ECONOMIC MODELING OF AGRICULTURE AND WATER IN CALIFORNIA USING THE STATEWIDE AGRICULTURAL PRODUCTION MODEL

A Report for the California Department of Water Resources

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ABSTRACT

Balancing the economic costs and benefits of water use in California is critical for evaluating the implications of policies and environmental changes. This paper introduces a Positive Mathematical Programming method for modeling agricultural production and water use called the Statewide Agricultural Production Model (SWAP). SWAP represents the most comprehensive economic modeling framework available and embodies over a decade of research, development, and applications. This paper reviews the theory and technical details of SWAP and summarizes results of applications to California in five recent studies: benefits from a politically viable water market south of the Delta during a drought, climate change effects on agriculture, yield and revenue reductions due to soil salinization, the Delta Agricultural Production Model, and economic implications of the 2009 physical and environmental drought. SWAP provides valuable insights for policy makers and water managers in California into the economics of water use and agricultural production across the state.

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INTRODUCTION

In California, agriculture is the largest user of water, an important source of employment and income for many regions, and source of tax revenues for the state. Statewide irrigated agriculture revenues are in the order $22 billion/ per year (www.opr.ca.gov) supporting 300,000 – 450,000 jobs. Additionally, the California Department of Water Resource (DWR) estimates that population in the state could top 65 million by 2050, implying significant increases in urban water demand and use. Further complicating the picture is an increasing awareness of the importance of the Sacramento-San Joaquin Delta as a key ecosystem for native fish and, by way of extension, parts of the fishing industry (Lund et al. 2007, Lund et al. 2008). Policies seeking to balance the needs of competing uses for water benefit from the guidance of a comprehensive economic analysis framework. The ideal framework can incorporate the complex interaction between the environment, urban users, and agricultural users for evaluating the economic benefits and costs of water policies and/or other external shocks and changes to the system.

This paper offers an analytical and practical approach to estimating the effects of particular water-related policies and external shocks to agriculture in California. The framework presented is a large-scale, self-calibrating agricultural production model called the Statewide Agricultural Production Model[1] (SWAP). SWAP is a Positive Mathematical Programming (PMP) model of agriculture and water use across the state of California. PMP was first introduced to the literature in the late 1980's, was formalized by Howitt in 1995 (Howitt 1995), and has subsequently been used extensively for agricultural modelling and evaluated critically in the literature (Heckelei and Britz 2005). In general, PMP is a deductive approach for evaluating effects at both intensive and extensive margins which calibrates exactly to a base year (or set of years) of observed input and output activities.

This paper is organized as follows. The first section provides a brief review of the literature on agricultural production modeling and areas of application. The next section summarizes the details of SWAP and the formal structure of the model. This is followed by a section which highlights some of the recent applications of SWAP with specific focus on climate change, soil salinization, water markets, the Delta Agricultural Production Model, and the 2009 California drought. These applications highlight the importance and robustness of SWAP for studying the economics of irrigated agriculture as part of a complex system. The paper concludes with a summary of current modeling efforts and the future of SWAP.

LITERATURE OVERVIEW - MODELING ECONOMICS OF AGRICULTURE

Study of the economics of irrigated agriculture was first introduced into the literature as a way of estimating irrigation water demand by Moore and Hedges seminal paper (1963). A recent paper by Scheierling *et al.* (2006) offers a comprehensive analysis of the evolution of agricultural water demand literature. Two general approaches emerges from this literature, statistical methods and mathematical programming methods. Initial approaches for mathematical programming were plagued by a tendency for overspecialization in production, however these issues were corrected with the formalization of PMP (Howitt 1995). In the subsequent years, PMP became a widely accepted method for analyzing water demand as these models work well with the multitude of resource, policy, and environmental constraints often observed in practice (Griffin 2006). Furthermore, PMP does not require large datasets, is directly based on profit-maximizing behavior of farmers, and is better suited to estimate policy response of

[1] http://swap.ucdavis.edu/

farming activities than strictly statistical methods. In general, PMP offers a flexible framework which calibrates exactly to observed data and can be used to accurately model agricultural adaptation to disaggregated environmental, resource, and policy constraints.

