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Case study on potential agricultural responses to climate change in a California landscape

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Abstract Agriculture in the Central Valley of California, one of the USA's main sources of fruits, nuts, and vegetables, is highly vulnerable to climate change impacts in the next 50 years. This interdisciplinary case study in Yolo County shows the urgency for building adaptation strategies to climate change. Climate change and the effects of greenhouse gas emissions are complex, and several of the county's current crops will be less viable in 2050. The study uses a variety of methods to assemble information relevant to Yolo County's agriculture, including literature reviews, models, geographic information system analysis, interviews with agency personnel, and a survey of farmers. Potential adaptation and mitigation responses by growers include changes in crop taxa, irrigation methods, fertilization practices, tillage practices, and land use. On a regional basis, planning must consider the vulnerability

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of agricultural production and the tradeoffs associated with diversified farmlands, drought, flooding of cropland, loss of habitat for wild species of concern, and urbanization.

1 Introduction

This paper examines climate change vulnerabilities and coping strategies for mitigation and adaptation in an agricultural landscape using a case study approach that considers agricultural sciences, economic issues, soil science, and land use change. The study focuses on Yolo County (Fig. 1) as it is representative of the diverse agricultural landscapes throughout the Central Valley of California: irrigated perennial and row crops on alluvial plains; upland grazed rangelands; small towns and cities; and a changing mixture of urban, suburban, and farming-based livelihoods through the past few decades.

Yolo County includes the Sacramento River floodplain and alluvial fans as well as terraces of the Coast Range. The area has a Mediterranean climate and rainfall mainly during the winter months. 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 climatic 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 capitol city of Sacramento.

Temperatures in this region are likely to increase 1.3°C–2°C by 2050 regardless of the postulated global emissions scenario, and 2.3°C–5.8°C by 2100 depending on the level of future emissions (Cayan et al. 2009). Warming effects are likely to be more severe in summer than winter, and precipitation will likely decline. Heatwaves will occur more frequently, last longer, experience higher peak and duration of temperature, and begin earlier in the summer than historically (Hayhoe et al. 2004; Miller et al. 2007).

Both mitigation of greenhouse gas (GHG) emissions and adaptation strategies are response options to decrease vulnerability to climate change, and they can have synergistic effects under some circumstances. This paper focuses on the potential

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Fig. 1 Location map of Yolo County in Northern California

modifications to farm and land use practices, rather than on changes in public policy decision-making processes (Smit and Skinner 2002). Responses to climate change are set within the larger context of other major changes in California during the next 50 years, including population growth, water availability, regulations that favor agricultural sustainability, and changes in agricultural markets. The interrelation of many of these factors is shown in Fig. 2. The goals of this research were to:

- Understand the vulnerabilities of a California agricultural landscape to climate change, based largely on review of the literature.
- Determine the key biophysical and socioeconomic uncertainties (local and regional) that will affect mitigation and adaptation to climate change in this landscape.
- Develop a template for exploring sustainable regional responses to climate change for California's agricultural counties.

2 Agricultural commodities and climate change

2.1 Crop responses to climate change

Anticipated climate change will have both positive and negative effects on the yield and quality of currently produced commodities. 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 may allow for more crops of lettuce outside of the coastal regions during the winter (Wheeler et al. 1993), expansion of citrus production (Reilly and Graham 2001), and heat and drought-tolerant trees such as olives. Major physiological impacts of anticipated temperature changes include diminished yields

