegetables	-1	a	-1	-72	-78	a	-56	-3	-211
Tomatoes	a	a	a	-102	-187	a	-366	7	-648
Fruits, nuts	59	-27	-140	-70	-27	-35	-25	11	-254
Small grains	-331	-362	-599	-699	-574	-156	-1,345	-67	-4,133
Subtropical	2	5	-4	a	a	-3	a	-3	-3
Total	**-710**	**-5,392**	**-3,860**	**-5,244**	**-8,719**	**-1,786**	**-4,270**	**-688**	**-30,669**

a Not produced in this county.

Source: Table extracted from: Lee, Sumner, and Howitt (1997).

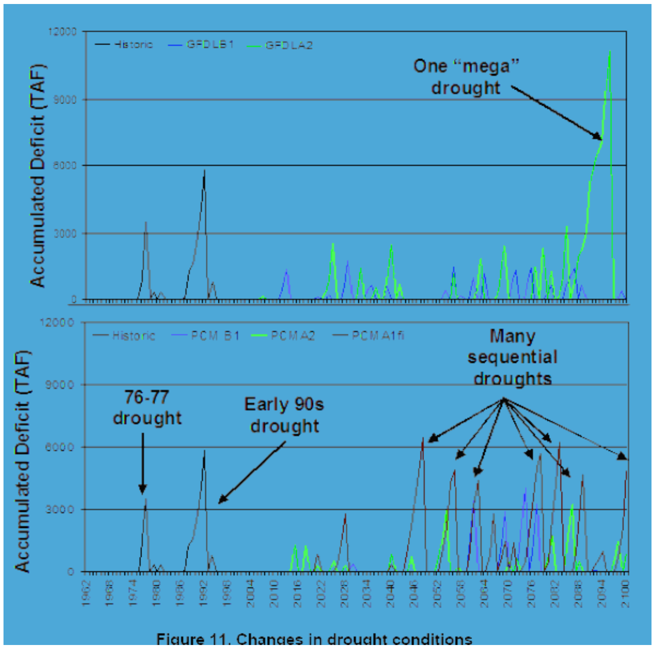


Figure 18. Modeling with the WEAP model to show water deficits during the next century based on GCM modeling of A2 and B1 scenarios. Under dry climate change scenarios (PCM A1fi and GFDL A2), the intensity, frequency and duration of droughts will increase, but larger droughts, may occur only late in the century.

Source: Joyce et al. 2006.

2.7. Potential for Biofuel Feedstock Production and Processing

To consider the possible availability of feedstock for a corn-based ethanol plant, we hypothesized a processing plant in Dixon, Solano County, drawing in feedstock from a 30 mile radius in Yolo and Solano Counties. The initial conditions were that economies of scale require that the plant must produce at least 50 million gallons of ethanol per year and 155,000 tons of dried distiller's grains, requiring 16.667 million bushels (bu) of corn per year or 95,000 acres (38,500 hectares) (at 175 bu/acre or 71 bu/hectare). The plant location in Dixon was assumed to have the following characteristics:

- The market for dried distillers grains would require 8,000 dairy cows <15 miles away
- Rail access would be available on the Burlington Northern Santa Fe Railway (BNSF) Rail line, plus spur, within 0.3 miles
- Interstate road access via I-80 would be within 0.6 miles
- Oil refinery at Vallejo and Benicia, California, would be 37 miles distant

The analysis was limited to a 30-mile radius in Yolo and Solano Counties (1.8 million acres, or 0.7 million hectares). The Vaca Mountains limit access to Solano and Yolo from Napa and Lake Counties to the west. The Sacramento River and the Sacramento metropolitan area form an eastern barrier. To the south lie San Pablo Bay and the Suisun Marsh. Limiting our analysis to the portion of Yolo and Solano County within a 30 mile radius decreased our focus to 1.1 million acres (50,000 hectares), which are now occupied by a diverse set of horticultural and grain crops (Figure 19) (Richter, Lee, and Sumner, unpubl. data).

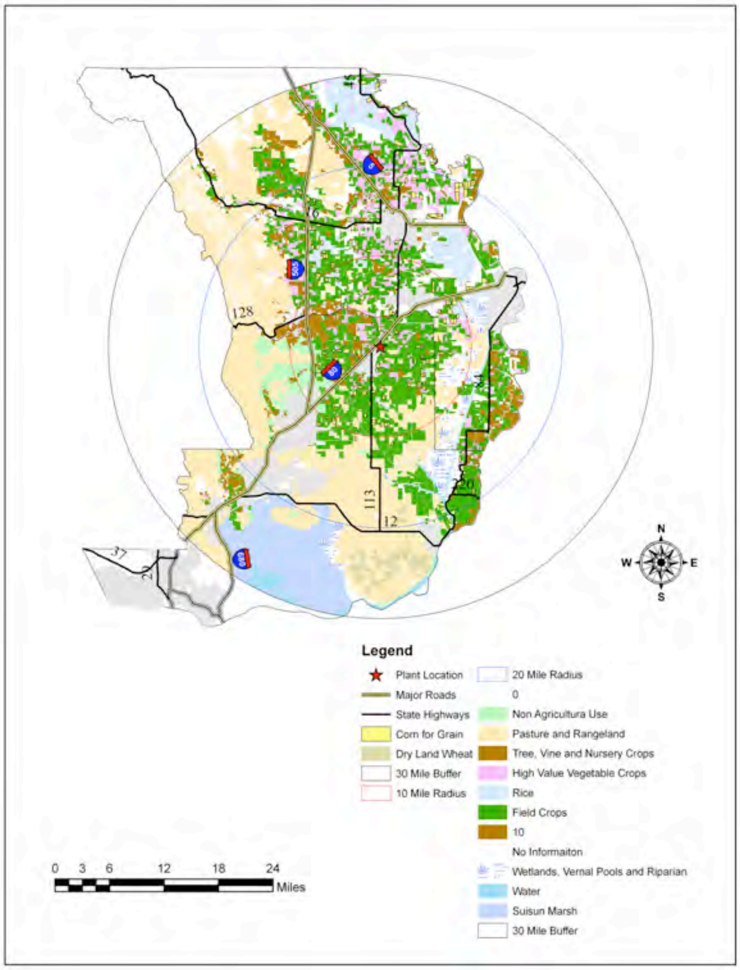


Figure 19. Hypothetical biofuel feedback production map for Yolo and Solano Counties. Within the designated 30-mile radius of the hypothetical processing plant in Dixon, 54,000 acres are urban, 135,000 are wetland, marsh or riparian areas, and 33,000 acres are not used for agricultural production. The remaining 838,000 acres include 361,000 acres of pasture and rangeland, 61,000 acres of tree, vine and nursery crops, 60,000 acres of high value vegetable crops, 43,000 acres of rice, 12,000 acres of dryland row crops, and 242,000 acres

of irrigated field crops. The field specific data leave 59,000 acres unaccounted for.

Source: Kurt Richter, Hyunok Lee, and Dan Sumner, unpubl. data.

Expanding to 95,000 acres (38,000 hectares) of corn would require that more than one-third of all other field crop land to be converted to corn. For example, satisfying demands of the ethanol plant would require converting 95% of the wheat and irrigated pasture land into corn production.

Corn is currently part of a crop rotation to prepare land for processing tomato production and other commodities, which can vary according to the expected price. Corn acreage also varies with the expected price of corn.

Over the last four years, there has been a 61% increase in the price of corn, which has triggered corn acreage to return to the high levels present in 2004 (Table 10). This change is similar to the statewide reaction to the recent increase in corn prices which has been an increase in corn grain acreage from a 2004–2006 average of 130,000 acres to 200,000 acres (53,000 hectares to 81,000 hectares) in 2007.

Table 10. Acres of corn grown in the designated 30-mile radius around the hypothetical biofuel processing plant in Dixon, California, and the price per bushel in the last four years

	2004	2005	2006	2007
Acres	18,380	9,083	3,688	18,278
Price per bushel	$2.44	$2.67	$3.16	$3.95

Source: Kurt Richter and Daniel Sumner, Agricultural Issues Center, UC Davis

The diverse agricultural geography in Yolo and Solano Counties clearly limits corn production. California ethanol plants must compete with Midwestern ethanol plants in the global ethanol market and California feedstock must compete with corn from the Midwest. California corn prices have adjusted along with national corn prices and producers have incorporated the expected increase in corn prices into their planting decisions. No ethanol plant could be expected to pay more than a 10% premium in price and recent history tells us that this cannot be sufficient to attract the needed crop acreage shifts from the other field crops. A Dixon-based ethanol plant would not be able to increase local price by a large enough margin to generate the additional acreage for local corn acreage to supply the ethanol plant.

3.0 Landscapes: How Land Use Options May Increase Mitigation and Adaptation to Climate Change

3.1. Landscape Responses to Climate Change: A Generalized Overview

Land use change in Yolo County during the next 50 years will be partly due to direct efforts to mitigate greenhouse gas emissions and adapt to higher temperatures and more variable weather, but several other factors are also important: population growth, urbanization, regulations that affect agriculture, external agriculture markets, and direct efforts to mitigate GHG emissions and adapt to higher temperatures and more variable weather.

Since 1850, California's agriculture has been in a constantly changing via growth, transition, and adjustment (Williams et al. 2005). Large changes have occurred within the last 150 years in Yolo

County beginning with early attempts to raise livestock, grow grains, and develop horticulture without much irrigation; followed by the era of ruminants and extensive wheat and barley production; followed by beginnings of intensive fruit, nut, and vegetable agriculture and large-scale cattle production; ending with the present management-intensive, technologically-dependent agricultural industry (Mikkelsen 1983; Johnston and McCalla 2004), and expanding organic production (Yolo County Crop Reports).

One of the greatest challenges is planning land use change to increase sustainability, i.e., that tradeoffs between agricultural productivity, environmental quality, and human livelihoods and well-being be assessed for the greatest long-term benefits to society as a whole. A major concern is that sustainability may be lost when climate change and urbanization increase the pressure for short-term financial gain from current agricultural lands, especially given increased potential losses from continuously changing and extreme weather conditions.

Using a GIS approach that "queries" current and potential land use, possible outcomes of these scenarios will be presented later in this document. The objective is to assess the tradeoffs involved in responding to climate change at the landscape level. For example, we can examine the changes in acreage and revenue if crops no longer are grown on poorly drained soils in the 100- or 500-year floodplain, the concomitant effects on C sequestration from restoring these lands to woodlands vs. simply allowing invasive species to dominate these lands. Another example is the effect of eliminating specific crops, e.g., rice due to its high water use and GHG emissions, relatively low revenue or even its negative impacts on wildlife, compared to other row crops (see below). By combining a set of GIS overlays of different landscape attributes (e.g., vegetation, soils, water resources), queries were set up on issues related to land use, and how this affects a set of ecosystem services.

3.2. Current Status of Land Use in Yolo County's Agricultural Landscapes

Current land use. Yolo County encompasses about 648,320 acres (262,370 hectares) (Yolo County 2005a). Agricultural land occupied 550,407 acres (222,742 hectares) in 2002 (USDA 2002), while only about 5% was classified as urban in the incorporated cities of Davis, West Sacramento, Woodland, and Winters. The majority is cultivated cropland (54%). Second in acreage is livestock grazing (22%), followed by public open space (8%) and orchards/vineyards (7%). Orchards/vineyards tend to be on smaller parcel sizes than other agricultural crops, and in the eastern area (Yolo County 2005a). Residential and rural residential are only 3% of the area.

In 1998, Yolo County alone contained about 43% 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 (Sokolow and Kuminoff 2000).

Recent land use change. From 1984 until 2004, there was a net loss of about 50,000 acres (20,000 hectares) of farmland, and a net gain of about 27,000 acres (11,000 hectares) of grazing land according to the 2006 California Department of Conservation Farmland Mapping and Monitoring Program (FMMP). In 1988, several thousand acres were converted from farmland of local importance to grazing land due to sign ups for the federal Conservation Reserve Program. Only 1% of Yolo County's total prime farmland has been lost (Sokolow and Kuminoff 2000).

Urbanization accounted for 5,500 acres (2,200 hectares) of agricultural land (including grazing land) between 1992 and 2004 (California Department of Conservation 2006) (Table 11a). Most of this was prime farmland and farmland of local importance, rather than grazing land. Very rough estimates calculated by Sokolow and Kuminoff (2000) show that in the Sacramento region, each acre of farmland converted to urban development houses only about 6.5 people (or about 2 residences per acre), where as a sample of 16 cities throughout the Central Valley had residential densities 12 to 25 persons per acre.

Table 11. (a) Yolo County agricultural land converted to urban/built-up land or "other" land between 1992–2004, (b) Future projections of Yolo County's land use conversions: absolute area of land lost and relative losses (percentage lost of Yolo County's total acreage for that land use type) due to projected urbanization.

a.

Agricultural land converted to:	1992–1996 (acres)	1996–2000 (acres)	2000–2004 (acres)	1992–2004 Net acreage changed
Urban/built-up land	1,325	1,837	2,401	5,563
Other[1] land	898	9,582*	10,493+	20,973

[1] Other land = land not included in any other mapping category, including but not limited to: low density rural developments; brush; timber; wetland; riparian areas not suitable for livestock grazing, confined livestock, poultry, or aquaculture facilities; strip mines; borrow pits; and water bodies smaller than forty acres; vacant and non agricultural land surrounded on all sides by urban development and greater than 40 acres.

* Conversion to other land is so large partly due to the establishment of the Yolo Bypass Wildlife Area.

\+ Conversion to other land is so large partly due to land left idle for three or more update cycles and the identification of ranchettes, aggregate mines, wetland areas, and rural commercial uses.

b.

	1998–2020		1998–2050		1998–2100	
	Acres	*%*	*Acres*	*%*	*Acres*	*%*
Total urbanized land area added	6,314	n/a	15,776	n/a	27,316	n/a
Steeply sloped (>15%) land lost	42	0	42	0	0	0
Wetlands lost	339	0	1,273	1	4,559	4
100m riparian zone lost	1,302	2	2,674	3	3,667	5
Prime farmland lost	257	0	3,223	1	7,010	3
State and locally important farmland lost	2,708	3	5,564	7	6,692	8
Unique farmlands lost	672	1	2,612	5	2,679	12
Grazing land lost	363	0	835	1	1,537	1
Good quality multi-species habitat lost	2,970	1	4,678	1	6,600	2
Outstanding multi-species habitat lost	104		272	0	314	0
Irreplaceable multi-species habitat lost	0	0	0	0	0	0

Source: (a) Landis and Reilly 2003; (b) FMMP 2006.

Land taken out of agricultural production for other purposes include, but are not limited to farming land that has been transferred to wetland and wildlife habitat, ranchettes, or open space land surrounded by urban developments.

Agricultural land use has a low impact on county revenues, and revenues are approximately three times higher than county expenditures, but this does not consider benefits not included in tax base formula, such as flood control, groundwater recharge, greenhouse gas mitigation, and wildlife habitat/open space/recreation (Yolo County 2002). Industrial and retail uses generate seven to eight times more revenue than expenditures, while expenditures are greater than revenues for cities as whole, which includes retail, commercial and residential, and approximately equal for housing (Yolo County 2005b).

Current projections for agricultural land use. Current projections, independent of climate change, suggest that Yolo County's losses of agricultural land area will be minimal to moderate, compared to the rest of the state (Landis and Reilly 2003). Yolo County adopted an agricultural conservation ordinance in 2000 which requires a one-to-one acreage mitigation requirement from conversion of agricultural land to another use (Kuminoff et al. 2000; Yolo County 2002). The county also has restrictions on the minimum size of parcels (Yolo County 2002). It has one of the state's highest percentages of land protected by the Williamson Act, which requires 10-year minimum contracts for enrolled parcels (Figure 20). In 1999, 75% of Yolo County's agricultural land was in contract, which was far more than the neighboring counties in the Sacramento Region (Kuminoff et al. 2000, Figure 9). Yet, this has steadily declined over the last fifteen years to 418,935 acres (169,537 hectares) in 2005 (Yolo County 2006a).

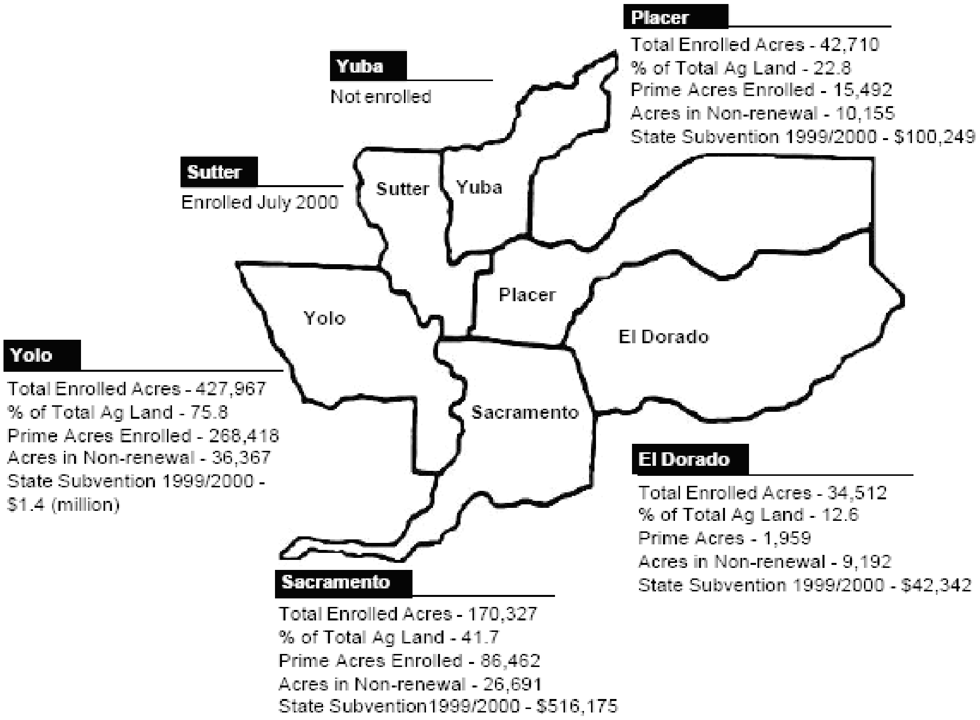


Figure 20. Williamson Act trends for the Sacramento Region, 1998–1999: During that period, 75% of Yolo County's agricultural land was in contract. Since then, it has steadily declined but is still maintained far more than the

neighboring counties in the Sacramento Region (Yolo County 2006a).

Source: Agriculture in the Sacramento Region (Kuminoff et al. 2000).

Yolo County's urban footprint is expected to double from the late 1990s, with a total of 27,316 acres (11,054 hectares) converted to urban land use from some other use (Landis and Reilly 2003, Table 9). City expansion is where the majority of the urbanization is expected to occur. The cities adjacent to I-80, including Dixon, Davis, and West Sacramento, are expected to experience most of the population growth, which are all largely surrounded by prime farmland (Sokolow and Kuminoff 2000; Landis and Reilly 2003; Yolo County 2005a). Nevertheless, losses of farmland in the county are projected to be smaller than many other counties in California.

Yolo County's projected losses in riparian areas, grazing lands, and multi-species habitat are also low compared to other areas in the state (Landis and Reilly 2003). By 2050, a total of 1,273 acres (515 hectares) of wetlands (or 1% of all of the county's wetlands) are projected to be lost, and by 2100 this increases to 4,559 acres (1,845 hectares) or 4% (Table 11b). It should be noted that great loss of wetlands have already occurred in this region during the past 150 years (Vaught 2007).

3.3. Vulnerabilities of Yolo County's Agricultural Landscapes to Climate Change

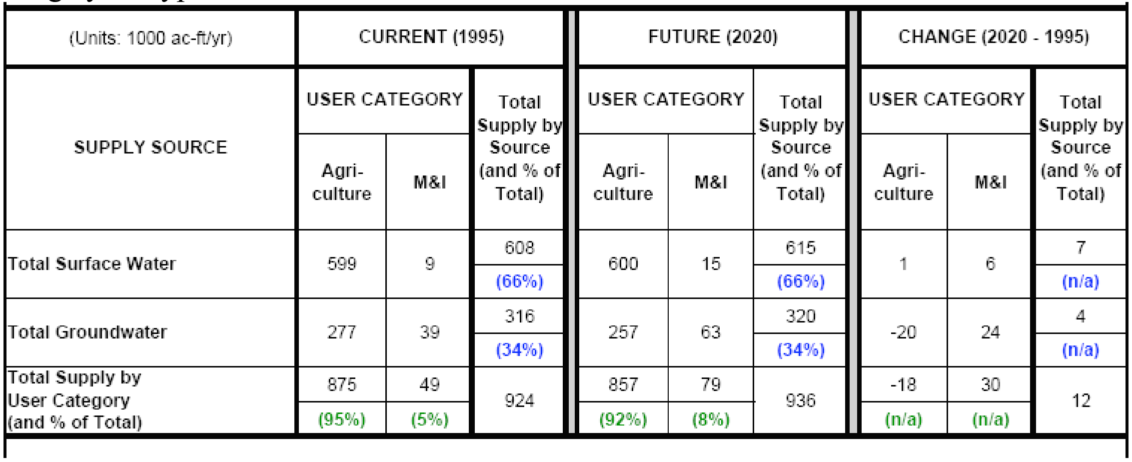
At the landscape scale, Yolo County agriculture faces several vulnerabilities that are likely be exacerbated by climate change, and thus affect land use decisions for agriculture differentially in the various regions of the county (e.g., flooding near the Sacramento River and increased wildfire frequency in the uplands). Most of the regions of Yolo County, however, are ultimately vulnerable if there is a long-term decrease in water supply from reduced rainfall.

Climate change could reduce Central Valley agricultural water deliveries by 37% from current deliveries in a dry climate warming scenario, based on GCM modeling combined with the CALVIN and SWAP models (Tanaka et al. 2006). With a shift to higher value crops, agriculture income only falls 6% while sustaining about a 24% decrease in agricultural water deliveries on 2100 urbanization adjusted water demands. These changes are unlikely to be as pronounced by mid-century, and in addition, Yolo County is in a more favorable location for water reserves that counties further south of the Delta.

On average, about two-thirds of the water used in the county is from combined surface waters (mostly by agricultural users), and only one third is from groundwater (Table 12) (Yolo County 2007a). In the future (2020), about 50% more groundwater supplies are projected to be needed under drought year conditions than would be needed under average-year conditions, not considering climate change (Yolo County 2007a). When modeling future water supply/demand for Yolo County it is assumed that that there will be an increase in urban water demands and decrease in agricultural demands.

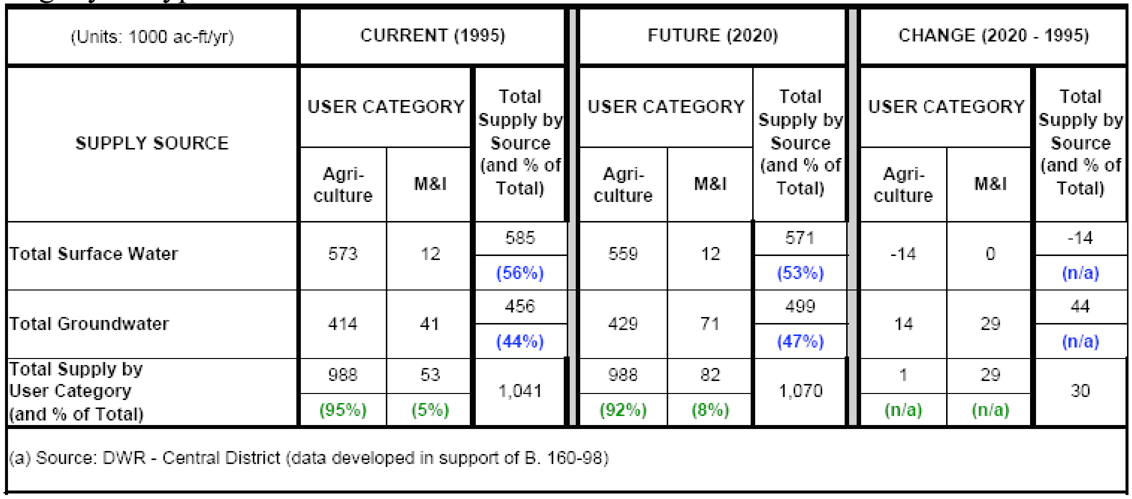
Table 12. Yolo County annual water supplies by user category for (a) average year-type conditions, and (b) drought year-type conditions. In the future (2020), about 50% more groundwater supplies are projected to be needed under drought year conditions.

a. Average year-type conditions



(Units: 1000 ac-ft/yr)	CURRENT (1995)			FUTURE (2020)			CHANGE (2020 - 1995)		
SUPPLY SOURCE	USER CATEGORY		Total Supply by Source (and % of Total)	USER CATEGORY		Total Supply by Source (and % of Total)	USER CATEGORY		Total Supply by Source (and % of Total)
	Agri-culture	M&I		Agri-culture	M&I		Agri-culture	M&I	
Total Surface Water	599	9	608 (66%)	600	15	615 (66%)	1	6	7 (n/a)
Total Groundwater	277	39	316 (34%)	257	63	320 (34%)	-20	24	4 (n/a)
Total Supply by User Category (and % of Total)	875 (95%)	49 (5%)	924	857 (92%)	79 (8%)	936	-18 (n/a)	30 (n/a)	12

b. Drought year-type conditions



(Units: 1000 ac-ft/yr)	CURRENT (1995)			FUTURE (2020)			CHANGE (2020 - 1995)		
SUPPLY SOURCE	USER CATEGORY		Total Supply by Source (and % of Total)	USER CATEGORY		Total Supply by Source (and % of Total)	USER CATEGORY		Total Supply by Source (and % of Total)
	Agri-culture	M&I		Agri-culture	M&I		Agri-culture	M&I	
Total Surface Water	573	12	585 (56%)	559	12	571 (53%)	-14	0	-14 (n/a)
Total Groundwater	414	41	456 (44%)	429	71	499 (47%)	14	29	44 (n/a)
Total Supply by User Category (and % of Total)	988 (95%)	53 (5%)	1,041	988 (92%)	82 (8%)	1,070	1 (n/a)	29 (n/a)	30

(a) Source: DWR - Central District (data developed in support of B. 160-98)

Source: Water Resources Association of Yolo County 2007.