Since PMP was formalized, subsequent research has focused primarily on improving calibration techniques. Generalized Maximum Entropy has been suggested as one method for calibration (Heckelei and Wolff 2003, Paris and Howitt 1998) although it has seen limited use in policy applications. When data provide multiple base years to calibrate against, Heckelei and Britz (2005) suggest direct estimation of first order conditions. They also note that when calibrating against a single base year, the general method of PMP is accurate. At the same time, research is progressing that focuses on compartmental and holistic integrated hydrologic and economic models. This research focuses on using PMP based economic models to directly integrate with hydrologic models in an attempt to improve feedback between two previously separate sets of models (Cai 2008).

Agricultural adaptation to changes can be analyzed from many angles including time, spatial aggregation, and uncertainty. PMP models are well equipped to handle all of these aspects. In the short run water use efficiency decisions are limited whereas in the long run farmers have significant flexibility in all input uses. Regionally disaggregated PMP models allow for explicit modeling of differences between regions and specification of disaggregated constraints which is important for accurate policy modeling (Taylor, Dyer and Yúnez-Naude 2005). To capture uncertainty, mathematical modeling can be extended to stochastic programming (SP) and its dynamic version (SDP) which have been used to represent uncertainty in agricultural decisions (Yaron and Dinar 1982). Additionally, as applications of SWAP in this paper will show, PMP is well suited to model changes in technology (through increased yields or irrigation efficiency), water quality, climate and environmental shocks, and changes in socio-demographic characteristics captured through changing agricultural commodity demands.

STATEWIDE AGRICULTURAL PRODUCTION MODEL

The SWAP model is the evolution of a series of production models of California agriculture and shares basic model regions with the Central Valley Production Model (CVPM) (Hatchett 1997). As will be discussed in this section, SWAP represents significant improvements over the CVPM model. The CVPM model has seen extensive use by DWR and consultants across the state in recent years. The first formal application of SWAP was as an ancillary model to the statewide hydro economic model CALVIN (Draper et al. 2003). Recently, SWAP applications have been greatly expanded to include salinity in soil and shallow groundwater in the Sacramento-San Joaquin Delta in California (Lund et al. 2007) and south of the Delta (Howitt et al. 2009a, Tanaka et al. 2008), climate change (Howitt, Medellin-Azuara and MacEwan 2009c, Medellin-Azuara, Howitt and Lund 2007), and drought impact analysis (Howitt, MacEwan and Medellin-Azuara 2009b). Furthermore, SWAP has motivated application of mathematical programming in other regions such as the US-Mexico border basins (Howitt and Medellín-Azuara 2008, Medellin-Azuara et al. 2009).

METHOD SUMMARY

The basis for SWAP is PMP. PMP in the SWAP model is a three-step procedure in which a non-linear cost function is calibrated to observed values of input use in agricultural production. The first step in PMP is a linear program of farm profit maximization with calibration constraints set to observed values of land use. All other production inputs are normalized to land. The Lagrangian multiplier on the calibration constraints is used in a second step to parameterize an exponential PMP cost function. The third step is a non-linear farm profit maximization program that includes the PMP cost function restrictions on land. A

fourth "step" concludes the program which is the model from the third step with any relevant policy shocks and constraints added.

An important result of the PMP approach is that SWAP calibrates exactly to a base year of observed data which increases accuracy within the program. This methodology is applied across model regions where each region can be viewed as representing a profit maximizing representative farmer. This level of aggregation allows for specification of disaggregated environmental and other resource constraints, allowing for more accurate policy modelling.

In the rest of this section the model will be detailed and will highlight the important aspects of SWAP.

MODEL DATA AND REGIONS

The SWAP model covers agricultural regions based on local hydrology and DWR's Detailed Analysis Units (DAU). The original 21 CVPM regions (Hatchett 1997) which have been broken down into 27 regions in collaboration with DWR to better reflect current hydrology. An additional ten regions were also added which include the Central Coast, Coachella, Palo Verde, Imperial Valley, San Diego, Santa Ana, Ventura, the South Coast, Yuma, and Borrego. Thus, there are a total of 37 regions, of which almost all agriculture is irrigated. Below, figure 1 shows the main SWAP regions, disaggregated from the CVPM regions and figure 2 shows the additional irrigated recently added.

SWAP calibrates to values of land and applied water in 2005 data from DWR, representing the most recent normal water year (in both water and agricultural prices). Crops are aggregated slightly into 20 groups, consistent with DWR data, based on a proxy crop for each group. Current crop groups include, alfalfa, almonds and pistachios, corn, cotton, cucurbits, dry beans, fresh tomatoes, grain, onions and garlic, other deciduous, other field, other truck, pasture, processing tomatoes, potatoes, rice, safflower, sugar beet, sub-tropic, and vine crops.

