Title: Hydro-economic modeling to assess climate impact and adaptation for agriculture in California

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Abstract

Warm-dry forms of climate change are likely to reduce surface water availability and agricultural production of most crops grown in California. This chapter explores potential economic impacts and adaptation to climate change in California using a hydro-economic approach. The roles of technological change, alternative water sources, urbanization, and water markets are considered in the modeling exercises. While significant agricultural land use reductions might occur under warm-dry forms of climate change in California; agricultural revenues should experience a more modest drop. This due to the California's potential for adaptation to change cropping patterns to less water-intensive and higher-valued crops.

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Introduction

Dry-warm forms of climate change may significantly change water availability and agricultural yields and revenues many parts of the world by the mid century. Growing population needing more water, urban footprint and environmental requirements may pose additional pressures to agricultural water uses. Counteracting factors such as technology improvements and price increases in some agricultural commodities may partially compensate losses to climate change and competing uses. In this paper, we present and further discuss results from previous studies (Medellin-Azuara *et al.*, In Review) on adaptation of agriculture to climate change by mid century in the midst of growing competing uses and technological change. We use irrigated agriculture in California as our case study. Previous studies on yield change suggest that various forms of climate change may severely affect most crops in California's Central Valley (Adams *et al.*, 2003; Lobell *et al.*, 2007; Schlenker *et al.*, 2005).

We employ the Statewide Agricultural Production Model (SWAP, http://swap.ucdavis.edu) a hydro-economic model for agricultural production in California. SWAP (Howitt *et al.*, 2001)uses positive mathematical programming (Howitt, 1995) a deductive method that self-calibrates a base case to observed values of production factors use. Climate warming, technological change and urban footprint are introduced to contrast historical climate and climate change by 2050 with the 2005 base case for agricultural production. Water deliveries under historical and climate change from larger hydro-economic modeling using CALVIN (http://cee.engr.ucdavis.edu/calvin Draper *et al.*, 2003) were used to estimate shortages in SWAP.

In the next sections we discuss the methods and the model. Datasets and a base case for agricultural production in selected regions is presented for year 2005. Population and technological change by year 2050 are then introduced in the model to study agricultural production adaptation with and without climate change. Discussion of results and policy implications close this paper.

Hydro-economic modeling and Positive Mathematical Programming

Hydro-economic modeling

Hydro-economic modeling research began in the 1960's and 70's with Bear and Levin (1970) who first used economic water demand functions to drive water allocation in an inter-tied regional water resources system (Harou *et al.*, 2009). Hydro-economic models provide a framework to represent economically-driven regional water resources systems. Usually, the objective is to maximize total net benefits or to minimize total scarcity and operating costs in a network. Harou *et al.* (2009) provide a comprehensive review of hydro-economic models concepts and their applications.

The CALVIN model

Hydro-economic modeling is undertaken for the present paper within the CALVIN modeling framework. CALVIN is an economic-engineering optimization model of California developed at the University of California – Davis CALVIN's major innovations are its statewide (rather than project) scale, representation of a broad range of water management options, explicit integration of broad economic objectives, and its consequent applicability to a wide variety of policy, operations, and planning problems.

Agricultural and urban water target demands by year 2050 cover more than 85% of the projected irrigated agriculture and population respectively. Both water demands are economically represented as loss functions on water scarcity. Scarcity or shortage is the difference between target demands and the economically-driven water deliveries and has cost associated as a convex piece-wise linear function. The SWAP model provides economic cost of water shortages for all agricultural demand locations in CALVIN (Howitt *et al.*, 2001).Likewise, urban demands are estimating using loss functions for residential, commercial and industrial uses following Jenkins *et al.* (2003).

The CALVIN model uses a 72-year monthly time series of hydrology (1921-1993) to represent system variability. CALVIN manages water infrastructure and demands throughout California's intertied water network to minimize net scarcity and operating costs statewide. The model employs HEC-PRM with a network flow optimization solver developed by the US Army Corps of Engineers (Draper *et al.*, 2003). A comprehensive review of CALVIN applications is presented in (Lund *et al.*, 2009) within the framework of the California Water Plan Update 2009.

The SWAP Model and Positive Mathematical Programming

The SWAP model originally developed as an ancillary model to CALVIN (Howitt *et al.*, 2001) continues to be improved and has been used in multiple applications including economic impacts of salinity in the Central Valley (Howitt *et al.*, 2009a; Medellin-Azuara *et al.*, 2008b), and in the Sacramento San Joaquin Delta (Lund *et al.*, 2007) and impact on employment of water shortages for agriculture (Howitt *et al.*, 2009b).

Positive mathematical programming (Howitt, 1995) is the underlying modeling framework of SWAP, and is a self-calibrating deductive three step procedure to represent agricultural production. Farmers are assumed to follow a profit maximizing behavior for a group of crops within a region, with land and water as the limiting constraints.