In western Yolo County, a strong effort for many years has been made for maximizing groundwater storage through recharge. Maintaining groundwater levels in aquifers is intended to reduce the need for construction of dams, as well as the loss of water through evaporation from water bodies (Yolo County Flood Control and Water Conservation District 2007). Not only the surface water from rain, lakes, and streams percolates into the aquifer, but >25% of the water released from the Clear Lake and Indian Valley reservoir systems goes directly to groundwater recharge. This is facilitated by having mainly unlined irrigation ditches and canals.

The 100- and 500-year floodplains of the Sacramento River extend westward into prime agricultural farmland (Figure 21) (California Department of Water Resources 2005; Spencer et al. 2006). If flooding occurs late in the spring (April–June), crops planted during March–May may be damaged or destroyed. It is often too late by this time to replant fields with new crops.

If soil remains wet, tillage is delayed, shortening the growing season and decreasing yields. Tomato farming in the Northern Yolo Bypass area has already become uneconomical due to the prolonged periods of late spring flooding that have occurred more frequently than in the past (Jones and Stokes 2001). Planting beds, furrows, ditches, and other agricultural related infrastructure (e.g., roads, canals, diversion structures, pumps, and wells) can also be damaged or destroyed by flooding.

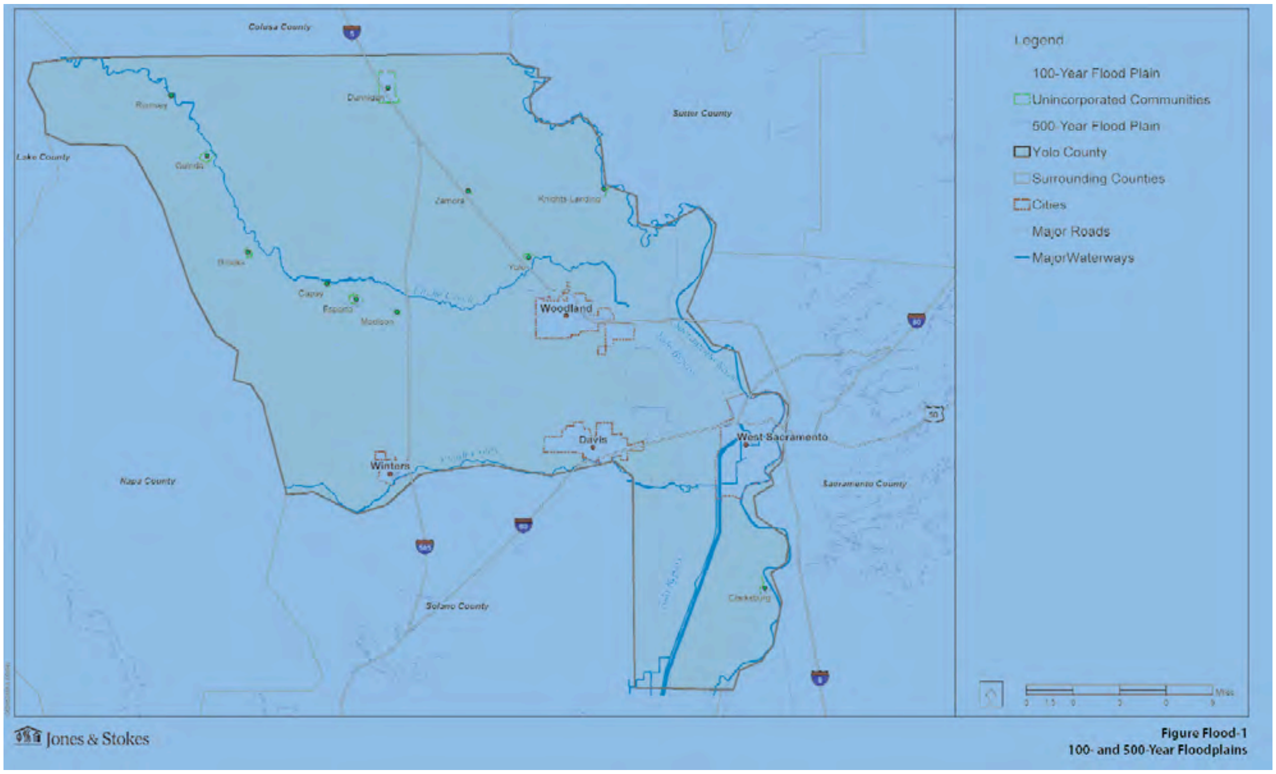


Figure 21. Yolo County's 100-year and 500-year floodplains of the Sacramento River extend westward into prime agricultural farmland.

Source: Yolo County (2005a).

Overall, spills from the Fremont Weir are the primary source of flooding that occurs during the Yolo Bypass major inundation events. In some wet years, even if the Fremont and Sacramento Weirs do not spill, the smaller tributaries alone can create localized flooding. The immense amount of flood water that the Bypass is engineered to convey (approximately 14,000 cubic meters per second [m^3/sec^{-1}]) has saved several Yolo County communities from flood damage (Sommer et al. 2001).

Increased flooding is recognized as a possible future effect of climate change, with more precipitation occurring as rainfall (instead of snowfall) than historically (Hayhoe et al. 2004; Joyce et al. 2006; Spencer et al. 2006). Yolo County's flooding potential will likely be spatially variable, and difficult to predict, since the watersheds in the Coast Range Mountains are sourced by rainfall, while others are sourced by snowmelt and rainfall from the Sierra Nevada. Flood control levees in the entire Sacramento region are in need of major upgrades; it is highly likely that Yolo County's levee system will fail if no maintenance takes place and increased flooding does occur (Spencer et al. 2006). Research and planning are underway to protect land and environmental resources from flooding risks (Spencer et al. 2006; Yolo County 2007a).

3.4. GIS Approach for Land Use Queries Using Geomorphic Units

The impacts of climate change and the associated adaptations in Yolo County will vary according to its diverse landscapes. The land uses and associated agricultural productivity differ among regions as a result of the soils, water resources, and terrain. To reflect these differences we used a GIS approach (see Appendix A), using soil map unit name, soil order, and soil great group, that stratified the county into the following four geographic units that represent similarities in land use, soil types and the environmental factors that formed them (Figure 22):

- **Region 1.** Flood basins
- **Region 2.** Recent alluvium (alluvial plains, fans and low terraces)
- **Region 3.** Old alluvium and hillslope colluvium (high terraces, dissected terraces and low hillslopes)
- **Region 4.** Uplands of the Coast Range

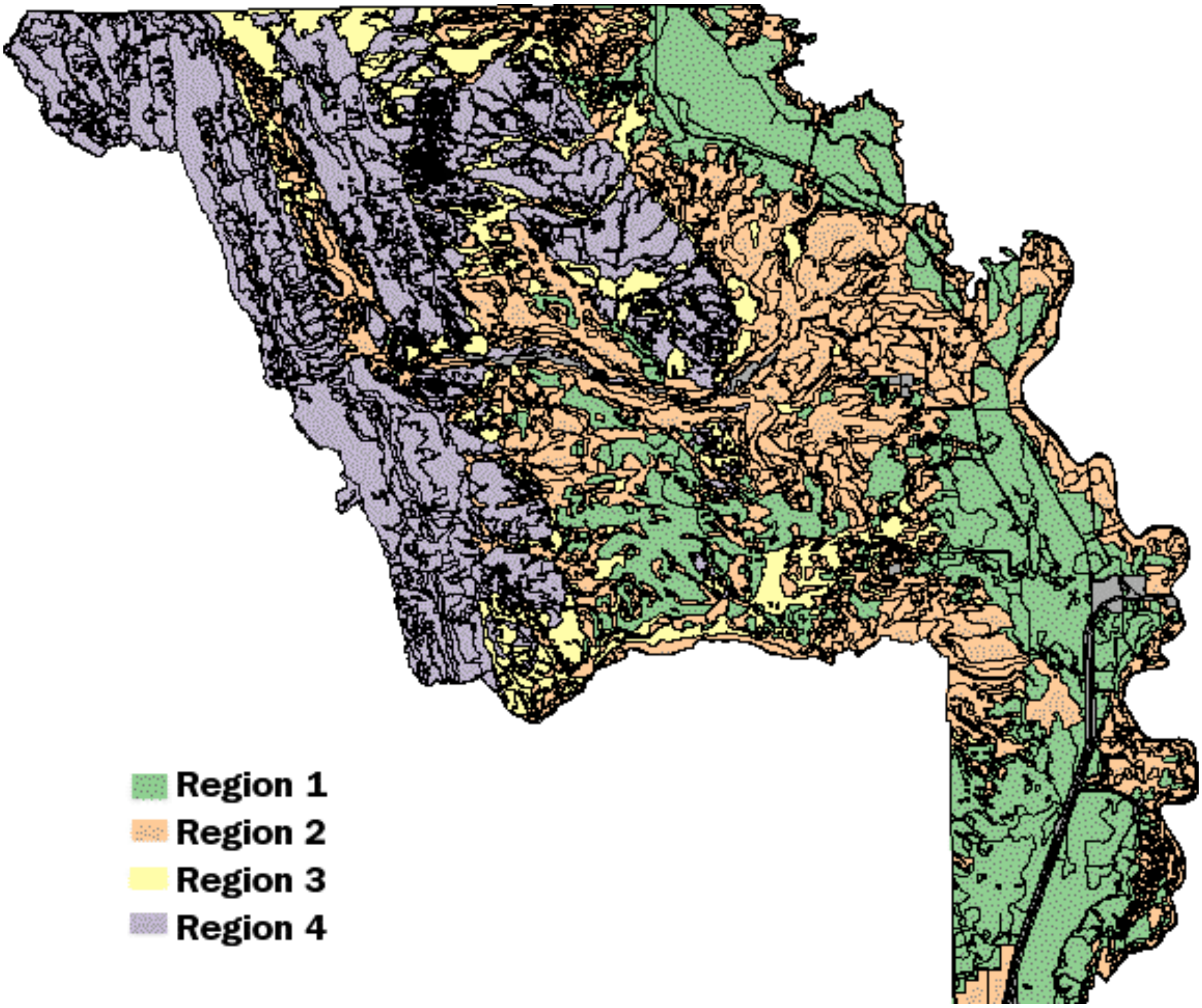


Figure 22. Zonation of landscape regions in Yolo County, based on the aggregation of soil survey data in a GIS. Region 1 represents clay-rich soils in basin alluvium, mostly suitable for rice production (green). Region 2 represents other alluvial soils in their initial stages of soil development (orange). Region 3 represents marginal agricultural lands on higher terraces with rolling foot slopes suitable for orchards and vineyards rather than irrigated row crops (yellow). Region 4 represents steeply sloping rangeland and wildlands (purple). See Appendix 1 for description of GIS approaches.

Source: USDA-NRCS-SSURGO2007. Map created by Allan Hollander, Toby O'Geen, and Fernando Santos , UC Davis

Within regions, the Storie Index Soil Rating was used to classify the potential land utilization and productive capacity across Yolo County (Figure 23). The Storie Index is available in the USDA-NRCS-SSURGO database. For simplification, six soil grades for Yolo County have been defined by combining soils with Storie Index ratings as follows:

- **Grade 1 (excellent):** Soils that rate between 80% and 100% and which are suitable for most crops, including alfalfa, orchard, vegetable, and field crops.
- **Grade 2 (good):** Soils that rate between 60% and 79% and which are suitable for a wide range of crops.
- **Grade 3 (fair):** Soils that rate between 40% and 59% and which are generally of fair quality with certain specialized crops.
- **Grade 4 (poor):** Soils that rate between 20% and 39% and which have a narrow range in agricultural possibilities. For example, a few soils in this grade may be good for rice, but not for many other uses.
- **Grade 5 (very poor)**: Soils that rate between 10% and 19% and are of very limited use except for pasture, because of adverse conditions such as shallowness, roughness, and alkali content.
- **Grade 6 (non-agricultural):** Soils that rate less than 10%, for example tidelands, riverwash, soils of high alkali content, and steep land.

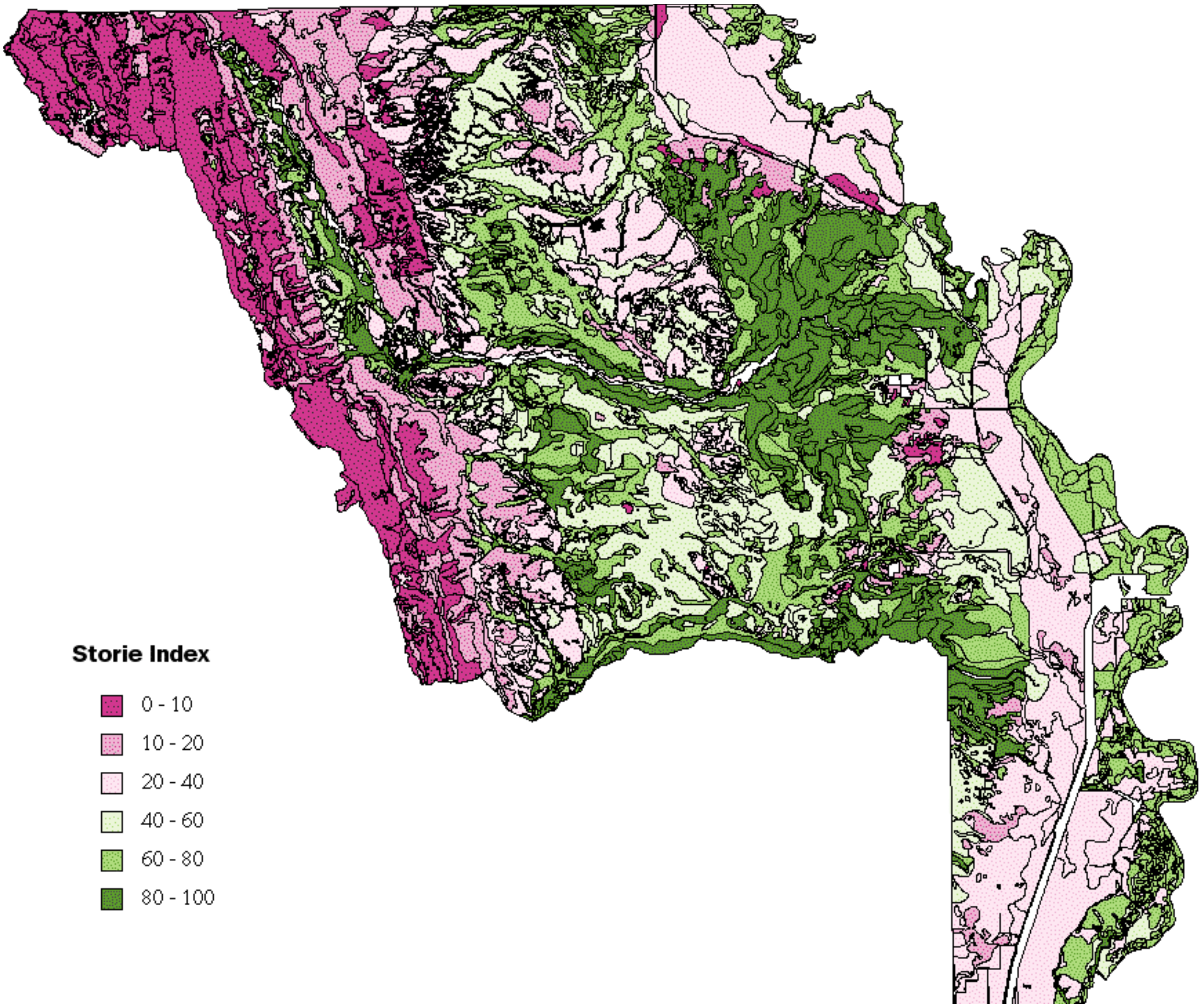


Figure 23. Yolo County Storie Index Soil Rating: *Excellent (80%-100%):* Soils that are suitable for most crops, including alfalfa, orchard, vegetable, and field crops. *Good (60%-79%):* Soils that are suitable for a wide range of crops. *Fair (40%-59%):* Soils that are generally of fair quality with certain specialized crops. *Poor (20%-39%):* Soils which have a narrow range in agricultural possibilities (i.e., soils that may be good for rice, but not for many other uses). *Very poor (10%-19%):* Soils that have very limited agricultural uses except for pasture. *Non-agricultural (0-10%):* Soils on tidelands, riverwash, with high alkali content, or steep land.

Source: USDA-NRCS-SSURGO 2007. Map created by Allan Hollander, Toby O'Geen and Fernando Santos, UC Davis.

Region 1: Flood Basins. Several large flood basins exist along the west side of the Sacramento River (Figure 22, Region 1). Smaller basins are present where streams from the Coast Range empty into depressions in the valley floor. These nearly level basins are adjacent to major water ways that experience flooding on an occasional to frequent basis. Gentle slopes associated with this region result in slow drainage of slack water left after flood events resulting in the preferential accumulation of silt and clay particles. The nature of the particle size distribution and clay mineralogy of these soils results in poorly drained soils with high shrink-swell capacity, which limits the potential uses of these soils. The dominant soil series in this region include Capay, Clearlake, Marvin, Merrit, Omni, Pescadero, Sacramento, and Willows (Andrews 1972). Many of these soils have large C stocks because they are deep and poorly drained, which slows organic matter decomposition. This region has mineral assemblages rich in vermiculite smectite clays, which have been shown to accumulate and stabilize humic substances (Saggar et al. 1996; Ramson 1998; Gonzalez and Laird 2003).

Land capability class for soils within this region ranges from II to IV depending on the degree of wetness, salinity, and flood frequency. Storie Index Ratings are low due to surface texture and drainage. Despite the poor agricultural ratings, a variety of crops are grown in the flood basins including, rice, other grain crops, processing tomatoes, and safflower. A rapidly expanding land use in this region is the conversion of farmland to wetlands for wildlife habitat (Diaz et al. 2008). Despite the flooding hazard, urban development is also expanding within this region.

Region 2: Recent Alluvium. The most productive agricultural region in Yolo County consists of alluvial plains, fans and low terraces of Region 2. This region is located west of the large flood basins extending throughout much of the center of the county (Figure 22, Region 2). This geomorphic region formed from the deposition of stream alluvium consisting of eroded soil originating from the surrounding Coast Range and old terraces. The alluvium is young in geologic time, and was likely deposited over the last 40,000 years. Soils in this region are well drained with loam, silt loam and sandy loam textures. Dominant soils include Yolo, Arbuckle, Brentwood, Reiff, and Zamora. Most soils in this region have been leveled for agriculture and irrigated for several years (Andrews 1972). These soils can be assumed to have moderate C stocks because they are deep and have vermiculite and smectite clays. These soils however are tilled frequently and are well-drained, which leads to more rapid oxidation of soil organic matter.

The land in this region is mainly prime farmland with Storie Index Ratings are excellent ranging from 80 to 100. The land capability class of soils is I. A wide variety of crops are grown in this region including processing tomatoes, tree crops, alfalfa, and truck crops. Urban expansion in this region is a concern, particularly the increase in small ranches with limited agricultural output. Landscapes of Region 2 are prime candidates for the Williamson Act.

Region 3: Old Alluvium and Hillslope Colluvium. Old terraces and hillslopes exist along the eastern margin of the Coast Range west of Region 2 (Figure 22, Region 3). Low hillslopes are located on the western edge of this region and represent the footslopes of the Coast Range. Much of this landscape exists as dissected terraces formed through erosion induced by rapid uplift associated with the rise of the Coast Range. Dominant soils of the dissected terraces include Corning and Positas which have subsoils with claypans (an abrupt increase in clay). Included in this region are low terraces formed on intermediately aged terraces. These soils often have abrupt clay increase with depth and include soils such as Hillgate, Rincon, and San Ysidro. Dominant soils forming in hillslope colluvium include Balcom and Sehorn. Balcom is common on hillslopes and has a bedrock contact within 100 cm. Sehorn is clayey throughout and has high shrink swell potential. Dryland grain crops have been grown throughout this region, particularly in the past. Irrigated pasture is also common. This landscape is also used as rangeland and may experience an expansion of tree crops and vines in the future. Land capability class for soils of this region range from II to VI depending on steepness of slope, depth to clay pan, and degree of erosion (Andrews 1972). Storie Index ratings are good to vary poor and range from 14 to 63 depending on slope and degree of soil profile development.

Region 4: Uplands. The uplands of the Coast Range occupy the western margin of the county (Figure 22, Region 4). The landscape consists of steeply sloping uplands extending up to 3,000 feet in elevation. The associated valleys are narrow and drain eastward. Bedrock consists of shale and sandstone. Steep slopes and rapid uplift result in soil erosion rates that exceed the rate of soil formation on uplands. As a result soils are often shallow. Soils forming in shale tend to be deeper and have more clay because this parent rock is more easily weathered compared to sandstone. Dominant soils of this region include Dibble and Millsholm. Rock outcrop is also a significant component of this landscape. These landscapes are used as rangeland and wildland. Land capability class for soils of this region is VII and VIII depending on slope and rock outcrop (Andrews 1972). Storie Index ratings are poor to non-agricultural and range from 8–34 depending on slope, surface rock content and depth to bedrock and degree of soil development.

Regional overview with some general implications of climate change. Issues and adaptations surrounding climate change are as diverse as the landscapes. The primary issue surrounding Region 1 is flood frequency. More frequent and intense flooding will prohibit timely planting. Intense flooding could affect permanent and temporary levees, which would require more frequent maintenance. In addition, there are few alternative crops suitable to this region. Tree crops are a potential option, but would have a difficult time in the poorly drained soils that flood frequently. Infiltration is low in these soils and careful irrigation is needed to maximize infiltration, but avoid saturating the soil.

The restoration of marginal farmlands into wetlands in Region 1 is one potential adaptation that could mitigate for climate change and greenhouse gas production. Wetlands have several environmental benefits including wild life habitat, buffering from flood events, and improving water quality via filtration. Many wetlands have been shown to sequester C. These systems, however, are prone to discharge other GHG such as N_2O and methane, which are more potent GHG than CO_2 (Section 2.5). Thus, restored wetlands may become a net source of GHG instead of a sink (Mitsch and Gosselink 2000). More research is needed in these landscapes to document C cycling and greenhouse gas emissions.

Landscapes of Region 2 may have the greatest potential for resilience to the effects of climate change. A variety of crops can be grown in this region, offering growers the opportunity to change commodities with lower potential losses. Some best management practices could be adopted to maintain or enhance C storage in soils such as the use of cover crops, organic agriculture, conservation tillage, irrigation management, buffer strips, and vegetative filter strips (Grismer et al. 2005; O'Geen et al. 2006; O'Geen and Schwankl 2006). While the effectiveness of these best management practices has been demonstrated to reduce erosion, their impact on C storage has not been thoroughly evaluated across the Yolo County and throughout California.

In Regions 2 and 3, soil and irrigation management practices that prevent soil erosion can maintain or boost the C stock. A switch to drip irrigation can conserve water and eliminate irrigation-induced soil erosion (Hanson et al. 2008). Other residue management practices such as conservation tillage, cover crops, compost and mulch can improve water infiltration, increase soil organic C and reduce storm water runoff (O'Geen et al. 2006). These practices have multiple positive feedbacks including enhanced productivity, improved water quality, better water use efficiency, and may increase C sequestration. Pressures associated with these two regions include the availability of water and water quality (of irrigation water and surrounding surface water supplies). An added pressure is the expansion of urban land.

Region 4 has the greatest potential to maintain its C stock. This landscape has tremendous aboveground and belowground C stocks that are relatively unaffected by the present land use. Best rangeland management practices exist that can maintain this stock by reducing soil erosion and promoting forage production. These include moderate to low stocking rates, rotational grazing, seasonal use of highly erodible land, appropriate seed mixtures and perennial grasses. Climate variability that adversely affects forage production will challenge rangeland managers. Vegetation management such as prescribed fire may be necessary to expand productive areas and avoid catastrophic fire.

3.5. Land Use: Agrobiodiversity as a Source of Innovation for Landscape Responses to Climate Change

One approach for dealing with climate change is increasing agrobiodiversity. Within Yolo County, the regional distribution of crops and other land uses will undoubtedly change in response to climate change. Here we consider a few climate change issues that are relevant to using agrobiodiversity as a source of mitigation and adaptation. As explained above (Section 2.4), one aspect of agrobiodiversity is the mix of crops on a farm, or at the landscape scale, and also includes the diversity of natural ecosystems within the same landscapes. In this section, these types of changes will be explored on a regional basis within the county, using a set of GIS queries about hypothetical situations that may arise.

The basis of these GIS queries, and of other queries related to soil and water issues (Sections 3.5 and 3.6) is a conceptual soil landscape model that uses soil survey (USDA-NRCS-SSURGO) information according to the regions discussed above within Yolo County (Section 3.4) that have similar soil characteristics, thus implying similar resource availability, management needs, and potential crop distribution (see Web Soil Survey at http://soils.usda.gov or Online Soil Survey http://casoilresource.lawr.ucdavis.edu/soilsurvey). Each of the four regional soilscapes consisted of aggregated soil map units through queries of USDA-NRCS-SSURGO data that were based on the soil great groups (see below). The Storie Index of each soil type in the relevant region or tract was calculated separately, and then a rating for the entire area was obtained by weighting each soil Storie Index value according to the proportion of the acreage of that soil in the tract. This classification is independent of other physical or economic factors that might determine the desirability of growing certain plants in a given location.

Based on the most recent complete set of data on land use for Yolo County (DWR, 1997) agricultural land and naturalized vegetation occupied most of the area while only about 4% was classified as urban in the incorporated cities (Figure 24), as was described above. Although many crops and land use types are available in the DWR data, nine groups were created for analyzing general patterns (Table 13). Based on 1997 data, row crops were the dominant crops; field crops (26%), represented by tomatoes and alfalfa, and grain crops (23%), represented by corn and wheat, are the major components. Rice occupied 6% of the land area, but it is not considered in the row crop category due to its unique, flooded management system. Other agricultural systems, such as orchards, vineyards and pasture compose only 8% of the total. A variety of other row crops are also grown as vegetables and fruits (truck crops), but this more diverse collection accounts for only 4% of the county area. These proportions are roughly similar to those in the Yolo County 2005 crop report, with slight exceptions (Section 3.2).