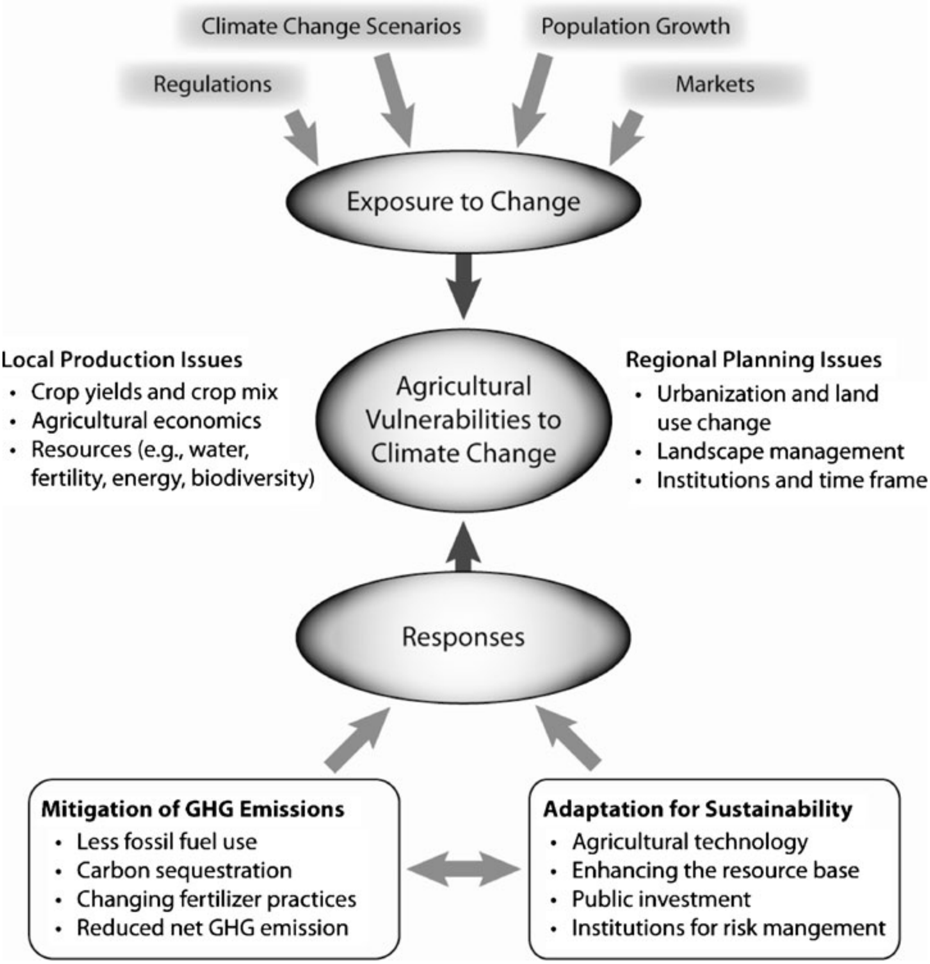

Fig. 2 Agricultural vulnerabilities to climate change, set within the context of exposure to changes driven by several societal issues, and the responses in terms of mitigation and adaptation options, including interaction and tradeoffs between them

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), and reduced product quality from unseasonal precipitation or adverse temperatures during fruit development (Southwick and Uyemoto 1999). Horticultural crops are more sensitive than field crops to short-term environmental stresses that affect reproductive biology, water content, visual appearance, and flavor quality, and are thus likely to be more impacted by climate change and extreme events (Backlund et al. 2008; Bazzaz and Sombroek 1996). Crop breeding is one approach to dealing with these problems, however, this requires purposeful action years in advance, especially for perennial crops.

To assess the effect of climate change on row crop productivity, alfalfa, maize, rice, sunflower, tomato, and wheat in Yolo County were modeled using DAYCENT, a process-based biogeochemical model (Del Grosso et al. 2002). We assumed current management practices (conventional management, fixed management schedules and a typical set of crop rotations, no changes in pests or diseases, and no effects of CO_2 or temperature on developmental biology) for the period 2000 to 2050 (Lee et al. 2010). Under both A2 (high emissions) and B1 (low emissions) scenarios (Cayan et al. 2009), average modeled maize, sunflower, and wheat yields decreased by 2% to 8% by 2050 relative to the 2000 to 2004 average yields (Table 1). The yields tended to decline slightly more under A2 than B1. In general, alfalfa was predicted to increase slightly under climate change in the same period, while rice and tomato were essentially unaffected by the modeled conditions.

Additional DAYCENT model runs were conducted to examine how extreme weather events may affect crop production. Early heat waves seem to have a profound effect on crop growth except for alfalfa and winter wheat (Table 1). 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. Repeated heat waves in May–July had the most profound effects on crop production by decreasing 3–19% of the 2000-2004 baseline yields. However, drought did not have much added effect on irrigated crop yields during heat waves.

Yolo County’s horticultural row crops (e.g., tomato, cucumber, sweet corn, and pepper) are warm-season crops with a temperature optimum of 20°C to 25°C for yield, and an acceptable range of 12°C to 30°C, with a maximum tolerance of 35°C (Backlund et al. 2008). Mean mid-summer maximum temperatures by mid-century may force a shift to hot-season crops such as melon and sweet potato, with higher acceptable temperature ranges

Table 1 Effects of heat waves[a] and drought[b] on field crop yields in Yolo County under A2 and B1 emission scenarios, as determined by the DAYCENT model (Lee et al. 2010)

Commodity	Emission scenario	2000–2004			2046–2050				
			Baseline climate change		Heat waves only				Heat waves & drought
					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	−6.3	−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

[a] 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 three months each year from 2000

[b] 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

(18°C to 35°C). 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.

Stone fruits, nuts and grapes require approximately 200 to 1200 h of winter chill to flower (Backlund et al. 2008). Chill hours are computed on a daily basis relative to a reference temperature. Using climate predictions for the Central Valley, winter chill hours are expected to decrease from a baseline of 1000 h, as observed in 1950, to about 500 h by 2100 (Baldocchi and Wong 2006; Luedeling et al. 2009). Lack of winter chill hours may be more important for these perennial crops than yield losses due to higher temperatures during the growing season (Lobell and Field 2009).

For non-irrigated rangelands that are limited by cool temperatures in winter and spring, higher temperature and CO_2 enrichment could potentially stimulate productivity. But field experiments with elevated CO_2 have demonstrated decreased grassland productivity with increased temperature, precipitation and soil NO_3- compared to current ambient levels (Shaw et al. 2002). Deposition of plant residues with lower nutrient content as well as greater demand for N under elevated CO_2 may reduce grassland production over the long-term (Schneider et al. 2004; Dukes et al. 2005; de Graaff et al. 2006). Alternatively, N-fixing legumes may become more abundant in annual grasslands, partly due to warmer winter temperatures, contributing more N supply to these ecosystems. But this will require adequate soil phosphorus and micronutrients such as iron and molybdenum to support N fixation (Hungate et al. 2004; Van Groenigen et al. 2006).