SWAP includes four inputs into production, supplies, land, labor, and water. Input costs for the DWR crop groups were derived from the regional cost and return studies from the UC Davis Extension Crop Budgets[2]. Likewise, crop yields and commodity prices for the base year (2005) in the model were obtained from the California County Agricultural Commissioner's reports published by the U.S. Department of Agriculture[3]. All crop groups are based on the aggregation of the underlying crops making up the entire group. Additionally, since USDA data is at the country level and SWAP regions are based on DAU weighted averages are used to generate region specific data.

All prices and costs are in 2005 dollars for consistency, model results are indexed up to the relevant year after the model is run.

Regional water supplies are specified by six sources, Central Valley Project, Settlement and Exchange, State Water Project, Friant Kern, Local Surface, and Groundwater supplies. These data correspond to 2005 and were prepared by DWR. Since SWAP is an economic model, these data correspond to water deliveries, from which applied water is what is used to determine costs of production.

[2] http://coststudies.ucdavis.edu

[3] http://www.usda.gov

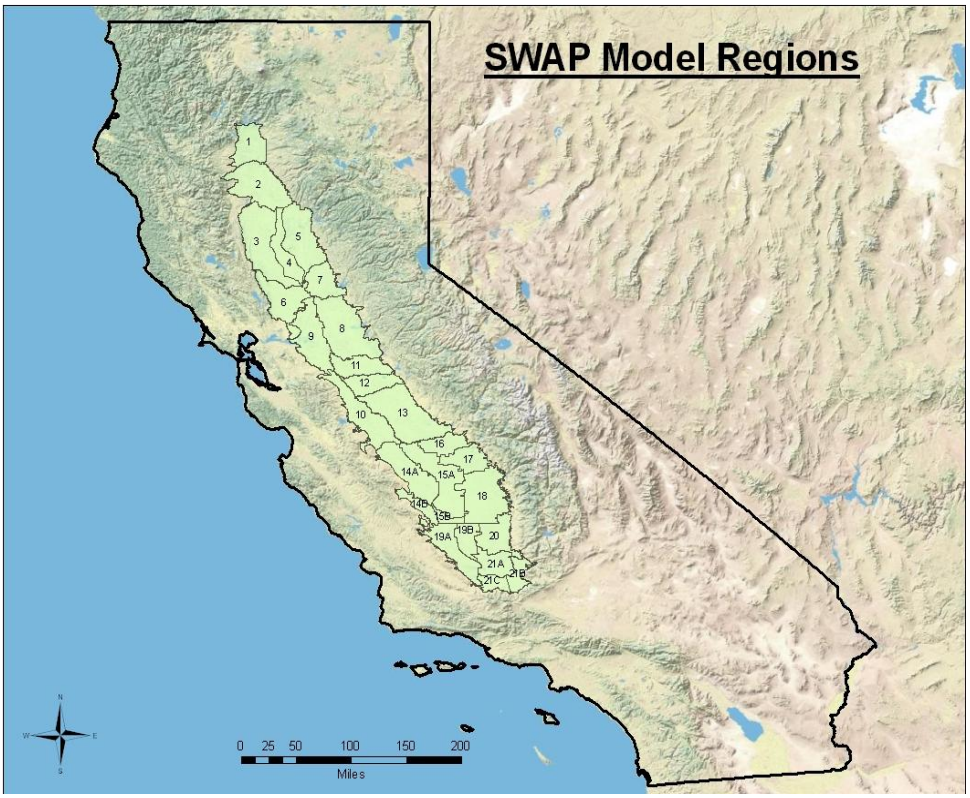

Figure 1. SWAP Regions

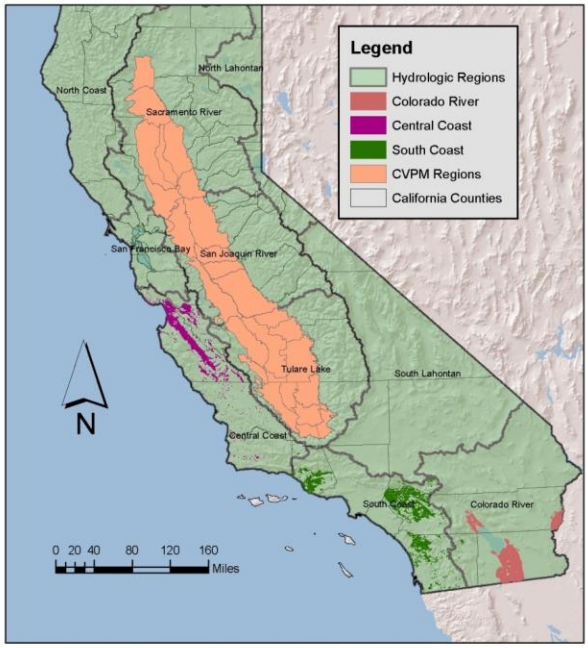

Figure 2. Additional Model Regions

SWAP MODEL CALIBRATION

SWAP is written in the software language GAMS (General Algebraic Modeling System) and solved using the non-linear third party solver CONOPT-3. As discussed previously, the fundamental objective is to maximize regional profits defined as revenue minus costs subject to constraints. SWAP runs on a resolution of one growing season (annual) but has been set up for monthly time frame as well. The sub-sections that follow detail this procedure.

A linear program is solved in the first step of PMP to obtain marginal values on calibration constraints. This enables the estimation of the cost function parameters in the next step. The linear program in step 1 is:

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

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

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

Equation 1 is the objective function of the linear program, maximize profits. x_{gi} is the decision variable representing land use for crop *i* in region *g*. 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, ω_{gji}, are used in the objective function of the linear program. The Leontieff coefficients, a_{gji}, are given by the ratio of total factor usage to land.