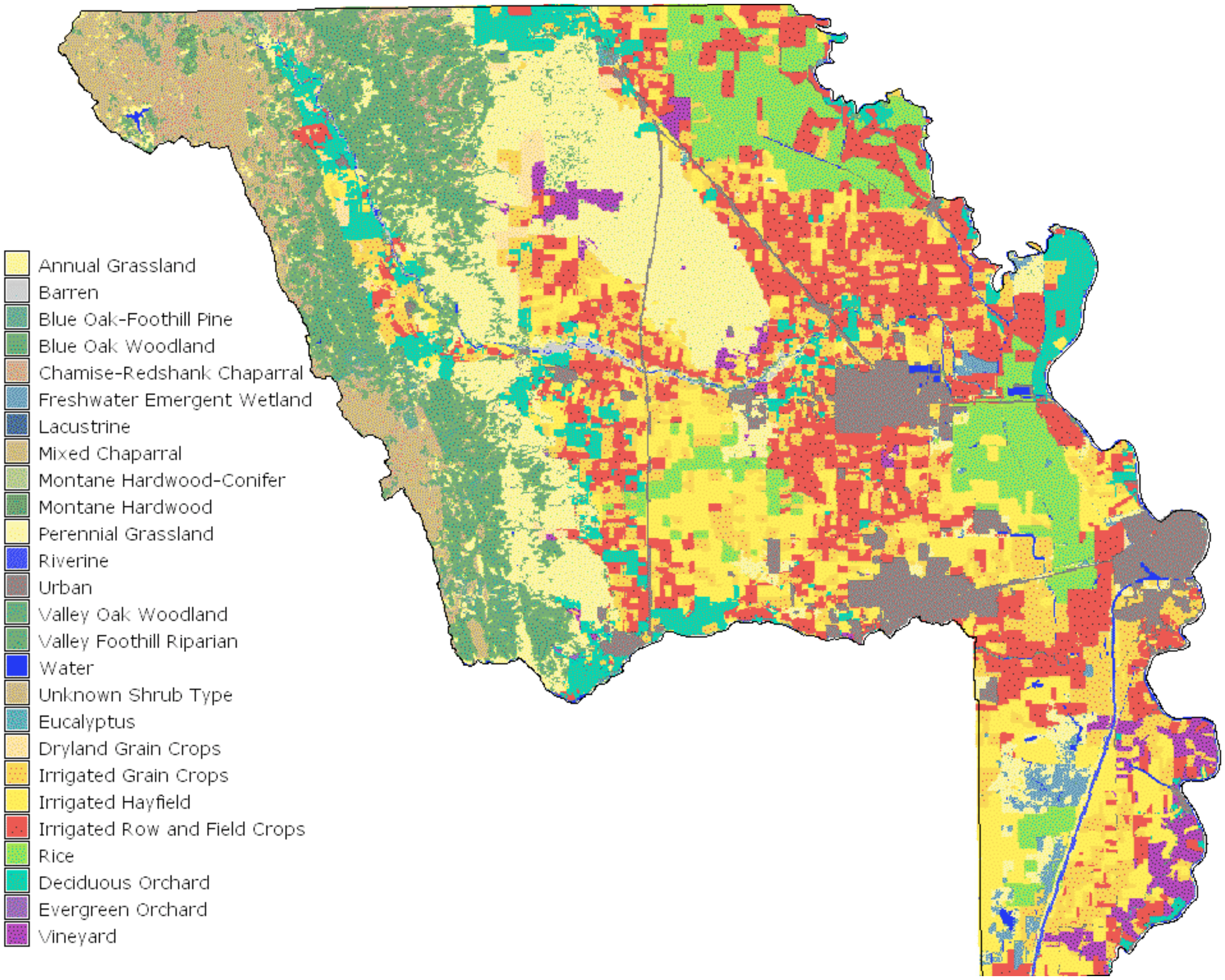


Figure 24. Yolo County land use distribution including agricultural, urban, and wildlands. See Appendix 1 for description of GIS approaches.

Source: California Augmented Multisource Landcover Map. Hollander 2007.

Table 13. Index for crop commodities of land use categories, based on the land uses in the Department of Water Resources (1997) database.

Category	Contents
Orchards	Almonds, Apples, Apricots, Cherries, Citrus, Deciduous Fruits and Nuts, Eucalyptus, Figs, Nectarines, Peaches, Pears, Pistachios, Prunes, Olives, Walnuts

Field crops	Alfalfa, Clover, Cotton, Dry Beans, Safflower, Sugarbeets, Sunflower, Tomatoes
Grain crops	Rice, Corn, Miscellaneous Grain (Wheat), Sudan, Miscellaneous and Mixed Grain and Hay, Grain Sorghum
Pasture	Mixed Pasture, Native Pasture, Pasture
Truck crops	Asparagus, Bush Berries, Cabbage, Carrots, Cole Crops, Cucumbers, Green Beans, Kiwis, Melons, Nursery Crops, Peppers, Onions and Garlic, Squash, Strawberries
Vineyards	Vineyards
Naturalized vegetation	Chaparral, Grassland, Eucalyptus, Montane Hardwood, Oak, Pine, Riparian, Shrub, Wetland, Woodland

According to the Storie Index soil quality distribution, Yolo County soils are fairly evenly distributed between poor and good to excellent soils (Figure 25). Poor soils (31%) comprise the largest fraction and are mainly present in Region 1, which is on the Sacramento River floodplain (Figure 26). Region 1 is predominantly cropped with rice, grain crops (corn and wheat) and field crops (safflower and tomato). These five crops combined occupy nearly 80% of the Poor and Very Poor agricultural land.

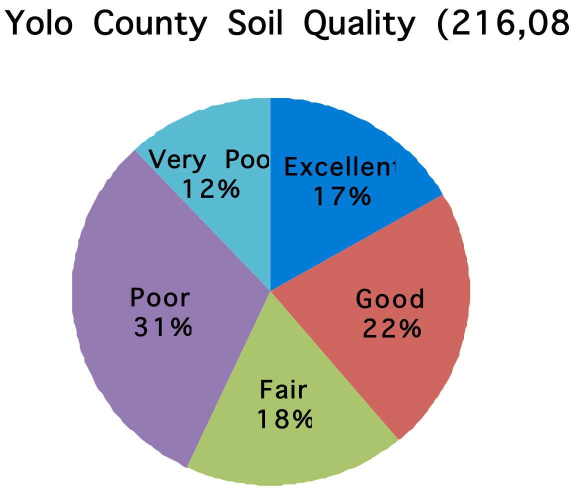


Figure 25. Summary of Storie Index categories for Yolo County’s soils. Poor soils (31%) comprise the largest fraction and are mainly present in Region 1, which is on the Sacramento River floodplain. Region 2 with most of the good agricultural soils, is located in the center of the county. See Appendix 1 for description of GIS approaches.

Source: USDA-NRCS-SSURGO 2007. Figure created by Fernando Santos and Joel Kramer, UC Davis.

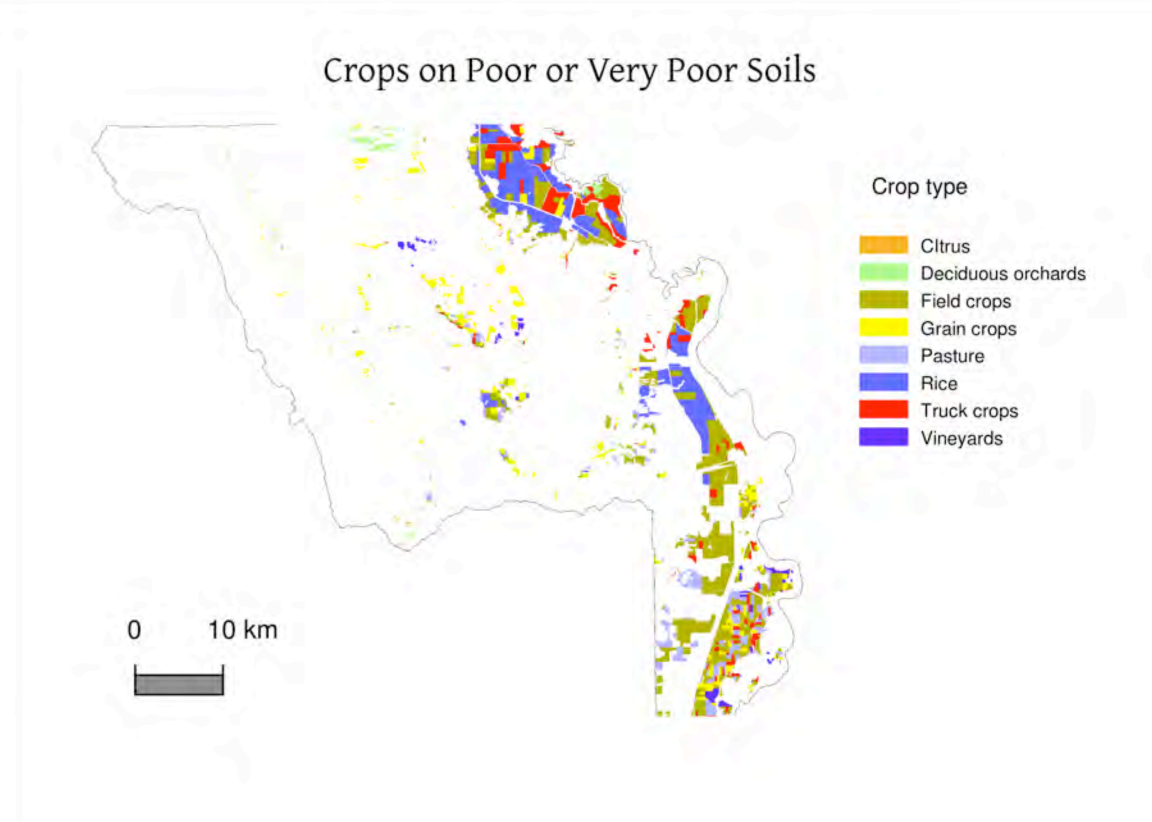


Figure 26. Map of crop types on Poor and Very Poor Agricultural Soils (designated from the Storie Index) in Yolo County. This land is predominantly cropped with rice, grain crops (corn and wheat) and field crops (safflower and tomato). These five crops combined occupy nearly 80% of this area, based on 1997 data. See Appendix 1 for description of GIS approaches.

Source: Data from USDA-NRCS-SSURGO 2007 and DWR 1997. Map created by Allan Hollander, Toby O'Geen, Fernando Santos, UC Davis.

Five field crops comprise 72% of the total area in Yolo County. This low crop diversity occurs especially on good quality soils. For example, Region 2 is located on the highest quality soils of Yolo County, with more than 85% considered good or excellent by the Storie Index (Figure 27). Within Region 2, tomatoes and wheat alone account for almost 50% of the area. Aside from field crops, vineyards and deciduous orchards, i.e., walnuts and almonds, are the next most abundant crops (12%), and other crops, consisting of more than 25 other commodities, account for only 16% of the total land area (Figure 28 and Figure 29).

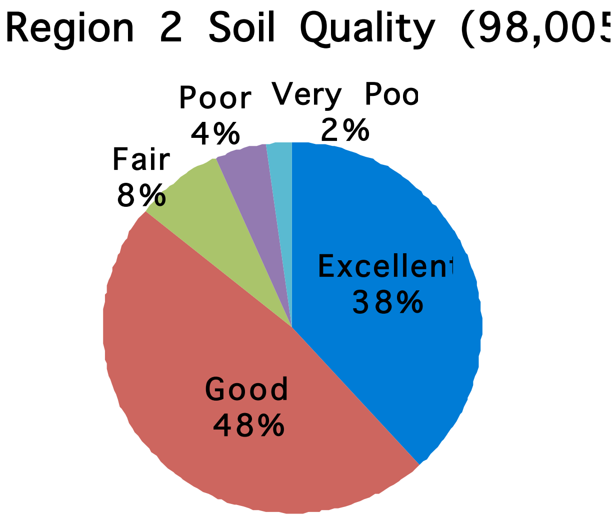


Figure 27. Storie Index categorization of soils in Yolo County Region 2, which occupies the center of the county. It contains rich alluvium soils suitable for most crops, including alfalfa, orchard, vegetable, and field crops (Figure 28). See Appendix 1 for description of GIS approaches.

Source: USDA-NRCS-SSURGO 2007 and DWR 1997. Figure created by Fernando Santos and Joel Kramer, UC Davis.

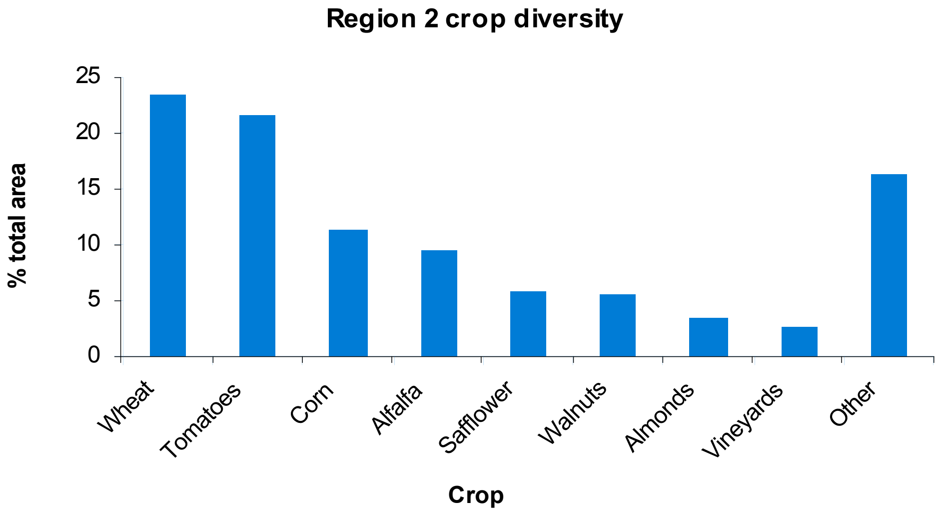


Figure 28. Crop diversity in Yolo County Region 2 by % total agricultural land (75,880 ha), based on 1997 data. Five field crops comprise 72% of the total area. Adding vineyards and deciduous orchards totals to 85% of the total area. Other crops,

consisting of more than 25 other commodities, account for only 15% of the total land area. See Appendix 1 for description of GIS approaches.

Source: USDA-NRCS-SSURGO 2007 and DWR 1997. Figure created by Fernando Santos and Joel Kramer, UC Davis.

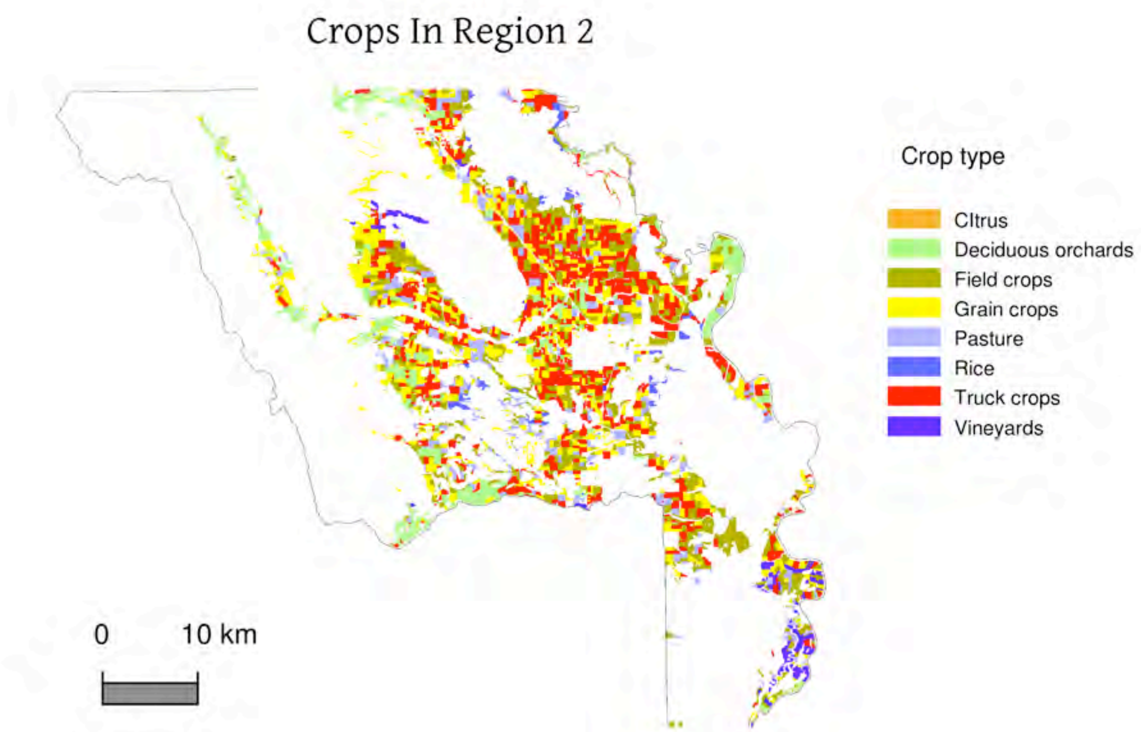


Figure 29. Crop distribution in Yolo County Region 2, which includes most of the county's highest quality soils. Tomatoes and wheat alone account for almost 50% of the area.

Source: Data from USDA-NRCS-SSURGO 2007 and DWR 1997. Map created by Allan Hollander, Toby O'Geen, and Fernando Santos, UC Davis.

Since a lack of crop diversity was hypothesized to be associated with economic risk in the context of possible climate change events such as drought or heatwaves, we explored the factors involved in diversifying farms using GIS queries and a set of assumptions about crop management. Two hypothetical farms were created. The *standard* farm represents a low diversity, major commodity farm with five of the most commonly grown crops in Region 2. The *diverse* farm contains a diversified crop mix that also includes pastureland and orchards with purposefully minimized water consumption. The production costs and quantities for all crops were attained from the Cost and Return Studies from the UC Davis Agriculture and Resource Economics Department (UC Davis 2008).

The standard, low diversity farm contains a total of 3,200 acres (1,300 hectares) to resemble a normal quantity of land that a Yolo County farm manager oversees. This hypothetical farm contains alfalfa (300 acres [121 hectares] in production, 100 acres [40 hectares] being established), field corn (600 acres or 243 hectares), safflower (dryland and irrigated, 200 acres [81 hectares] each), tomato (900 acres [364 hectares]) and wheat (900 acres) to represent the dominant field crops in the county (Table 14a).

Table 14a. Hypothetical standard farm with low crop diversity in Yolo County Region 2. It contains five major crops representative of the current dominant land uses in the county. The production costs and quantities for all crops were attained from the Cost and Return Studies from the UC Davis Agriculture and Resource Economics Department.

Crop	Specific Management	Acreage
Alfalfa	In production, Sprinkler irrigation	300
Alfalfa	Being established, Sprinkler irrigation	100
Corn	Field; Well/Canal furrow irrigation	600
Safflower	Dryland	200
Safflower	Flood irrigation	200
Tomato	Transplanted, Well/Canal furrow irrigation	600
Tomato	Seeded, Well/Canal furrow irrigation	300
Wheat	Well/Canal furrow irrigation	900
Total		3200

Source: Agriculture and Resource Economics Department, UC Davis 2008.

Table 14b. Hypothetical diversified farm with high agrobiodiversity in Yolo County Region 2. A portion of the standard farm's crops (Table 10a) are replaced with deciduous trees and pasture to simulate a diversified crop mix. Low water irrigation methods are chosen whenever possible. The production costs and quantities for all crops were attained from the Cost and Return Studies from the UC Davis Agriculture and Resource Economics Department.

Crop	Specific Management	Acreage
Alfalfa	In production, Sprinkler irrigation	300
Olive (Table)	Microsprinkler irrigation	40
Pasture	Flood irrigation	50
Corn	Field; Well and canal irrigation	600
Safflower	Dryland	200
Almonds	Low volume sprinkler irrigation	100
Walnuts	Sprinkler irrigation	105
Tomato	Transplanted, Well/Canal furrow irrigation	600
Olive (Oil)	High density, Drip irrigation	120
Prunes	Low volume irrigation	105
Wheat	Well/Canal furrow irrigation	900
Total		3220

Source: Agriculture and Resource Economics Department, UC Davis 2008

In the hypothetical diverse farm, a portion of the standard farm's crops are replaced with deciduous trees and pasture to simulate a diversified crop mix. Table olives and irrigated pasture replace the establishing alfalfa crop; almond and walnut orchards replace the flood-irrigated safflower crop; almonds, prunes, and high-density oil olives replace one third of the

900-acre tomato crop. Low water irrigation methods are chosen whenever possible (Table 14b). The diversified acreage occurs on a fifth of the acreage of the standard farm, totaling 3,220 acres for the diversified farm.

A review of production costs for each crop (Figure 30), shows that tomato cultivation was the most costly of all the field crops ($2,271/ac). For example, producing tomato is three times more expensive than producing corn on average. However, orchard trees, based on cost at maturity, are even more expensive to produce than any field crop. Each farm was assessed for average cost per acre based on cultural, harvest, cash overhead and non-cash overhead costs. The cost per acre of rice was also included for reference purposes.

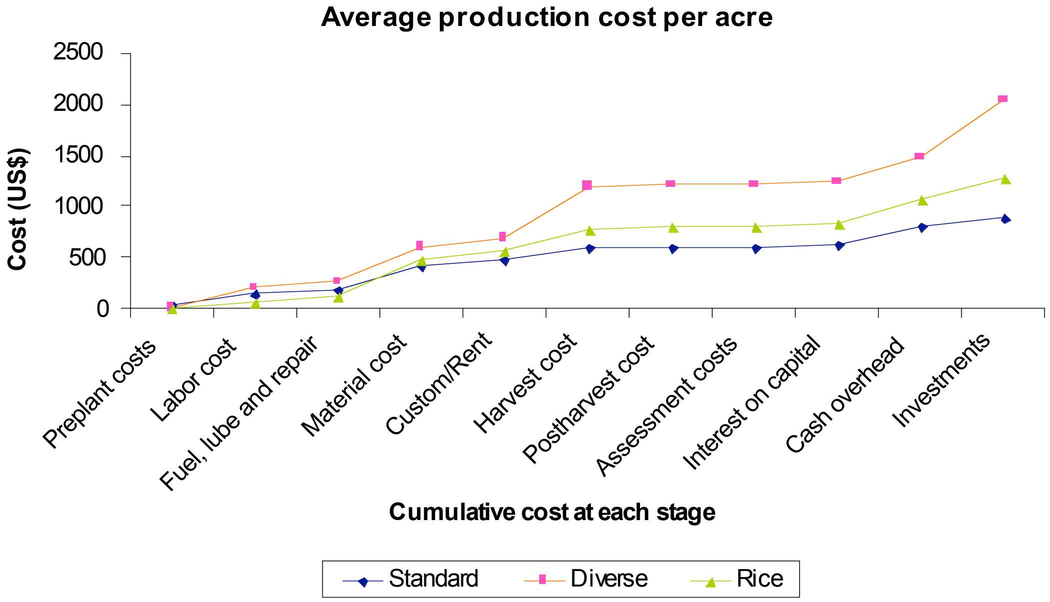


Figure 30. Average production cost per acre for hypothetical standard and diverse farms. Rice costs are shown for comparison. Cost analysis shows that the diversified farm costs 2.5 times that of the standard farm, and requires high long-term investments. Three major stages of material cost, harvest cost, and non-cash overhead, or investments, contribute to the heightened cost of the diverse farm.

Source: Cost and Return Studies from the UC Davis Agriculture and Resource Economics Department (UC Davis 2008). Figure created by Fernando Santos, Joel Kramer, and Kurt Richter, UC Davis.

Cost analysis shows that diversification to orchard crops is a costly adaptation strategy, and thus it requires high long term investments (Figure 31). The diversified farm costs 2.5 times that of the standard farm. Three major stages of material cost, harvest cost and non-cash overhead, or investments, contribute to the heightened cost of the diverse farm. Relative costs are compared to material inputs and returns for the two farms (Figure 32a). Due to the orchard trees, the diverse farm demanded slightly more fertilizer and water than the standard farm, even with the stricter water management practices, for example, sprinklers and low volume irrigation as opposed to the solely flood- or furrow-irrigated crops of the standard farm. Consequently, the environmental benefits of diversifying with orchard trees and pasture will be related to an increase C stocks and a reduction in tillage and soil erosion rather than a significant reduction of fertilizer, energy inputs for water deliveries, or other input requirements.

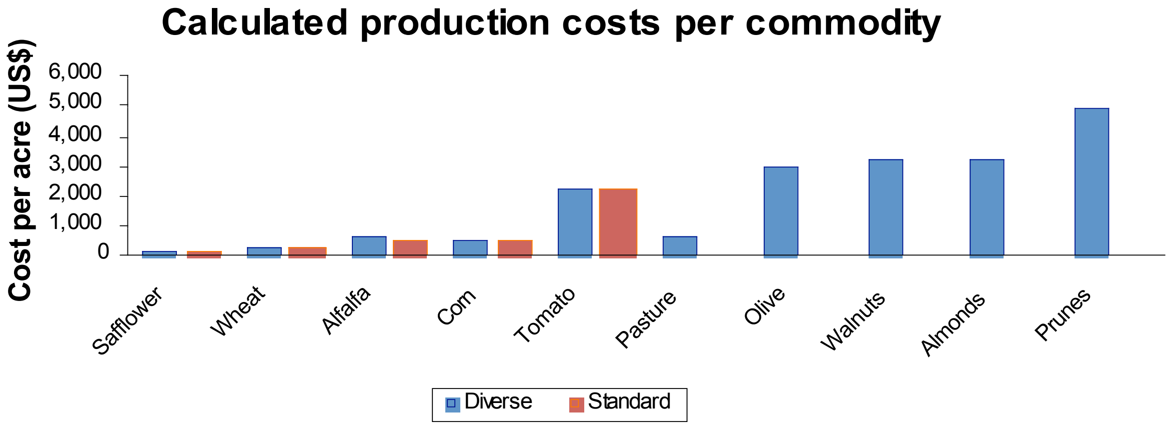


Figure 31. Production costs for 10 commodities on hypothetical standard vs. diverse farms. Results show that producing orchard trees, based on cost at maturity, are more expensive to produce than any field crop. Among the field crops, tomato is the most expensive to produce.