For livestock, high summer temperatures, e.g., above 35°C, cause physiological stress and low consumption of feed (Conrad 1985). Dairy cows with high body temperatures have been shown to have lower milk yield (West 2003), and this is also important for cow-calf operations on rangelands. Overall, current evidence suggests that livestock forage on these rangelands may decrease due to climate change, especially in dry years and in response to N limitation, leading to lower livestock stocking rates, and earlier animal removal dates, requiring transport to irrigated, permanent pasture.

Other environmental factors contribute to the uncertainty of crop responses to climate change. Elevated CO_2 is generally considered to increase biomass production of annual crops by 10% to 20% under field conditions (Long et al. 2006). But under elevated CO_2, rates of nitrogen (N) assimilation by roots often do not keep up with shoot accumulation of carbohydrates (Reich et al. 2006; de Graaff et al. 2006). Also, nitrate (NO_3-) assimilation may decrease under elevated CO_2 due to inhibition of photorespiration, resulting in reduced growth and yield of C_3 plants (Rachmilevitch et al. 2004; Bloom 2009). Adaptation will require changes in N management. Elevated CO_2 concentration may also reduce stomatal conductance and evapotranspiration (ET), but will depend on changes in the wind environment and resulting micrometeorological resistances. If the growing seasons of certain crops shorten, then ET per crop may decrease slightly. Of course, alternative crop mixes and rotations will affect ET due to inherently different water use patterns.

2.2 Crop pests and climate change

Agricultural weeds, pests, and diseases will be impacted by climate change in uncertain ways (Field et al. 1999; Scherm 2004). Even a 2°C temperature rise can result in one to five additional generations per year 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 (Hill et al. 1999; Parmesan and Yohe 2003).

Climate change is likely to lead to a northern migration of weeds in the Central Valley, and disease and pest pressure will increase with earlier spring arrival and warmer winters, allowing greater proliferation and survival of pathogens and parasites (see Cavagnaro et al. 2006). Predicting these changes requires better understanding of ecophysiology, and the complexity of the trophic interactions.

Pierce's Disease has caused severe damage to grapevines in southern California, 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 USA that is more mobile than leafhoppers already present, and is now limited to climates with mild winters such as southern California (Purcell and Hopkins 1996).

Some other possible effects of higher temperature 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, tomato spotted wilt virus, and earlier activity of perennial weeds such as bindweed.

2.3 Crop water needs

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

Farmers in Yolo County rely on groundwater for almost 40% of their supply in a normal water year, and this dependency is expected to increase under possible future drought and population growth conditions (Yolo County 2007). Rice, pasture, and hay have the highest applied water and ET, and are therefore the most vulnerable to water shortages. Using economic modeling, hypothetical surface water irrigation cutbacks (25% less during a normal, non-drought year with no supplemental groundwater) in Yolo County had higher impacts on high water-demanding crops including alfalfa, vegetable crops such as tomatoes, and most importantly rice (Lee et al. 2001). Crops with more return per ha and per unit of water showed less acreage reductions.

California had fewer periods of extended drought in the latter part of the last century than in the period of 1915 to 1935, when severe drought occurred, although the early 1990s also brought a serious drought. The historical runs of the global GCM models are in agreement with these records (Cayan et al. 2009). Present climate models do not predict any prolonged droughts until the end of this century. However, drought 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 would impact the amount and timing of water deliveries.

Adaptation to a more uncertain water supply requires that crops be planned and managed to reduce water use by applying alternative technologies, such as using drip irrigation rather than furrow irrigation; finding ways to reduce ET, such as crop breeding for greater canopy cover; switching to crops that use less water; and/or reducing overall irrigated crop acreage.

Specific management challenges vary across the county. Eastern Yolo County relies more strongly on water originating from snowmelt from the north and east Sierra Nevada. Western Yolo County relies on rainfall runoff coming from the Coast Range, and will be more vulnerable to water shortages, although groundwater supplies are plentiful at present. Higher temperatures and increasing population and urbanization would place greater demands on water resources in Yolo County and lead to a more uncertain water supply for agriculture.

