ESTIMATING THE ECONOMIC IMPACTS OF AGRICULTURAL YIELD RELATED CHANGES FOR CALIFORNIA

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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.

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- 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.

Table of Contents

Preface ii
Abstract vii
1.0 Introduction 1
2.0 Model Description and Methods 1
2.1. The Statewide Agricultural Production Model, SWAP 1
2.1.1. Model Regions and Crop Groups 2
2.1.2. SWAP Model Architecture 3
2.2. Model Innovations for Year 2050 5
2.2.1. Changes in Land Use 5
2.2.2. Technological Change 6
2.2.3. Shifts in Crop Demands for California 7
2.2.4. Model Innovations from Climate Change 10
2.2.5. Regional Crop Data in SWAP 11
2.3. Policy Simulations 12
3.0 Results 12
3.1. Results for the Pilot Region 13
3.2. Statewide Results 14
3.3. Model Limitations and Extensions 24
4.0 Conclusions 26
5.0 References 27
6.0 Glossary 29

List of Figures

Figure 1. Map of coverage of the Statewide Agricultural Production Model (SWAP) 3
Figure 2. Land Use in CVPM region 19 12
Figure 3. Total cultivated land per crop under climate scenarios in the Sacramento region 20
Figure 4. Total cultivated land per crop under climate scenarios in the San Joaquin Basin 21
Figure 5. Total cultivated land per crop under climate scenarios in the Tulare Basin 22
Figure 6. Total cultivated land per crop under climate scenarios in Southern California 23
Figure 7. Percent change in land use under climate scenarios for all crops and regions 25

List of Tables

Table 1. Expected changes in land area between 2020 and 2050 (adapted from Landis and Reilly 2002) and CALVIN-SWAP region crop areas 6

Table 2. Technological change projection summary 7

Table 3. Real (2005 dollars) percent changes in price, base 2005 8

Table 4. Elasticities by SWAP crop group 9

Table 5. Demand shifts 10

Table 6. Expected percent change in yields as a result of a warm-dry climate scenario 10

Table 7. Expected percentage reduction in available water 11

Table 8. Agricultural land use per crop groups at CVPM 19 11

Table 9. Crop acreage in CVPM region 19 14

Table 10. Changes by 2050 at the intensive margin (water use per acre) CVPM 19 14

Table 11. Base land use (in thousands of acres) per region 15

Table 12. Price changes under standard and climate change scenarios 16

Table 13. Total agricultural revenues by region and scenario (in millions of 2005 dollars) 16

Table 14. Water use by region (in TAF/yr) 16

Table 15. Percentage change price, production, revenue (historical vs. warm-dry climate scenarios) for year 2050 17

Table 16. Land use (in acres) per crop and region under 2050 historical climate 18

Table 17. Land use (in acres) per crop and region under 2050 climate change 18

Table 18. Total land use (in acres) by crop under climate scenarios 19

Abstract

This research measured the economic effects of climate-related yield change in California crops. Agricultural yields may be adversely affected by climate warming, resulting in increased production costs per unit. These effects may be partially offset by higher crop prices if California can maintain its position as the dominant supplier. Yield reductions vary by crop and region, but initial results show significant revenue losses for farming activity in California. A statewide mathematical programming model, the Statewide Agricultural Production Model (SWAP), was used to generate the estimations of revenue impacts. Advantage of explicitly modeling crop production is that one can formally link the results from hydrologic models, or climate-related agronomic the model directly into the economic model. The base regional cropping pattern was established using geo-referenced data of land use for twenty-one regions in California's Central Valley and five regions in Southern California including Palo Verde, Imperial, Coachella, Ventura and San Diego. As such, a total twenty-six (26) regions were included. Results show significant reductions in irrigated acres that range regionally from 28 percent to 17 percent, and 10.5 percent to 16.3 percent reductions in revenues due to partial offsets from price and crop changes. Changes in prices and productivity contribute to changes in total revenue. Revenues across all regions are reduced under climate change, as is water usage. Since the 26 regions that were considered have comparative advantages in different crops and different endowments and prices of inputs, all of these effects vary by region. The overall conclusion from model runs is that, while the effect of climate change is manifest through yield changes, after economic adaptation, the results on irrigated crop production are predominately shown in economic terms and changes in aggregate land and water use.

Keywords: climate change, mathematical programming, crop yield, production functions, SWAP

1.0 Introduction

In California, agriculture is a significant contributor to the state's gross state product, employment and development. Agriculture in the state's Central Valley, the largest production region in California, may be severely affected by climate warming. Previous studies on yield change due to global warming indicate that most crops suffer from reduced yields in California's Central Valley (Adams et al. 2003; Lobell et al. 2007; Schlenker et al 2005). Furthermore, it has been found that the fertilizing effect of higher carbon dioxide (CO_2) concentrations may also inhibit photorespiration in C3 species such as tomato, wheat and barley (Bloom 2006). An advantage of explicitly modeling crop production is that one can formally link the results from the above hydrologic, or climate related, agronomic models directly into the economic model. It is no exaggeration to say that these current model results are a direct function of the results from other climate related studies in this project.

A modified version of the Statewide Agricultural Production Model, (SWAP, after Howitt et al. 2001) is used to generate the results that follow. Data from a geo-referenced land use survey from the California Department of Water Resources (DWR) is combined with information from United States Department of Agriculture (USDA) surveys and corroborated by county agricultural commissioner's reports. Cost information was obtained from crop production budgets from the University of California (UC) Davis cooperative extension and the Agricultural Issues Center (AIC). The results show differences between projections to 2050 under a historical climate and a warm-dry climate change scenario.

2.0 Model Description and Methods

This section details the SWAP model and data used in the analysis. Several innovations have been added to the SWAP model to generate more accurate results; these are discussed as well.

2.1. The Statewide Agricultural Production Model, SWAP

The Statewide Agricultural Production Model (SWAP) was developed by Howitt and collaborators (2001) and continues to be improved upon. The original use for this model was to provide the economic scarcity cost of water for agriculture to CALVIN (Jenkins et al. 2001), a statewide economic engineering optimization model for water management in California.[1] More recently, SWAP has been used to estimate economic losses due to salinity in the Central Valley (Howitt et al. 2008), economic losses to agriculture in the San Joaquin Delta (Appendix to Lund et al. 2007) and economic losses for agriculture and confined animal operations in California's Central Valley (Appendix to Lund et al. 2008).

SWAP, at its root, is a mathematical programming model for major crops and regions in California and uses Positive Mathematical Programming (or PMP, after Howitt 1995). Implicit in this model is the assumption that farmers optimize their production input use to maximize their own profit.

[1] http://cee.engr.ucdavis.edu/CALVIN.

To generate more accurate results, this version of SWAP contains several innovations including:

- Endogenous crop group prices for the year 2050
- Geo-referenced land use information
- Updated price and production cost information
- Use of an exponential constant elasticity PMP cost function
- Updated information on yield reduction due to climate warming

Positive mathematical programming (after Howitt 1995) is a deductive approach to evaluating the effects of policy changes on cropping patterns at the extensive and intensive margins. SWAP is a three-step, self-calibrating programming model that assumes that farmers behave in a profit-maximizing fashion. In the first step, a linear program for profit maximization is solved. In addition to the traditional resource and non-negativity constraints, a set of calibration constraints is added to restrict land use to observed values. In the second step, the optimization first order conditions are used to derive the parameters for an exponential cost function and a non-linear Constant Elasticity of Substitution (CES) production function. The third and last step incorporates the parameterized functions from step two into a non-linear profit maximization program, with constraints on resource use.

2.1.1. Model Regions and Crop Groups

Agricultural regions in SWAP include 21 Central Valley Production Model (CVPM) regions (Hatchett 1997) plus irrigated agriculture in Coachella, Imperial, Ventura, San Diego and Palo Verde in Southern California. These are shown in Figure 1. Areas in light green show coverage from previous studies (Howitt et al. 2001); the dark green areas for Ventura and north of San Diego have been incorporated into SWAP recently.

For this study, the Sacramento region includes CVPM regions 1 thru 7, the San Joaquin region includes CVPM regions 8 thru 13, and the Tulare Basin is represented by CVPM regions 14 thru 21. Southern California is comprised of agriculture in the Imperial Valley, Palo Verde, Coachella, San Diego, and Ventura. The total base acreage for SWAP in this study is of 8.3 million acres using 26.3 million acre feet (MAF)/yr (31.9 billion cubic meters [BCM]/yr) of applied water according to DWR data for year 2005.

Irrigated crops in each SWAP region are classified into twelve SWAP crop groups: alfalfa, citrus, corn, cotton, field crops, grains, grapes, orchards, pasture, sugar beet, tomato, and truck crops. This grouping follows previous SWAP versions (Howitt et al. 2001; Medellin-Azuara et al. 2007).