Source: Analysis based on UC Davis Agriculture and Resource Economics Department Cost and Return Studies data (UC Davis 2008). Figure created by Fernando Santos, Joel Kramer, and Kurt Richter, UC Davis.

The values for yields and price were chosen along the guidelines of the Cost and Return analysis conducted for Yolo County (UC Davis, 2008). The values that were chosen were intermediate between extreme years. If returns are calculated with long-term intermediate commodity prices and yields, the standard farm produces a net loss of 5% while the diverse farm yields a 4% profit (Figure 32b). These results suggest that for a low diversity farming operation, there is a slight associated economic risk that more diverse farms are able to avoid.

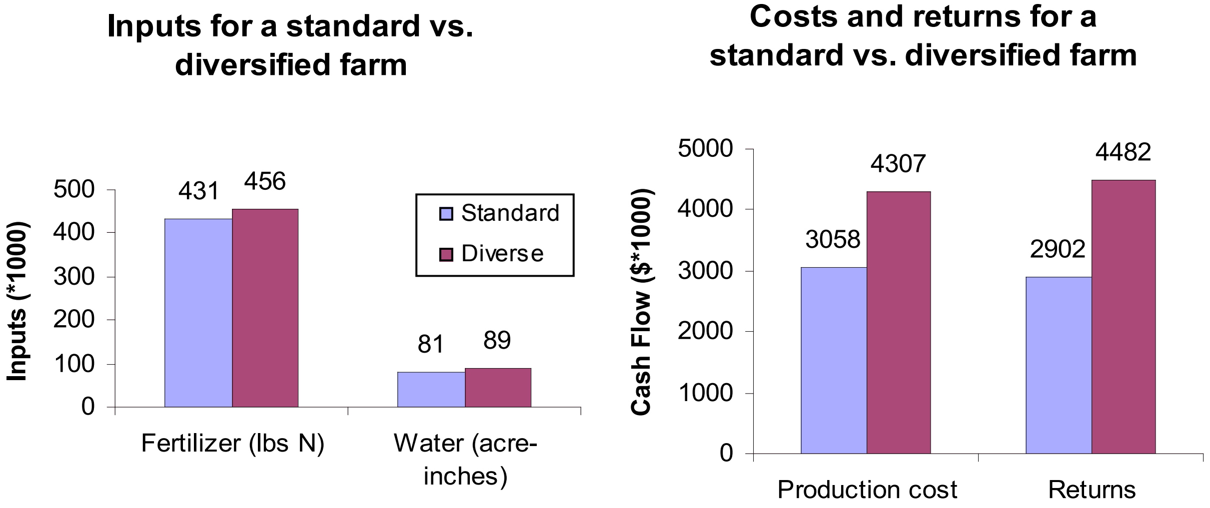


Figure 32 (a) Comparison of input requirements for a hypothesized standard farm and a diversified farm for a one year period. The diverse farm demanded slightly more fertilizer and water than the standard farm, even with the stricter water management practices. Consequently, the environmental benefits of diversifying with orchard trees and pasture will be related to an increase carbon stocks and a reduction in tillage and soil erosion rather than a significant reduction of fertilizer, and energy inputs from water deliveries; (b) Comparison of all costs and returns for the hypothesized farms in one year. Results suggest that for a low-diversity farming operation, there is a slight associated economic risk that more diverse farms are able to avoid.

Source: Analysis based on UC Davis Agriculture and Resource Economics Department Cost and Return Studies data (UC Davis 2008). Figure created by Fernando Santos, Joel Kramer, and Kurt Richter, UC Davis.

Of course, there are additional issues associated with the increase in crop diversity, such as the availability of processors and markets. Also, there will be new set of production vulnerabilities such as equipment needs, disease susceptibility and vulnerability to heat stress. One important constraint in Yolo County for the adoption of some tree and nut crops is the high concentration of boron, especially in soils with high clay, based on conversations with Yolo County UC Cooperative Extension farm advisors.

To projecting the changes in zonation of crops within Yolo County and California, it may be useful to develop a better understanding of soil, water and market constraints in Merced County and further south. The practicality of moving crops from one area to another area is not simple (Easterling et al. 1997; Lambin et al. 2001). Shifts in land use are not considered a market impact and therefore, are not included in most economic projections, but they potentially have large economic and environmental effects on people and the resource base in agricultural landscapes. Long-term agricultural research that involves land use planning is needed to examine novel scenarios for agriculture to minimize vulnerabilities and facilitate coping strategies for extreme events, perhaps at the expense of short-term financial gains by agricultural producers or urban developers.

3.6. Land Use: Soil and Land Management Options for Landscape Responses to Climate Change

As an example of issues involved in making decisions for soil and land management responses to climate change, a GIS approach was selected for Region 1. Analysis of this region alone provides an interesting context in which to examine land use change near the dynamic border with the Sacramento River. Region 1 contains the largest portion of poor agricultural soils that are very high in clay (Figure 33). With a total area of 168,874 acres, or 68,341 ha, almost 60% of the land in Region 1 is rated as having poor soil conditions for agricultural purposes. Yet the region is heavily farmed, largely with rice because it is the highest value crop suitable to be grown under these soil conditions. Therefore, Region 1 is even less diverse than the others, with more than 80% of its agricultural land occupied by six major row crops in 1997 (Figure 34). In 1997, more than 10,000 acres (4,000 ha) of rice fields were grown in the occasionally or frequently flooded areas in Region 1 (Figure 35). Additionally, the proximity of these agricultural systems to the floodplain implies higher vulnerability to flooding of the region in the context of global warming, as increased temperatures and warm spring rains would cause the Sierran snowmelt to surge more suddenly during springtime than it currently does (Figure 36). This likely affects both yields and infrastructure.

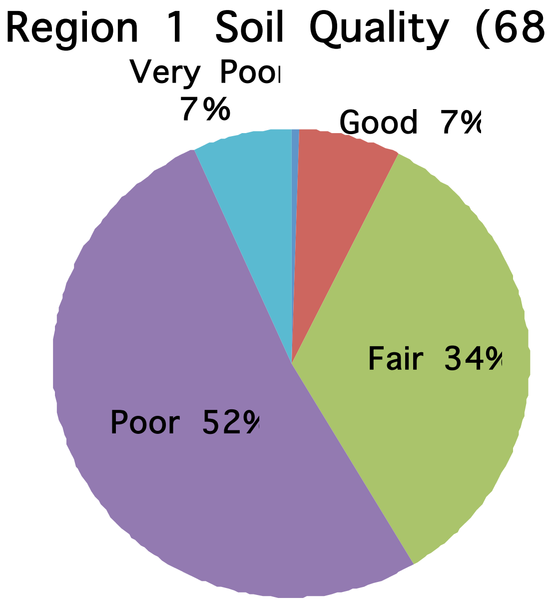


Figure 33. Soil quality distribution for Yolo County Region 1, which is located near the Sacramento River. While it contains the largest portion of poor agricultural soils, Region 1 is heavily farmed, largely with rice since it is the highest value crop suitable to be grown under these soils conditions.

Source: USDA-NRCS-SSURGO 2007 and DWR 1997. Figure created by Fernando Santos and Joel Kramer, UC Davis.

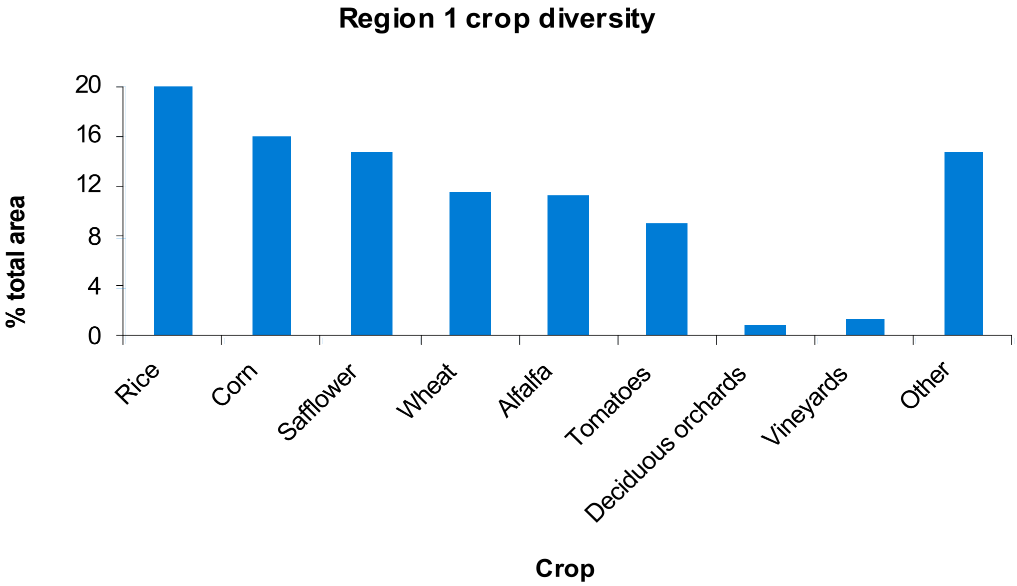


Figure 34. Crop diversity in Yolo County Region 1, which occupies the eastern edge of the Sacramento River floodplain, by % total agricultural land (54,480 ha). This region has more than 80% of its agricultural land occupied by six major row crops and with minimal representation by orchards trees and vineyards.

Source: DWR 1997. Figure created by Fernando Santos, Allan Hollander and Joel Kramer, UC Davis.

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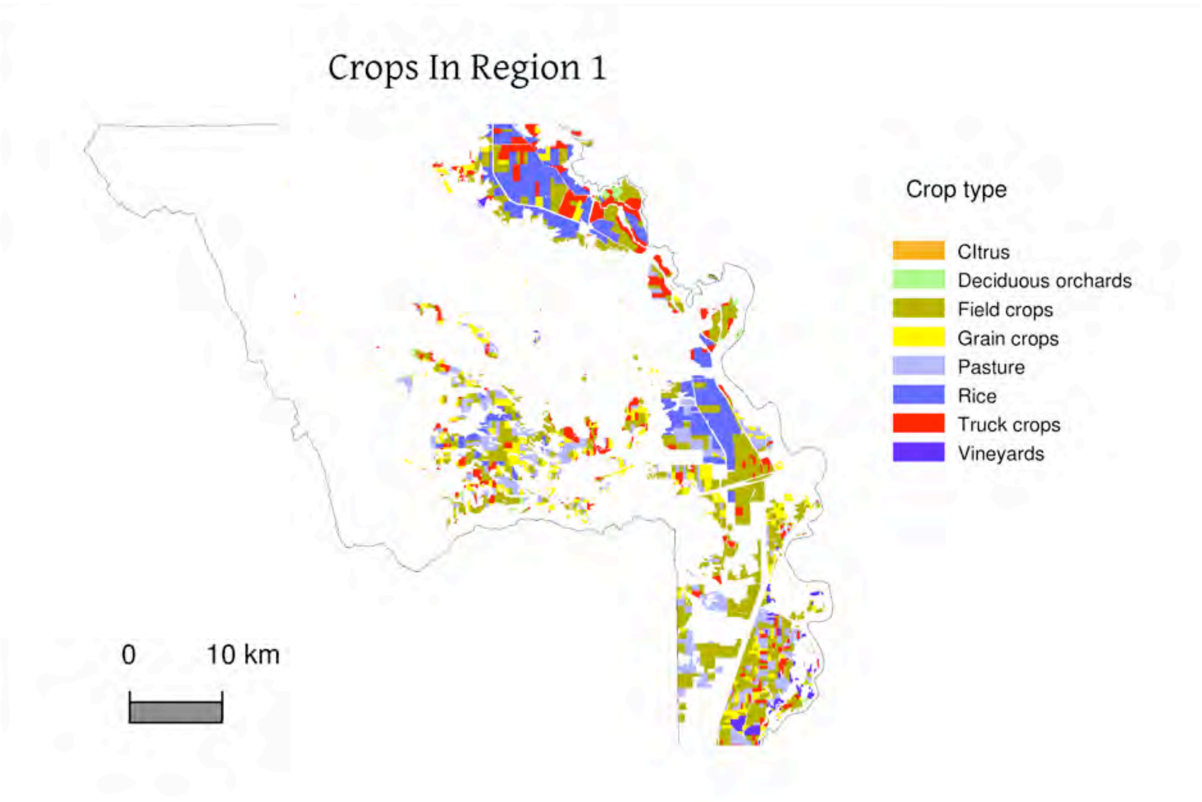


Figure 35. Crop distribution in Yolo County Region 1, which includes most of the county's lower quality soils. The proximity of these agricultural systems to the floodplain implies higher vulnerability to flooding in the context of global warming, as increased temperatures would cause the Sierran snowmelt to surge more suddenly during springtime than it does now.

Source: DWR 1997. Map created by Allan Hollander, Toby O'Geen, and Fernando Santos. UC Davis.

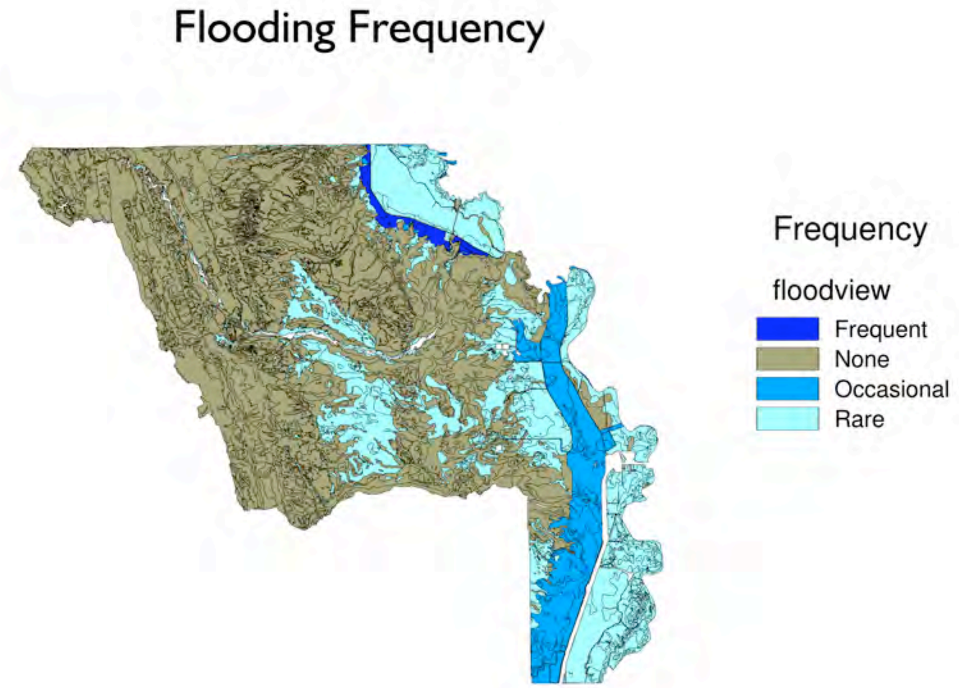


Figure 36. Flooding frequency overview in Yolo County. *Frequent* is defined as at least 1–2 times per year (2,334 ha); *Occasional* is at least 5 times every 50 years (16,904 ha); *Rare* is once every 100 years (42,124 ha).

Source: USDA–NRCS-SSURGO 2007. Map created by Allan Hollander, Toby O'Geen, and Fernando Santos, UC Davis.

To assess the viability of Region 1 for agricultural practices under changing climate conditions, we quantified the economic cost of converting the agricultural lands closest to the river to riparian habitat. This strategy could be achieved through a vigorous restoration program to plant native trees, shrubs, and perennial graminoids. Some of the trees could then be harvested periodically as a method of storing additional C as consumer products.

A simpler method would be to leave the land to successional processes that would be, at least initially, communities of herbaceous perennials. This strategy would protect higher elevations of Region 1 from further flooding and would simultaneously sequester more C and possibly reduce N_2O emissions, a practice which can earn profit on the cap-and-trade market. Additionally, shifting rice fields to riparian vegetation in strategic locations would provide opportunities for to promote biodiversity gains through habitat restoration (but see Section 3.9).

Soils currently classified in the frequent and occasional flood zones categories occupied 31% of total agricultural land in Region 1 (Table 15). Because rice is the major crop with the highest probability to be affected by future flooding events (Figure 37), we quantified the economic potential of reforesting these most vulnerable cropping systems. Rice production is currently supported by USDA subsidies at an average rate of $119 per acre per year (UC Davis 2007). Even so, the average profit per acre for rice borders the breakeven line, which in many cases results in a net financial loss (UC Davis 2007). Thus, shifting part of these funds to other land use options may be a reasonable alternative in the future.

Table 15. Category definitions for flooding zones in Region 1 near the Sacramento River.

Flood zone	Probability of flooding	Area (ha)
Frequent	At least 1-2 times per year	2,334
Occasional	At least 5 times every 50 years	16,904
Rare	Once every 100 years	42,124

Source: USDA-NRCS-SSURGO 2007.

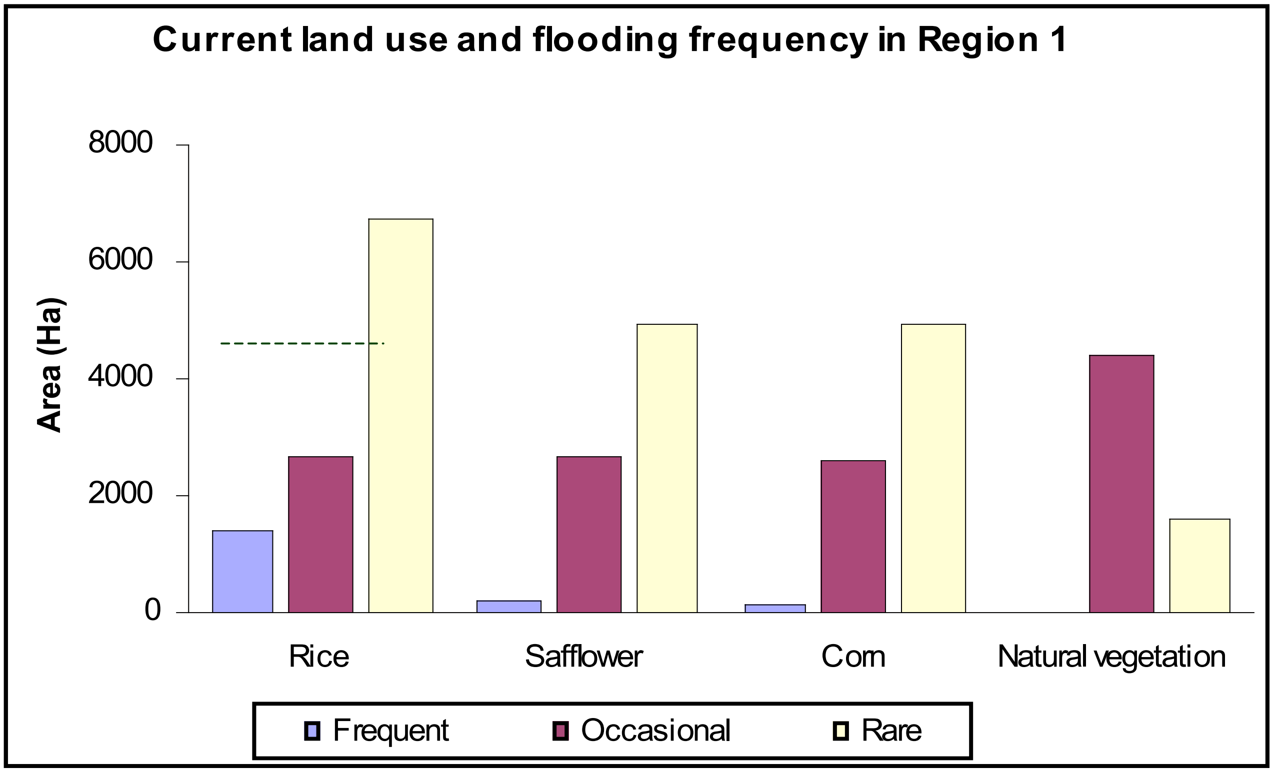


Figure 37. Current major land uses in Region 1 near the Sacramento River, and their association with various probabilities of flooding. For example, more than 4,000 ha of rice fields are currently grown in the combined occasionally or frequently flooded areas, based on 1997 data. Hashed line represents suggested area under future vulnerability for rice cropland.

Source: USDA-NRCS-SSURGO 2007 and DWR 1997. Figure created by Fernando Santos, Allan Hollander, and Joel Kramer, UC Davis.

For example, new funding opportunities envisioned by state agencies (e.g., as suggested by ARB) will encourage the reforestation of agricultural lands to both mitigate GHG emissions and provide wildlife habitat. There are also existing programs such as the federal EQUIP and Wetland Reserve Program, which could serve this purpose. If several million dollars were available statewide, Yolo County would likely be eligible to participate, due to the sensitivity of this particular region. Under such an opportunity, we wondered if these areas in Yolo County that are anticipating more frequent flooding could gain an economic advantage by transitioning their cropland to riparian reforestation.

To take an extreme example, we quantified the economic feasibility of converting all of the currently frequent and occasionally flooded rice cropland into natural wetlands, using such designated funds in the future (Figure 38). There are a total of 4,041 acres (1,635 hectares) of rice cropland currently threatened with frequent to occasional flooding. According to the Climate Action Team (CalEPA), reforestation costs an average of $700 per acre including site preparation, planting and maintenance. Under such a program, it is likely that $500 of the $700 could be from the State while the remaining \$200 would be assumed by the land owner, as can often occur in participatory programs. Additional revenues could potentially be procured from grants at the local, federal and global level. One source of future revenue is through C markets which could offer \$9.71 per ton of CO_2E according to one recent estimate (Brown 2004). If, during the first 20 years of establishment, reforested land sequesters 5 tons of CO_2E per acre annually, then one acre would generate \$48.5 per year in market value. This, in fact, depends greatly on the availability of water supplies to irrigate the growing trees before they tap into groundwater. Other sources of revenue could be from firewood or timber, or possibly, for paying the farmer to maintain high biodiversity and high quality stands for wildlife habitat and a set of other multiple ecosystem benefits for water quality, recreation, etc. This might be more likely if certain parts of the area were converted to a natural reserve.

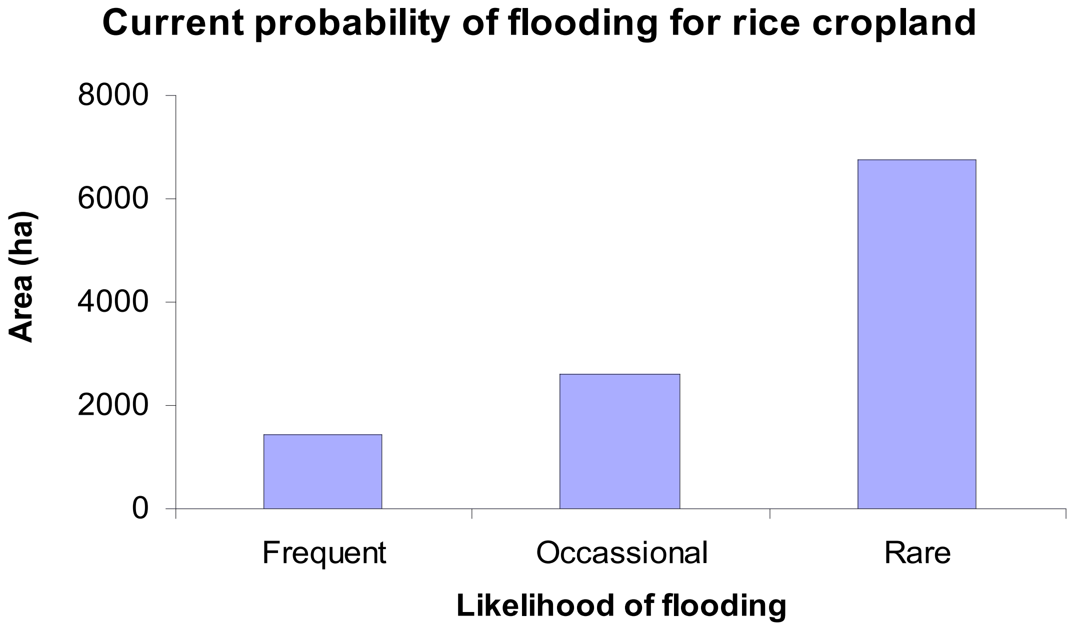


Figure 38. Current frequency of flooding for rice cropland in Yolo County. To suggest the area that will be vulnerable in the future, we summed frequent and occasional categories, and this amounts to a total of 4,041 acres, based on DWR (1997) data.

Source: USDA-NRCS-SSURGO 2007 and DWR 1997. Figure created by Fernando Santos, Joel Kramer, and Allan Hollander, UC Davis.

3.7. Land Use: Adaptation and Mitigation through Management of Water Resources

In California, irrigation water is a critical component of agricultural production, and makes possible the farming of numerous crops that would otherwise not be possible. In addition, annual weather patterns greatly affect the rainfall that supports non-irrigated rangelands and livestock production. Statewide, in a normal precipitation year (2000), 41% of the total annual surface and groundwater use is by agriculture (UCAIC 2006). Environmental uses and urban uses account for 48% and 11%, respectively. The sources of water include surface supplies (70%) and groundwater (30%).