2.4 Strategies for responses to climate change

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

- **Crop diversity.** Growers will shift toward hot-season species, with greater winter potential for cool-season crops such as lettuce and broccoli. A shift to greater crop diversity will offset some of the risks from weather variation due to climate change. A switch is expected to higher cash value crops with greater income per amount of applied water.
- **Crop breeding.** Selection for genotypes that benefit from elevated CO_2 and are N-use efficient is essential, but breeding for water use efficiency often results in lower growth and yield (Condon and Hall 1997).
- **Irrigation.** If water supply becomes threatened, shifts toward drip irrigation, deficit irrigation, and crops that provide higher income per amount of applied water are potential adaptive responses. Subsurface drip irrigation has been shown to reduce GHG emissions (both CO_2 and N_2O), with no differences in tomato yields in Yolo County (Kallenbach et al. 2010). Reduction in water use and GHG emissions must be weighed against the need for investment, labor, energy for pressurization, and the lower potential for groundwater recharge during wet years.
- **Fertilizer use.** Reducing inputs of N-based fertilizers is a strategy to reduce emissions of N_2O, a potent GHG. Current average application rates of N fertilizers are up to 25% higher than needed for optimal yield (Krusekopf et al. 2002; De Gryze et al. 2010). Farmers may need to increase N fertilization, however, to compensate for physiological changes in N uptake and lower crop protein.
- **Cover cropping.** Cover cropping is a strategy to improve soil fertility, increase soil C sequestration, and decrease fertilizer use, but would prevent the possibility of cool-season cash crops, and potentially reduce soil water recharge for summer crops.
- **Tillage.** Low-till or no-till methods have generally not shown a soil carbon (C) benefit to the Central Valley (Veenstra et al. 2006), but can decrease fossil fuel inputs (Jackson et al. 2004). For many of Yolo County's crops, however, tillage reduction presents production constraints, such as seed establishment or efficient movement of furrow irrigation water. Also, alternative tillage practices can increase N_2O emissions due to higher soil moisture content and increased activity of anaerobic microorganisms (Kong et al. 2009). Net GHG reduction is likely only after many years of low-till practice (Six et al. 2004), which is often not feasible.
- **Manure management.** Manure management activities are important for achieving reduction in GHG (principally methane) and local air pollutants. Methane digesters are useful for dairy production (Mitloehner et al. 2009), but most livestock in Yolo County is beef cattle.
- **Farmscaping.** Use of perennial vegetation in marginal lands on farms, such as farm edges and riparian corridors, can increase C storage, reduce N availability and N_2O

emissions, and benefit water quality, habitat, and biodiversity (Young-Mathews et al. 2010). Cost-share programs would hasten widespread implementation.

- **Carbon sequestration in tree crops and vines.** Perennial woody crops are a potential opportunity for growers to receive GHG mitigation credits. But such a policy mechanism does not yet exist, and may be difficult to justify in terms of permanence of C storage.
- **Organic production.** Yolo County currently contains more than 50 organic farms, most producing a diverse mix of crops for local markets (4% of total agricultural value; Yolo County Agricultural Commissioner 2007). Organic production may hold adaptive advantages in that its diversity of crops can better respond to a changing climate. Net GHG and losses of N also may be lower than conventional production (Poudel et al. 2001; Smukler et al. 2010). New and increased pest and disease pressure may be an even greater problem for organic than conventional farms. New markets would need to be developed to support expanded organic production.
- **Biomass utilization for energy and fuel production.** Over the 40-year time horizon assumed for this study, a potential higher-value value market for agricultural commodities may be energy. Second and third generation biofuels based on ligno-cellulose (biomass) and microbial systems in both terrestrial and aquatic systems are more likely candidates than grain feedstocks for ethanol. Construction of an ethanol processing facility would not be able to increase local grain prices by a large enough margin to generate the additional acreage for local corn (Lee and Sumner 2009). Utilization of existing crop residues such as orchard and vineyard prunings, rice straw, and animal manures for bioenergy production can provide additional revenue to farming operations, or at least fix energy costs if produced and used onsite.

We conducted a survey of growers through the Yolo County Resource Conservation District and the Agricultural Commissioner's office in the summer of 2008, which found that 67% of the 36 respondents considered climate change "very important" or "somewhat important" to their investment decisions. Nearly half (43%) of growers reported that they "always" or "frequently" consider climate change in their production decisions. Growers with land in Williamson Act set-asides (a state program through which growers receive tax benefits for agreeing to keep land in production for 10 years) were more likely to be concerned about climate change. No differences were found in climate change concern between organic and non-organic producers. Ranchers were significantly more likely to be concerned about climate change than other types of farmers. The survey indicates that Yolo County farmers may be a receptive audience for strategies that could help them mitigate and adapt to a changing climate.

2.5 Agrobiodiversity as a facet of crop response 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 as well as species in habitats outside of farming that affect processes such as pollination, pests and pest control, and water quality (Jackson et al. 2007). Maintenance of high levels of inter- and intra-species diversity is considered a strategy to decrease vulnerability and enhance resilience to uncertainty and to climate change (O'Farrell and Anderson 2010; Palm et al. 2010).

To assess the effect of fluctuations in crop acreage on crop diversity, we applied the Shannon-Weaver Index (Weaver and Shannon 1949), using 45 different crops found in the Yolo County Agricultural Crop reports. The index measures species richness (H) and evenness (*E*). It essentially assesses the proportion (*p*) of each crop with respect to its production category's total, and then exaggerates that relationship.

$$H = \sum p_i \ln p_i$$
$$E = H / \ln(\text{number of crops})$$

According to this Index, orchard/vineyard and grain categories share a higher average richness than other crops (Fig. 3). The Index for orchard-/vineyard 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. Grain crops are annuals such as corn and wheat, occupy a much larger amount of land overall, and are more prone to annual variation in diversity and acreage. While the diversity index for truck (i.e., vegetables and melons) and field crops (e.g., hay and alfalfa) were both initially higher, the last 25 years has brought a species-poorer crop mix. Evenness as a whole across the entire county is generally decreasing, indicating that dominant crops occupy more of the acreage with time (Fig. 4).