The first step in PMP starts with the linear program described by equations (1) to (3) below:

$$Max_{x\geq 0}\prod=\sum_{g}\sum_{i}(v_{gi}yld_{gi}-\sum_{j}\omega_{gij}a_{gij})x_{gi,land} \tag{1}$$

$$\sum_{i}a_{gij}x_{gi}\leq b_{gi}\quad \forall \text{g, j} \tag{2}$$

$$x_{gi,land}\leq\ \tilde{x}_{gi,land}+\varepsilon\quad \forall\ \text{g,i} \tag{3}$$

The first equation is the objective function of a linear program. Decision variables are defined as follows: x_{gi} is 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, ϖ_{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. The second and third equations represent the constraint sets, equation (2) is for limiting resources (usually, land and water) and equation (3) is for calibration on land. The perturbation term ε, is used to decouple the resource constraints.

A PMP exponential cost function (equation 4) is parameterized through ordinary least squares in a second step, with restrictions, on the PMP formulation and elasticity of supply for each crop group. δgi and γgi are the intercept and the elasticity parameter for the exponential acreage response function, respectively. Lagrange multipliers on the calibration constraint set are also used and a constant elasticity of substitution production function (5) is parameterized detailed in Medellin-Azuara (2006).

$$TC_{gij}(x_{gij}) = \delta_{gi} e^{\gamma_{gi} x_{gi,land}} \tag{4}$$

$$Y_{gi} = \tau_{gi} \left[\sum_{j} \beta_{gij} X_{gij}^{\rho_i} \right]^{\upsilon/\rho_i} \tag{5}$$

In the third and last step, a non-linear program using the exponential cost function (4) and the parameterized production function in the following program.

$$Max_{x\geq 0} \prod = \sum_{g} \sum_{i} yred_{gi} v_{gi} Y_{gi} - \sum_{g} \sum_{i} \delta_{gi} e^{\gamma_{gi} x_{gi,land}} - \sum_{\mathrm{g}} \sum_{i} \sum_{j,j\neq land} (\omega_{igj} x_{gij}) \tag{6}$$

$$\sum_{i} X_{gij} \leq b_{gj} \, \forall \, g,j \tag{7}$$

Constraint set in equation 7 is as in 3 above. In Equation 6, the parameter *yred* is a scaling factor to accommodate different modeling policies such as yield changes due to salinity or climate change. In this model formulation water is assumed to be interchangeable among crops within a region.

Changes resulting from different water management policies, physical conditions and market driven exogenous events can be simulated by changing parameters and changes in production can be evaluated both the extensive and the intensive margins.

In this study we used the most recent California Climate Assessment with CALVIN (Medellin-Azuara *et al.*, 2008a) and SWAP (Howitt *et al.*, 2009c). CALVIN provides economically-driven water deliveries under historical and warm-dry forms of climate change by year 2050 to SWAP in a second round of modeling this is illustrated in Figure 1 below.