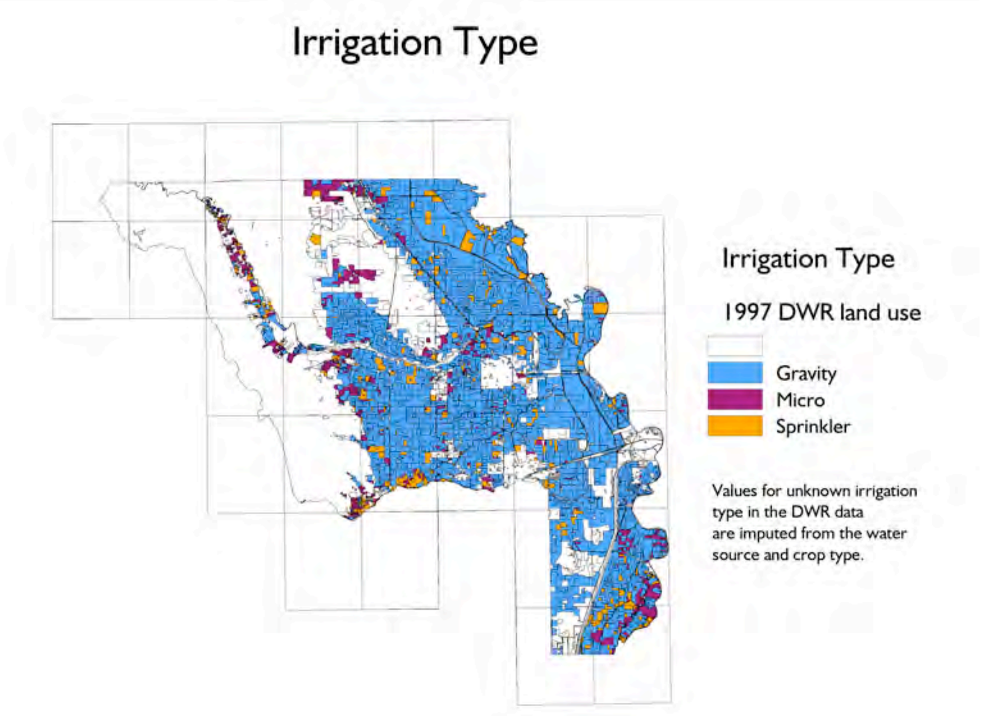
In Yolo County, under both A2 and B1 scenarios, the agricultural water supply may be negatively affected through changes in snowmelt, rainfall distribution and rainfall amount, but there is great uncertainty around these projections. For example, precipitation is very different for the six GCM models that have been run for the region, ranging from an increase of 10 cm yr^{-1} to a decrease of 15 cm yr^{-1} in the period of 2045–2050 (Figure 7).

Although groundwater pumping may compensate for changes in surface water supplies, it is uncertain whether the amount or quality of groundwater will meet the needs of future agriculture production in Yolo County (Table 12; Section 3.3). Both climate and population growth will dictate the amount of water available from all sources to maintain Yolo County's agricultural enterprise.

Yolo County is a small portion, 3.8% (1,034 square miles) of the large Sacramento Hydrologic Region or watershed, which covers 26,960 square miles of land (Water Resources Association of Yolo County 2007). There are four main sources of water for Yolo County's domestic, industrial, and agricultural needs: Cache Creek, the Sacramento River, the Colusa Basin Drainage Canal, and most importantly, groundwater (USDA 1972).

Cities rely predominantly on groundwater, whereas agricultural water users rely more heavily on surface water, although some areas, especially in the western part of the county, use groundwater or some combination of the two. (See Figure 39, a map of agricultural water sources throughout the county). Most surface water irrigation deliveries in the county are by gravity flow, which is less expensive than pressurized, on-demand deliveries (Figure 40). Along the eastern edge of the county, water is pumped from Sacramento River, Colusa Basin Drain or the Tule Canal/Toe Drain in the Yolo Bypass.

Water availability for agriculture. Irrigation water is supplied by the various districts In Yolo County (Figure 41) via an intricate network of privately and publicly owned canals and ditches. The creeks and sloughs throughout the county are mainly used as a drainage source for irrigation water, although water is also diverted for irrigation. The management of water resources in Yolo County is complex and involves at least 40 public and private entities who maintain, monitor and/or deliver the county's surface water and groundwater (Table 16). Water is delivered through artificial canals or modified natural waterways and most private landowners develop and maintain their own ditches for conveying the irrigation water deliveries onto and off of their property.



Values for unknown irrigation type in the DWR data are imputed from the water source and crop type.

Figure 39. Water source for irrigation across Yolo County. Most surface water in Yolo is delivered by gravity flow, which is less expensive than pressurized, on-demand deliveries. Along the eastern edge of the county, water is pumped from the Sacramento River, Colusa Basin Drain, or the Tule Canal/Toe Drain in the Yolo Bypass.

Source: DWR 1997. Map created by Allan Hollander, Toby O'Geen, Fernando Santos, and LAWR, UC Davis.

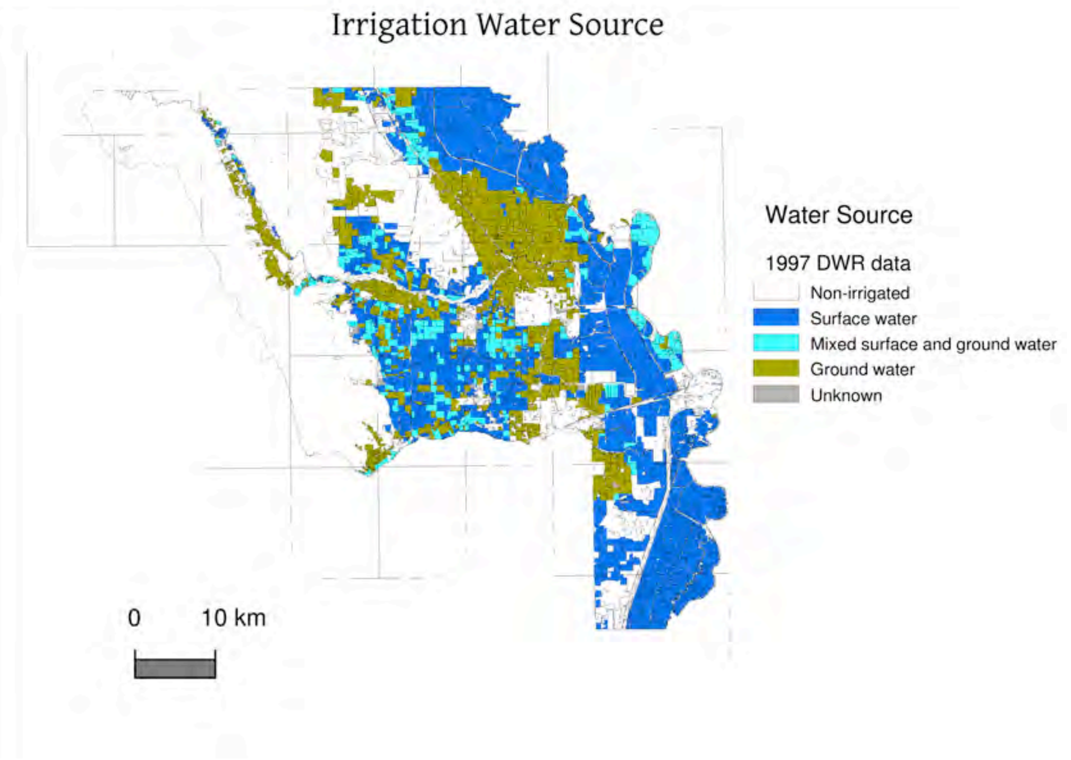
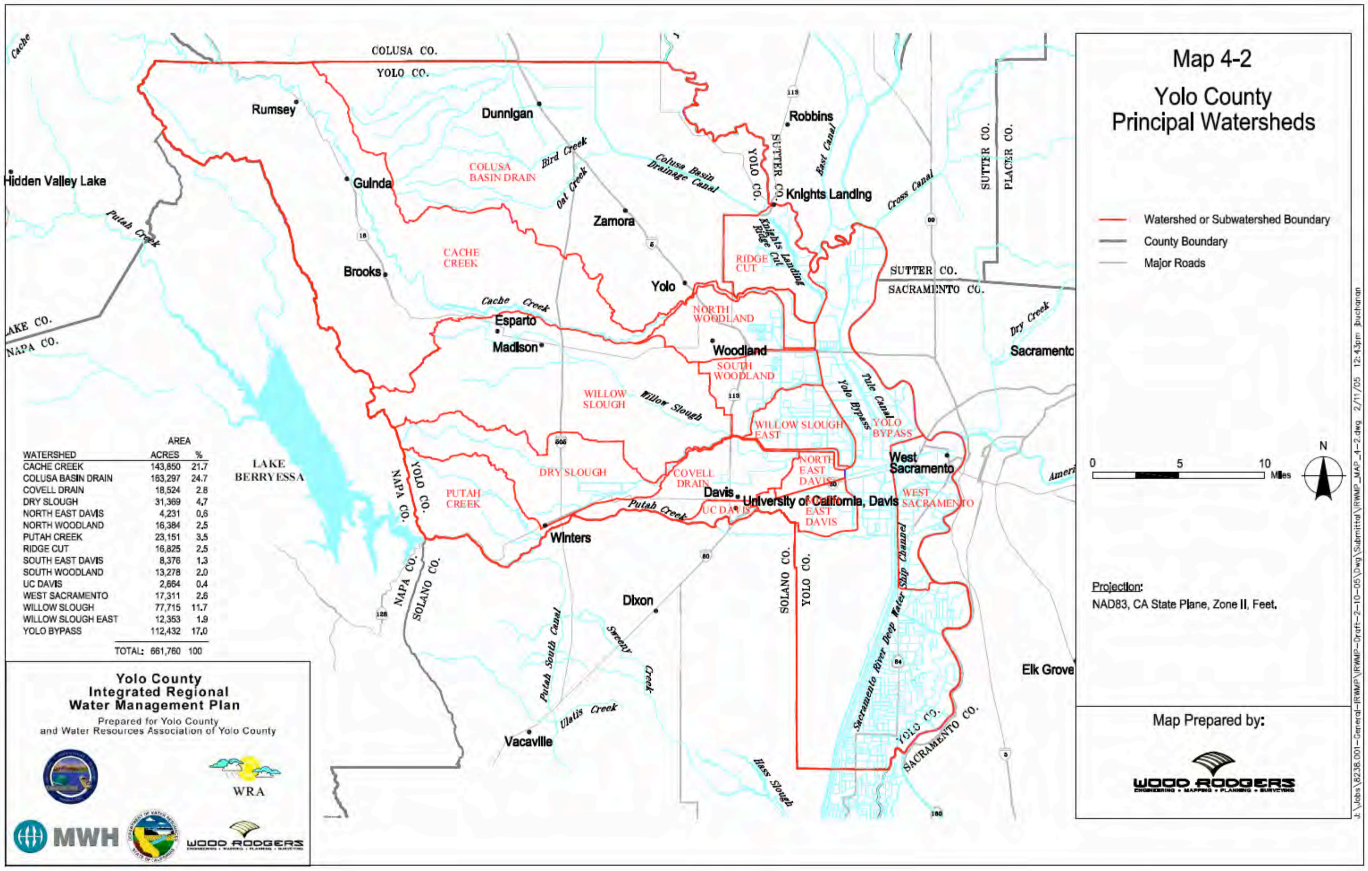


Figure 40. Use of different types of irrigation in Yolo County. Cities rely predominantly on groundwater, whereas agricultural water users rely more heavily on surface water. However, some agricultural areas, especially in the western and north-central part of the county, use groundwater or some combination of the two.

Source: DWR 1997. Map created by Allan Hollander, Toby O'Geen, and Fernando Santos, UC Davis.



WATERSHED	AREA ACRES	AREA %
CACHE CREEK	143,850	21.7
COLUSA BASIN DRAIN	163,297	24.7
COVELL DRAIN	18,524	2.8
DRY SLOUGH	31,369	4.7
NORTH EAST DAVIS	4,231	0.6
NORTH WOODLAND	16,384	2.5
PUTAH CREEK	23,151	3.5
RIDGE CUT	16,825	2.5
SOUTH EAST DAVIS	8,376	1.3
SOUTH WOODLAND	13,278	2.0
UC DAVIS	2,664	0.4
WEST SACRAMENTO	17,311	2.6
WILLOW SLOUGH	77,715	11.7
WILLOW SLOUGH EAST	12,353	1.9
YOLO BYPASS	112,432	17.0
TOTAL:	661,760	100

Figure 41. Yolo County's principal watersheds. The creeks and sloughs throughout the county are mainly used as a drainage source for irrigation water, although water is also diverted for irrigation.

Source: Water Resources Association of Yolo County 2007.

One of the greatest challenges for the water managing entities in Yolo County is to maintain sufficient water reserves to prepare for dry years, while at the same time keeping the water levels in the local reservoirs low enough to provide flood protection. Water storage and groundwater availability (such as in Clear Lake, Indian Valley Reservoir, and the aquifers) is a major challenge for drought preparedness in summer and flood protection in winter. In the context of future flooding, levees are insufficient at Cache Creek and the Lamb Valley Slough (Water Resources Association of Yolo County 2007). At Cache Creek, levees are experiencing erosion, and vegetation along Cache Creek is currently impeding flood capacity. At the Yolo Bypass it is recommended that future land use changes be carefully calculated so as not to create further impediments to flow or capacity (See Section 3.8).

The Yolo County Flood Control and Water Conservation District, in coordination with the Department of Water Resources and other engineers, have developed a computer simulation model that can predict groundwater availability in Yolo County under various levels of drought, population growth, active groundwater recharge, or importation of Sacramento River water to Davis and Woodland (Water Resources & Information Management Engineering 2006).

Yolo County's ultimate back-up supply of water during extended drought periods is groundwater. Yet the total amount of groundwater available in the county is unknown, difficult to estimate, and varies spatially. However, currently groundwater levels are considered

Table 16. Yolo County's primary watersheds and their important features. One of the greatest challenges is to maintain sufficient water reserves to prepare for dry years, while at the same time keeping the water levels low enough to provide flood protection.

	Primary water source feeding the watershed	**Land/water use in the watershed**	**Water supply availability for Yolo County**	**Flooding issues/flood control purposes**
Sacramento River	Sierra-Nevada mountain's snowmelt	Now, only farms along the edge of the river and city of West Sacramento have water rights, but the cities of Davis, Winters, Woodland, and UCD are trying to obtain rights	Year round; winter/summer surface flows recharge Yolo County's aquifers (but to what extent is unknown)	Federal flood control levees border Sacramento River along entire eastern edge of Yolo County; Yolo Bypass serves as the primary flood control
Yolo Bypass	Sacramento River; partially local tributaries (Colusa Basin Drain, Cache Creek, Willow Slough, Putah Creek)	Land use within the area, when not flooded, is restricted by flood conveyance easements.	N/A; winter/summer surface flows recharge Yolo County's aquifers (but to what extent is unknown)	Serves as major flood control for City of Sacramento
Colusa Basin Drain	Irrigation water from north of Yolo County, Sacramento River, and runoff from well water and summer irrigation within Yolo County	Man-made canal to convey irrigation drainage for discharge into Sacramento River; farms along the edge of the canal have water rights	Summer months & possibly late summer and fall until March/April for irrigation; winter/summer surface flows recharge Yolo County's aquifers	Extent of flooding that has occurred has been exacerbated by land-subsidence between Zamora and Knights Landing; generally not used for conveying flood flows
Cache Creek	Water from coast range mountains (stored in Clear Lake and Indian Valley Reservoir)	Water supply varies year-to-year depending on water level in Clear Lake in May each year; and farms along the edge of the creek have water rights	Summer irrigation; winter/summer surface flows recharge Yolo County's aquifers	Indian Valley Reservoir partially serves as flood control water storage; Cache Creek settling basin to collect sediment from Cache Creek before entering Yolo Bypass
Willow Slough	Water from Coast Range (Cache Creek) and runoff from well- and irrigation water deliveries from summer irrigation within Yolo County	Drains most of the central part of Yolo County to the Sacramento River; water supply for southern part of Yolo County; and farms along the edge of the slough have water rights	Summer irrigation; winter/summer surface flows recharge Yolo County's aquifers	Provides flood control for eastern part of Yolo County; Largely influenced by maintenance of (or lack thereof) privately owned sloughs
Putah Creek	Water from Coast Range mountains (stored in Lake Berryessa)	Majority of water used by Solano County; a little bit used by UCD; and farms along the edge of the creek have water rights	Year round; winter/summer surface flows recharge Yolo County's aquifers	Historically, flooding was frequent and disastrous, but now reduced due to Monticello Dam on Lake Berryessa

Source: Water Resources Association of Yolo County 2007.

high and stable. The lowest recorded levels were during the 1975–1977 drought, when pumping of groundwater increased when surface water availability declined. The aquifers beneath Yolo County are recharged by runoff and groundwater from the east-facing foothills, rainfall percolation, and surface water infiltration.

The only watershed in the county that benefits from Sierra Nevada snowmelt is the Sacramento River, and this is a small amount of the irrigated acreage in the county (Figure 41). All other watersheds are fed by surface water from rainfall in the Coast Range, and run-off from the surrounding agricultural areas. Only about 1,034 square miles of the watersheds originate in the boundaries of the county itself, compared to about 25,000 square miles of watersheds that originate outside the county and flow through or adjacent to the county (Yolo County 2007a). Most of the land in the county is ultimately drained by the Sacramento River during the storm season in fall and winter. During the irrigation season, most of western Yolo County is a closed basin. A summary of the basic watershed features are provided in Table 16.

Changes in irrigation technologies, especially subsurface drip, may reduce the negative impacts of irrigation runoff but will have little impact on winter runoff. A detailed analysis of adaptation to warm, dry climate change scenarios is very much needed. While Yolo County may be able to adapt at a regional level, there will likely be regions that suffer losses, giving a false sense of balance in the county. There is a substantial amount of data from the California Department of Water Resources (DWR) that could be used to assess climate change scenarios, e.g. on irrigated crop area by crop type, crop water use (crop ET, effective precipitation, crop evapotranspiration of applied water, consumed fraction, and applied water) by crop type, urban water use (water use by customer class, % ground versus surface water used, indoor/outdoor split, population), and managed wetlands water use.

For the different regions in Yolo County, future research must focus on monitoring key hydrologic variables, modeling regional-scale climate changes, comparing precipitation forecasts, and evaluating the implications of changing the hydrologic system of rivers, riparian areas and wetlands (Joyce et al. 2007). In addition, the implications of changes in groundwater use, and in urban, agricultural and ecosystem water demands for economic outcomes must be evaluated. Analysis of climate change scenarios would point out advantages and disadvantages of existing water policies. While most research for the sake of local water management has been focused on local precipitation, adaptation to climate change requires better understanding of high-elevation physical processes and of the transition area between rain-dominated and snow-dominated regions of the key watersheds affecting the Sacramento River.

Water quality. The following issues are already of concern for water quality in Yolo County, as outlined by the Water Resources Association of Yolo County in their 2007 Integrated Regional Water Management Plan, even without the possibility of lower water availability from climate change. High levels of nitrate and pesticides from agricultural practices are likely to be of concern to an increasingly urban population. Erosion from agricultural fields results in suspended sediment in surface water sources, harming aquatic life and ecosystem functions related to water quality. High levels of mercury, specifically in Cache Creek and the Yolo Bypass, contaminate the fish eaten by humans and wildlife. Lastly, efforts to enhance agrobiodiversity through increased perennial orchard crops and vineyards, and to restore woody vegetation along sloughs and drainage ditches to improve water quality will likely be affected by shallow boron-enriched groundwater aquifers, since boron toxicity damages young woody perennials and reduces crop yields. The export of dissolved organic carbon (DOC) to the Delta is a complex issue. While DOC is beneficial in supporting aquatic organisms, some forms of DOC pose a serious water quality problem that impacts drinking water production through the formation of trihalomethane compounds, which are known carcinogens, during chlorination. These disinfection byproduct precursors have been shown to form in restored wetlands that receive agricultural tailwaters, but only in wetlands with long water residence times (Diaz et al. 2008). Preliminary results from agricultural studies indicate a strong diurnal response to DOC production where small increases in temperature can increase DOC export (Horwath, pers. comm.).

Predictions of water quality change due to climate change will be intimately linked to models of land use change. For example, wetlands produce more DOC than most agricultural crop fields, but act as a filtration system removing sediments and nutrients and a variety of other water quality contaminants such as pathogens, pesticides, nitrate, and particulate (P). Urban landscapes contribute different types and amounts of pesticides and herbicides than agriculture due in part to the loosely regulated nature of home owner applications. Other contaminants tied to urban landscapes include leaking fluids from automobiles and constituents in waste water such as nutrients or pharmaceuticals.

Regional coalitions will potentially provide a framework for adapting more vigorously to the water quality concerns from warm, dry climate change scenarios. The Regional Water Quality Control Board regulates irrigation through the Irrigated Lands Regulatory Program. All people irrigating pastureland or crops must be a part of the local coalition, connected with the local Farm Bureau, which is the Sub-Watershed of the Sacramento Valley Water Quality Coalition. To become a member, people apply to the Yolo County Farm Bureau, and pay a per irrigated acre fee.

Several programs have been undertaken by the Yolo County Resource Conservation District (RCD) to enhance the quality of agricultural water. The Agricultural Water Quality Program offers financial assistance to Yolo or Solano County farmers who install sediment traps, vegetated ditches or winter cover crops, for the issues addressed above. The "Irrigation & Ecosystems" program installs tailwater retention basins and canal, roadside and riparian vegetation systems in the Willow Sough Basin where winter precipitation and flooding pass on to the eastern part of the county. Increased funding and greater emphasis on such programs would be a means to increase adaptation to climate change, by improving water quality, especially under dry scenarios.

Many of the programs through the RCD function on an intercounty basis, incorporating both Yolo and Solano Counties. Working on a multi-party, regional scale, rather than solely at a county scale can increase the efficiency and benefits of any given management plan. In the case of runoff, the failure of one party to improve their water quality for their own uses will carry over to pass the same problem to the party downstream.

3.8. Specific Issues for the Yolo Bypass

One of the most contentious local water issues is the hydrologic region is the Yolo Bypass, a 59,000 acre floodplain located at the eastern edge of Yolo County that carries floodwaters from northern California to the Sacramento–San Joaquin River Delta. Hydric soils indicate that most of the area has always been either entirely flooded or partly flooded. Its primary function is flood control, although farms along the edge of the bypass divert water for irrigation under their riparian water rights (Jones and Stokes 2001).

The most recent controversy in the Yolo Bypass is the purchase of land by two of Southern California's largest water agencies, The Metropolitan Water District of Southern California and Westlands Water District (Weiser 2008). By buying land, and jointly planning restoration projects in the bypass to increase endangered fish populations, their intention is to protect their access to water from the Sacramento-San Joaquin Delta. These agencies are the two largest diverters of water from the Delta.

The plans include breaching levees on farm parcels in the area to create more tidal-type wetlands to increase the numbers of Delta smelt, which now may be near extinction due to long-term water diversions and pollution in the estuary. Since the bypass provides critical habitat to a variety of species including numerous plant and bird species, there is concern that management to increase the Delta smelt may have adverse effects on other species. Flood conveyance and water quality are other issues being raised (California State University, Sacramento, Center for Collaborative Policy 2008).

The 3-mile wide, 40-mile long stretch of land in the Yolo Bypass extends from the confluence of the Feather and Sacramento rivers southward toward the city of Rio Vista, where it returns excess flow water to the Sacramento River. Water primarily enters through the Fremont Weir in the north. Water can also enter from the east via the Sacramento Weir, adding additional flows from the American and Sacramento rivers, but this generally only occurs during major storm events (Sommer et al. 2001). From the west side, the basin also can receive water from Knights Landing Ridge Cut, Cache Creek, Willow Slough Bypass, and Putah Creek; these tributaries can create flooding within the bypass before the Fremont Weir spills occur. The seasonal flooding of the bypass provides riparian and wetland wildlife habitat (Figure 42). In more than half of all water years (from October l to September 30), the bypass is inundated, with water depths ranging from 10 feet in a heavy water year to 6 feet in a normal year (Sommer et al. 2001). Recent years have had the two largest floods on record, and the highest number of successive years of inundation, raising speculation that climate change is occurring, upstream urbanization is increasing runoff, or flood operations at upstream reservoirs are changing.

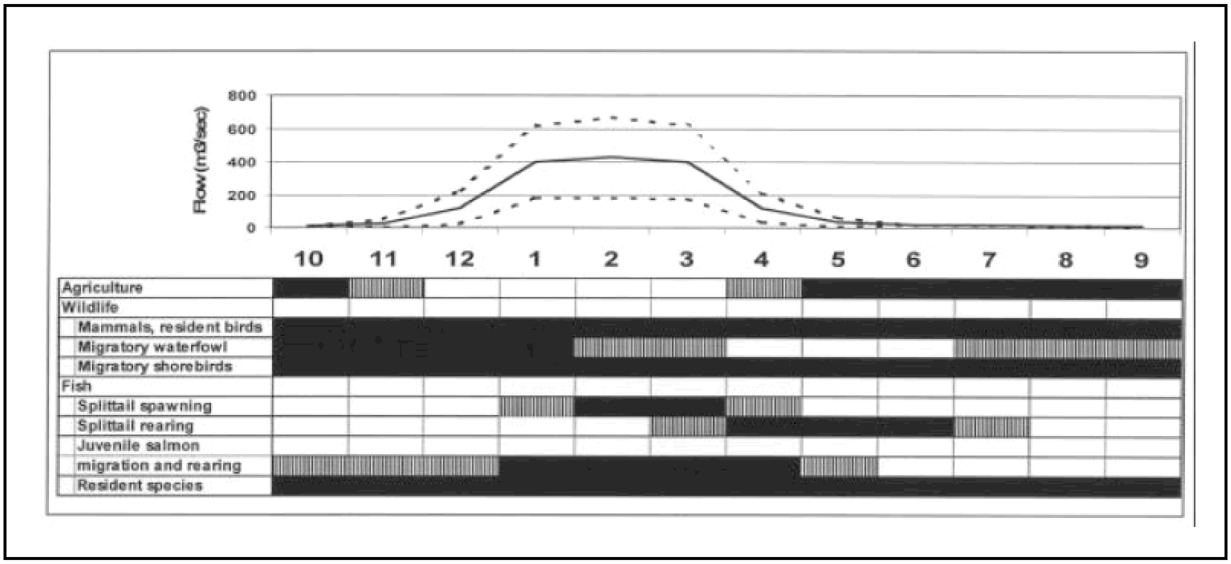


Figure 42. Yolo Bypass hydrograph relative to agricultural and environmental activity in the floodplain by month (x-axis). The mean (solid line) and standard error (dashed line) or total daily Yolo Bypass flow is shown for October 1967–September 1996, the period when all major dams were completed in the Sacramento Valley. For agricultural and environmental uses of the floodplain the primary (solid bars) and marginal (dashed bars) periods are shown. During dry periods (e.g., flows <100 m^3/sec) resident fishes are confined to the perennial waters which occupy less than 5% of the total floodplain area.

Source: Sommer et al. 2001.