Several pathways exist to increase agrobiodiversity as an adaptation to climate change. One is to breed and select crop varieties resistant to heatwaves and drought, and to take advantage of the elevated CO_2 that will occur later in the century. Another is to target new crop taxa for the region, and begin the process of adaptive management. Diversified farm systems are another possibility (see Section 3.2). Long-term planning must also include processors, shippers and market opportunities.

2.6 Soil and land management options for mitigation of climate change

California's agricultural and forestry sectors contribute 8.3% of all anthropogenic GHG emissions in the state (CEC 2006), which is roughly 37.5 million metric tons of CO_2 equivalents ($MMTCO_2E$) annually, based on the fact that over 450 $MMTCO_2E$ annually is attributed to human activity in California. If California's agricultural and forestry sectors proportionately 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.

Half of the California agricultural emissions is emitted as N_2O (CEC 2005) mainly due to microbial nitrification and denitrification of fertilizer N 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

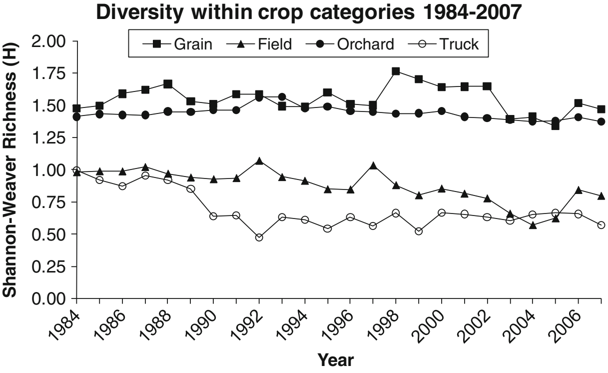

Fig. 3 Crop species richness using the Shannon-Weaver Diversity Index based on acreage 1984–2007 in Yolo County. Orchard/vineyard and grain crops maintain a higher level of species richness than other categories. The number of commodities in use continues to decline overall for grain, field and truck (i.e., vegetable) crops. Data from Yolo County Agricultural Commissioner (1984–2007)

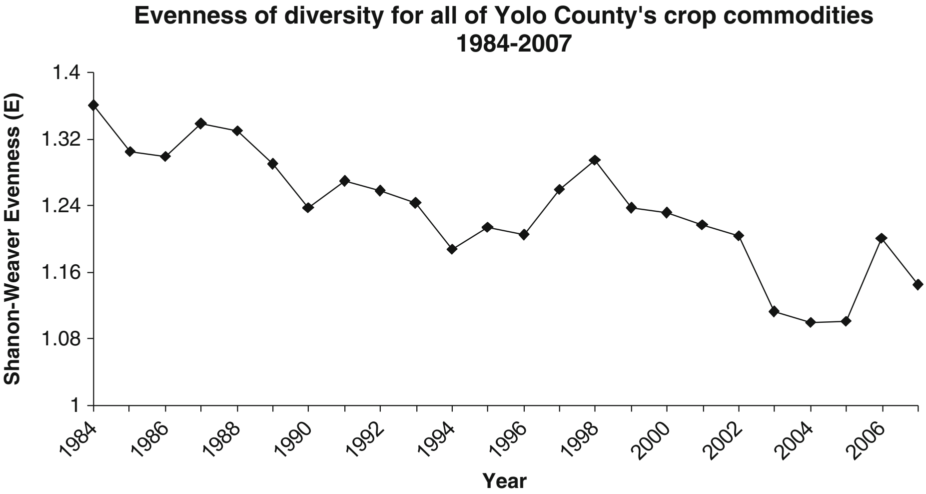

Fig. 4 Total crop species evenness using the Shannon-Weaver Diversity Index based on acreage 1984–2007 in Yolo County. Consistent total decline in the evenness between the acres of each species cropped indicates that a few commodities increasingly occupy more of the acreage with time. Data from Yolo County Agricultural Commissioner (1984–2007)

enteric fermentation of livestock. The latter source is less important in Yolo County than statewide due to the presence of very few dairies and feedlots.

Long-term research at UC Davis suggests that the use of cover crops and manure can contribute to up to 300 kg of soil C sequestration per ha under consistent management (Horwath et al. 2002). However, after five years the rate of soil C sequestration diminished significantly. Using the DAYCENT model, De Gryze et al. (2010) found that there was biophysical potential to reduce soil GHG flux up to 4577 kg CO_2E ha^{-1} yr^{-1} in agricultural soils in the Sacramento Valley, and that organic management practices had higher mitigation potential than cover crops or conservation tillage. In all cropping systems, reduction of N_2O emissions was more important for mitigation than changes in soil C.

There is uncertainty and a wide range of variability for GHG emissions estimates from agriculture in California depending on crops, management systems, and soils. Research is on-going but in the meantime, estimates should be taken with care, and 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.