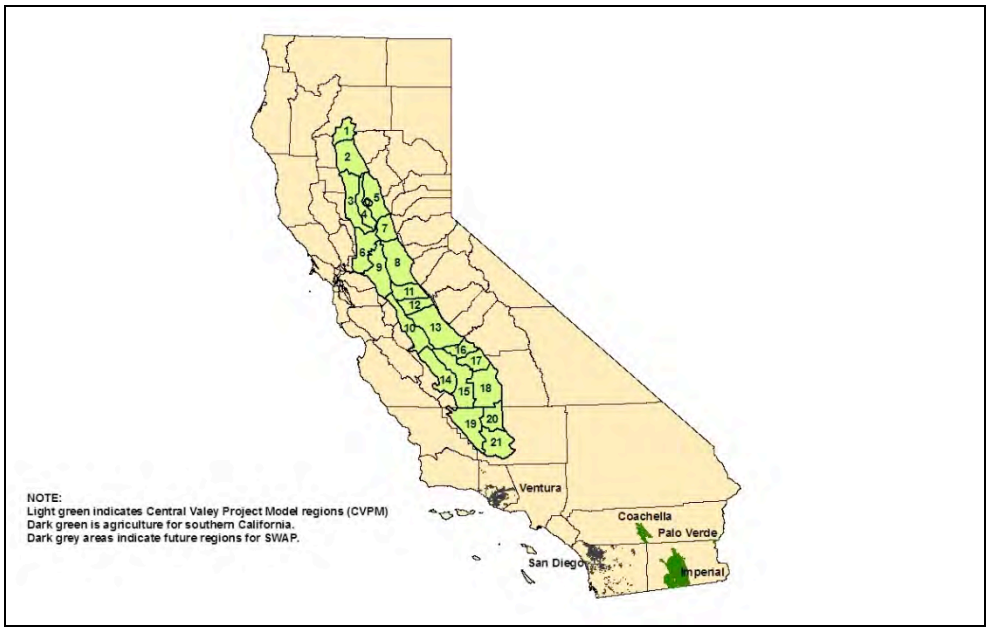

Figure 1. Map of coverage of the Statewide Agricultural Production Model (SWAP)

2.1.2. SWAP Model Architecture

The following section lays out the technical details of the SWAP model. For a more comprehensive treatment, see the references cited below.

A CES production function is defined and parameterized as in Howitt (2006). The elasticity of substitution between inputs is assumed to vary by crop but not by region. The specification of the generalized CES production function is:

$$Y_{gi} = \tau_{gi}\left[\sum_j \beta_{gij} X_{gij}^{\rho_i}\right]^{\upsilon/\rho_i} \tag{1}$$

Sub-index g corresponds to the CVPM region, i refers to crops and *j* to production factors or inputs. The model in this study has four inputs: land, labor, water, and supplies. Y_{gi} represents the output for crop *i* in region or group *g*. The scale parameter of the CES production function is referred as τ_{gi}, whereas the share parameters for the resources for each crop are represented by β_{gij}. X_{gij} denotes usage of factor *j* in production of crop *i* in region *g*. The elasticity of substitution for crop *i* is defined as ρ_i and $\rho_i=(\rho_i-1)/\rho_i$. The returns to scale coefficient is given by υ.

The first step in PMP is to obtain marginal values for the calibration constraints to enable the derivation of the cost function parameters in the second step. The linear program with calibration constraints is as follows:

$$Max_{x\geq 0}\prod = \sum_g \sum_i (v_{gi} yld_{gi} - \sum_j \omega_{gij} a_{gij}) x_{gi,land} \tag{2}$$

$$\sum_i a_{gij} x_{gi,land} \le b_{gj} \forall g, j \tag{3}$$

$$x_{gi,land} \le \tilde{x}_{gi,land} + \varepsilon \quad \forall \text{ g,i} \tag{4}$$

Equation 2 is the objective function (profits) of the linear program. Decision variables are defined as follows: $x_{gi,land}$ are the total acres planted for region or group g and crop i. The marginal revenue per ton of crop i in region g is given by v_{gi} and average yields are given by yld_{gj}. Average variable costs, $\square_{gji}$, are used in the linear objective function 2. The Leontieff coefficients, a_{gji}, are given by the ratio of total factor usage to land.

Equations 3 and 4 represent the constraint set. Parameter b_{ij} is the regional limit on resource j. Constraint four (4) is for the upper bound calibration constraints, $\tilde{x}_{gi,land}$ is the observed value of resources usage, and $\square$ is small perturbation that decouples the resource and calibration constraints.

The second step in PMP estimation is to calculate parameters needed by the exponential cost function and the CES production function. The constant elasticity cost function is given by Equation 5 below:

$$TC_{gi,land}(x_{gi,land}) = \delta_{gi} e^{\gamma_{gi} x_{gi,land}} \quad \forall g, i \tag{5}$$

$\square_{gi}$ and $\square_{gi}$ are the intercept and the elasticity parameter for the exponential acreage response function, respectively. These parameters are obtained from an ordinary least squares regression, with restrictions, on the PMP formulation and elasticity of supply for each crop group.

The last step in PMP is to solve a non-linear constrained profit maximization program. The objective function is defined as:

$$Max_{x \ge 0} \prod = \sum_g \sum_i yred_{gi} v_{gi} Y_{gi} - \sum_g \sum_i \delta_{gi} e^{\gamma_{gi} x_{gi,land}} - \sum_g \sum_i \sum_{j, j \ne land} (\omega_{igj} x_{gij}) \tag{6}$$

subject to:

$$\sum_i x_{gij} \le b_{gj} \forall g, j \tag{7}$$

$$xm_{gm} \le \sum_i met_{gim} x_{gi,water} \quad \forall g, m \tag{8}$$

$$\sum_m xm_{g,m} \le availwater \cdot b_{water,g} \quad \forall g \tag{9}$$

In Equation 6, $\square_{gi}$ is defined by the production function in Equation 1 above and the derivation of parameters $\square_{gi}$ and $\square_{gij}$ of the production function is detailed in Medellin-Azuara (2006). The second term in the equation is the PMP cost function, calibrated in the previous step. Constraint 7 is as in 3 above, except that all resources are included not just those limited by fixed quantities. In Equation 6, the parameter $yred_{gi}$ is a scaling factor for yield changes due to climate and technological change.

A new constraint on monthly water use has been included. Variable xm_{gm} in Equation (8) is monthly water use in region g in month m. Three underlying assumptions need to be discussed. First, water is assumed to be interchangeable among crops within a region. Second, a farm group (or region) maximizes profits on a yearly basis, equalizing marginal revenue of water to its marginal cost every month. Third, a region or farm group selects the crop mix that maximizes profits within the region. In other words, the shadow value of water will be the same for all months and for all crops i in a region or farm group g. This assumes sufficient levels of water storage and internal water distribution capacity and flexibility. To accurately model the effects of snowpack and water storage reductions under warmer and drier climate scenarios CALVIN was used to generate water availability and shortage levels (Medellin-Azuara et al. 2008) in SWAP regions.

The last constraint set in Equation 9 is for regional water in which $b_{water,g}$ corresponds to that in the right-hand side of Equation 7 for water. The parameter *"availwater"* is used later to obtain shadow values of water by constraining water regionally, such that 0 < availwater < 1. The constraint set assumes that yearly water is available in a limited amount for every region or group. Less realistically, it also implies that water is not re-traded across groups or regions under the basic calibration assumptions.

2.2. Model Innovations for Year 2050

In this study, modifications and assumptions for projections until 2050 follow Medellin-Azuara et al. (2007). Specifically, we consider land use projections (Landis and Reilly 2002), crop demand projections and yield changes as a result of technological improvement (Brunke et al. 2004) and climate change (Adams et al. 2003; Lee et al. 2008; Lobell et al. 2007). These innovations are applied to both models: 2050 under historical climate and 2050 under climate change.

2.2.1. Changes in Land Use

Urbanization and agricultural land conversion in this study follow estimates from Landis and Reilly (2002) for prime farming land, locally important farms, unique farms, and grazing lands.

Table 1 shows statewide and regional land use patterns by the year 2050. Most of the land conversion from agriculture occurs south of the Sacramento Valley, where population growth is rapid. A statewide reduction in agricultural land use close to 5.0% is expected between years 2020 and 2050 (and of about 8.5% between 2005 and 2050. Changes in land use were applied to both 2050 standard (historical) and 2050 climate change (warm-dry) climate scenarios.