More than two thirds of the land are within the Yolo Bypass are farmed (Table 17). Crop yields are generally lower in the Yolo Bypass area than other parts of Yolo County because of the high clay content soils and occasional late-season flooding (Sommer et al. 2001). The areas that are not farmed year round (about 1/3 of the land area) are generally maintained as managed wetlands for wildlife habitat and recreation (Jones and Stokes 2001; Sommer et al. 2001). Unlike in most of the Northern Bypass, tomato production in the Southern Bypass, on the high-quality soils and at high elevations near Putah Creek, has not been affected by increased frequency and duration of flooding during the last 5 to 10 years, therefore still does well. Livestock grazing is also utilized on some of the farm areas in the Southern Bypass.

Table 17. Predominant crops grown in the Yolo Bypass. More than two thirds of the land within the Yolo Bypass is farmed. Crop yields are generally lower in the Yolo Bypass area than other parts of Yolo County because of the high clay content soils and occasional late-season flooding. The areas that are not farmed year round (about 1/3 of the land area) are generally maintained as managed wetlands for wildlife habitat and recreation.

Predominant crops grown	**Northern Bypass (north of I-80)**	**Southern Bypass (south of I-80)**
Rice	+	-
Wild rice	-	+
Corn	+	+
Tomato	+	+
Melons	+	-
Safflower	+	+
Milo	-	+
Beans	-	+
Sudan grass	-	+
Livestock grazing	-	+
Note: Plus (+) sign signifies that the crop is commonly cultivated versus minus (-) sign signifies it is not commonly grown.		

Source: Jones and Stokes (2001).

In a study that evaluated the restoration potential for the Yolo Bypass, existing wetlands were considered the most highly suitable for enhancement (Jones and Stokes 2001). For example, duck club wetlands can be enhanced by improving water delivery systems, repairing dikes and levees, and extending periods of flooding to benefit greater diversity of wildlife. In contrast, for riparian forest, current floodway restrictions restrict establishment of dense stands of trees. Valley oak savanna is a more viable opportunity because planting at low densities may not inhibit floodflows. Many restoration settings are amenable to restoration with native perennial grasses, which provide nesting cover for waterfowl and other ground-nesting species and foraging habitat for raptors, and could potentially increase soil C sequestration compared to disturbed soil (Potthoff et al. 2005).

3.9. Potential Vulnerabilities of Wild Species to Climate Change

There are several tools that can help do a rapid assessment of the potential vulnerabilities of natural systems to the threat of climate change in Yolo County. A recent effort by the county to engage in a Habitat Conservation Plan / Natural Community Conservation Plan to abide by the federal and state endangered species acts has resulted in a thorough biological assessment report as well as a Science Advisors' commentary on this paper (HCP/NCCP). Both of these documents present, in considerable detail, the unique biological features of the county and their threats. Included in the Science Advisors' report is a statement regarding the potential vulnerabilities to climate change.

One of the planning recommendations from a group of independent science advisors for the Yolo County Natural Community Conservation Plan/Habitat Conservation Plan (NCCP/HCP) is to "Retain and manage large areas of non-natural or semi-natural 'working landscapes' to sustain and enhance their contributions to biodiversity and viable focal species populations." Planning should conserve biological resources in Yolo County, regardless if land use is "natural" or agricultural. Also, the paper calls for explicit attention to flood-susceptible areas, and recommends that the NCCP/HCP work synergistically with other planning processes (such as CALFED and the county's Integrated Regional Water Management Plan) to plan for conservation and mitigation solutions that benefit both natural and human communities, with the awareness that climate change may change distribution and habitat of focal species. Swainson's Hawks receive special attention in the paper, and for this reason, we have addressed their habitat requirements in GIS analysis in relation to land use change (see below).

Ongoing work by the county includes more work to create predictive habitat maps for vulnerable species. The work of this consultant is including an assessment of responses to global climate change. As a consequence, Yolo County will find it possible to evaluate current models in order to discuss possible consequences of warming to biota. Major foci of interest in biotic response are: (1) Swainson's Hawk foraging and nesting habitat (discussed in more detail below); (2) vernal pool endemic species; (3) salmonid fishes in Putah and Cache Creeks; (4) serpentine endemics in the coast range portions of the county; and (5) valley oak woodlands and other riparian habitats.

At present, any of the predictions for biotic response to global change may, in the end, be rather vague and unsatisfying. For example, the direction of response of vernal pool endemics to climate change are likely to hinge on more than changes in annual precipitation values, but on the seasonal distribution of precipitation and the inter-annual variation in that precipitation. These values are very difficult to obtain from existing climate models.

Yolo County is a primary nesting area for Swainson's Hawk. This species has an apparent strong preference for nesting in old valley oak trees near alfalfa fields. Rodent-rich alfalfa crops and grain crops provide favorable foraging areas for Swainson's Hawk (Herzog 1996; NCCP/HCP 2006). The Swainson's Hawk is of particular interest as a species of special concern in Yolo County because it is closely tied to the agricultural landscape. Its habitat pattern is to nest in large hardwoods such as remnant valley oaks and to forage in the surrounding fields especially in newly harvested row and hay crops. Thus, future populations of this species will depend on the behavior of farmers with respect to (1) fostering single trees associated with field crops; (2) the economics of irrigating alfalfa as a cash crop under climate change, and (3) how the water district manages vegetation along levees within the county (another location of roost trees).

We examined the dependence on agricultural habitat types by calculating the habitat proportions in surrounding nest sites (Table 18). In Figure 43, nesting observations of Swainson's Hawks (*Buteo swainsoni)* from the California Natural Diversity Database are overlaid on a map of Yolo County with the road network indicated in light gray. (See Appendix B for description of GIS methodology). Taking a value for the mean home range size for the Swainson's Hawk to be 4000 hectares (Babcock 1995), we approximated this home range area by a circular buffer 3.5 km in radius. The area in light yellow on the figure is the polygon resulting from merging the 3.5 km buffers around each nest site.

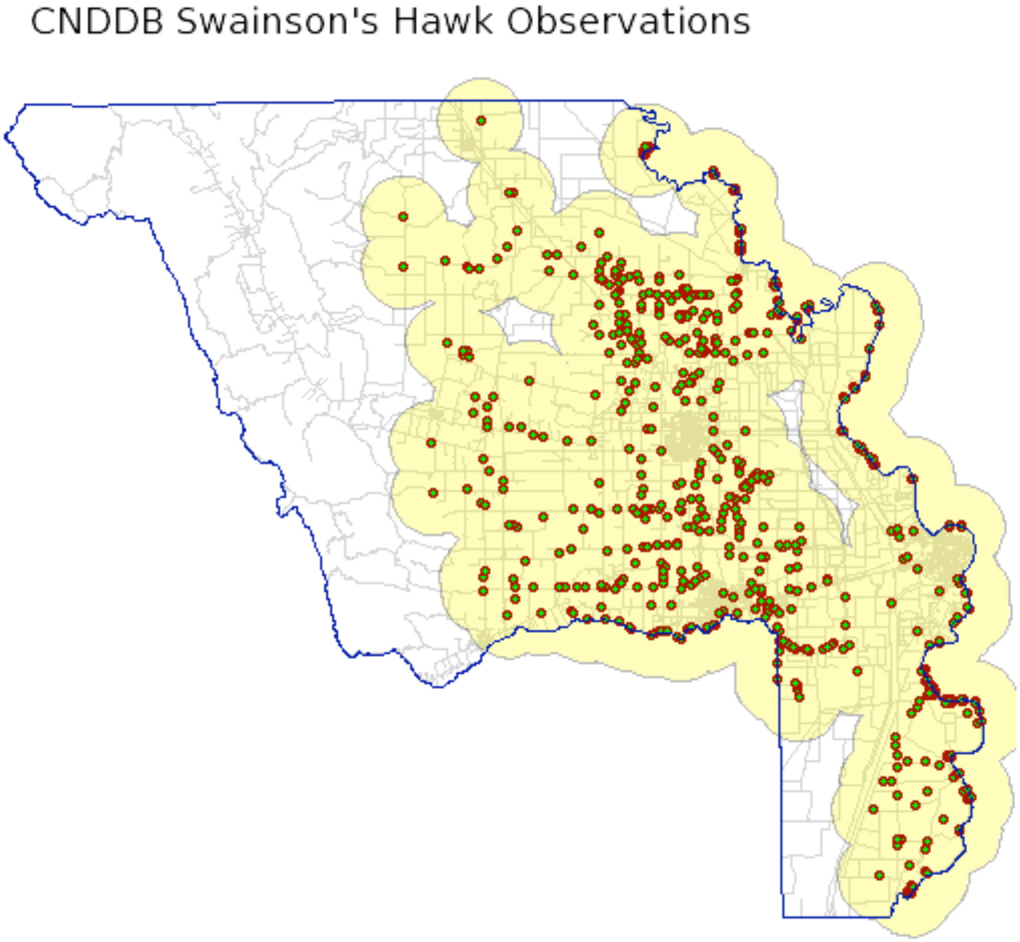


Figure 43. Swainson’s Hawk nests, and associated territories using the California Natural Diversity Database. The area in light yellow on the figure is the polygon resulting from merging the 3.5 km buffers around each nest site. (See Appendix 1 for description of GIS methodology).

Source: California Natural Diversity Data Base 2007. Map created by Allan Hollander 2007.

The top three categories, as percentage land area, are all irrigated field crops and comprise about 51% of the home range area of the Swainson’s Hawk in Yolo County. In fact, natural vegetation comprises only 15.9% of the home range area. A shift away from irrigated crop agriculture in dry climate change scenarios could thus significantly reduce foraging habitat for the Swainson’s Hawk.

The Giant Garter Snake (*Thamnophis gigas*) is a highly aquatic garter snake that is on the Federal Threatened species list. It has a very localized distribution within the Central Valley and is found in slow-moving waterways such as sloughs and irrigation canals and is also reliant on flooded rice fields and managed marshlands. As such it is a species that is very tied to land use practices in the surrounding agricultural landscape.

Table 18. Habitat types occupied by the hypothesized territories surrounding Swainson's Hawk nests in Yolo County. The top three categories, as % land area, are all irrigated field crops and comprise about 51% of the home range area. A shift away from irrigated crop agriculture in dry climate change scenarios could thus significantly reduce foraging habitat for the Swainson's Hawk. See Appendix 2 for a description of the methodology used to obtain these results.

Habitat type	Hectares	%
Irrigated row and field crops	45,649	21.91
Irrigated grain crops	33,588.6	16.12
Irrigated hayfield	27,216.8	13.06
Urban	26,016.4	12.49
Annual grassland	24,677	11.84
Rice	21,585.1	10.36
Deciduous orchard	13,069.7	6.27
Vineyard	6,559.87	3.15
Freshwater emergent wetland	2,757.79	1.32
Water	2,508.71	1.20
Dryland grain crops	1,425.41	0.68
Valley foothill riparian	1,007.29	0.48
Blue oak woodland	992.283	0.48
Riverine	574.164	0.28
Barren	345.098	0.17
Valley oak woodland	137.039	0.07
Eucalyptus	131.037	0.06
Evergreen orchard	62.0177	0.03
Unknown shrub type	48.0137	0.02
Perennial grassland	20.0057	0.01
Montane hardwood	16.0046	0.01
Lacustrine	10.0028	0.00
Blue oak-foothill pine	4.00114	0.00

Source: Data from California Natural Diversity Data Base 2007

To profile the habitat proportions in Yolo County used by the Giant Garter Snake in a manner similar to the analysis of the Swainson's Hawk, the source of the snake observations was the California Natural Diversity Database (Figure 44).

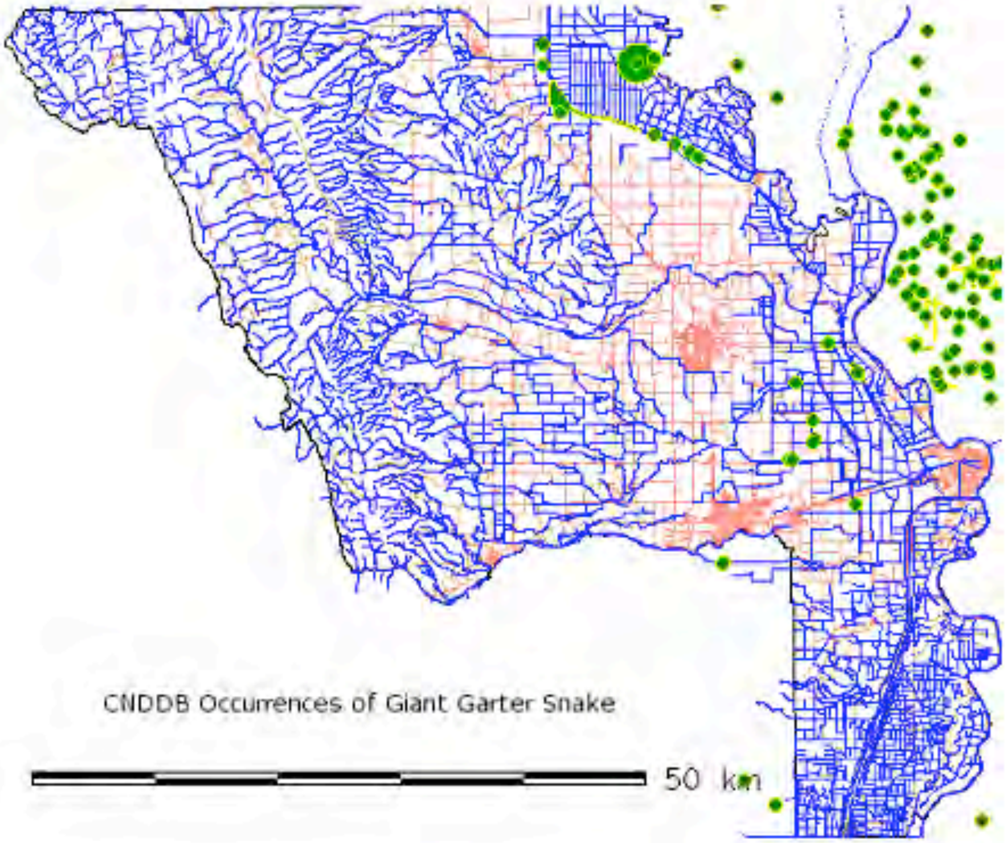


Figure 44. Observations of the Giant Garter Snake using the California Natural Diversity Database mapped in green overlaid on the hydrography network (blue) and the road network (pink).

Source: Data from California Natural Diversity Data Base 2007 and National Hydrography Dataset 2007. Map created by Allan Hollander 2007.

The mapped occurrences clearly undersample the complete range of the garter snake species in the county. This range may be approximated by tracing out along the hydrographic features a buffer surrounding the observation points. We arbitrarily set this buffer to a distance of 5 km. Figure 44 shows a map of the buffered observation points, with the observation points in green, the hydrological network in blue, and the road network in light gray. A likely explanation for the higher density of snake observation points in Western Sacramento County is the presence of a U.S. Geological Survey research program to sample Giant Garter Snakes in the Natomas Basin

(Wylie et al. 2004), which generated more sampling activity than occurred slightly to the west in Yolo County.

Using the same land cover map as for the analysis of the Swainson's Hawk, we tabulated the proportions of the habitat types in a 100-meter buffer surrounding the hydrological network indicated in blue on the map in Figure 45. As in the case of the Swainson's Hawk, the habitats encompassed by the Giant Garter Snake's range in Yolo County are predominantly agricultural, occupying a total of 88.2% of the range, with rice the leading category (occupying 47.8% of the range) (Table 19). Any change in agricultural land use is likely to have a substantial impact on the species. In particular, a shift away from rice production with its artificial wetland habitat for the snake will adversely affect the species' viability

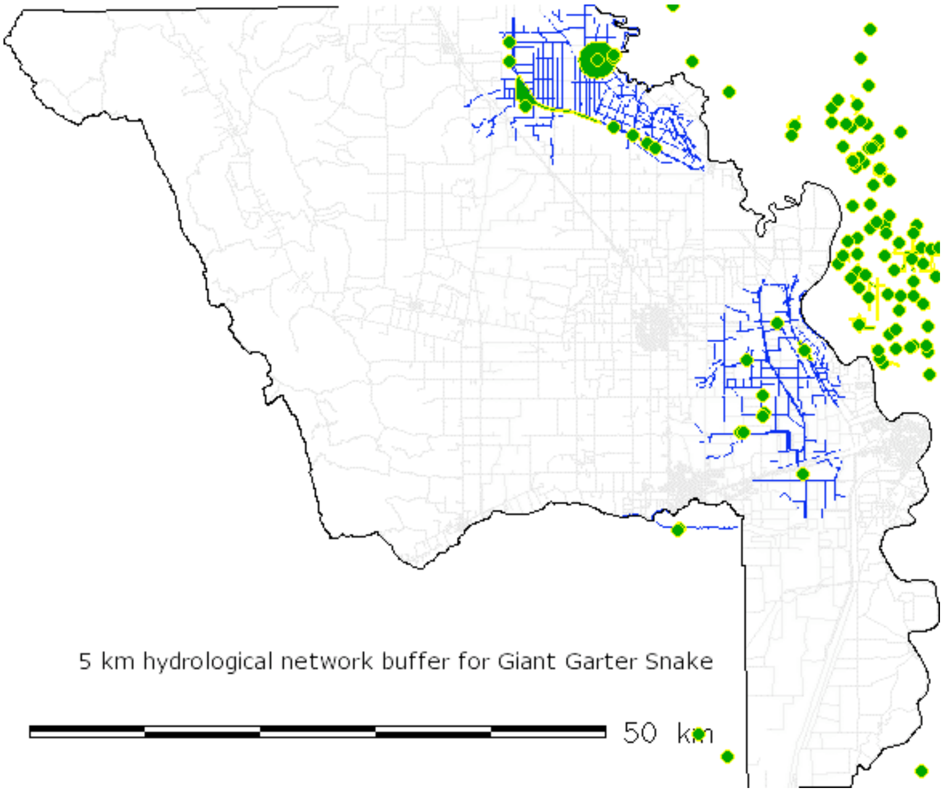


Figure 45. Observations of the Giant Garter Snake using the California Natural Diversity Database mapped in green overlaid on the 5 km hydrological network buffer for Yolo County (blue). (Note that identified populations are more numerous in Sacramento County).

Source: Data from California Natural Diversity Data Base 2007 and National Hydrography Dataset 2007. Map created by Allan Hollander 2007.

Table 19. Habitat types for Giant Garter Snake observations in Yolo County. Agricultural land occupies a total of 88.2% of the hypothesized range, with rice as the leading category (occupying 47.8% of the range). Any change in agricultural land use is likely to have a substantial impact on the species. In particular, a shift away from rice production with its artificial wetland habitat for the snake will adversely affect the species. See Appendix 2 for a description of the methodology used to obtain these results.

Habitat type	**Hectares**	**%**
Rice	3,042.52	47.78
Irrigated row and field crops	1,379.69	21.69
Irrigated grain crops	566.28	8.89
Irrigated hayfield	447.22	7.02
Urban	237.12	3.72
Annual grassland	219.11	3.44
Water	119.06	1.87
Freshwater emergent wetland	110.01	1.72
Deciduous orchards	107.05	1.68
Vineyards	67.03	1.05
Valley foothill riparian	52.03	0.82
Riverine	8.00	0.12
Dryland grain crops	7.00	0.10
Eucalyptus	2.00	0.03
Barren	2.00	0.03
Evergreen orchard	1.00	0.02

Source: Data from California Natural Diversity Data Base 2007 and National Hydrography Dataset 2007. Map created by Allan Hollander 2007.

For edaphically restricted species (e.g., serpentine endemics), rather than endangered species, climate change will probably have relatively little effect in this time period. However, climate change may affect flammability of coast range woodlands and chaparral in the areas grazed by livestock in the western part of the county. Alteration of fire frequency could have strong repercussions on habitat. For example, increased incidence of summer lightning, as in the summer of 2008, could increase fire and reduce the tree cover and C storage in oak savannas. In blue oak (*Quercus douglasii*) savannas, which are the main type in Yolo County, oaks are rarely re-establishing themselves as seedlings (Barbour et al. 1993), then fire is likely to convert savanna to grassland. Any predictions here, however, will be somewhat weak as fire within the county is also a function of anthropogenic ignitions. Although fuel loads may change with climate change, changing population density, which is a driver of changes in ignition frequencies, is also a major factor.

With mostly low density savannas and woodlands, there will need to be strong restoration efforts to create large contributions within the county toward C sequestration. One possibility is woodland restoration in the flood plain areas where flooding and groundwater storage will increase. For the upland areas, Yolo County already has an active set of programs designed to help farmers plant native trees, shrubs and grasses on their marginal lands and riparian corridors, to provide habitat for wildlife and provide other ecosystem services. Since farmscaping has the potential to sequester significant amounts of C, reduce N_2O losses (Section 2.5), it will be expected to increase in response to climate change mitigation. Audubon California is working with farmers and ranchers, mainly in the Willow Slough watershed and the Lower Putah Creek system, to implement 40 restoration projects that are compatible with existing agricultural operations. The Yolo County Resource Conservation District is also a key player in restoration of native habitat (Robins 2001).

Finally, invasive species are likely to continue to have a large impact on natural habitats. Invasive species, are notoriously plastic with respect to climate and may be expected to continue to be a problem under all climate change scenarios. Predictions in this realm may be difficult.

3.10. Urban Conversion and Population Growth

The main issues in this section include whether population growth and related land conversion will significantly decrease Yolo County agricultural land during the time period of this study (until 2050), and how policies for climate change mitigation and adaptation are likely to influence land conversion and agriculture.

Population Growth. Due to county policies of preserving agricultural land and the slow-growth policies of cities such as Davis, Yolo County remains less populated and slower growing than many other counties in the Sacramento metropolitan area. Yolo County's population grew an average of 2.2% per year from 1985–2007, from 120,300 to 197,530 residents (Table 20). Meanwhile the Sacramento Metro region (El Dorado, Placer, Sacramento, Sutter, Yolo, and Yuba Counties) and California statewide annual growth rates were 2.4% and 1.7%, respectively.

A model created by Hans Johnson (2008) from the Public Policy Institute of California, estimates future population growth for all counties in the state based on three scenarios: a low series, middle series, and a high series (Figure 46). These projections are being used by all California Energy Commission Scenarios Analysis Project, including this study of Yolo County.

Table 20. Yolo County population estimates, projections, and % growth, 1971–2050. Yolo County's population grew an average of 2.2% per year from 1985–2007. This is slightly slower than the Sacramento Metro Region's growth rate due to factors such as the county's policy of preserving agricultural land, and slow growth policies adopted by cities such as Davis.

Years	Population count	Population growth
U.S. Census Bureau: Population estimates		
1971–1981	95,307 – 115,239	+21%
1981–1990	115,239 – 142,214	+26%
1990–2000	142,214 – 169,761	+20%
Dept of Finance: Population projections		
2000–2010	169,882 – 222,277	+31%
2010–2020	222,277 – 271,040	+22%
2020–2030	271,040 – 320,434	+18%
2030–2040	320,434 – 363,663	+13%
2040–2050	363,663 – 407,691	+12%

Source: USCB, 2008; CDC, 2007.

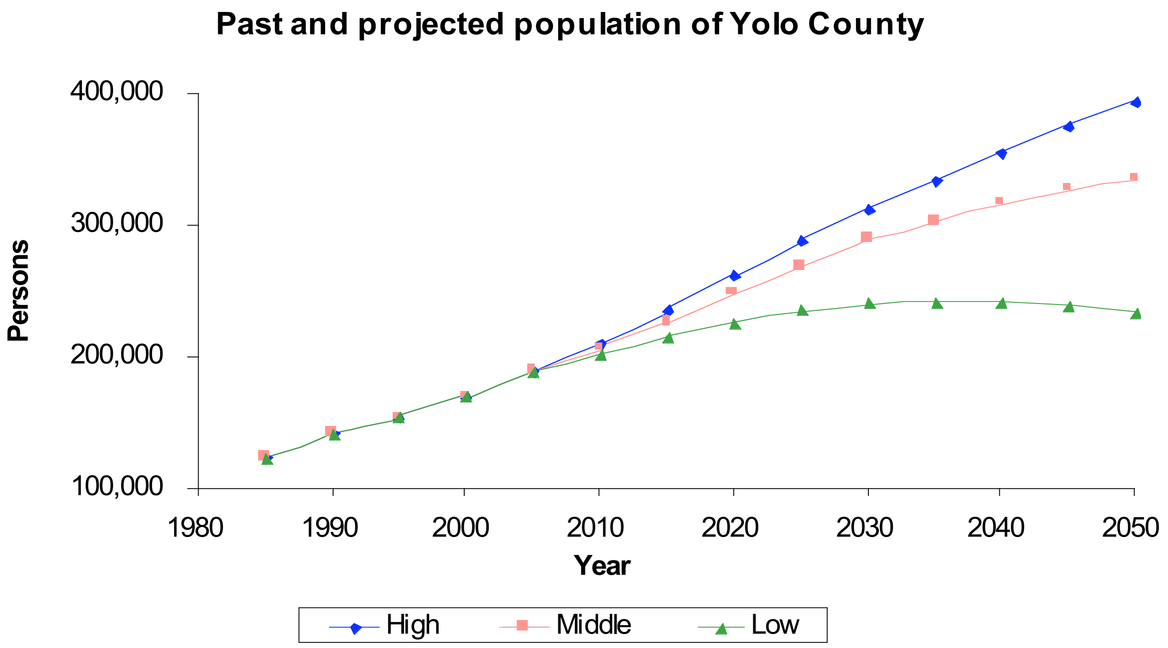


Figure 46. Past and projected Yolo County population from 1985–2050. The projections present three very different demographic futures. In the low series, population growth slows as birth rates decline, migration out of the state accelerates, and mortality rates show little improvement. In the high series, population growth accelerates as birth rates increase, migration increases, and mortality declines. The middle series is consistent with California Department of Finance projections which extend to 2050.

Source: Data from Hans Johnson/California Energy Commission Scenarios Analysis Project, 2008. Figure created by Stephen Wheeler, Fernando Santos and Joel Kramer, UC Davis.

The projections present three very different demographic futures for the county. In the low series, population growth slows as birth rates decline, migration out of the state accelerates, and mortality rates show little improvement. In the high series, population growth accelerates as birth rates increase, migration increases, and mortality declines. This scenario correlates approximately with the 2050 population estimate for Yolo County of Landis and Reilly (2003). The middle series, consistent with California Department of Finance projections that extend to 2050, assumes future growth in California will be similar to patterns observed over the state's recent history, patterns that include a moderation of previous growth rates but still large absolute changes in the state's population. The projections assume that no long-lasting catastrophic events will occur (H. Johnson, pers. comm.).