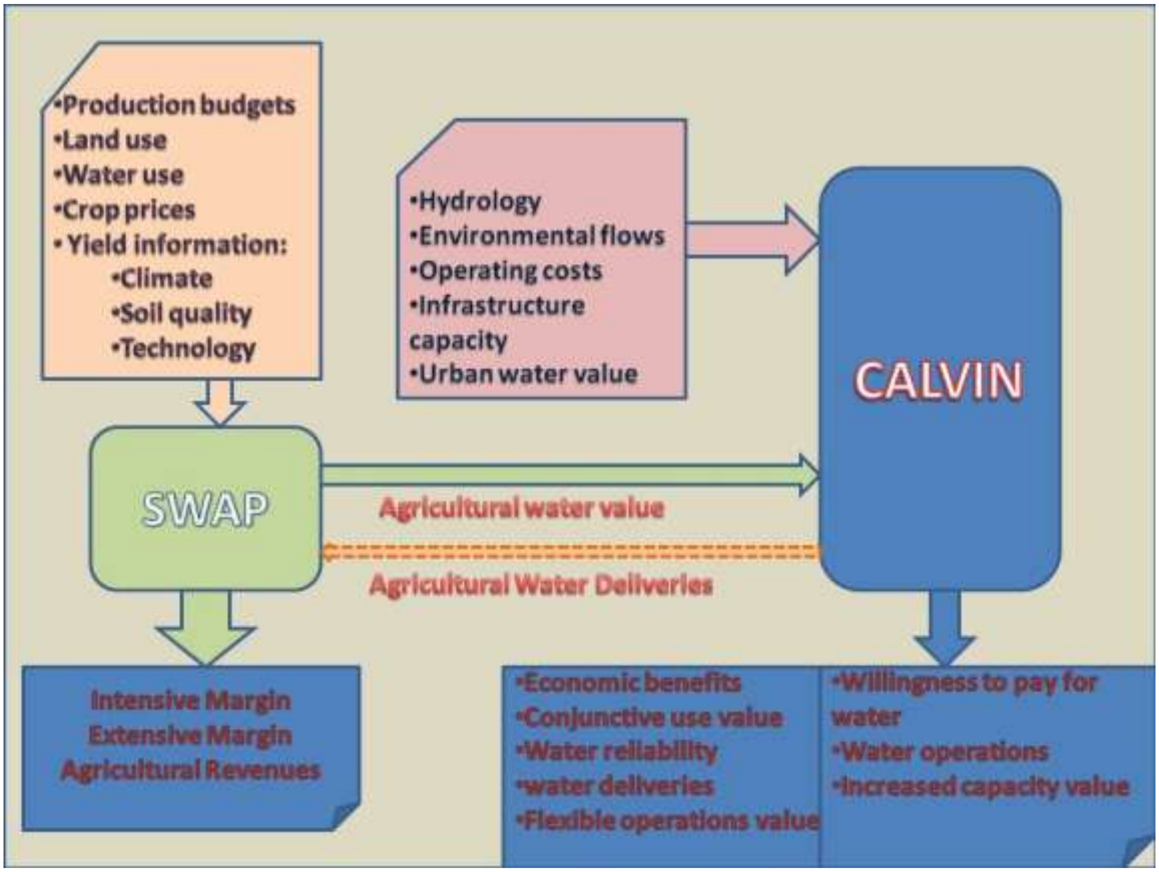

Figure 1. SWAP and CALVIN model interaction.

Climate Change and Agriculture in California

California is characterized by virtually all-irrigated agriculture. Every year, about 3.65 million hectares are irrigated statewide using nearly 35 hm^3 and yielding more than $20 billion (2008) dollars in revenues. Agricultural commodities in California make a large list that includes field, orchard, vine, truck and fodder crops.

The SWAP in the present study includes 21 regions in the Central Valley known as CVPM regions (USBR 1997), plus agriculture in Coachella, Imperial, Palo Verde, Ventura and San Diego. Coverage for 5 out of 10 hydrological regions is shown in Figure 2. The Sacramento River hydrological region Covers CVPM regions 1 through 7 with portions of 8 and 9. The San Joaquin River Basin includes portions of 8 and 9 plus CVPM regions 10 to 13. The Tulare Basin covers CVPM regions 14 to 21. Datasets for crop budgets in SWAP are from UC Cooperative Extensions. Land and water use information was obtained from the California Department of Water Resources (DWR).