Table 1. Expected changes in land area between 2020 and 2050 (adapted from Landis and Reilly 2002) and CALVIN-SWAP region crop areas

	Urbanized Land			Agricultural Land*		
	Regional Total Area, Acre (ha)		% Change	CALVIN Regional Total Area, Acre (ha)		% Change
	2020	2050		2020	2050	
Northern California and Sacramento	1,337,465 (540,737)	1,663,876 (660,576)	22.2	1,713,900 (693,590)	1,656,771 (670,495)	-3.3
San Joaquin Valley and Tulare	646,381 (261,587)	1,044,333 (422,224)	61.4	5,083,100 (2,057,057)	4,797,749 (1,941,649)	-5.6
Southern California	2,550,040 (1,030,981)	3,442,696 (1,391,882)	35.0	964,360 (390,262)	905,394 (366,413)	-6.1
Statewide	4,534,516 (1,833,305)	6,120,905 (2,474,682)	35.0	7,761,360 (3,140,911)	7,363,711 (2,980,094)	-5.1

*Note: For agriculture, Northern California includes Central Valley Production Model (CVPM) regions 1 to 7. The San Joaquin Valley and Tulare represents CVPM regions 8 to 21. Southern California considers projections of Landis and Reilly (2002) for agricultural areas in the counties that include Coachella, Imperial Valley, Palo Verde, and the counties of Ventura and San Diego.

2.2.2. Technological Change

Technological change by year 2050 is represented as increasing crop yields. This is calculated based on extrapolating current trends as detailed in "Future Food Consumption and Production in California Under Alternative Scenarios" (Brunke et al. 2004). Current trends are detailed in Table 2, below. Growth rates marked with an asterisk (*) are unavailable and, consequently, are set equal to the average log-linear growth rate of 1.2. We assume that the rate of yield increases will level out in the future and we cap the extrapolations and use a slower rate of technical change from 2020–2050. Yield related technological growth is capped at 2020 since there is an inherent limit to the rate of carbon fixation through photosynthesis. Thus technology likely will not improve yields at the same rate indefinitely over time. Specifically, we assume a log-linear growth rate of 0.25 for 2020–2050. Based on the assumptions above the total rate of growth is extrapolated out and reported in Table 2.

Table 2. Technological change projection summary

Technological Change by 2050		
Crop	**Log-Linear Annual Growth Rate**	**2050 Total % Yield Increase**
Alfalfa	1.2*	29.05
Citrus	1.17	28.47
Corn	1.01	25.42
Cotton	1.2*	29.05
Field	1.2*	29.05
Grains	1.2*	29.05
Grapes	0.9	23.37
Orchards	1.57	36.41
Pasture	1.2*	29.05
Rice	1.35	31.98
Tomato	1.75	40.14
Truck	1.01	25.42

2.2.3. Shifts in Crop Demands for California

Over time, the demand for California crops, with the exception of global commodities in the Grain, Rice, and Corn groups, is expected to increase with increasing population and incomes. As such, demands for crops in 2050 are changed to reflect population growth and income projections. This effect on crop demand is captured through the income elasticity of demand for California crops, income, and population growth. In the absence of alternative information on long-term trends in world crop production, the proportion of California crops exported is assumed to remain constant through 2050. Details of this method are laid out below.

First, we list the demand assumptions for Grain, Rice and Corn. The demand for California Grain, Rice and Corn is essentially perfectly elastic. This assumption is justified because there is no separate demand for these crop groups from California since they are global commodities, and California production is a small proportion of national production. As such, California can be seen as a price taker implying that demand is equal to price, and shifts in demand can be directly related to changes in world prices. As such, the only necessary information is long run projections of real prices. Forecasting long run prices for these crops is difficult with current conflicting evidence on the trends in agricultural prices. Over the last few years real prices have increased, which is in stark contrast to the historical downward trend. To reconcile these differences for use in our analysis we assume that prices will continue to trend up for several years into the future and will eventually resume the downward trend. The details of this analysis are as follows. We assume that prices will increase in accordance with the results of the World Bank's report, *Double Jeopardy: Responding to High Fuel and Food Prices* (World Bank 2008) which projects price increases (in real terms) out to 2015. At 2015 we assume that real prices will resume the historic downward trend. We quantify this effect using UC Davis Agricultural Issues Center data, which shows the real prices of Corn, Grain, and Rice over the last 100 years. Using this data an exponential time trend regression is fit and used to project prices from 2015–2050. Results are summarized in (Table 3).

Table 3. Real (2005 dollars) percent changes in price, base 2005

Crop Group	% Change in Price by 2015 (Total)	% Change in Price 2015-2050 (per year)	% Shift in Demand Intercept (Total)
Rice	60	-1.45	-4.05
Corn	48	-0.67	17.00
Grain	40	-1.58	-19.88

The demand shift for all other crop groups is calculated using the following methodology. The U.S. population is expected to grow into the foreseeable future, and this will generate increased food demands. We assume that 1% increases in population will lead to 1% increases in food demand; in essence assuming a "population elasticity" of unity. According to the 2000 Census[2] the U.S. population is projected to increase by approximately 5% every five years until 2030. These projections are based on the 2000 census and include five-year interval population projections until 2030. We use U.S. population growth as a proxy for total population-generated sources of increased California crop demand. Using the census results, we assume 5% growth every five years from present to 2020. From 2020–2050 we reduce the rate of population growth to 2.5%, half of current projections. At these growth rates, the U.S. population is expected to increase from approximately 290 million (base of 2005) to 415 million by 2050.

In addition to increasing population, real incomes are expected to increase. According to the Bureau of Labor Statistics[3] average incomes in the United States have increased 6.9% annually between 1982–1992, 5.6% annually between 1992–2002, and are projected to increase 5.4% annually until 2012, nominally. Using this projection and extrapolating out to 2050 we assume incomes increase 5.4% on average annually. With 3.4% average historical inflation this is approximately 2% real annual income growth. Following the method for population expansion, we assume the real income growth rate is halved in 2020 to 1% real annual growth. Extrapolating out, average U.S. annual income is expected to increase from approximately $36,000 to $90,000 annually in real terms.

We assume that shifts in demand are solely a result of increasing incomes and population and that California's export share grows in proportion to the domestic market. Income and population increases can be directly mapped to increases in quantity through respective elasticity estimates. Furthermore, for simplicity in calculations, we assume a perfectly elastic long run supply of each crop. As such, our estimates represent an upper bound on the demand shifts. Crop demands are linear, and we are interested in parallel shifts of demand, thus it is assumed that the increase in quantity produces a change in price that is constant at every quantity along the demand schedule.

Our calculations follow the methodology of Muth (1964), a seminal paper in equilibrium displacement models. Specifically, we calculate that the percentage shift in the intercept of the demand curve as a result of increasing incomes as: □=-□$_i$/□ dln(I), where α represents the percentage shift along the price axis, ε_i is income elasticity of crop demand, η is the own price elasticity of demand, and $d\ln(I)$ is the change in log income over the relevant range (2005–2050

[2] www.census.gov/population/www/projections/projectionsagesex.html.

[3] www.bls.gov/opub/mlr/2007/11/art2full.pdf.

in our analysis). This equation is calculated separately for each crop and the procedure is repeated for changing population. As a proxy for "population elasticity" we assume unity, 1% increase in population leads to a proportional percentage increase in demand. The shifts from income changes and population are combined to determine the overall shift in demand. The details and derivation of this result can be found in Muth (1964), elasticity estimates and data are summarized in Table 4 below. It should be noted that the literature on income elasticity estimates is sparse and many, including authors of some studies used here, caution that these estimates often capture other unintended effects. As such, when reliable income elasticity estimates are unavailable, 0.2 is assumed for low value crops and 0.5 is assumed for high value crops; in Table 4 these are denoted by asterisks (*). Most of these estimates and references to others used can be found in the paper "Estimation of Supply and Demand Elasticities of California Commodities" (Green, Howitt, and Russo 2006).

Table 4. Elasticities by SWAP crop group

Crop Group	Income Elasticity	Price Elasticity (D)
Alfalfa	0.2*	-0.107
Citrus	0.5*	-1.25
Corn	0.2*	-0.5
Cotton	0.05	-0.95
Field	0.2*	-0.86
Grain	0.2	-0.38
Grapes	0.51	-0.28
Orchards	0.51	-1.2
Sugar beet	0.254	-0.042
Tomato	0.89	-0.25
Truck	0.99	-0.16

Using the Muth results and the elasticity estimates outlined above, the respective demand shifts are calculated. Based on the assumptions detailed above, calculated demand shifts are presented in Table 5, and two exceptions are denoted by asterisks (*). First, alfalfa is not calculated independently. Because alfalfa demand is largely tied to the expansion of livestock and substitution between grain and alfalfa, instead it is pegged to the field crop group which is estimated at 3.34. Similarly, due to the reduction in sugar beet processing facilities and other exogenous factors, we expect the level of California sugar beet production to be zero by 2050. All results are detailed in Table 5, below.

Table 5. Demand shifts

Crop Group	% Shift in Demand Intercept
Alfalfa*	3.34
Citrus	3.63
Corn	5.74
Cotton	2.14
Field	3.34
Grain	7.56
Orchards	3.83
Grapes	16.42
Tomato	26.86
Truck	45.45

2.2.4. Model Innovations from Climate Change

Changes in yields due to climate change follow Adams et al. (2003), as well as ongoing research by Lobell et al (2007) and Lee at al. (2008). Table 6 shows expected percent change in yields as a result of climatic change in GFDL2 for the Sacramento Basin, San Joaquin Delta. Citrus and orchard are projected to be the most affected crop groups under a warm-dry form of climate change. These shifts are one of the driving factors in the crop reaction to climate change.