3 Landscapes and land use options

Since 1850, California's agriculture has been constantly changing via growth, transition, and adjustment (Williams et al. 2005). Large changes have occurred within the last 150 years in Yolo County's alluvial plains, beginning with early attempts to raise livestock, grow grains, and develop horticulture without much irrigation. This was followed by an era of ruminants and wheat and barley production, and then intensive fruit, nut, and vegetable agriculture and large-scale cattle production began, ending with the present management-intensive, technologically-dependent agricultural industry (Mikkelsen 1983; Johnston and McCalla 2004), and expanding organic production (Broome and Worthington 2009).

Despite pressure of urbanization, Yolo County's agricultural landscapes have remained relatively stable in recent years. From 1992 until 2008, a net loss of about 12,000 ha of agricultural land occurred, and this includes a net gain of about 6,500 ha of grazing land according to the 2008 California Department of Conservation Farmland Mapping and Monitoring Program (FMMP). In 1988, several thousand ha were converted from farmland of local importance to grazing land due to sign ups for the federal Conservation Reserve Program. Urbanization has been slow, due to strong local agricultural preservation policies, and is likely to remain so unless agriculture becomes less viable. Overall, only 1% of Yolo County's total prime farmland was lost up until 2000 (Sokolow and Kuminoff 2000). Since 1998, the rate of agricultural conversion to wetlands along the Sacramento River for wildlife conservation has increased to approximately 800 ha yr^{-1} (Landon 2009), which may continue given the threats of flooding due to earlier Sierra Nevada snowmelt (see Section 3.1).

3.1 Vulnerabilities of Yolo County's agricultural landscapes to climate change

The impacts of climate change and the associated mitigations and adaptations in Yolo County will vary according to its diverse landscapes. To investigate these differences we employed a geographic information system (GIS) approach to stratify the county into the following four geographic units that represent similarities in land use, soil types and the environmental factors that formed them (Fig. 5; Appendix A):

Region 1. Flood basins, largely along the Sacramento River
Region 2. Recent alluvium (alluvial plains, fans and low terraces)
Region 3. Old alluvium (undulating dissected terraces, terraces)
Region 4. Uplands of the Coast Range

In low-lying Region 1 near the Sacramento River, farmlands are at risk of flooding due to earlier snowmelt in the Sierra Nevada. The 100- and 500-year floodplains of the Sacramento River extend westward into prime agricultural farmland (California Department of Water Resources 2006; 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 is already subject to prolonged periods of late spring flooding that now occur more frequently than in the past (Jones and Stokes 2001). Planting beds, furrows, ditches, and other agriculture-related infrastructure (e.g., roads, canals, diversion structures, pumps, and wells) can also be damaged or destroyed by flooding.

The restoration of marginal farmlands into wetlands may have several environmental benefits including wildlife 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 GHGs such as N_2O and methane, which are more potent GHGs than CO_2. 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 GHG 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 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

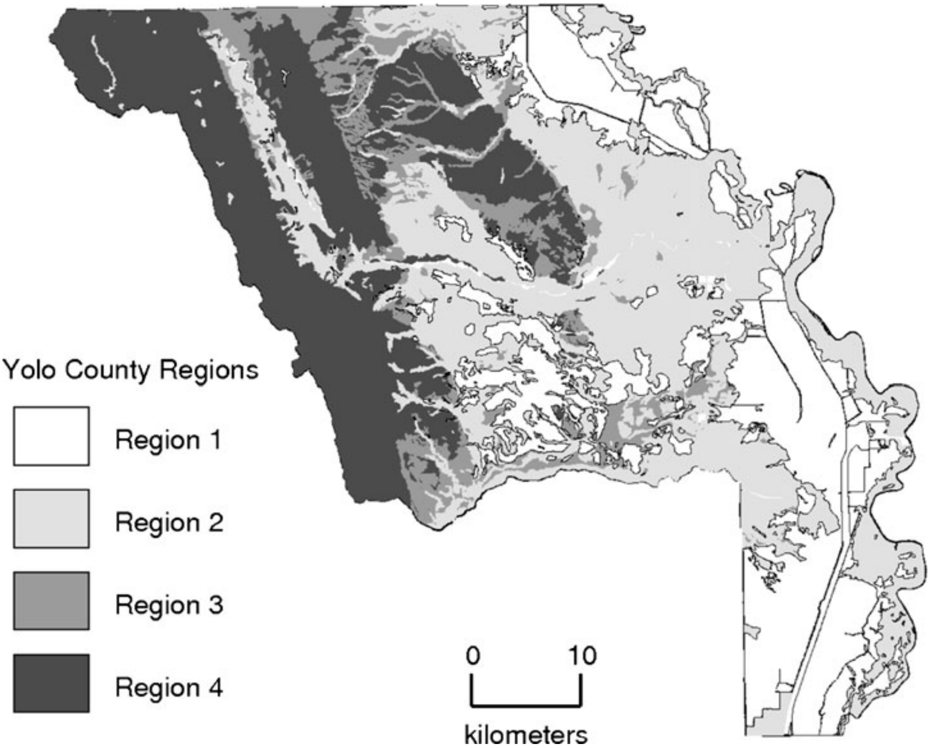

Fig. 5 Zonation of landscape regions in Yolo County, based on the aggregation of soil survey data (USDA-NRCS SSURGO database) in a GIS. Region 1 represents clay-rich soils in basin alluvium, mostly suitable for rice production. Region 2 represents other alluvial soils in their initial stages of soil development supporting a wide mix of crops. Region 3 represents marginal agricultural lands on rolling dissected fan terraces suitable for orchards and vineyards. Region 4 represents rangeland and wildlands of the Coast Range