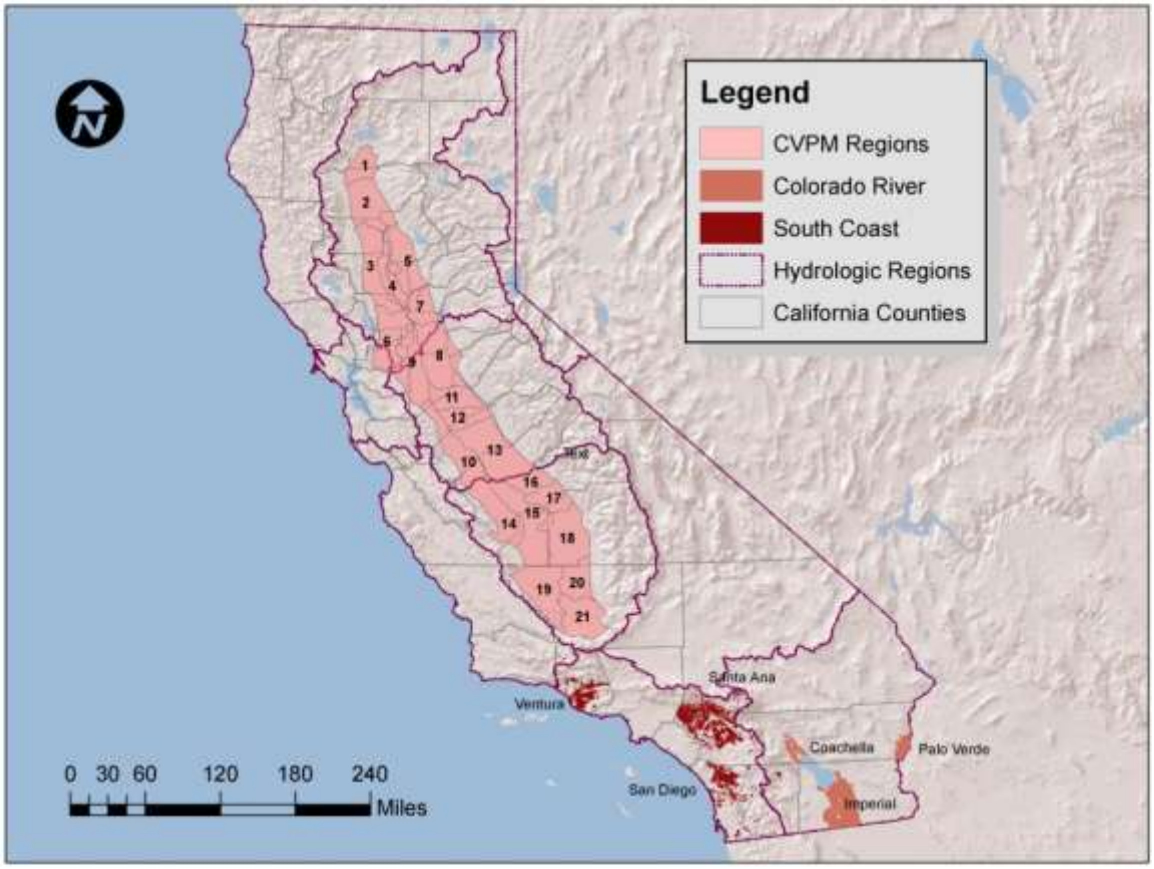

Figure 2. SWAP Coverage including 21 CVPM regions, and agriculture in Coachella, Imperial, Palo Verde, Ventura and San Diego.

Base Case

In the base case, SWAP includes 3.36 million hectares of irrigated agriculture and 31.9 million m^3 per year for year 2005. Agricultural commodities in California are collapsed into twelve

SWAP crop groups: alfalfa, citrus, corn, cotton, field crops, grains, grapes, orchards, pasture, sugar beet, tomato, and truck crops. More recent versions of SWAP further disaggregate these crop groups into twenty groups.

Land Use, Technology and Climate Change for year 2050

We employ estimates on urban footprint growth by year 2050 from Landis and Reilly (2002) that suggest an overall 8.5 % reduction in agricultural land use from 2005 to 2050. Sandstat *et al.* (2008) provide estimates on population footprint for the century and their results for 2005 and 2050 are illustrated in Figure 3 below.

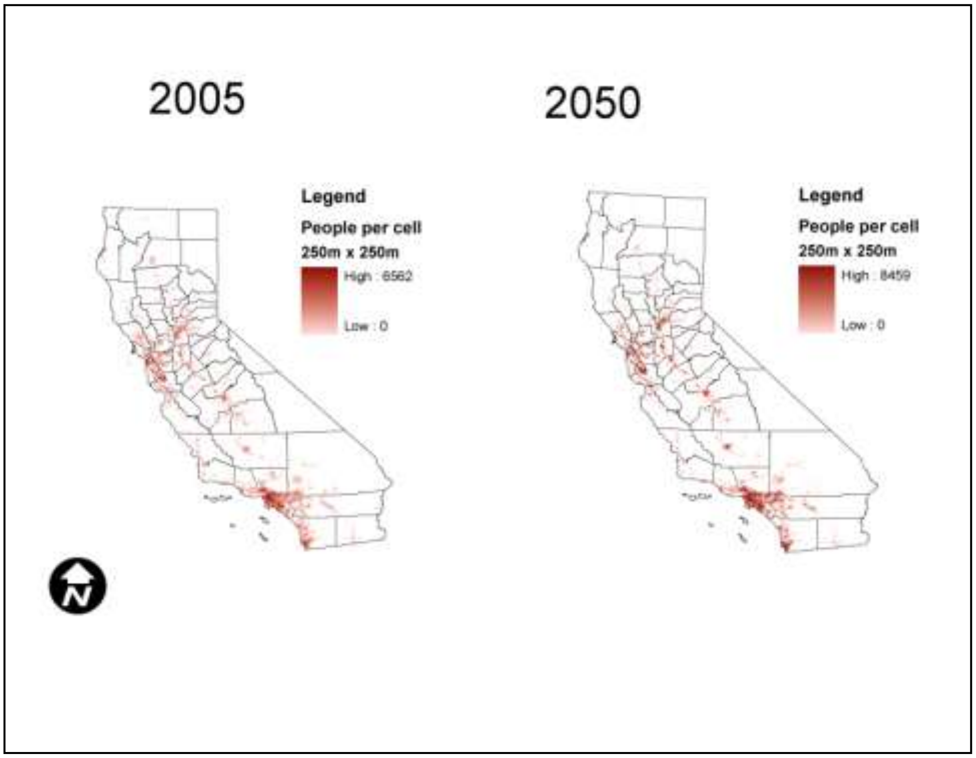

Figure 3. Urban footprint 2005 versus 2050 (with data from Sanstad *et al.*, 2008). TO BE IMPROVED

Agricultural crop yields are assumed to increase over time due to technological improvements up to a certain physical photosynthetic limit. A historical 1.42% annual rate of yield improvement was assumed to continue at the same rate as estimated Brunke *et al.* (2004) till year 2020. After year 2020 this improvement is assumed to have reached a plateau due to carbon fixation limits from photosynthesis. Technology likely will not improve yields at the same rate indefinitely over time. This results in a log linear growth rate of 0.25 for the period 2020-2025 and an average increase in crop yields of 29% among all SWAP crop groups by year 2050. A breakdown by crop group is presented in Howitt *et al.* (2009c).