Table 6. Expected percent change in yields as a result of a warm-dry climate scenario

Crop Groups	Sacramento	San Joaquin
Alfalfa	4.9	7.5
Citrus	1.77	-18.4
Corn	-2.7	-2.5
Cotton	0.0	-5.5
Field	-1.9	-3.7
Grain	-4.8	-1.4
Orchards	-9.0	-9.0
Pasture	5.0	5.0
Grape	-6.0	-6.0
Rice	0.8	-2.8
Tomato	2.4	1.1
Truck Crops	-11.0	-11.0

Sources: Adams et al. 2003; Lee et al. 2008; Lobell et al. 2007

In addition to yield changes as a result of climate changes, the model results are driven by changes in available water under climate change. Available regional water supplies are determined from CALVIN model runs that optimize the statewide economic returns to all water uses under climate change. As such, the climate change model, relative to the historical model, incorporates water reductions by considering an optimal percentage decrease in water by region determined by simulating profitable water trades that could be realized with the existing water infrastructure. Table 7 summarizes this input, below. The regional allocations in

the table reflect water trades from agricultural to urban regions. Thus while the total average reduction in water deliveries is 14% the average reduction for agricultural regions is 21%, indicating that a statewide optimal market solution would induce voluntary sales of an additional 7% of agricultural water supplies to the urban sector to largely offset supply reductions. In the absence of such a market, the social costs of climate change would be significantly higher.

Table 7. Expected percentage reduction in available water

Region	Agriculture	Urban	Total
Sacramento	24.3	0.1	19.1
San Joaquin	22.5	0.0	17.6
Tulare	15.9	0.0	13.5
Southern California	25.9	1.12	8.9
Total	21.0	0.7	14..0

2.2.5. Regional Crop Data in SWAP

An example of a region in SWAP is shown in Table 8, which corresponds to CVPM region 19 (Figure 1). This region is distinct because it is within a single county (Kern) and has been used as a pilot for ongoing research on salinity south of the San Joaquin Delta (Howitt et al. 2008). Kern is within the service area of the State Water Project. Agricultural land use, recorded by parcel by DWR is at www.sjd.water.ca.gov; Table 8 shows agricultural land use at CVPM 19.

Table 8. Agricultural land use per crop groups at CVPM 19

Crop	Acres
Alfalfa	60,916
Citrus	2,399
Corn	16,469
Cotton	50,998
Field Crops	75,584
Grains	15,685
Grapes	6,199
Orchards	51,890
Pasture	2,474
Tomato	2,198
Truck Crops	57,361
Total	342,173

Source: DWR Land use surveys.

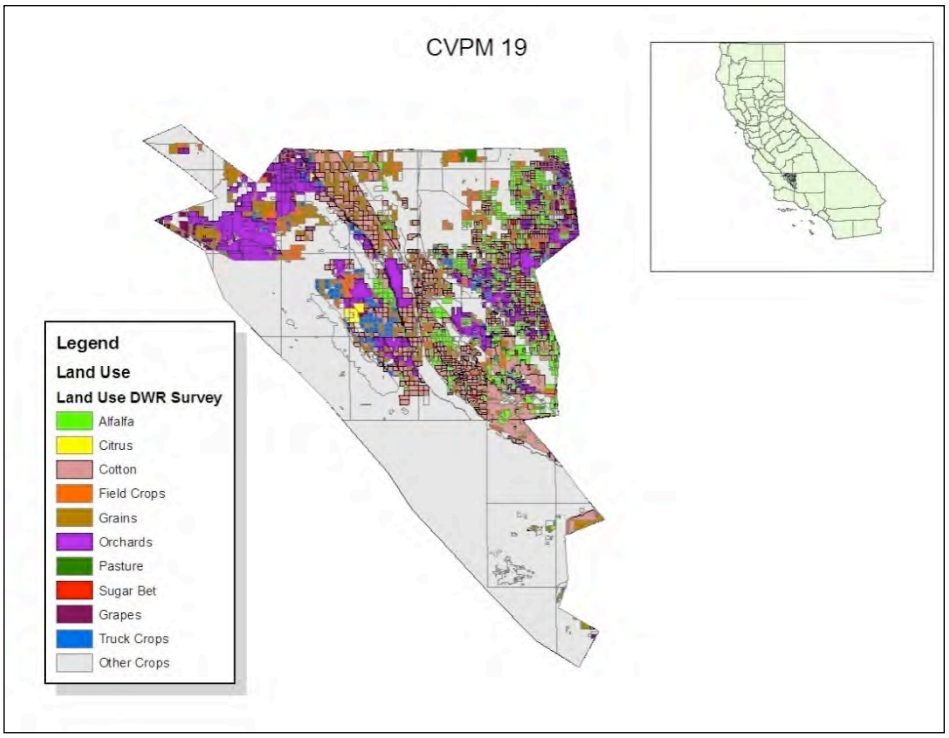

Figure 2. Land Use in CVPM region 19

Source: DWR Land use surveys.

2.3. Policy Simulations

The use of inputs is based on Medellin-Azuara et al. (2007). Inputs to the production function in the model include water, labor, land and supplies. The last group of inputs was normalized to use per acre and comprises farm budgets on fertilizer pesticides and all other inputs. A constraint on corn silage was imposed on the optimization program to account for the feeding needs of dairy farm operations. The total California dairy herd is assumed to decline slightly from 1.503 million cows in 2005 to 1.25 million in 2050. This reduction in dairy cows in the Central Valley is based on restrictions that result from current dairy waste disposal technology, costs, and projected regulation (Howitt et al 2008). Corn used for silage tends to displace marginal field crops and cotton.

Analysis of agricultural activity for the year 2050 in SWAP is based on a set of algorithms that incorporate the 2050 adjustments discussed in the model description section. First, the land use from a linear programming program was constrained to the *observed* values of land use from DWR land use surveys and average production input use in the base years. Second, a PMP exponential cost function was calibrated so that, in the base case, input use from a non-linear optimization problem calibrates to observed values. The parameters for the CES production function are derived from the first order profit maximization conditions for each crop and region. Given these parameters, the calibrated non-linear program is used to simulate the economic effects of changes in crop yield parameters and policies.

3.0 Results

This section details the results of the SWAP model runs. First, a pilot region, CVPM 19, is considered in detail to highlight the workings of SWAP and breadth of results. Next the state-

wide results are summarized. Since it is unwieldy to consider results from 26 separate regions results are aggregated into four "meso-regions" including Tulare Basin, Sacramento, San Joaquin and Southern California. Region-specific findings are highlighted and discussed in addition to universal findings. All results are discussed with the results from the 2050 historical climate conditions compared to results in 2050 under climate change.

3.1. Results for the Pilot Region

The pilot region is CVPM 19, which was discussed in detail in Section 2.2.5. Table 9 summarizes changes in irrigated crop acres for CVPM 19 under historical climate and 2050 climate change (warm-dry) scenario. Comparing the projection under standard conditions to that under climate change conditions we note there are both positive and negative crop acreage changes. This is to be expected, as some crops suffer serious reductions under climate change and others are relatively resilient. As such, comparative advantage dictates adjustments by profit-maximizing farmers. This also takes into account the counteracting price effect on crops. However, it is important to note that this comparison is based on the direct effect of climate change.

Overall, results show that there is a significant reduction in water-intensive crops and moderate shifts in others. One important finding is that corn acreage is relatively constant under both climate scenarios. This is a direct result of the dairy industry, which necessitates a lower bound constraint on silage corn. Specifically, as discussed above, we assume that the California dairy industry will not be directly affected under climate scenarios, thus there will be a minimum amount of feed that is necessary. The model runs attain this lower bound, thus acreage is unaltered under climate change. Corn grown for sale as grain is essentially driven to zero by 2050.

Changes in water use per acre (intensive margin adjustments in economic parlance) are mixed under climate change and are shown in Table 10. It is important to note that these reflect contributions from CALVIN and assume socially optimal water markets in California, to be discussed more in Section 3.2. Results show that in CVPM 19 (Kern County) water use per acre of farmland is going to increase for most crops. This is a result of substitution between inputs and reduced farming acres. Since there are markets for water, CVPM 19 is able to buy supplies from northern regions. Model results indicate that the changes in applied water occur within reasonable ranges.