Equations 2 and 3 are the constraint set. Parameter b_{gi} is the regional limit on resource *j*. Constraint 3 is for the upper bound calibration constraint, $\tilde{x}_{gi,land}$ is the observed value of resource usage and ε is small perturbation that decouples the resource and calibration constraints (Howitt 1995).

Using the dual values obtained in the linear program exponential cost functions are calibrated and parameters of the Constant Elasticity of Substitution (CES) production functions are calculated. These are discussed in turn in the following sections. In general, the exponential cost functions are calibrated using prior acreage response elasticity estimates and a simple ordinary least-squares routine, more details can be found in Howitt (1995). Similarly, CES parameters are calculated as detailed in the appendix of Howitt (1995).

EXPONENTIAL PMP COST FUNCTION

An innovation in the SWAP model over the CVPM model and related PMP models is the use of exponential cost functions. The exponential form of the cost function has several advantages over the more frequently specified quadratic cost function. The most important practical advantage is that the exponential cost function is better able to fit a desired elasticity of supply without forcing the marginal cost of production of the initial unit to assume unrealistic values. When using the quadratic PMP cost function, a modeller is often faced with the choice between an unrealistic elasticity, which influences policy response, or an unrealistic initial marginal cost of production. In many cases, a realistic elasticity for a linear supply function forces a negative marginal cost for the first units of production. This is clearly an unrealistic situation for a production model. Figure 3 shows the difference between the two

cost functional forms for the same calibration values and marginal supply elasticities. It shows under low acres, possibly the result of a large environmental shock/drought, the marginal cost of additional acres is negative under a quadratic functional form, an obviously impossible result.

Formally, the second step of PMP estimation is to calculate parameters that calibrate the exponential cost function and the CES production function. The constant elasticity cost function is defined as:

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

where δ_{gi} and γ_{gi} are parameters to be estimated by the least squares estimation. These parameters are obtained from a regression of the calibration shadow values on the observed quantities, restricted by the first order conditions, and an elasticity of supply for each crop group obtained from relevant studies.