A big challenge in establishing 2050 year conditions for agricultural production is the estimation of realized crop prices. Therefore some simplifying assumptions and an endogenous crop price model was employed. It was assumed that California was a *price-taker* for grain, rice and corn crop groups. However, crop demand for the rest of the crops in California was assumed to increase with population and income, keeping a constant proportion of California production sold as out of state exports. Howitt *et al.* (2009c) provide additional details on demand shifts by crop group. In general most crops prices are expected to increase by year 2015 in real terms with a drop following afterwards. Thus rice, corn and grain might experience price drops of 1.45, 0.67 and 1.58 respectively with resulting demand shifts of -1.4% for rice, -17% for corn and -19.9% for grain. For crops for which California has market power, population and income projections were employed to estimate 2050 demand shifts. A U.S. population increase of 43% and ratio of real income of 2.5 with respect t 2005 were used as inputs to shift crop demands following Muth (1964). Shifts in the demand intercept range from 3.44 for field crops to 45 for truck crops. Details on the endogenous model formulations and demand shift estimations are presented Howitt *et al.* (2009c).

Climate related crop yield changes are expected for in California and elsewhere. These expected changes are largely result of changes in precipitation and temperature under different climate scenarios. A handful of studies have been conducted taken these environmental conditions into account for California (Adams *et al.*, 2003; Bloom, 2006; Lee *et al.*, 2009; Lobell *et al.*, 2007). However, many of these studies are crop, climate-scenario and region specific without a comprehensive assessment of all crop groups and regions in California. Thus we divided the state in two larger regions: the Sacramento and the San Joaquin River basins. Furthermore, we used a warm-dry climate scenario since most crop groups have been found more sensitive to water stress than to temperature changes. Among the IPCC panel climate scenarios we used GFDL CM2.1 A2 This warm-dry scenario yields a statewide-average 4.5°C temperature rise and an 18% reduction in precipitation by the end of the century (Cayan *et al.*, 2008). Table 1 presents a summary of yield changes by crop group.

Table 1. Expected climate-relatated yield changes for a warm-dry climate scenario (adapted from Howitt *et al.*, 2009c).

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

Warm-dry climate change also affects water deliveries to agricultural locations as water availability is reduced. For California under the GFDL2 climate scenario a reduction in precipitation of 27%, a reduction in inflows of 28%, and an increase of 15% in reservoir evaporation are expected (Medellin-Azuara *et al.*, 2008a). In the Central Valley, groundwater inflows can be reduced by nearly 10% under this climate scenario. The resulting reduced availability of water for agriculture are summarized in Table 2. SWAP takes into account water availability with and without climate change (Figure 1) to estimate economically optimal cropping patterns under climate change.

Table 2. Expected percent reduction in water availability under the warm-dry climate scenario versus the historical climate scenario under using CALVIN hydro-economic optimization (adapted from Medellin-Azuara *et al.*, 2008a)

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

SWAP model policy runs

To estimate the effect of climate change in crop production in California by year 2050, we used the CALVIN and the SWAP model as shown in Figure 1. Three scenarios were evaluated in SWAP: 1) 2005 Base Case with historical climate, 2) 2050 historical climate, and 3) 2050 with warm-dry climate. Base case includes 2005 land use at current farm budgets, whereas the 2050 scenarios account for technological change, urban footprint, and climate related yield changes. Results for these three scenarios are discussed in the next section.

Results and water management insights agricultural production under climate change

SWAP provides agricultural production results at the extensive and intensive margins. In this section we present statewide results from Medellin-Azuara *et al.* (In Review) from the three policy scenarios. In some cases, we have grouped SWAP coverage into four larger regions: Sacramento (CVPM regions 1-9), San Joaquin (CVPM regions 10-13), Tulare (CVPM regions 14-21) and Southern California (Coachella, Imperial, Palo Verde, San Diego and Ventura).