Table 9. Crop acreage in CVPM region 19

Crop Name	2050 Historical	2050 Climate Change	% Change
Alfalfa	53,940	58,580	8.60
Citrus	2,448	2,408	-1.62
Corn	16,469	16,469	0.00
Cotton	46,433	45,778	-1.41
Field Crops	53,629	50,290	-6.23
Grains	14,222	14,302	0.57
Grapes	6,455	6,416	-0.60
Orchards	52,293	52,217	-0.15
Tomato	2,377	2,385	0.30
Truck Crops	61,085	60,505	-0.95
Total	309,352	309,352	8.60

Table 10. Changes by 2050 at the intensive margin (water use per acre) CVPM 19

Crop	2050 Historical Applied Water per Acre	2050 Climate Change Applied Water per Acre	% Change
Alfalfa	4.38	4.41	0.58
Citrus	3.40	3.26	-4.08
Corn	3.59	3.42	-4.73
Cotton	2.88	2.76	-4.15
Field Crops	2.48	2.38	-3.90
Grains	1.62	1.58	-2.49
Grapes	2.97	2.89	-2.93
Orchards	3.22	3.21	-0.26
Tomato	3.61	3.54	-1.76
Truck Crops	2.11	2.02	-4.20

3.2. Statewide Results

This section provides results for California under historical and climate change trends. For clarity, we group the 26 SWAP regions into four larger regions, namely Sacramento, San Joaquin, the Tulare Basin and Southern California. The Sacramento region includes CVPM regions 1 to 7, San Joaquin includes CVPM regions 8 to 13, Tulare Basin includes CVPM regions 14 to 21, and Southern California comprises agriculture in Coachella, Palo Verde, Imperial, Los Angeles, San Bernardino, San Diego, and Ventura.

Table 11 shows the land use under the standard 2050 climate and the 2050 climate change scenarios. The results under climate change reflect insights from the CALVIN water model. This assumes that by 2050 California has developed a reliable and economical method of transferring water between northern and southern regions, such as a peripheral canal. Additionally, CALVIN posits that socially optimal water markets exist and function between regions in

California. As such, this model presents an optimistic view of future water markets and infrastructure in California by 2050. Implications of CALVIN are further discussed below.

There is an overall land use reduction of 20.15% under climate change compared to standard climate scenarios. Results show that Sacramento and San Joaquin are the hardest-hit regions in terms of land use reductions. Since warm-dry (climate change) land use takes into account CALVIN water shortages for a warm-dry climate (Medellin-Azuara et al. 2008) and allows for water transfers through functioning water markets, we expect these regions to be water exporters as production shifts to higher-value crops in regions like Tulare. As such, there is a reduction in irrigated land in Sacramento as many farmers opt to sell water to southern regions. Similarly, Southern California land use reductions are dampened by the ability to import water. Land use changes are broken down by crop and summarized in more detail below.

Table 11. Base land use (in thousands of acres) per region

Scenario	Sacramento	San Joaquin	Tulare	Southern California	Total
2050 Standard	1,920,878	1,886,535	953,569	2,966,229	7,727,211
2050 Climate Change	1,461,989	1,463,179	745,236	2,499,987	6,170,391
% Change	-23.89	-22.44	-21.85	-15.72	-20.15

Tables **Error! Reference source not found.** and **Error! Reference source not found.** show respectively a decrease in land and various changes in prices. **Error! Reference source not found.** shows projected 2050 crop group prices (in 2005 dollars) under both scenarios. Most crop prices are expected to increase with climate change, although most changes are moderate. The only exception is tomato, due to a slight increase in production as it will be show below (Table) resulting in increased acreage pushing down the price of the crop under climate change (Table 12).

Table 13 shows total agricultural revenues by region with and without climate change. Results show a varying ability of agricultural regions to adapt to climate change, which is to be expected. San Joaquin is the most affected with a 10.4% reduction in revenues. Clearly, over the time horizon considered, both the impact of climate change and the ability to adapt to it are most constrained in the Southern California region, which, however, shows the lowest impacts on revenue and land. The two effects of price increases and shifts in the mix of crops toward higher valued crops provide a partial offset to yield and acreage reductions from climate change. Note that a comparison of Tables 11 and 14 shows that the statewide reduction in irrigated land and water use are 20.15% and 20.73%, respectively; but the reduction in revenues is 11.1% (Table 13).

Table 12. Price changes under standard and climate change scenarios

	Historical 2050 Price, $/Ton	Climate Change 2050 Price	% Change
Alfalfa	111	116	3.90
Citrus	410	460	12.26
Corn	119	119	0.02
Cotton	1739	1759	1.16
Field Crops	305	305	0.06
Grains	238	238	0.04
Grapes	962	980	1.87
Orchards	1257	1358	8.05
Pasture	80	80	0.07
Rice	273	277	1.55
Tomato	61	61	-0.38
Truck Crops	410	421	2.72

Table 13. Total agricultural revenues by region and scenario (in millions of 2005 dollars)

Scenario	Sacramento	San Joaquin	Tulare	Southern California	Total
2050 Historical	6,101	5,253	13,044	3,973	28,371
2050 Climate Change	5,157	4,709	11,863	3,488	25,217
% Change	-15.5	-10.4	-9.1	-12.2	-11.1

A breakdown of total water use is shown in Table 14. Reductions in water use are forced on the production model as a consequence of climate change reduced water availability and optimal allocations from the CALVIN model. Water use is constrained and climate change and demand growth for crops further increase the scarcity value of water. Furthermore, urban growth will place increasing strain on the system. These factors contribute to reductions in the total use by irrigated agriculture, as would be expected.

Table 14. Water use by region (in TAF/yr)

Scenario	Sacramento	San Joaquin	Tulare	Southern California	Total
2050 Standard	6,149.8	5,772.6	3,655.5	8,856.0	24,433.9
2050 Climate Change	4,623.4	4,490.0	2,794.7	7,460.8	19,368.9
% Change	-24.82	-22.22	-23.55	-15.75	-20.73

SWAP model results show that climate changes induces changes in price, reduced yields, reduced land use and reduced revenue under climate change relative to historical climate. Table 15 shows change in price, production, and revenue for each crop group, broken down across all regions. Revenue losses stem from changes in price, production, or both. For example, tomato is expected to experience a decrease close to 0.4% in its price per ton; however, an increase in production yields leads to a net positive change in total revenues (the product of yields, acreage, and crop price). Other crops, like orchards, may face a large increase in price but a large decrease in production yields, which ultimately result in an overall loss in revenues. This seemingly counterintuitive result is likely a result of shifting regional production and the availability of water markets.

Table 15. Percentage change price, production, revenue (historical vs. warm-dry climate scenarios) for year 2050

Crop Group	% Change Price	% Change Production	% Change Revenues
Alfalfa	3.90	-6.2	-3.20
Citrus	12.26	-18.7	-8.36
Corn	0.02	-22.9	-22.61
Cotton	1.16	-23.6	-20.59
Field	0.06	-48.9	-48.40
Grains	0.04	-31.3	-30.05
Grapes	1.87	-7.3	-5.60
Orchards	8.05	-10.2	-2.94
Pasture	0.07	-95.7	-95.70
Rice	1.55	-22.4	-21.22
Tomato	-0.38	1.4	0.96
Truck	2.72	-13.3	-10.88

A more comprehensive table of disaggregated land use by region is shown below in tables 16 and 17. Total land use for all crops under both climate scenarios is shown in Table 18. To better illustrate adaptation, the last column of Table 18 shows how the proportion of each crops changes with respect to the total crop mix. Land use share decreases for some water-intensive crop groups such as field crops and grains. This is mostly caused by water shortages on the order of 20% estimated in CALVIN under a warm-dry climate. Therefore under a warm-dry climate the crop mix becomes higher valued and less water intensive, despite the likely loss in climate-related agricultural yields.

Table 16. Land use (in acres) per crop and region under 2050 historical climate

Historical 2050 Climate Scenario					
Crop Name	**Sacramento**	**San Joaquin**	**Tulare**	**Southern California**	**Total**
Alfalfa	74,124	242,178	325,766	186,327	828,394
Citrus	28,719	7,148	215,332	121,240	372,440
Corn	26,066	267,556	208,385	9,366	511,374
Cotton	1,244	105,676	499,435	25,887	632,242
Field Crops	377,633	476,446	424,512	68,325	1,346,916
Grains	41,724	64,115	158,571	225,106	489,517
Grapes	13,755	253,176	351,088	15,362	633,381
Orchards	23,618	209,671	512,260	1,514	747,062
Pasture	63,882	102,743	3,764	81,067	251,456
Rice	541,104	14,244			555,348
Tomato	79,510	113,094	125,621	89	318,313
Truck Crops	649,499	30,487	141,496	219,286	1,040,768
Total	**1,920,878**	**1,886,535**	**2,966,229**	**953,569**	**7,727,211**

Table 17. Land use (in acres) per crop and region under 2050 climate change

Warm-Dry 2050 Climate Scenario					
Crop Name	**Sacramento**	**San Joaquin**	**Tulare**	**Southern California**	**Total**
Alfalfa	57,087	238,463	270,885	158,942	725,377
Citrus	28,689	7,148	209,536	120,980	366,353
Corn	10,567	207,421	187,954		405,942
Cotton		76,151	425,219	8,363	509,732
Field Crops	208,018	272,338	160,928	60,097	701,381
Grains	0	41,794	126,860	163,458	332,113
Grapes	13,553	251,128	345,595	15,215	625,491
Orchards	22,453	207,743	505,850	1,644	737,691
Pasture		7,101	2,811		9,912
Rice	416,583	11,104			427,687
Tomato	78,306	112,819	125,466	92	316,685
Truck Crops	626,734	29,970	138,881	216,443	1,012,028
Total	**1,461,989**	**1,463,179**	**2,499,987**	**745,236**	**6,170,391**