Johnson's high scenario (average growth of 1.6% each year) would double the county's 2007 population by 2050, from 197,530 to 399,043 residents, almost exactly the same as the

Sacramento Area Council of Government's Base Case estimate developed through its regional Blueprint process (SACOG 2004a). Under the middle scenario population nears stability at around 320,000, somewhat less than SACOG's Blueprint Preferred Scenario estimate for the county of 357,000, and under the low scenario county population stabilizes and actually declines after about 2035, reaching a 2050 population of about 210,000 (Figure 46). These population scenarios correlate approximately with the three climate change storylines presented earlier (A2, B1, and AB 32 Plus).

Urbanization and loss of agricultural land. According to the FMMP, farmland is by far the largest land use component of Yolo County. When combined with grazing, what is defined as agricultural land occupies 83% of the total county area. As population has increased in past decades, development of various sorts has occurred on formerly agricultural land. As a result, the county lost a total of 57,665 acres (23,336 hectares), of farmland between 1984 and 2006 (FMMP 2006), or 13% of the 1984 total of 447,917 acres (181,266 hectares). On average, Yolo County lost 2,621 acres (1,061 hectares) of farmland annually during this period. If this rate continues unchanged, between 2006 and 2050 the county will lose 115, 324 acres, or 30%, of its 2006 agricultural land.

During the 1984–2006 period every other land use category defined by FMMP increased in area (Table 21). Grazing land increased 50%, urbanized areas grew 15%, and "Other" rural uses expanded by 34%. The last of these figures is particularly noteworthy, since it represents more than twice the growth in urbanized area. FMMP states that these "other" uses include livestock, poultry, or fish facilities, mining activities, small water bodies, natural areas unfit for grazing, and low density rural activities. The latter category may in turn include horse stables, hobby farms, golf courses, estate homes, and other low-density land uses that are sometimes known collectively as "rural sprawl." Nationwide, rural sprawl is growing extremely rapidly and constitutes the majority of land area developed in many metropolitan areas (Wheeler 2008). It is not correlated with population growth so much as with land use policy and lifestyle changes.

Table 21. Yolo County land use change from 1984–2006. Farmland is the largest component. Agricultural land is defined as farmland and grazing land, which together occupies 83% of the total county area. As the population has increased in the past decades, urban expansion has occurred on formerly agricultural land. On average, 2,621 acres of farmland per year has been lost, most of which was converted to grazing land (50%) or urban expansion (15%).

FMMP category	contents	1984–2006 net area changed	Average annual acreage change
Farmland	Land cropped within past six years of any soil quality	- 57,665	- 2,621
Grazing land	Suitable to livestock grazing	+ 28,463	+ 1,294
Urban	Building density > 1 unit per 1.5 acres; 6 structures per 10-acre parcel	+ 8,488	+ 386
Other	Low density rural; natural areas unfit for grazing; livestock, poultry or fish facilities; mining activity; water bodies < 40	+ 19,814	+ 901

	acres		
Water	Water bodies > 40 acres	+ 902	+ 41

Source: Data from CDC 2006. Figure created by Stephen Wheeler, Fernando Santos, and Joel Kramer, UC Davis.

Whether such "other" uses continue to consume a large amount of agricultural land in Yolo County will depend upon county zoning and growth management policies, as well as whether additional state and regional policies are adopted to protect agricultural land and discourage very low-density residential development.

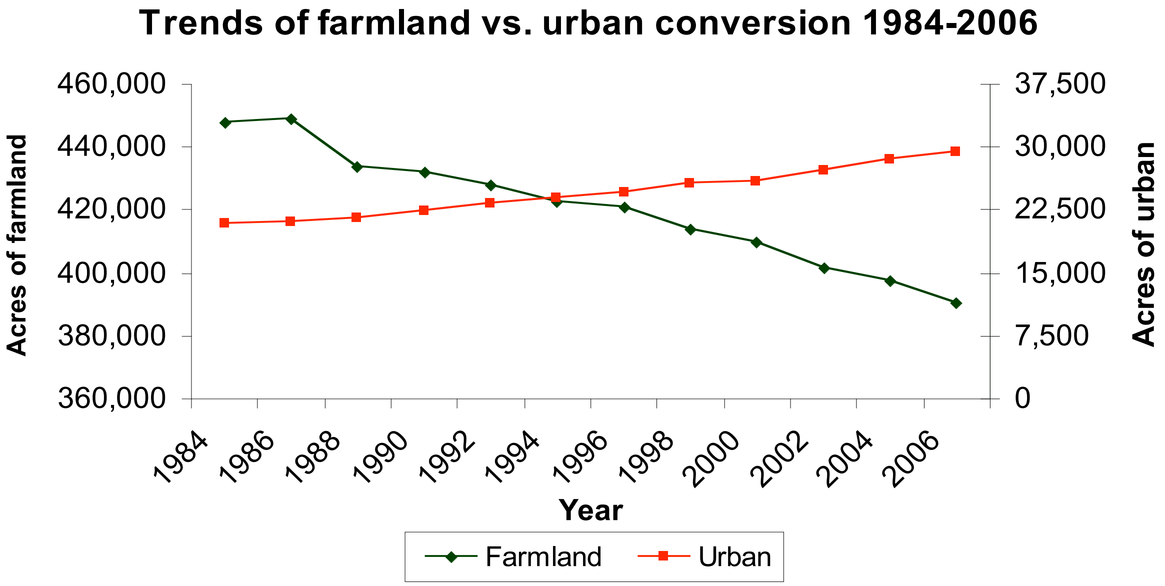


Figure 47. Farmland vs. urban land conversion in Yolo County from 1984–2006. During the last 20 years Yolo County urban area has expanded 1.6% per year while farmland has had the inverse trend with an annual loss of 0.6%.

Source: CDC 2006.

During the last 20 years Yolo County urban area has expanded 1.6% per year. Farmland has had the inverse trend with an annual loss of 0.6% (Figure 47). Based on the 1984–2006 rates of population growth and urbanization, we have created an Index of Urban Expansion showing how much farmland has typically been lost per thousand new residents in Yolo County:

$$\text{Urban Expansion} = \frac{\text{116 acres loss of cropland}}{\text{1,000 new residents}} = \frac{\text{47 hectares loss of cropland}}{\text{1,000 new residents}}$$

In the future this rate of urban expansion may slow if land is used more efficiently (i.e., if rural sprawl is restricted, if a greater percentage of development is infill, if land is zoned for higher density housing types such as rowhouses and apartments, and if average lot sizes fall for single family dwellings). However, this figure helps provide an approximate estimate of agricultural land that would be lost if current building patterns continue.

We then used this index to project future potential agricultural land loss for each of the three population growth scenarios of Johnson (2008) (Figure 48). Under the high scenario the county would maintain a constant rate of urban expansion until 2020, after which the rate of land conversion decelerates while maintaining positive values. From 2005 to 2020, urban land in the county would nearly double under this scenario from 4.6% to 8.4%. By 2050, 25,989 more acres (11,240 hectares), of agricultural land would be lost from the 2006 total, making the county 8.5% urban.

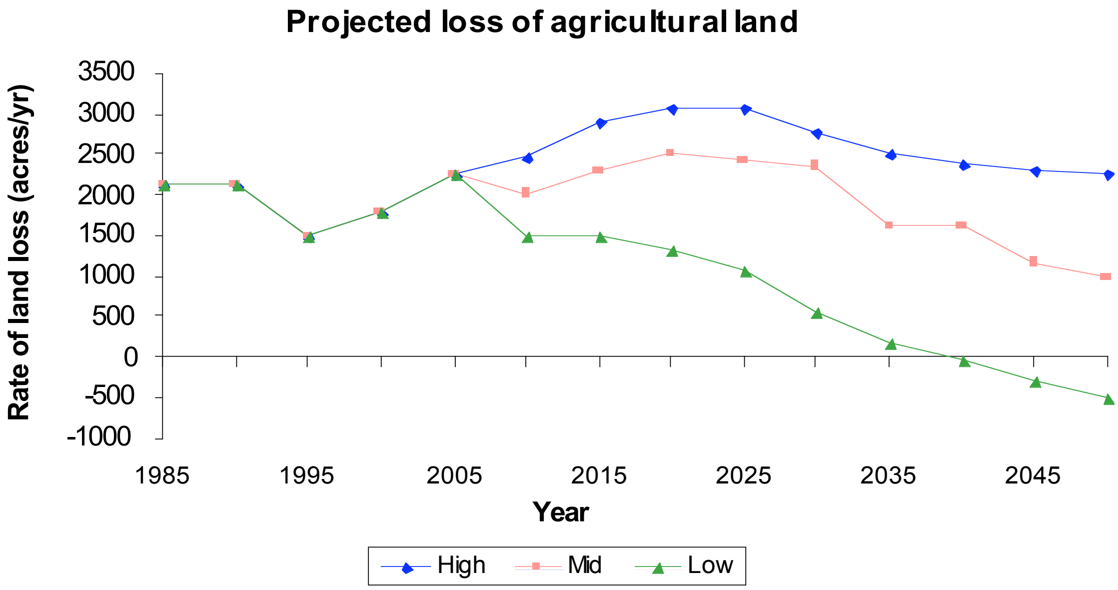


Figure 48. Past and hypothesized projected urban expansion by year in Yolo County, using an urban expansion index described in the text. In this exercise, the high population scenario would predict that until 2020, Yolo County will maintain its constant rate of urban expansion and after reaching that peak land conversion will decelerate while maintaining positive values. Meanwhile, the low scenario suggests that area of agricultural land converted to urban will decrease as the county population stabilizes.

Source: Data from CDC 2006 and CDF 2007. Figure created by Stephen Wheeler, Fernando Santos, and Joel Kramer, UC Davis.

Under the mid-range scenario, land conversion would peak around 2020, and a total of 19,200 acres of agricultural land would be lost in 2050 from the 2006 total, making the county 7.4% urban. Meanwhile, under the low scenario the amounts of agricultural land converted to urban uses drop as the county population stabilizes, for a total 2050 loss of 4,522 acres, making the county 5.8% urban. The negative value for land lost from 2035 and beyond in the low scenario, as shown in Figure 48, does not imply that agricultural land is regained, only that no new land is needed for expansion.

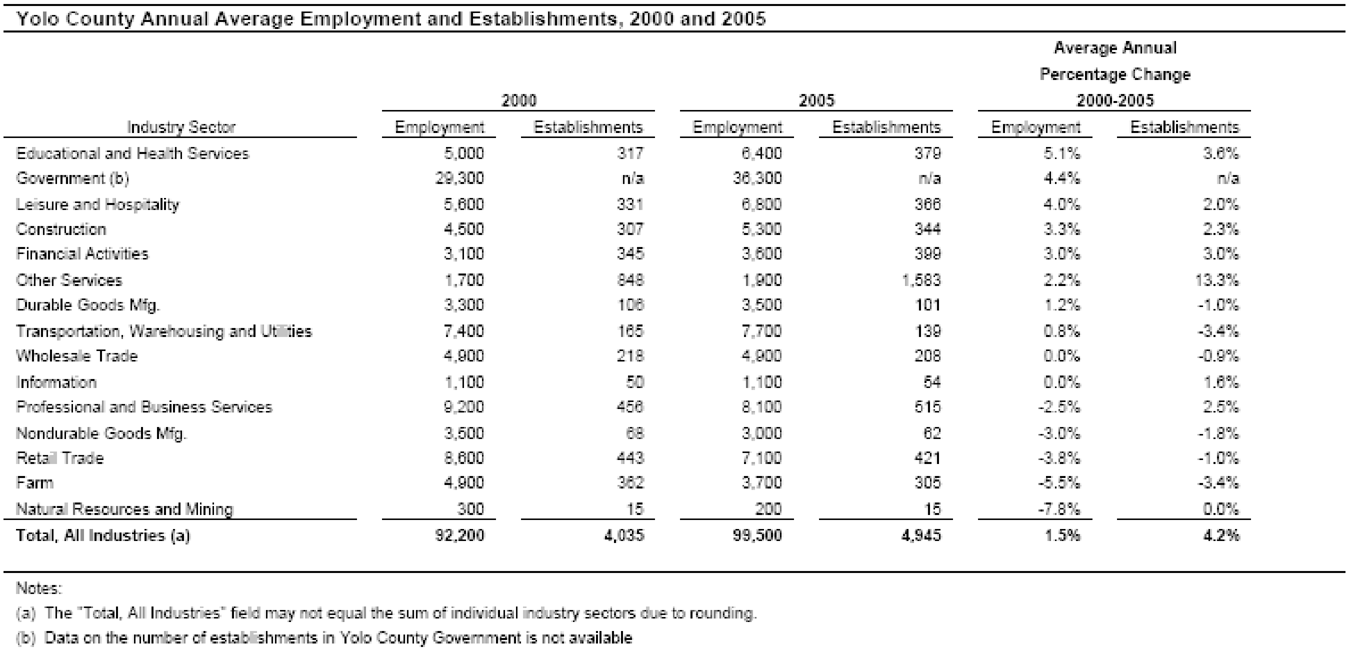
This analysis accounts just for farmland conversion to urban uses. If "Other" uses are correlated with population growth, as might reasonably be expected if agricultural property is converted to very low-density residential use and recreational use, substantial additional losses of agricultural land would occur. If the 1984–2006 rate of change is used as a guide, this farmland loss would be more than double the urbanized losses presented above.

The amount of future urban expansion is also dependent on how much additional growth occurs within existing urban areas (the "infill percentage"). This percentage has been relatively low in California historically, around 10% for many non-urban counties. However, Landis and Reilly (2003, 112) estimate a very high infill percentage of 40% for Yolo County for the 1980–1998 period, and project the same rate for subsequent periods through the year 2100. If this percentage increases further, for example through intensive city efforts to redevelop already-built lands in West Sacramento, Woodland, and Davis, more agricultural land would be saved. But this infill rate is already relatively high. As with urban growth generally, the infill percentage is highly dependent on government policy.

Judging by past trends, urbanization and related loss of agricultural land would most likely occur near the existing towns of Davis, Dixon, West Sacramento, and Woodland. Freeway interchanges are also likely sites for growth, for example along Interstate 5 in Yolo County north of Sacramento, along I-80 in the southern portion of the county, and to a lesser extent along I-505 in the western part of the county. Exact locations for urbanization would be subject to city and county decisions on rezoning land and/or state, regional, and local incentives for particular types and densities of development.

Economy, workforce, and commuters. Although agriculture is by far the largest land use in Yolo County and is important to the county's culture and character, it accounts for a relatively small percentage of direct employment. (Additional agriculture-related jobs occur in other sectors such as food processing and transportation.) Total farm employment was 6.1% in 1990 and 5.3% in 2000 (4,900 of 92,200 jobs in 2000) (Table 22), decreasing 21% during the 1990s. There are several unique assets in the county that support agriculture, such as the agriculture and biotechnology programs of UC Davis, the increasing presence of biotechnology firms, seed industry research and production facilities, and large and small food processors (Yolo County 2007a). However, as urban portions of the county grow, the percentage of workers engaged in agriculture is likely to decline further in the future.

Table 22. Yolo County employment and establishments in 2000 and 2005. Total farm employment was 6.1% in 1990 and 5.3% in 2000 (4,900 of 92,200 jobs in 2000), a decrease of 21% based on previous records. Another 7.8% of employment was lost as farm jobs between 2000 and 2005.



Yolo County Annual Average Employment and Establishments, 2000 and 2005

	2000		2005		Average Annual Percentage Change 2000-2005	
Industry Sector	Employment	Establishments	Employment	Establishments	Employment	Establishments
Educational and Health Services	5,000	317	6,400	379	5.1%	3.6%
Government (b)	29,300	n/a	36,300	n/a	4.4%	n/a
Leisure and Hospitality	5,600	331	6,800	366	4.0%	2.0%
Construction	4,500	307	5,300	344	3.3%	2.3%
Financial Activities	3,100	345	3,600	399	3.0%	3.0%
Other Services	1,700	848	1,900	1,583	2.2%	13.3%
Durable Goods Mfg.	3,300	106	3,500	101	1.2%	-1.0%
Transportation, Warehousing and Utilities	7,400	165	7,700	139	0.8%	-3.4%
Wholesale Trade	4,900	218	4,900	208	0.0%	-0.9%
Information	1,100	50	1,100	54	0.0%	1.6%
Professional and Business Services	9,200	456	8,100	515	-2.5%	2.5%
Nondurable Goods Mfg.	3,500	68	3,000	62	-3.0%	-1.8%
Retail Trade	8,600	443	7,100	421	-3.8%	-1.0%
Farm	4,900	362	3,700	305	-5.5%	-3.4%
Natural Resources and Mining	300	15	200	15	-7.8%	0.0%
Total, All Industries (a)	**92,200**	**4,035**	**99,500**	**4,945**	**1.5%**	**4.2%**

Notes:
(a) The "Total, All Industries" field may not equal the sum of individual industry sectors due to rounding.
(b) Data on the number of establishments in Yolo County Government is not available

Source*:* Sacramento Regional Research Institute 2002 and California Employment Development Department 2006.

Climate change does, however, offer new opportunities for agriculture. The use of various crops to produce biofuels is one opportunity, though tradeoffs exist with use of those crops for food or animal feed. More promising is potential use of agricultural waste or woody materials to produce cellulosic ethanol, a form of biofuel production that would not detract from food production. Other new technologies, such as use of algae or sewage sludge to produce biofuels, are under research at UC Davis.

Employment in government, manufacturing and farm has decreased while construction, transportation, trade, finance insurance and real estate, and services have increased in 1990–2000. UC Davis provides jobs in the state education category, and also attracts other sectors, e.g., relocation of federal agencies that collaborate with UC Davis (such as the U.S. Department of Agriculture).

Increasingly, people work in the Sacramento or Bay Area regions, and reside in Yolo County (Anderson and Lamborn 2003). The population is expected to increase more than the number of jobs, with Yolo County cities becoming "bedroom communities." This trend is evident in county-to-county commute patterns in 1980 vs. 2000 (U.S. Census Bureau 2007) (Figure 49). The ratio of people residing and working in Yolo County to residents working elsewhere has declined from about 2.5 (1980) to 2.05 (2000). Substantial commuting into the county also occurs; the Sacramento Regional Research Institute (2002) found a net inflow of working commuters from the more affordable residential areas outside of Yolo County. The overall picture seems to be one of increased commuting in both directions. Not surprisingly, freeways in Yolo County have seen large increases in traffic volumes, and over the next few decades are expected to experience congestion levels that were previously only seen in highly urbanized areas (Anderson and Lamborn 2003).

This trend towards increased commuting seems likely to raise the value of Yolo County land for bedroom communities for Sacramento and other job centers, fueling the demand for urbanization and raising pressures to convert agricultural land to residential uses. However, SACOG's preferred Blueprint scenario views Yolo County as still primarily an agricultural county in 2050, with few urbanized areas outside of its existing cities and towns. According to SACOG West Sacramento, at the extreme east of the county, is likely to experience the fastest urban growth due to its proximity to the regional hub of Sacramento (SACOG 2004b).

Income and poverty. The personal income and poverty levels in the county are slightly below average when compared to the rest of the state of California. The median household income in 2005 was $50,157 for Yolo County versus $53,629 for California (U.S. Census Bureau 2005a, 2005b). In 2005, 16% of the people living in Yolo County were living in poverty, compared to 13% in California as a whole. However, income and poverty levels vary substantially across the county, with relatively affluent communities such as Davis benefiting from far higher income levels than small, primarily agricultural communities such as Knights Landing and Esparto.

Due to inadequate infrastructure, drainage, and flooding problems, several of the unincorporated communities in Yolo County (including Esparto, Madison, Knights Landing, East Yolo and Dunnigan) have been identified as "disadvantaged" (Yolo County 2007a). These communities also typically have lower income levels than others, and may have more difficulty in responding to climate change-related problems such as flooding, extreme heat incidents, depleted water resources, and loss of certain crops and related employment.

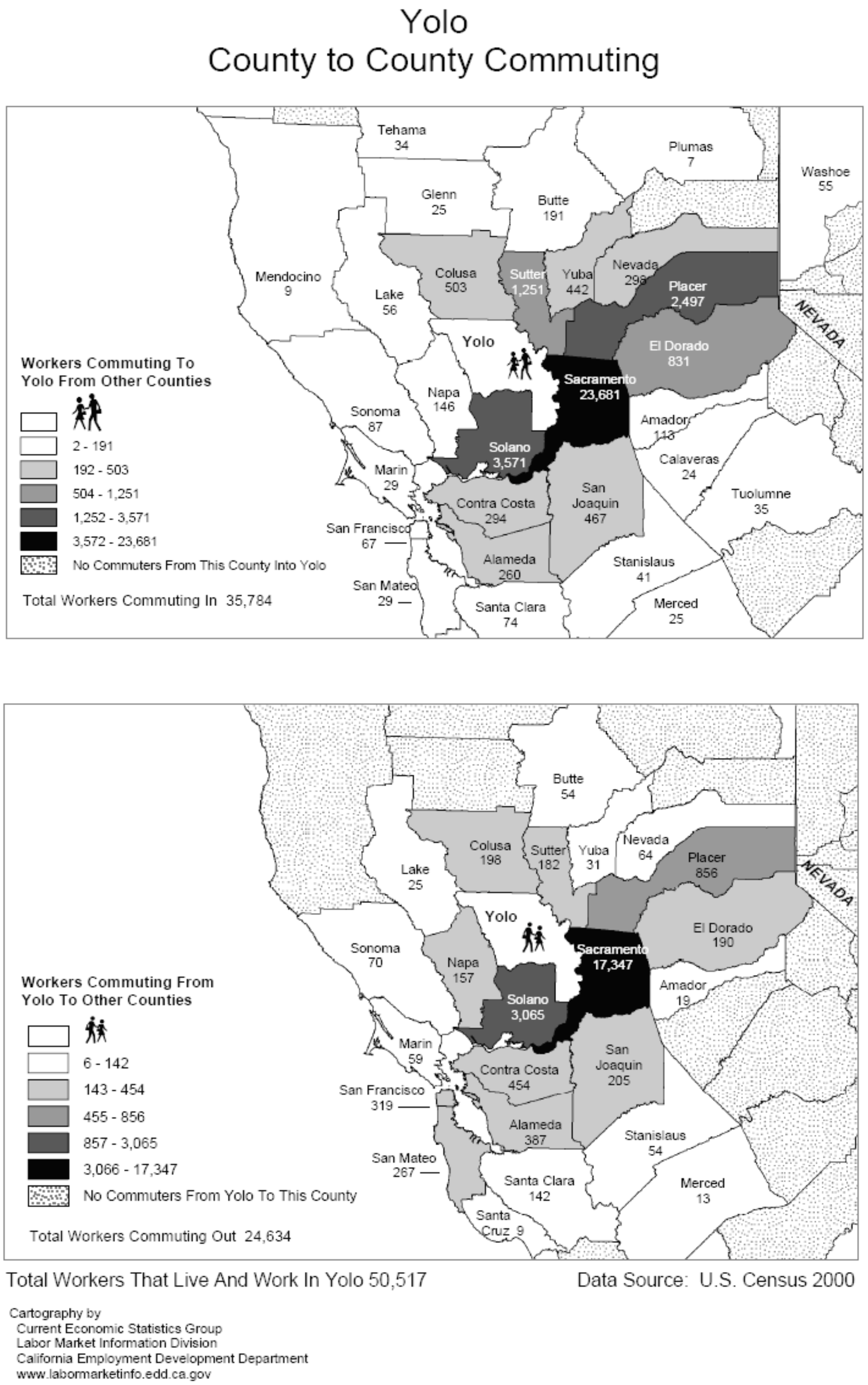


Figure 49. Yolo County to County Commuting. Increasingly, more people in Yolo work in the Sacramento or Bay Area regions. This trend is evident in county-to-county commute patterns in 1980 vs. 2000 where the ratio of people residing and working in Yolo County versus those

working elsewhere has declined from about 2.5 (1980) to 2.05 (2000).

Source: U.S. Census Bureau 2007b.

4.0 Mechanisms to Implement Climate Change Mitigation and Adaptation

4.1. Planning Horizons: Climate Change as Perceived by Growers

This project examines the factors that influence grower decision-making, particularly with regard to time horizons, that is, how far in the future do growers look, when making decisions. These factors include economic variables (costs, rates of return, expected risk) and cultural values (profit-making, land stewardship, continuity of farm enterprise). These patterns of decision-making can assist the modeling of grower adaptation to climate change (Rabl 1996; Groom et al. 2005).

To remain viable or to maintain marketable asset values all farm decisions must incorporate long-term time horizons. Sometimes choices, such as whether to plant wheat or barley on a specific field have only tiny implications for the future beyond the current year. Other choices, such as the choice to include alfalfa in a rotation have implications for several years. Many farm decisions, including choices to purchase equipment, plant tree or vine crops or invest in learning about a new crop, involve a planning horizon that may last for decades because they affect the capital value of the farm and its viability and an on-going enterprise. For these decisions affecting costs and returns over decades, climate change can become a relevant factor. In addition, we note that farms may differ in the underlying tastes and preferences of the operator and owner. In many cases, farms may chose to forgo long-term wealth in order to achieve some other personal goal, such as feeling more environmentally benign. One may think of the choice to voluntarily mitigate GHG consequences of farming, even at a cost to long-term wealth, as a kind of consumption choice and as with other such choices, more such choices will occur if the costs are lower.

One can consider planning horizons on different temporal scales. On an intra-seasonal level of weeks to months, growers make decisions about applications of water and agrochemicals, about the use of labor and other modifications to production decisions. On an annual scale, growers often decide about specific crops and varieties, and also about specific loans. On the short-term scale of a few years, growers could decide to switch to organic or perennial crops, and could make some investment decisions about equipment. In the medium-term scale of a decade or so, growers can choose to become involved, or to remain, in the Williamson Act that sets land aside from conversion to housing, in exchange for lower tax rates. Growers also make decisions at the scale of generations, seeking to assure continuity of the enterprise within the family, and at a multi-generational scale of land stewardship and of assurance of the continuity of agricultural communities.