For the agricultural areas covered by SWAP, total land, water and agricultural revenues are presented in Table 3 below. From the base case, with respect to year 2005, a reduction in agricultural land use of 7.3% is expected under historical climate due to footprint. Under warm-dry climate change, further limited water supplies would further reduce land use by 18.7% with respect to 2005 giving a total reduction of 26%. Water use behaves similarly. Total applied water under the base case scenario is 32.4 Mm^3/yr, but under historical climate scenario drops to 30.1 Mm^3/yr by year 2050, a reduction of 7%. Under climate change however, a reduction of 26.3% is expected. Adaptation of agricultural production to climate drives cropping patterns to more profitable and less water intensive crops making total water use reduce more than total land use in agriculture. This is shown as an increase in total agricultural revenues for the areas covered by SWAP. In the base case about $20 billion dollars (2008) in revenues concentrated in the Central Valley (9 billion in the Tulare basin) are increased to $28.4 billion under historical climate. Climate change by year 2050 is likely to reduce agricultural revenues with respect to historical climate. However these revenues will not be reduced with respect to the base case, as more profitable and less water intensive crops are likely to make up future crop mix.

Table 3. Statewide agricultural land, water and revenues for the three analyzed scenarios (adapted from Medellin-Azuara *et al.*, In Review)

Scenario	Land Use (1000ha)	Water Use (Mm^3/yr)	Revenues ($2008 billion)
Base 2005	3,375	26,295	20.1
Historical 2050	7,727	24,433	28.4
Climate Change 2050	6,170	19,368	25.2

This outcome is also illustrated in Figure 4, which compares runoff reductions agricultural land use and revenues. Water deliveries follow closely land use patterns. In isolation, the effects of climate change will have detrimental effects on agricultural production and revenues. However, the revenue losses are partially compensated by higher crop prices technology and adaptation to less water intensive crops. To reinforce this finding, maps in Figure 4 show agricultural land use, water use, and revenues or the two 2050 historical climate and climate change scenarios.

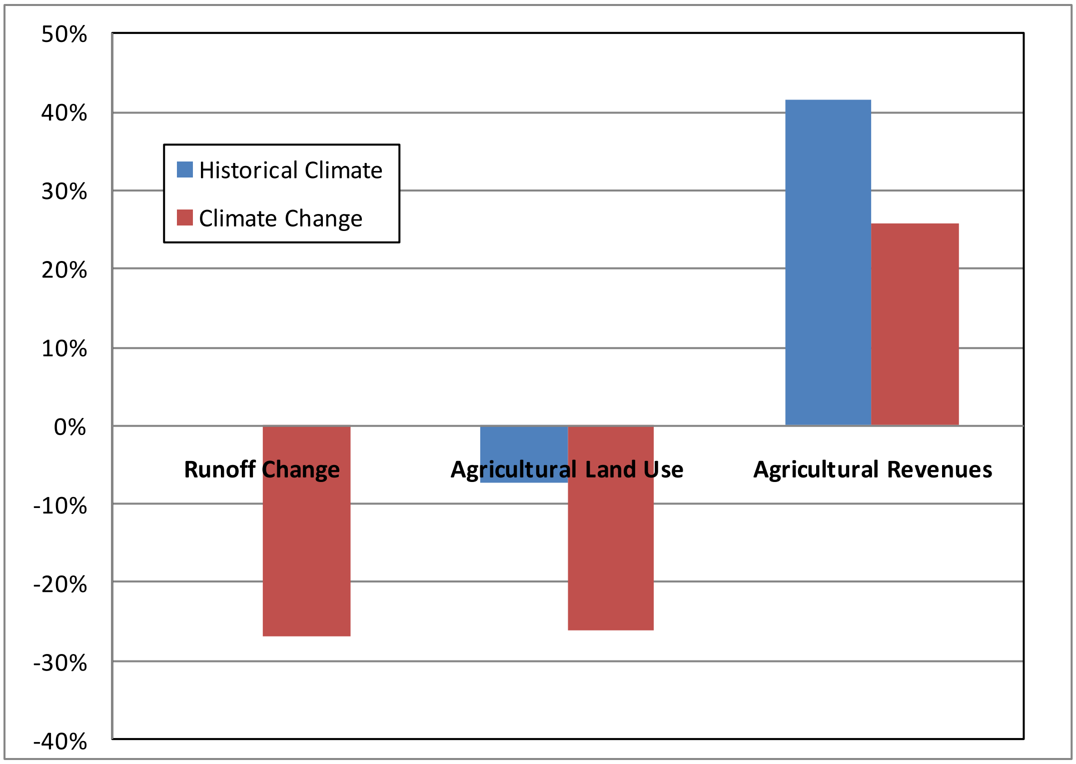

Figure 4, change in runoff, agricultural land use and agricultural revenues with respect to the 2005 Base Case (adapted from Medellin-Azuara *et al.*, In Review).