Table 18. Total land use (in acres) by crop under climate scenarios

Crop Name	Historical	Climate Change Total	% Change Acres	%Change in Crop share
Alfalfa	828,394	725,377	-12.4	9.66
Citrus	372,440	366,353	-1.6	23.18
Corn	511,374	405,942	-20.6	-0.59
Cotton	632,242	509,732	-19.4	0.96
Field Crops	1,346,916	701,381	-47.9	-34.79
Grains	489,517	332,113	-32.2	-15.04
Grapes	633,381	625,491	-1.2	23.67
Orchards	747,062	737,691	-1.3	23.66
Pasture	251,456	9,912	-96.1	-95.06
Rice	555,348	427,687	-23.0	-3.56
Tomato	318,313	316,685	-0.5	24.59
Truck Crops	1,040,768	1,012,028	-2.8	21.77
Total	**828,394**	**725,377**	**-20.1**	

As shown, total land use changes and crop substitution occurs in response to climate change. Large reductions occur in pasture, field crops, grains, and rice; water intensive activities that have seen recent declines in California. Note that the crops most heavily affected are water-intensive or low-value crops; more resilient crops include, higher-value, price responsive crops such as grapes and tomatoes.

For more clarity Figures 3-6 show agricultural land use graphically. The figures that follow compare 2050 Historical and 2050 warm-dry (climate change) scenarios.

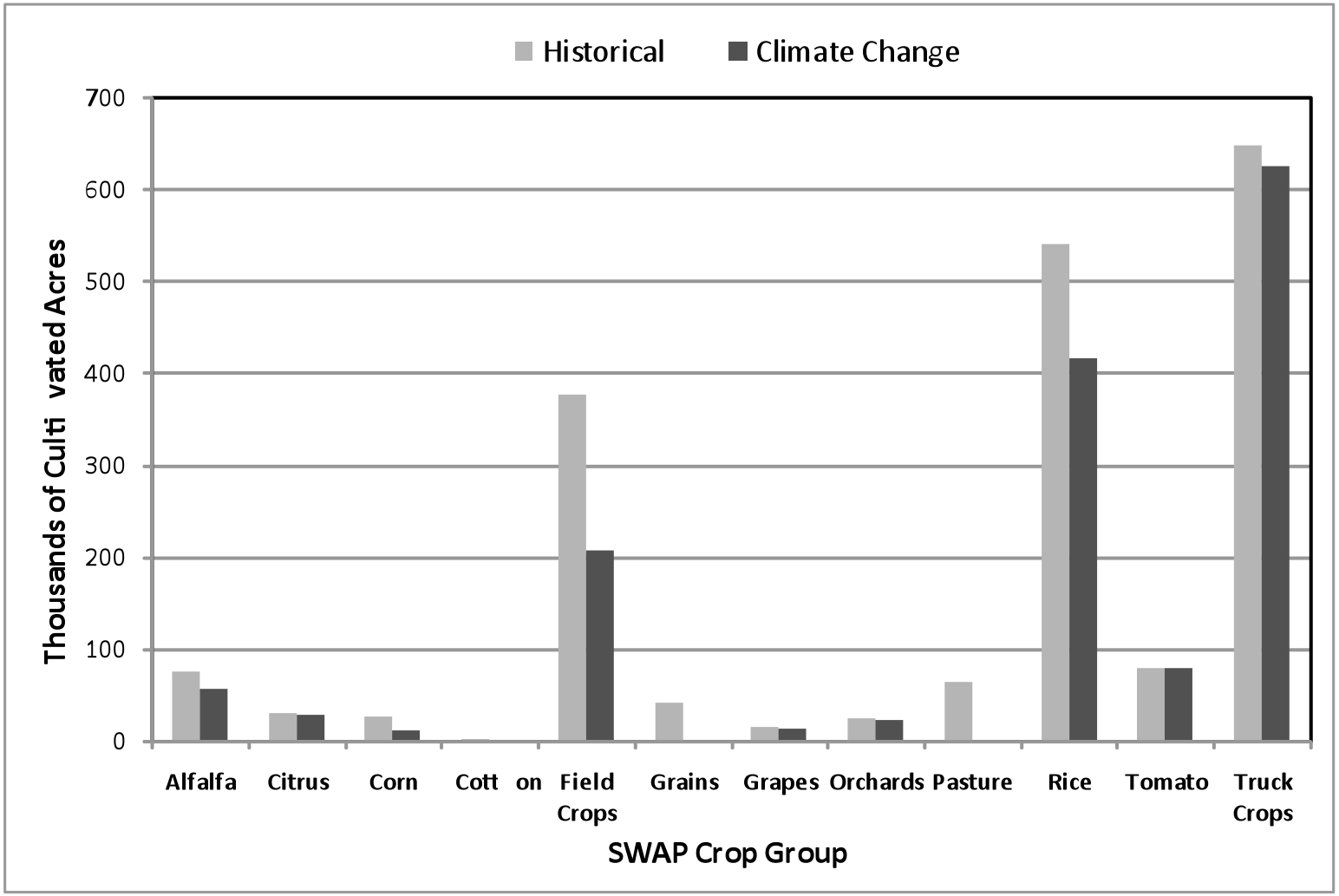

Figure 3. Total cultivated land per crop under climate scenarios in the Sacramento region

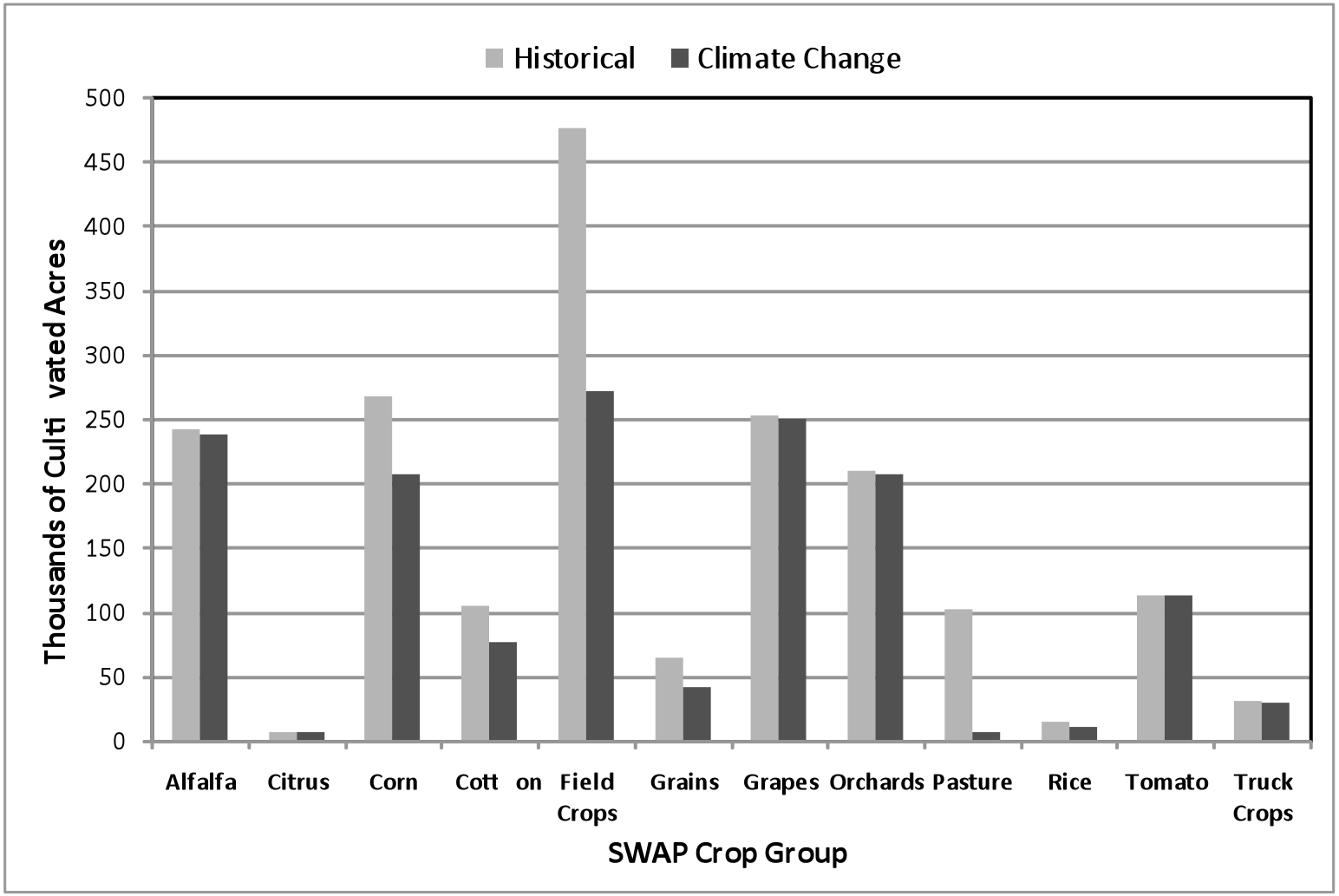

Figure 4. Total cultivated land per crop under climate scenarios in the San Joaquin Basin