Many farm decisions, particularly in the short-term time scales of months to years, are dominated by the economic goals of optimizing costs and returns. Faced with pressures to pay off loans and to make profits, growers choose the combination of inputs that is likely to generate high net income while meeting preferences for risk levels. However, several programs demonstrate that growers, particularly on the medium-term time scales of decades, make decisions that might reduce their expected or potential income but that meet other cultural goals, such as preserving particular farm enterprises and protecting the farm sector at large (maintaining agricultural land and open space). Some growers participate in programs, such as conservation easements and Williamson Act agricultural preserves, that reduce their ability to convert agricultural land to urban uses. In addition, many growers make other medium-term plans (organic certification, planting of tree crops, establishment of hedgerows, and cooperation with wildlife managers) that involve the interaction of economic and cultural goals. These decisions often protect environmental quality more than decisions based entirely on economic goals.

This project examines the characteristics of farms that influence adoption of these medium-term decisions and this attention to cultural as well as economic goals. In particular, we conducted a survey of growers to examine the size of the operation and the particular cropping and production systems on the operation. We also look at social variables, such as age and gender. We contrast farmers who grew up in the county with those who grew up elsewhere—a proxy for length of ownership, since individuals who grew up in the county are more likely to have inherited land. We also drew on the Agricultural Commissioner of Yolo County's parcel map to see how many other parcel-owners shared the same last name as the individual who answered the survey—a proxy for family networks, since people with the same last name are often (though not always) relatives, and relatives often (but not always) share the same last name.. We hope to study forms of ownership in greater detail in the future. This discussion will assist in evaluating different potential adaptations and in anticipating which adaptations might match with different types of growers.

An initial survey was conducted through the Yolo County Resource Conservation District and by the Yolo County Agricultural Commissioner in summer of 2008 of agricultural producers and ranchers in Yolo County. Though our initial survey does not let us assess directly the actual steps that growers are taking in investment and production decisions, we did ask them to state the importance that they place on climate change issues in planning investment decisions, and to describe the frequency with which they consider climate change issues in production decisions. (In social science language, the former is a behavioral scale and the latter an attitudinal scale.) The growers offered a range of responses on these two questions. For the importance of climate change issues on investment decisions, 31% stated they were very important, 36% somewhat important, 22% somewhat unimportant, and 11% very unimportant. For the frequency with which they considered climate change issues in production decisions, 21% of the growers stated "always," 21% "frequently," 22% "occasionally," 18% "seldom," and 18% "never": (The former is thus a four-point scale, since the additional of a fifth point, "often," would have been confusing; the latter, like many attitudinal scales, is a five-point scale.) Table 23 shows the distribution of these responses. Two facts are striking. Firstly, the responses to these two variables are very highly correlated ($p < .001$), so that an individual who gives a high rank to the importance of climate change for production decisions is likely to consider it very often for investment decisions. This association indicates both that individuals answered the survey carefully (since if they were checking boxes randomly or inattentively, they would not have high correlations) and that there is some association of concern about climate change across the shorter time horizon of production decisions and the longer time horizon of investment decisions. Secondly, individuals tend to give a higher ranking to climate change for investment decisions than for production decisions, though the significance is not as high

(P < 0.1). This association suggests that growers recognize that the impacts of climate change lie further in the future, years ahead, beyond the months-long time horizon of production decisions.

Table 23. Relationship between ranking of importance of climate change for production decisions and investment decisions.

		Importance of climate change issues on production decisions					
		Very important	**Somewhat important**	**Neutral**	**Somewhat unimportant**	**Very unimportant**	**Total**
Importance of climate change issues on investment decisions	**Very important**	7	3	0	1	0	11
	Somewhat important	1	4	7	1	0	13
	Somewhat unimportant	0	0	2	3	3	8
	Very unimportant	0	1	0	2	1	4
	Total	8	8	9	7	4	36

We found associations between some characteristics of farms and of growers with these questions. The most striking one is between Williamson Act set-asides to preserve agricultural and open space use and the importance of climate change on investment decisions (Table 24). Growers who have most, or all, of their land in such set-asides are significantly (P < 0.01) more likely to consider climate change issues as very important or important. It could be that both involvement in Williamson Act set-asides and a strong consideration of climate change issues are the result of some third variable, or it could be that participation in the Williamson Act—with a commitment to at least ten years of preserving land for agriculture—predisposes growers to consider climate change issues more seriously. We had anticipated that growers of organic produce would take climate change more seriously than other growers, but the results did not support this hypothesis.

Table 24. Relationship between land in Williamson Act set-asides and views on importance of climate change issues in investment decisions

		Importance of climate change issues on investment decisions				
		Very important	Somewhat important	Somewhat unimportant	Very unimportant	Total
Amount of land in Williamson Act set-asides	**None**	0	1	1	0	2
	Some	0	1	0	0	1
	Most	1	1	4	2	8
	All	10	8	2	1	21
	Total	11	11	7	3	32

Of the various production activities (ranching, growing grains, growing hay, growing vegetables, and having orchards or vineyards), ranching is the one with the strongest association; growers who list ranching as one of their activities are significantly ($P < 0.025$) more likely to consider climate change issues as very important or important for investment decisions (Table 25.; the totals differ from table to table because incomplete cases, with missing answers to questions, are not included). It could be that ranching predisposes growers to consider climate change issues more seriously, perhaps because of the long-term nature of investment in livestock, or because ranching is less buffered from environmental fluctuations (by the use of irrigation and agrochemicals) than other cropping systems such as growing vegetables. We looked to see whether ranchers participated more extensively in the Williamson Act (Table 26); there is a positive association between these two variables, though it is not significant at the $P < 0.05$ level. It is possible that ranchers anticipate, or hope, that they stand to gain from the cap-and-trade policy to mitigate greenhouse gas emissions. Their grassland soils store more C and emit less N_2O than tilled, fertilized soils in row crops or hay. Moreover, the wood in the native oaks on ranchlands may well be "registered" to participate in the new state policy coming from AB 32.

We had also anticipated that the growers who had orchards and vineyards would similarly be more concerned about climate change, but the results did not support this hypothesis. Orchards and vineyards do not qualify because the trees are not native, and are more likely to be cut down and thus have less permanence.

Table 25. Relationship between involvement in ranching and views on importance of
climate change issues in investment decisions

		Importance of climate change issues on investment decisions				
		Very important	Somewhat important	Somewhat unimportant	Very unimportant	Total
Ranching as one of the production systems	**Yes**	6	3	0	0	9
	No	5	10	8	4	27
	Total	11	13	8	4	36

Table 26. Relationship between involvement in ranching and participation in Williamson Act set-asides

		Amount of land in Williamson Act set-asides				
		None	Some	Most	All	Total
Ranching as one of the production systems	**Yes**	0	0	1	10	11
	No	2	1	7	15	25
	Total	2	1	8	25	36

We considered certain attributes of growers. In particular, we thought that growers raised in Yolo County might have a longer time-horizon than those who were raised elsewhere, as reflected by the level of concern about climate change, but the data did not bear out this hypothesis. We did find an association between strength of family ties (as measured by the number of individual parcel-holders with the same last name as the respondent) and concern about climate change. This association, significant at the $P < 0.05$ level (Table 27), was that individuals with more widely-represented last names in the county are less, rather than more, likely to express strong concern about climate change. This was the reverse of our expectation, which was that strong social networks and family ties might create a sense of stewardship for the land, or for the long-term continuity of agriculture as a livelihood, that would in turn lead to greater concern about climate change.

Table 27. Relationship between strength of family ties and views on importance of climate change issues in investment decisions

		Strength of family ties			
		0	1–3	4–6	Total
Importance of climate change issues on investment decisions	**Very important**	5	2	2	9
	Somewhat important	2	2	2	6
	Somewhat unimportant	0	3	2	5
	Very unimportant	1	0	3	4
	Total	8	7	9	22

We also found a weak association between gender and concern, though, as shown by the individuals who provided information about this variable. Women are more likely than men to report that they consider climate change issues as very or somewhat important (Table 28), but this is not significant. Because the number of women in the sample is so small; it bears further attention. In many agricultural societies around the world, women express a greater risk-aversion than men (Fisher et al. 2000), and incorporate concerns about younger generations more extensively than men do into their economic planning, and Yolo County may reflect this trend.

Table 28. Relationship between gender and views on importance of climate change issues in investment decisions

		Importance of climate change issues on investment decisions				
		Very important	Somewhat important	Somewhat unimportant	Very unimportant	Total
Gender	**Male**	6	7	6	4	23
	Female	4	2	0	0	6
	Total	10	9	6	4	29

In sum, these results from a small survey do show variability among growers and among enterprises in the stated importance of climate change issues for investment decisions—a matter with a longer time-horizon than production decisions, for which no significant correlations were found. It is particularly striking to see that growers who are involved in ranching are more concerned about climate change; future research can determine whether this effect is a result of from their greater perceived vulnerability to climate change, their greater perceived benefits of participation in mitigation programs, or other sources. It is interesting to note as well that participation in Williamson Act agricultural set-asides is also correlated with concern about climate change. These results indicate the responsiveness of farmers and suggest the possibility of targeting specific groups for the use of adaptations.

4.2. Grower Decision Tools and Community Strategies

In planning for climate change, farmers will need to make decisions that affect of their management operations, and that will have outcomes at different time scales. There will be a need for new information and tools that help in making these decisions, and merging mitigation and adaptation strategies. This is one of the most pressing new directions for climate change research, and effective tools will benefit from participatory input and outlook sessions with growers and other industry representations.

The following are a few ideas for the types of education and decision tools that will make the agricultural community more aware and proactive in dealing with mitigation and adaptation to climate change:

- Guidelines for management practices for individual crops and cropping systems (e.g., organic vs. conventional) that mitigate GHG emissions with potential pitfalls such as associated yield or pest problems
- Educational websites, e.g., the Marin Carbon Project, has launched a website related to rangeland C sequestration that will allow growers to estimate their GHG footprint
- Development of mechanisms to facilitate farmer participation in the California Climate Action Registry https://www.climateregistry.org/Default.aspx?TabID=3414
- Web-accessible spreadsheets and queries for individual crops and cropping systems to comply with ARB protocols for manure management, forest tree C: assessment, audits, certification
- Rules and regulations that affect the adoption of GHG mitigation practices, e.g., on the planting of woody, non-agricultural species on crop margins, canals, or sloughs

- Development of different levels of participation in mitigation that are relevant to local cropping systems and land use types, e.g., cap & trade policy developed by the State of California, labeling as a sales incentive, marketing to showcase the environmental benefits of mitigation practices
- Weather forecasting tools (e.g., AgClimate for the SE USA http://agclimate.org/Development/apps/agClimate/controller/perl/agClimate.pl) to predict crop phenology and harvest from extreme events for specific crop-location effects and design adaptive management
- Designing more efficient produce distribution centers to reduce GHG emissions and encourage diversification; one example is a trucking center for organic crops to reduce the miles traveled to pickup partial loads around the state; diversification to satisfy "one-stop shopping"
- Programs for simplification and clarity in provisions for crop failure, e.g., insurance, subsidies etc.
- Creation of auction systems for farmers to engage in ecosystem restoration that is based on spatially explicit modeling and direct interaction with growers for best management practices on specific sites, e.g., Ecotender www.napswq.gov.au/publications/books/mbi/round1-project20.html

5.0 Synthesis and Implications for A2, B1, and AB 32-Plus Scenarios

Planning for climate change is necessary for California to continue to improve its environmental quality and economy. Planning strategies simultaneously reduce vulnerabilities and increase the level of responses to mitigate and adapt to new changing conditions. Scenarios and storylines offer a way to explore possibilities and compare different outcomes. In Section 1.6, we presented three scenarios (high growth (IPCC A2 - high emission), more sustainable (IPCC B1 - lower emission), and most precautionary (AB 32-Plus). Storylines for these are outlined in Table 2. Here we compare and analyze these storylines in light of the information presented earlier.

Since temperature change and atmospheric CO_2 concentrations are likely to be roughly similar in 2050, differences among scenarios are largely associated with decision-making strategies. Two main adaptation strategies to climate change, autonomous and planned adaptation, have been recognized. Autonomous adaptation is the reaction of, for example, a farmer who voluntarily changes crops or uses different harvest and planting/sowing dates in response to changing precipitation patterns. Planned adaptation measures are conscious policy options or response strategies, aimed at altering the adaptive capacity of the agricultural system or facilitating a specific adaptation. Both strategies are considered here.

New commodities. Frequent changes in crops and crop rotations may be more likely under the A2 scenario due to trial and error strategies rather than planning for adaptation to climate change as would occur in the B1 and AB 32-Plus scenarios, assuming a "business-as-usual" short-term planning strategy for changes agricultural technology. This could result in a lack of consistency, and vulnerability to changing processing and shipping infrastructures and constraints. The A2 storyline places lower priority on agricultural adaptation, and thus on research on crop breeding and diversification. The AB 32-Plus storyline represents the greatest diversification, not only for crops, but also for farmscaping options across the landscape. Statewide research programs that forecast new growing regions for specific crops and new locations for processing and distribution centers would be more likely in the B1 and AB 32-Plus scenarios. The facilitation of movement across regions would be expected to be higher in these scenarios. This would increase adaptive capacity by farmers and ranchers.

Farm management practices. At the farm level, choices of farm management practices will differ considerably among scenarios, with more negative environmental outcomes expected in the A2 than B1 and AB 32-Plus scenarios. B1 and AB 32-Plus storylines would result in progressively less use of synthetic fertilizers, inefficient irrigation, and deep tillage, with greater use of cover cropping and organic practices. More land might also be converted to orchards and buffers of native vegetation around farm margins and riparian corridors for carbon sequestration and habitat benefits. Less immediate research on water, energy and fertility management efficiency in response to climate change is assumed in the A2 scenario, due to the lack of investment in planning. Investment in greater efficiency and more reliance on renewable inputs in the B1 and AB 32-Plus scenarios, however, will require financial investment now, and adoption of technologies that could reduce current income. Compared to A2, the B1 and AB 32-Plus scenarios will be more likely to benefit from merging mitigation and adaptation, because GHG emission reduction credits can serve as incentives to cover some of the costs of adaptation. As an example, funds received from mitigating N_2O through fertilizer reduction could partially cover the costs of improved fertilizer systems that deliver N more efficiently to crop roots, and thereby reduce the risk of inadequate N availability.

Water availability for agriculture. Overall, Yolo County's water supply is likely to see little impairment under the B1 and AB 32-Plus scenarios, based on the current modeling projections for the period 2010-2050. Unlike other California counties further south in the Central Valley that may be more susceptible to reductions in Delta deliveries, Yolo County can depend more reliably on groundwater reserves and recharge from the Sacramento River, fed by earlier Sierra snowmelt. Flooding is likely to increase along the Sacramento River, so that crop production is more variable from year to year in this region. Depending on the magnitude of population growth, urban water demands could begin to compete with agricultural needs. Under the A2 scenario, increasing population growth will demand increasing amounts of water.

Changes due to water deficits. Lower water availability in A2 (due to greater urban demands) could deter a switch to perennials due to concerns with a consistent annual water supply. Even under severe summer water shortages, winter cereals would likely still be grown; these were the first crops in the county before an irrigation water infrastructure was established. But this would greatly reduce the cash value of agriculture, and would make agricultural abandonment more attractive, further increasing urban growth. If precipitation does become less abundant due to climate change, the higher water allocation to urban use in the A2 scenario may cause agricultural crops to suffer more drastically from inadequate water supplies. Crop modeling showed that when heatwaves coincide with drought, there is as much as a 10-20% reduction in yield in field crops. The modeling exercise assumed current practices and no adaptive responses to reduce vulnerability. Since our storylines for the B1 and AB 32-Plus scenarios would support research and planning for more drought-tolerant cultivars and crop rotations, as well as improved water use efficiency, less yield loss would actually be expected compared to the A2 scenario. Yolo County is likely benefit from the research on water conservation that will be more necessary for counties further to the south, which are more likely to experience water shortages.

Water quality. Water quality is likely to be lower in the A2 scenario, the scenario that favors population growth, urban growth, and non-agricultural livelihoods. Nutrient and sediment loads may be lower if agriculture decreases in extent, but hydrocarbon inputs from urban landscapes may increase. Under B1 scenarios with greener technologies and higher emphasis on agricultural sustainability, some constituents of concern, such as nitrate and phosphate, might decrease due to improved management practices, but DOC production could be exacerbated with the use of cover cropping, manure, and sludge applications to increase soil C sequestration (B1 and AB 32-Plus scenarios). The small fraction of DOC constituents that act as drinking water contaminants, however, may be reduced to low importance if chlorination is substituted with other purification processes.

Landscape diversification. Under A2, current monoculture trends would be expected to continue. Intensive agricultural operations would still dominate the central part of Yolo County, with grazed grasslands in the uplands. Near the Sacramento River, the vulnerability to flooding would increase with time, leading to spatially intermittent abandonment, and replacement of agriculture by weedy, ruderal wetland systems. In contrast, greater diversification would be expected in all regions in the B2 and AB 32-Plus scenarios, especially in AB 32-Plus due to a change to more locally-based food systems. Planned conversion of the Yolo Bypass to support native plant, wildlife and fish communities would require expenditures for set-up and maintenance, but could accrue benefits in terms of GHG emissions reductions.

Land use change. Different directions for land use change would be expected in the three scenarios. Under the A2 storyline, assuming our high population growth scenario, Yolo County is likely to lose approximately 8% of its agricultural land by 2050. However, if population stabilizes in the B1 or AB 32 Plus storylines, as in our middle and low scenarios, a much smaller loss of agricultural land is likely. The B1 and AB 32-Plus scenarios might involve conversion of some row-crop agricultural land to woodland, orchards, or other C sequestration/GHG emission reduction uses (especially in the AB 32-Plus scenario), although quantities of such conversion would be highly dependent on economic incentives and flooding vulnerabilities, and are not estimated here.

Agricultural preservation. In Yolo County, which currently strongly supports farmland preservation, the A2 scenario is likely to place fewer obstacles in the conversion of agricultural lands to housing subdivisions, while the B1 scenario represents a commitment to agricultural preservation through measures like the Williamson Act. Since participation in this Act is associated with greater attention to the medium-term planning horizons, as shown by our grower survey, B1 might well encourage growers to look further in the future. The AB 32-Plus scenario goes even further in this direction. Both B1 and AB 32-Plus storylines might also encourage growers to extends their planning horizons by offering payments for C sequestration, thus providing incentives for soil management that extend beyond individual growing seasons.

Urbanization. A number of influences are likely to encourage B1 or AB 32-Plus storylines for Yolo County. Policy directions drafted by the Land Use Subgroup of the California Action Team call for the state to promote more compact, less automobile-oriented land uses through means such as supporting regional Blueprint planning processes, targeting state infrastructure investment towards existing urban areas, citing state facilities within existing urban areas so as to reduce driving, and offering incentives for land use policies that reduce transportation emissions. SACOG's regional Blueprint planning process supports preservation of agricultural land in Yolo County, increased housing densities, a move towards multifamily housing and other attached housing types, and increased infill of existing urbanized areas. At the county level, staff reports that planning policies being developed for the new Yolo County General Plan are likely to emphasize sustainability themes, reduction of greenhouse gas emissions, and preservation of agricultural land. Finally, economic trends such as rising gas prices are likely to encourage more compact growth patterns as well, both statewide and in Yolo County.

Agricultural planning strategies. In planning for climate change in the B1 and AB 32-Plus scenarios, three main strategies to increase agricultural sustainability are to develop new agrobiodiversity-based practices; improve soil and land management to offset and reduce GHG emissions and increase soil quality; and adjust agricultural practices and land use to cope with changing water resources. To implement these adaptation strategies, a set of grower decision tools is needed, e.g., guidelines for choosing new crops, biofuel production, or site-specific management alternatives, using weather forecasting information, and understanding cap and trade policies for getting involved in GHG emission reduction. More radical changes require more research and outreach. Thus the information needed for the AB 32-Plus scenario is clearly far beyond the current knowledge base, for example, to farm without fossil fuels or to develop locally-based food systems, and it is uncertain whether the expense of research would have an immediate or adequate payback.

Multiple influences in the state and region may dovetail with the types of land use policies consonant with B1 and AB 32-Plus storylines. But to what extent such land use changes will actually come about is ultimately a political question. What we can say at present is that if B1 or AB 32-Plus storylines are followed, they are likely to result in substantial preservation of agricultural land in Yolo County compared with A2, as well as greater resilience due to a wider variety of crops and more intensive exploration of alternative farming practices, and environmental benefits due to reduced consumption of water and energy as well as the creation of habitat at farm margins and in restoration sites.

Other California counties will experience different vulnerabilities to climate change, such as greater changes in availability of water resources, higher risk of soil salinization, less potential for diversification, and more urbanization than Yolo County. The report is relevant to other counties mainly in terms of its interdisciplinary approach to climate change and its engagement of different stakeholders to assess mitigation and adaptation potential in different subregions.

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Appendix A

GIS Analyses of Agricultural Land Use and Soil Patterns

Appendix A

GIS Analyses of Agricultural Land Use and Soil Patterns

1. Geomorphic regions. The analysis to stratify Yolo County into four geomorphic regions used soil characteristics from the SSURGO database (USDA SSURGO). In particular, for each map unit, the component table in SSURGO was used to identify the name, soil order, and soil great group of its dominant soil component. The map unit was then assigned to one of the four geomorphic regions using a lookup table based upon the soil characteristics.

2. The Storie index, which is a measure of soil suitability for agricultural use, was computed for each map unit of the SSURGO map for Yolo County. This index was computed by weighting the value of the Storie index within a soil component in the SSURGO database by the fraction each component occupies within a map unit. Six classes within the Storie index values were created, namely: Excellent (Storie index values of 80–100), Very Good (values of 60–79), Fair (values of 40–59), Poor (values of 20–39), Very Poor (values of 10–19), and Non-agricultural (values of less than 10).

3. Crop types and soil characteristics. The relationship between cropping types and soil characteristics was analyzed by overlaying the 1997 DWR land use map on the SSURGO map for Yolo County. In particular, the DWR land use map gives 54 different crop types and 91 different land use types in total, as determined by combining values in the CLASS1 and SUBCLASS1 columns in the attribute table. The soil characteristics that were used included the geomorphic region and the Storie index classes, both calculated as described above. The overlay of the land use map and the soils information facilitated cross-tabulating the areas and proportions of crop types with respect to the different geomorphic regions and Storie index classes. In particular, the proportions of the crop types within Region 1 (flood basins) and Region 2 (recent alluvium) were examined in detail. The spatial overlays and cross-tabulations were performed using the spatial database PostGIS (http://postgis.refractions.net).

4. Flood frequency. Flood frequency values were taken from the dominant condition flooding frequency column in the map unit aggregated attributes table in the Yolo County SSURGO database. Four categories of flood frequency were listed in this table: Frequent (1–2 times/year), Occasional (>5 times every 50 years), Rare (once every 100 years), and None.

5. Irrigation sources. The map of irrigation water sources (Figure 40) was produced using the water source column in the 1997 DWR land use map.

6. Irrigation type. The map of irrigation type (Figure 39) was produced using the primary irrigation type column (IRR_TYP1PA) in the 1997 DWR land use map. Because there were a large proportion of map units with an unknown irrigation type, the irrigation type for these unknown values were imputed by referring to the crop class and the irrigation source for the map unit. Specifically, a contingency table was made that gave the number of map units of each combination of crop class, irrigation source and irrigation type for

map units with known irrigation types. From this contingency table, a simple Bayesian model was made to predict irrigation type given the crop class, the irrigation source, and a prior probability for the irrigation type.

Appendix B

GIS Modeling of Swainson’s Hawk Nests and Land Use in Yolo County

Appendix B

GIS Modeling of Swainson's Hawk Nests and Land Use in Yolo County

A fine-scale (4-meter resolution) land cover map of Yolo County was done in two separate pieces: natural vegetation agricultural land, covering the eastern two-thirds of Yolo County. For the land cover classification in the natural vegetation portion, we worked with the NAIP (National Agriculture Imagery Program) imagery available from the California Spatial Information Library at http://gis.ca.gov. This is natural color imagery covering the state of California at a resolution of 1 meter. Despite the fact this imagery is only available in three bands (red, green, and blue) and lacks the additional information from a near-infrared band, we opted to use an unsupervised classification approach in producing the land cover map of the natural vegetation region. To do this we first segmented the image into a natural vegetation portion and an agricultural landscape portion. These two portions were separated using the Department of Water Resources' 1997 land cover mapping for Yolo County. This land cover map classifies agricultural areas to great detail but lumps natural vegetation into only several categories. In addition to the natural vegetation boundaries from the DWR land cover map, we also extracted the streams and canals in the study region from the National Hydrography Dataset, buffered these by 10 meters, and added these to the natural vegetation boundary dataset. The natural vegetation portion of the image thus included both the western portion of the study region as well as buffers around the streams and canals that transversed the agricultural portion of the study region.

Using a clustering algorithm where we decided *a priori* the number of clusters (the software being i.cluster and i.maxlik in the GIS GRASS), we created 12 initial clusters from the image. We decided to classify these clusters into 5 different land cover types: annual grassland, blue oak woodland, and sparse, medium, and dense valley riparian woodland. Identifying the annual grassland clusters was straightforward by inspection, but the four woodland cluster types needed further work. Classifying these was aided by combining information on elevation using the 70 meter contour to indicate the break between the agricultural lowlands and the uplands, wooded vegetation density based on calculating the percentage of wooded vegetation surrounding a given pixel, and whether the pixel fell within 10 meters of a hydrological feature.

The agricultural portion of the study region was classified by recategorizing the 128 land cover types that fell within the study region in the DWR land cover map. The vector DWR land cover map was then rasterized at a 4 meter resolution and the pixels were assigned to these 128 land cover types within the agricultural subsection of the study region. This agricultural raster map was then patched together with the natural vegetation portion from the image classification to produce the combined classification for the entire study region.

For the analysis we used a land cover layer that was ultimately derived from the California Department of Fire and Forest Protection Multi-source Land Cover map. This Multi-source Land Cover map was enhanced with data from the DWR land cover mapping and crop data from the Department of Pesticide Regulation Pesticide Use Reports to give added information about agricultural types. Using this enhanced map, we tabulated the proportions of the habitat types within the buffer area.