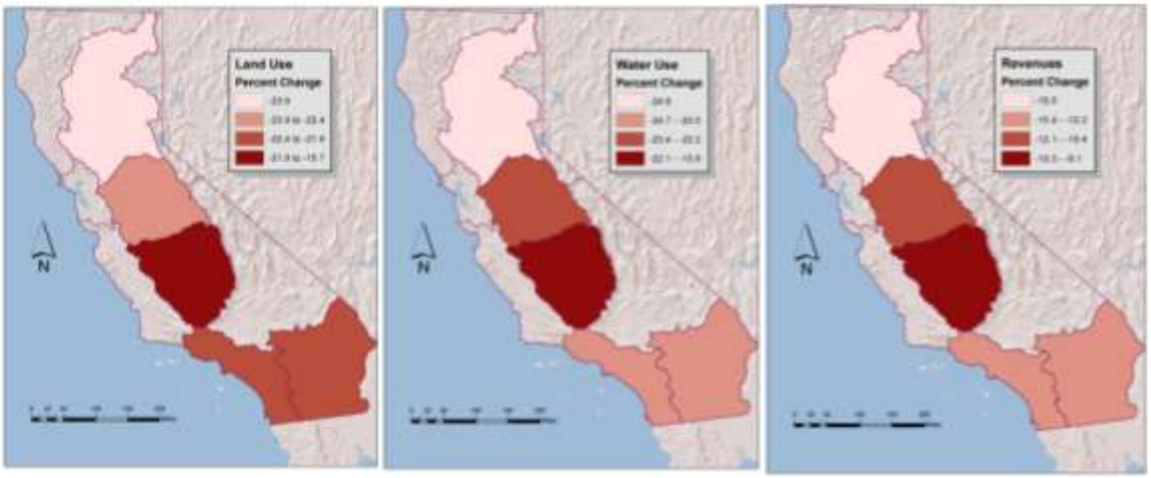

Figure 5. Percent change in land, water use and agricultural revenues between historical and climate change scenarios by year 2050 (adapted from Medellin-Azuara *et al.*, In Review)

Changes in statewide cropping patterns between historical and climate change scenarios by year 2050 are shown in Figure 6. Pasture is reduced substantially in regions that cannot afford that land use if a 27% reduction in rim inflows that occurs under climate change. Corn and cotton follow a similar response. One limitation of the representation of SWAP of corn and pasture in Medellin-Azuara *et al.* (In Review) is that silage constraints were not included in the model.

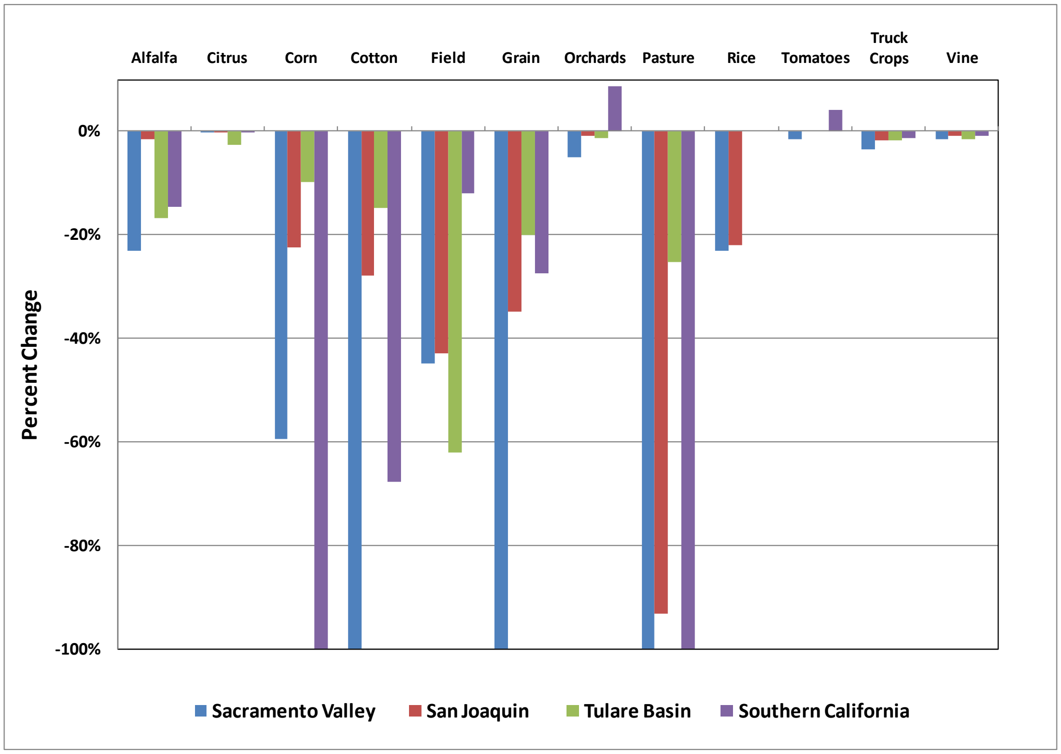

Figure 6. Percent change in crop area between historical and climate change scenarios in year 2050 (adapted from Medellin-Azuara *et al.*, In Review).