opportunity to change commodities with lower potential losses. Best management practices to maintain or enhance C storage in soils include the use of cover crops, organic agriculture, conservation tillage, irrigation management, buffer strips, and vegetative filter strips, and many of these practices have other benefits as well, such as reduced erosion (Grismer et al. 2005; O’Geen and Schwankl 2006).

Region 3, an area of terraces and low hillslopes, can benefit from practices to increase crop diversification and practices that increase C storage. A switch to drip irrigation could conserve water and eliminate irrigation-induced soil erosion (Hanson et al. 2008). Residue management practices such as conservation tillage, cover crops, compost and mulch can improve water infiltration, increase soil 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, less erosion and possible C sequestration. An added pressure in this area is the expansion of urban development, which could become more pervasive if agricultural productivity and income decline due to climate change.

Region 4 has the greatest potential to maintain its C stocks. This upland 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, strategies to ensure oak regeneration, use of appropriate seed mixtures, and reseeding of perennial grasses. Climate variability that adversely affects forage production will, however, challenge rangeland managers. Vegetation management such as prescribed fire may be necessary to expand productive areas and avoid catastrophic fire.

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 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, and at least initially, to ruderal, herbaceous plants. An active restoration program would protect higher elevations of Region 1 from further flooding and would simultaneously sequester more C and possibly reduce N_2O emissions. Additionally, shifting rice fields to riparian vegetation in strategic locations would provide opportunities for other sources of revenue, such as from firewood or timber, from paying the farmer to maintain high biodiversity and wildlife habitat, and from other ecosystem benefits related to water quality and recreation.

3.2 Agrobiodiversity as a source of innovation for landscape responses to climate change

Dealing with climate change can also be achieved by increasing agrobiodiversity at the landscape level. These types of changes were explored on a regional basis within the county. In one example, two hypothetical farms were created, each 1,300 ha to resemble a normal quantity of land that a Yolo County farm manager oversees. 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 pasture and orchards with purposefully minimized water consumption. The production costs and quantities for all crops were obtained from the Cost and Return Studies from the UC Davis Agriculture and Resource Economics Department (UC Davis 2008).

In the hypothetical diverse farm, some 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 an establishing alfalfa crop; almond and walnut orchards replace the flood-irrigated safflower crop; almonds, prunes, and high-density plantations of oil olives replace one-third of the 370-ha tomato crop. Three major components (material cost, harvest cost and non-cash overhead, and investments) contribute to the higher cost of the diverse farm (data not shown; see Jackson et al. 2009). 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. Consequently, the mitigation benefits of diversifying with orchard trees and pasture will be related to increased C stocks and a reduction in tillage rather than a significant reduction of fertilizer, energy inputs for water deliveries, or other input requirements.

If returns are calculated with long-term intermediate commodity prices and yields, the diverse farm yields a 3–4% profit (depending on the sequence of the crop rotation), while the standard farm produces a net loss of 5%. Of course, there are additional issues associated with the increase in crop diversity, e.g., equipment needs and availability of processors and markets. But crop diversity may ensure less vulnerability to heatwaves and drought, as the different species vary in tolerance as well as timing of growth. This cost analysis suggests that a diversified farm may offer economic benefits to farmers in an era of climate change.

Farm margins offer another set of options for diversification. Only 33% of riparian zones in an irrigated cropland area in Region 2 contain stands of trees and shrubs (Young-Matthews et al. 2010). Wood C stocks, however, can increase 10-fold when native tree and shrub diversity is enhanced in restored areas along waterways, and if levee setbacks are made slightly wider than the typical steep-edged channel, then flooding potential and bank stability also improve. Planting hedgerows on field edges and installing tailwater ponds with planted edges are practiced by only a few farmers on a very small amount of land (Brodt et al. 2009). Public and private sector programs that provide assistance to farmers for restoration of farm margins are beginning to reverse these trends in Yolo County (Robins et al. 2001).

Climate change will undoubtedly impact wild species in the agricultural landscape (NCCP/HCP 2006). Swainson's Hawk is a species of special concern with a preference for nesting in old valley oak trees near alfalfa fields. Rodent-rich alfalfa crops and grain crops provide favorable foraging areas (Herzog 1996; NCCP/HCP 2006). Thus, future populations of this species will depend on the behavior of farmers with respect to: (1) fostering single, roost 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 (another location of roost trees). In the upland savannas and woodlands, oaks are expected to decline with climate change, due to shrinking of habitat ranges, and to increased fire frequency (Hayhoe et al. 2004; Kueppers et al. 2005). Conversion to grassland will affect C stocks, forage quality and shade for livestock, and wildlife populations (Barbour et al. 1993).