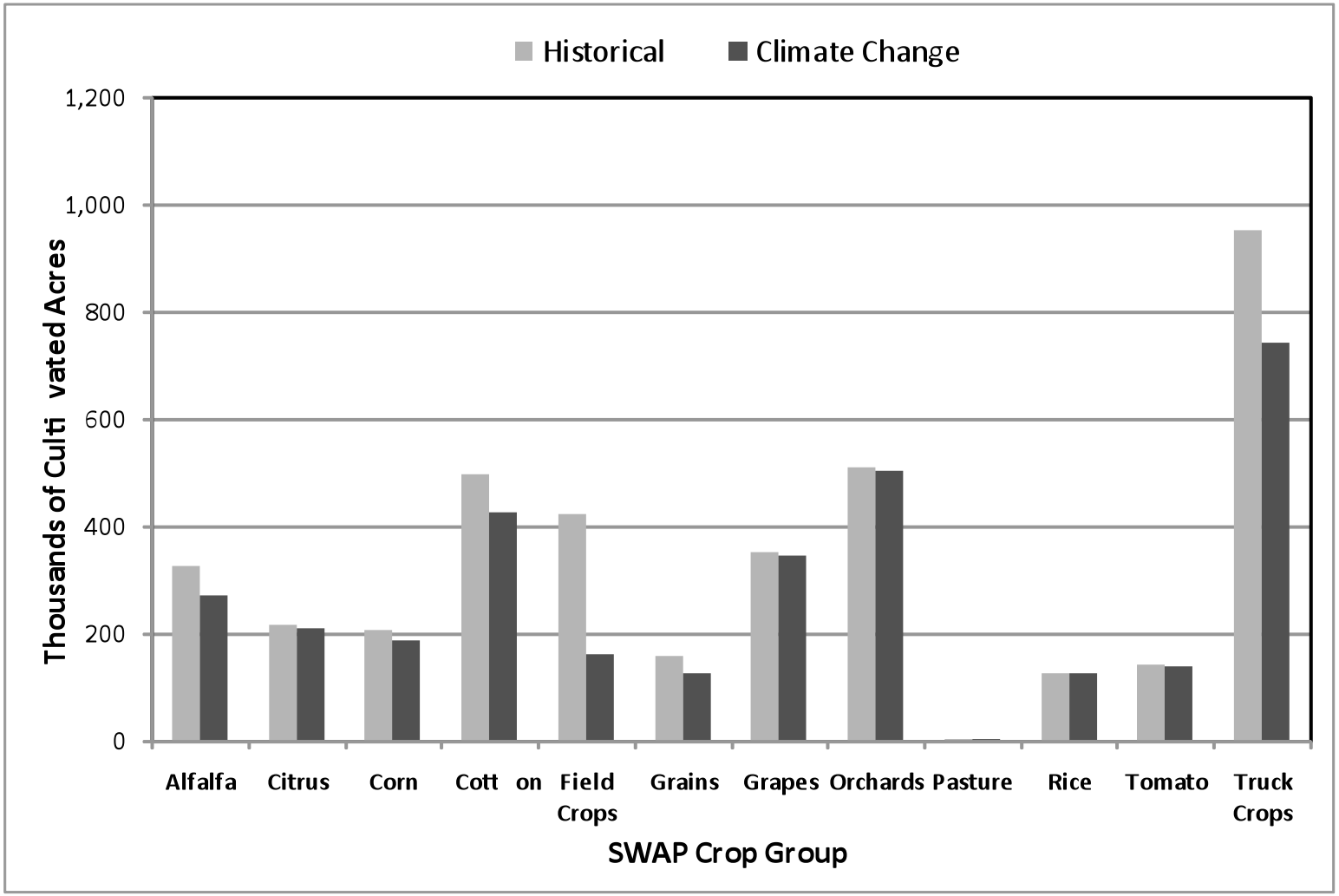

Figure 5. Total cultivated land per crop under climate scenarios in the Tulare Basin

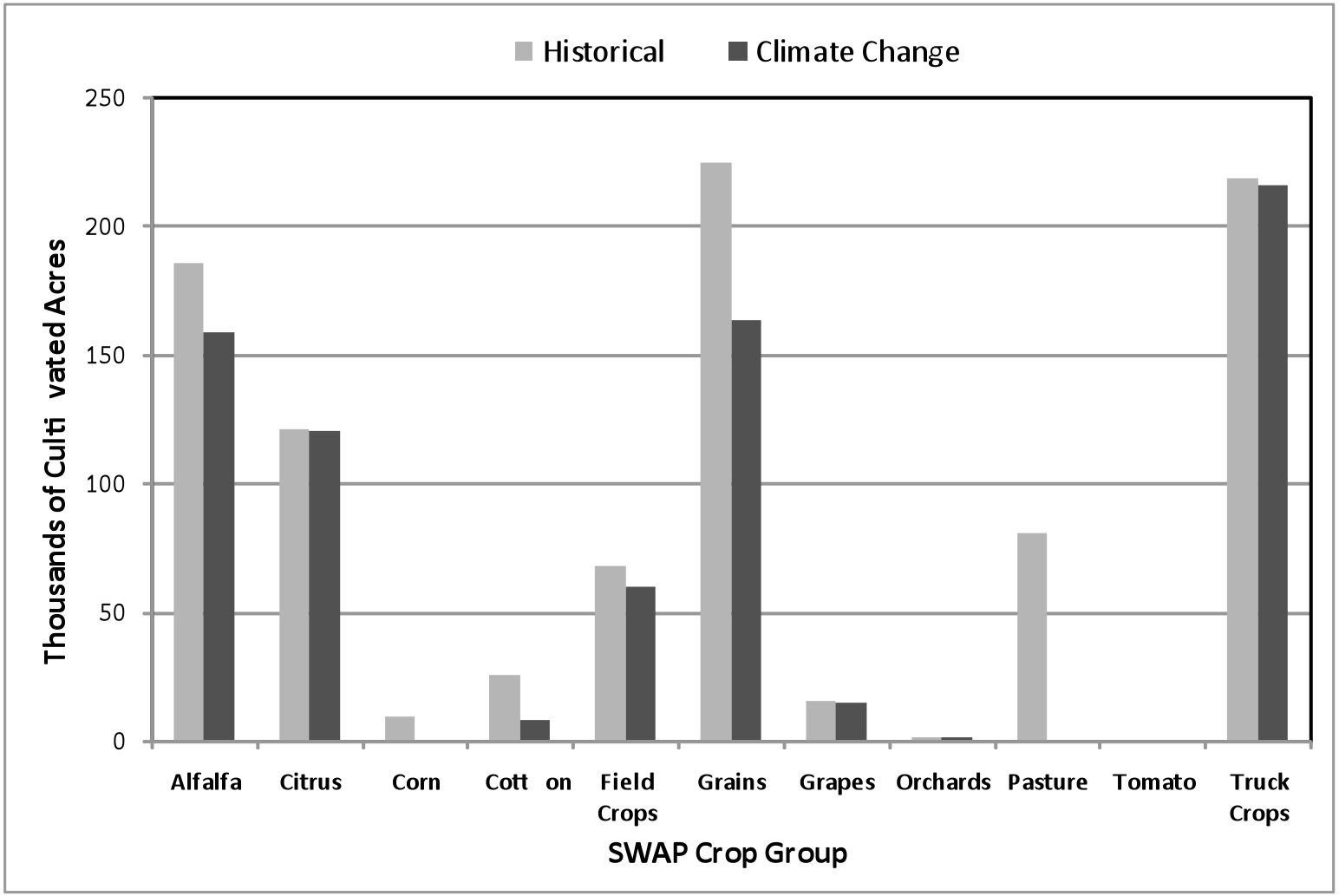

Figure 6. Total cultivated land per crop under climate scenarios in Southern California

Figure 7 shows percent differences between Historical and Climate Change Scenarios in 2050 for all regions and crops in the study. As discussed above, both the total land use and relative cropping patterns are shown to change between the regions.

Sacramento sees the largest reductions in both water-intensive and low-value crops. This is because CALVIN, used to generate optimal regional water allocations under climate change, assumes there are markets for water and a means to transport the water. Consequently, it becomes more profitable for farmers in the Sacramento region to sell water to southern regions. Those crops that are still profitable to continue growing tend to be the high-value crops with significant increases in both yield and demand in California.