To better show the difference in cropping patterns between historical and climate change scenarios by year 2050, Table 4 in column 5 shows the changes in land share among crops. Lower value and water intensive crops such as pasture will have their land share reduced to almost zero. Also, even when crops such as alfalfa, citrus and grapes have statewide reductions in total land use; these crops increase its land share relative to other crops under climate change.

Table 4. SWAP crop group cultivated area by year 2050 under historical and climate change scenarios (adapted from Medellin-Azuara *et al.*, In Review)

Crop Name	Historical	Climate Change	% Change Land Use	% Change in Crop share
Alfalfa	828,394 (335,239)	725,377 (293,550)	-12.4	9.66
Citrus	372,440 (150,721)	366,353 (148,258)	-1.6	23.18
Corn	511,374 (206,946)	405,942 (164,279)	-20.6	-0.59
Cotton	632,242 (255,859)	509,732 (206,281)	-19.4	0.96
Field Crops	1,346,916 (545,078)	701,381 (283,839)	-47.9	-34.79
Grains	489,517 (198,101)	332,113 (134,401)	-32.2	-15.04
Grapes	633,381 (256,320)	625,491 (253,127)	-1.2	23.67
Orchards	747,062	737,691	-1.3	23.66

	(302,325)	(298,533)		
Pasture	251,456 (101,761)	9,912 (4,011)	-96.1	-95.06
Rice	555,348 (224,741)	427,687 (173,079)	-23	-3.56
Tomato	318,313 (128,817)	316,685 (128,158)	-0.5	24.59
Truck Crops	1,040,768 (421,184)	1,012,028 (409,553)	-2.8	21.77
Total	7,727,211 (3,127,091)	6,170,392 (2,497,069)	-20.1	N/A

SWAP crop group prices are show in Table 5. Most SWAP crop groups have price increases by year 2050. Climate change puts additional pressure on land and water use further driving up prices.

Table 5. SWAP crop groups price changes among the three scenarios (adapted from Medellin-Azuara *et al.*, In Review). Figures in $2008 dollars.

	Base Case 2005 Price, $/Ton	Historical 2050 Price, $/Ton	Climate Change 2050 Price $/Ton	% Change 2050 Historical vs climate change
Alfalfa	117	111	116	3.90

Citrus	436	410	460	12.26
Corn	102	119	119	0.02
Cotton	1701	1739	1759	1.16
Field Crops	295	305	305	0.06
Grains	298	238	238	0.04
Grapes	847	962	980	1.87
Orchards	1445	1257	1358	8.05
Pasture	76	80	80	0.07
Rice	290	273	277	1.55
Tomato	50	61	61	-0.38
Truck Crops	277	410	421	2.72

The results above show that climate change will adversely affect water availability and water use in agriculture by year 2050. Reductions in most crop yields are also likely under to most climate change scenarios. However, improvements in technology and rising crop prices offset climate change losses.

Some model limitations are worthwhile discussing. From the hydro-economic modeling with CALVIN, it is assumed that water can be traded freely among users. Some institutional constraints and high transaction costs may prevent some CALVIN economically optimal water allocations from happening. From modeling with SWAP in year 2050 crop demand projections is an endeavor tinted by many changing variables. These include exports, competition from foreign production, growth in exports demand and changing preferences. On the other hand, livestock production in California significantly influences cropping patterns of alfalfa, pasture, and corn. To the extent that the agronomic estimates used to calibrate the SWAP and the CALVIN models are uncertain; this uncertainty will be reflected in the integrated results of these models.

Conclusions

In this paper we assessed the effects of climate change in California agriculture by year 2050 using the California Agricultural Production Model (SWAP) in combination with CALVIN, a statewide hydro-economic model for water resources in California. In estimating production conditions to year 2050 urban footprint, technology improvements, and likely crop demands and price trends were taken into account. In addition, estimates from associated agronomic studies were used in the calibration of the economic production model. Then warm-dry form of climate change, the GFDL CM2.1 A2 was used to evaluate changes in water deliveries to agriculture from CALVIN and changes in agricultural yields in SWAP.

Results show that water shortages for crops is one of the major outcomes of climate change in California. Climate induced agricultural land loss significantly exceeds the area needed to accommodate the 2050 urban footprint in agricultural areas. 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.

Increases in yield due to technological improvements and in prices of some crops in California are expected by year 2050. Under climate change, relative to historical climate, we model changes in yields (mostly negative) and changes in water availability. 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. Revenues across all regions decline under climate change, compared with a continuation of historical climate. However, total revenue increases with respect to the 2005 base case. Adaptation by reductions in land area and water use can be compensated by changes in cropping pattern, water use, market prices and crop productivity. 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.

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