4 Mechanisms to implement climate change mitigation and adaptation

4.1 Grower decision tools and community strategies

In planning for climate change, farmers must make decisions that affect their management operations at different time scales. There will be a need for new information and tools to help make these decisions, and for merging mitigation and adaptation strategies. Decision support tools represent 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 discussion of potential pitfalls such as associated yield or pest problems.
- Educational websites for growers to estimate their GHG footprint. For example, the Marin Carbon Project has launched a website related to rangeland C sequestration.
- Development of mechanisms to facilitate farmer participation in the California Climate Action Registry.
- Web-accessible spreadsheets and queries for individual crops and cropping systems to comply with California state government protocols to calculate, report, and verify GHG emission reductions.
- Rules and regulations that affect the adoption of GHG mitigation practices, e.g., 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.
- Weather forecasting tools (e.g., AgClimate for the SE USA) to predict crop phenology and harvest after extreme events, for specific crop-location effects, and to design adaptive management.
- Designing more efficient produce distribution centers to reduce GHG emissions and encourage diversification. One example is a trucking center for small farms to reduce the miles traveled to pick up partial loads around the state.
- 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.

4.2 Scenarios for the future of agriculture and agricultural landscapes in Yolo County

Scenarios and storylines offer a way to explore possibilities and compare different outcomes. Consequently, we developed and analyzed three scenarios for the county for the period until 2050, in cooperation with farmers and personnel from governmental agencies and other organizations: high growth (IPCC A2—high emission), more sustainable (IPCC B1—lower emission), and most precautionary (AB 32-Plus, stricter than the climate change policy framework being established in California under AB 32). The narrative storylines ‘downscaled’ the emissions scenarios to regionally relevant situations, and were initially based on information in regional planning documents, but were then edited and augmented by stakeholders and a steering committee (Jackson et al. 2009). While the storylines are too locally-specific to be presented here, the process was essential in gaining access to new viewpoints and initiating awareness of climate change responses in the local community.

A2. “Regional enterprise.” In this rapid growth and economic development scenario, the county population expands rapidly, urban land doubles, and farmland is lost. 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 show little change, 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 more environmentally oriented scenario, the county population expands more slowly, and urban and rural residential encroachments on agricultural land are proportionally less. Growers diversify their crop mix for resilience, and reduce intensity of N-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 C sequestration in soils, and these and other farming practices help reduce GHG emissions.

AB 32-Plus. “Precautionary change.” In this greenest scenario, the county population stabilizes slightly above the current level, the urban footprint remains constant, farmland is strongly protected, and GHG emissions are most strongly reduced. Growers further diversify their crop mix, substantially increase heat- and drought-tolerant orchard crops, increase production by double cropping, and eliminate fossil fuel inputs to agriculture, both through fertilizers and motor vehicle fuels. Water use efficiency in dry years increases through crop mixes that reduce ET, and by alternative irrigation methods. Extensive conservation practices sequester C in wetlands and woodlands along waterways, using practices that minimize N_2O and methane emissions. Biodiversity increases in cropped and non-cropped areas of the landscape. Novel food systems encourage reduction of GHG emissions as well as new markets and greater resilience, creating the greatest long-term agricultural sustainability of all of the three scenarios.

Multiple influences in the state and region may dovetail with the types of agricultural practices and 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 benefits to farmers and agricultural stakeholders in this county. These benefits include preservation of agricultural land, greater economic resilience due to a wider variety of crops and more intensive exploration of alternative farming practices, resource benefits related to reduced consumption of water and energy, and environmental benefits due to continuation of working agricultural landscapes on which some species depend as well as creation of additional habitat at farm margins and in restoration sites.

5 Conclusion

Sustainable regional responses to climate change for California's agricultural counties will undoubtedly vary from county to county, but based on our experience in Yolo County, exploration will be facilitated by including the following elements:

- Scaled-down modeling runs from GCM to determine likely temperature and precipitation impacts for the county or region in the 2050 and 2100 time frames.
- Crop-level analysis of likely impacts and adaptation strategies given the particular crops, climate, and ecology of the county or region.
- Landscape-level analysis of likely impacts and adaptation strategies given the particular crops, climate, and ecology of the area.
- Analysis of other factors potentially affecting the future viability of agriculture in the county or region: population growth and urbanization trends; economic factors affecting existing crops; potential economic feasibility of new crops including biofuels; and analysis of environmental variables including water use and availability, habitat status, and endangered species.
- Collaborative engagement throughout the research process with stakeholders, including farm organizations and local governments, to determine likely strategies and potential operational concerns.

Appendix

GIS Analyses of Agricultural Land Use and Soil Patterns

Geomorphic regions. The analysis to stratify Yolo County into four geomorphic regions used soil characteristics from the USDA SSURGO database. 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.

Crop types and soil characteristics. The relationship between cropping types and soil characteristics was analyzed by overlaying a land use map (California Department of Water Resources 1997) on the SSURGO map for Yolo County. The 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 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. The spatial overlays and cross-tabulations were performed using the spatial database PostGIS (http://postgis.refractions.net).

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.

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