San Joaquin shows significant reductions in crop acreage as well. Referring to Table 7 and noting that average water reductions are 17%, we see that San Joaquin is a large exporter of water. This is a result of comparative advantages in other California regions and high-value crop production shifts to regions like Tulare. Tulare follows a similar pattern of land reductions, although effects are less dramatic as they import water from other regions, Sacramento and San Joaquin, to provide water for high value crops.

Southern California is shown to have relatively small percent changes in acres between the climate scenarios. It is important to note that while there is less change in percentage terms, the Southern California regions have fewer planted acres under both scenarios. The availability of water markets allow for the reduced impact on total acres.

We should emphasize that these shifts in land use are in contrast to the substantial economic effects of climate change on total revenue, as discussed above. Results indicate that revenues are expected to go down by less than the land and water reductions, which is consistent with economic theory.

3.3. Model Limitations and Extensions

The model results for 2050 should be viewed as a plausible scenario that results from the most probable assumptions. Given the very long time horizon required in this study, the results should not be considered a projection or forecast, but as a probable outcome of the interaction of several uncertain driving forces. California agriculture has always been driven by the interactions between technology, resources, and market demands, and future production can be viewed as a balance between the rates of change in these three variables. Accordingly, we have attempted to make the assumptions, mathematics, and the parameter values used in this study as transparent as possible to enable the reader to assess the basis for the results.

Limitations of this model have been discussed in Medellin-Azuara (2007) and in Howitt et al. 2001). SWAP is in the process of major updates to address most of these limitations. Worthwhile discussing here is that estimated changes in yields from other studies vary widely depending on the set of considerations. These considerations include CO_2 fertilization, location, and crop variety. Another limitation is that some SWAP crop categories are coarse, and yields may vary within each category. Risk preferences are implicit in the calibrated production model of SWAP,

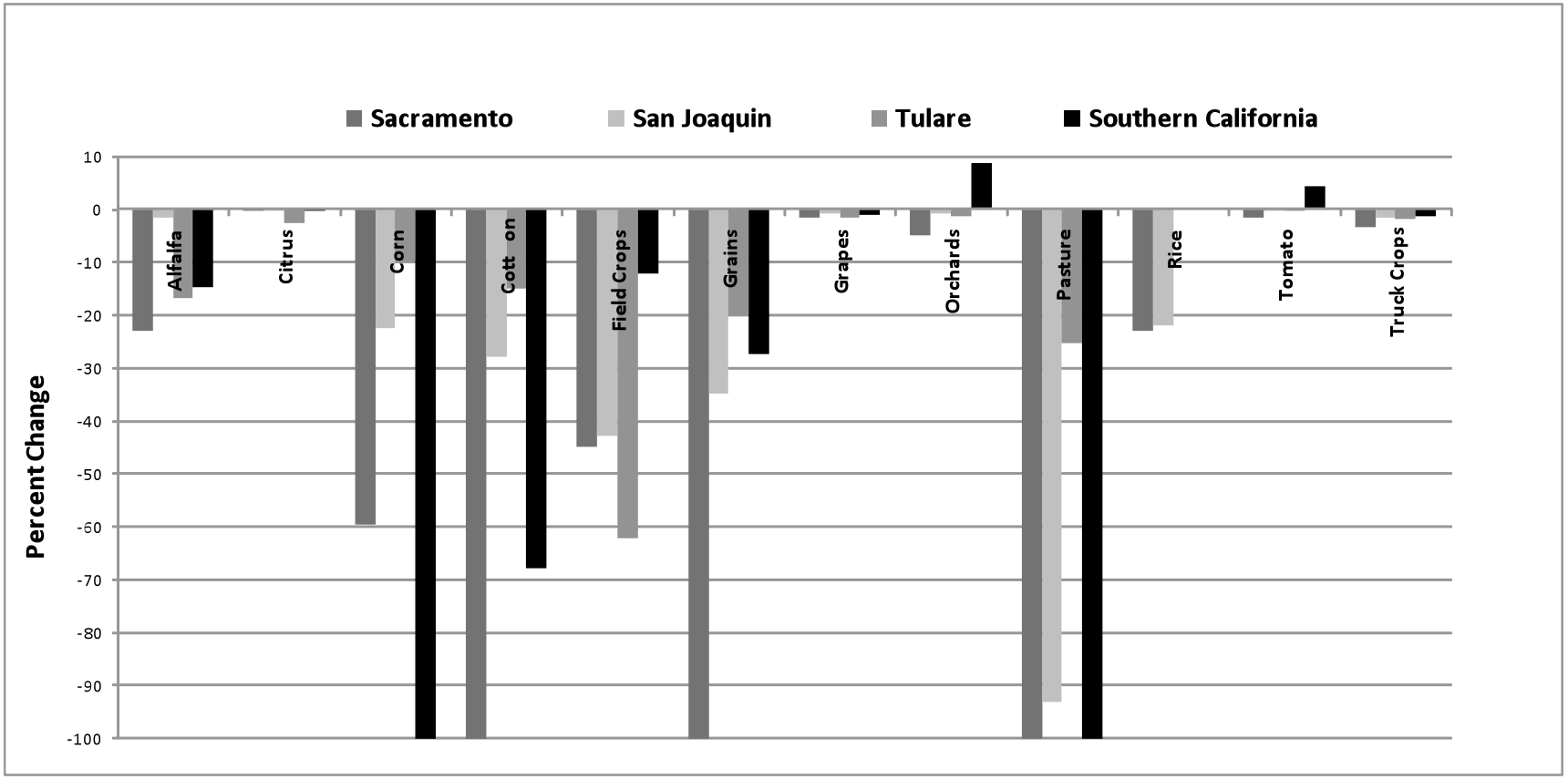

Figure 7. Percent change in land use under climate scenarios for all crops and regions

Extensions and other improvements to the model include agriculture in regions other than the Central Valley and Southern California, such as coastal areas of California. Future versions of the model will also include more disaggregated estimations of changes in yields and shifts in future demands that incorporate results from research in-progress. Production cost information is also continuously updated in the SWAP database. Inputs, in addition to fertilizer and other supplies, are being added. More inputs added to the production function allow for a more accurate representation of the response of farmers to reduced yields from climate warming.

4.0 Conclusions

This paper has considered the effects of climate change on California agriculture in 2050. We have quantified these results using SWAP, a PMP model of California agriculture. Several innovations and improvements have been added to the model and this has significantly improved realism of the results. These improvements include calibrating to geo-referenced data, CALVIN expected water cutbacks to agriculture by 2050, changes in crop yields caused by climate differences and estimated by other parts of the research program, introducing demand shifts, introducing technological change, and including corn silage restrictions. It is important to note that results generated hinge on the assumptions of the model and every attempt has been made to clearly convey them.

The results show that the calibrated SWAP model represents profit maximizing farmer reactions to global climate-based yield changes at all the three margins. First, extensive margin adjustments are shown by changes in the total and proportional areas allocated to each crop. Second, intensive margin adjustments are reflected by the change in input use per acre. Third, there are changes in market prices received by farmers that result from the change in total output produced. Since climate induced yield changes differ in their intensity (and sign) among crops, we would expect the comparative advantage of different crops to be changed by climate.

The results are consistent with expectations. A central result is that the major effects of climate change on California agriculture are manifest through water shortages. The climate-induced reductions in water supply cause reductions in irrigated crop area that significantly exceed the area needed for urban expansion in the Central Valley. This unused cropland with minimal water supplies will pose a challenge for conversion to environmental habitat. The increasing value of water, which accompanies the increased scarcity, induces changes in crops and technology that are reflected in the results of the production model.

Results can be summarized and generalized as follows. Both model scenarios see increases in yield due to technological improvement and prices because of changing demands over time. Under climate change, relative to historical climate, we model changes in yields (mostly negative) and changes in water availability. Water availability changes in accordance with CALVIN statewide market allocations and varies by region; it is assumed that there exists a means to transport the water and functioning water markets by 2050. Given these and other assumptions the SWAP model is run for historical and climate change scenarios. Prices are shown to increase (moderately, and some actually decrease) in response to climate change. There are changes in production of each crop and changes in total land use as a result. Changes in prices and productivity have been broken down and the total effect on revenue was shown. Revenues across all regions are down under climate change, as is water usage. Both the revenue and resource effects are shown to vary by region. The overall conclusion from model runs is

that, while the effect of climate change is manifest through yield changes, after economic adaptation, the results on irrigated crop production are predominately shown in economic terms and changes in aggregate land and water use. There are very significant reductions in irrigated acres that range regionally from 16% to 24%, and 9% to 16% reductions in revenues due to partial offsets from price and crop changes.

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6.0 Glossary

af	acre-foot
AIC	University of California Agricultural Issues Center
BCM	Billion cubic meters
CALVIN	University of California, Davis Economic-Engineering Water Model
CES	constant elasticity of substitution
CVPM	Central Valley Production Model
DWR	California Department of Water Resources
MAF	million acre feet
PMP	positive mathematical programming
SWAP	Statewide Agricultural Production Model
TAF	thousand acre-foot
UC Davis	University of California, Davis
USDA	United States Department of Agriculture