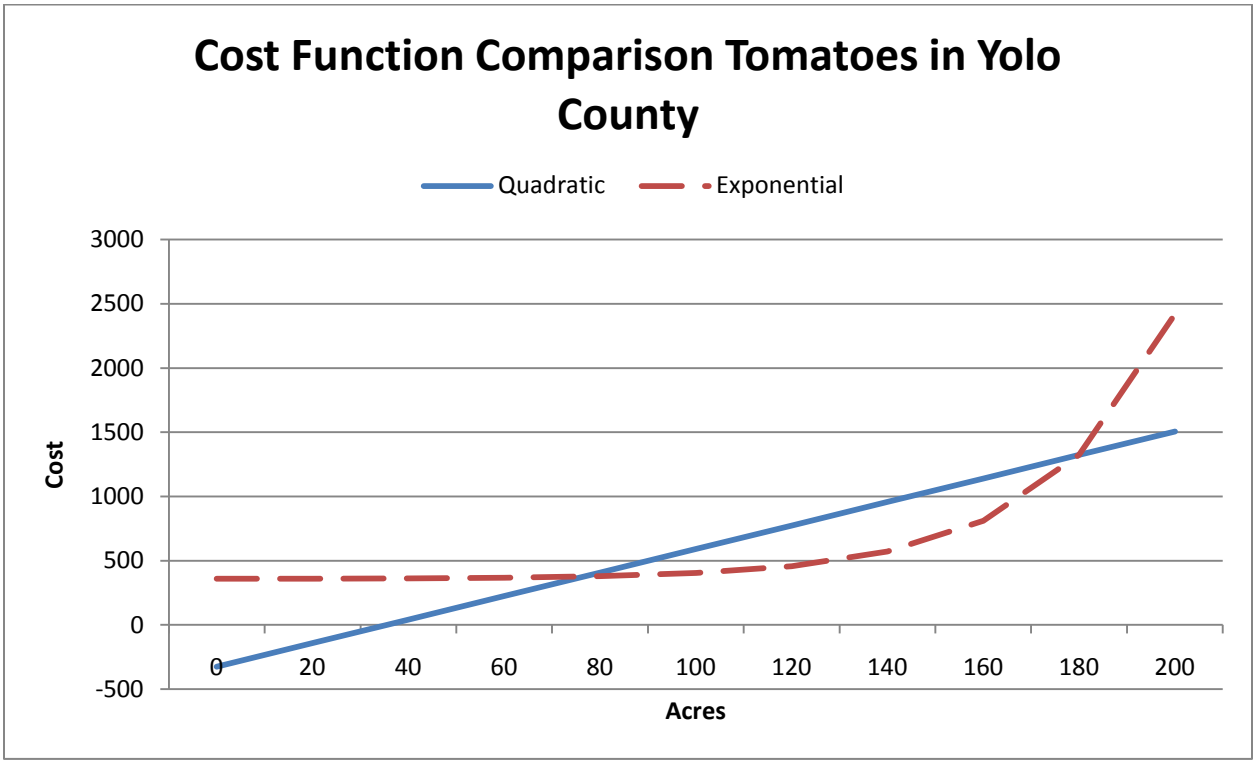

Figure 3. Cost Function Comparison

CONSTANT ELASTICITY OF SUBSTITUTION PRODUCTION FUNCTION

A second key improvement of SWAP over previous modelling efforts is specifying CES region and crop specific production functions. Cai (2008) provides a review of some of the relevant literature on production function specification. Production functions simply relate inputs (water, land, labor, supplies) to output (crop production) in the SWAP model. SWAP uses a production function for each crop in each region, or about 20 individual functions per region. It is common to use various types of quadratic functions (Cai 2008; McKinney et al. 1999) however SWAP improves on these previous approaches and incorporates a Constant Elasticity of Substitution (CES) production function which allows for limited

substitutability between inputs. Beattie and Taylor (1985) discuss the properties of the generalized CES production function which is defined as:

$$Y_{gi} = \tau_{gi}\left[\beta_{gi1}X_{gi1}^{\rho_i} + \beta_{gi2}X_{gi2}^{\rho_i} + \ldots + \beta_{gij}X_{gij}^{\rho_i}\right]^{\upsilon/\rho_i} \tag{5}$$

As defined previously, the sub-index *g* refers to an agricultural region, either a farm or irrigation district, *i* refers to crops and *j* to production inputs. The analytical derivation of the beta and the tau parameters in (5) are available in Medellin-Azuara (2006). The SWAP model has four inputs: land, labor, water and supplies. Y_{gi} represents output of crop *i* in tons for region *g*. The scale parameter is τ_{gi}, and the relative use of production factors is represented by the share parameter β_{gij}. Production factor use is given by X_{gij}. The elasticity of substitution of crop *i*, is defined as σ_i where $\rho_i = (\sigma_i - 1)/\sigma_i$ (and the returns to scale coefficient is υ). In SWAP, an elasticity of substitution of 0.22 is assumed for all crops and regions which allows for limited substitution among production factors.

To further emphasize the added benefit of using the CES production function figure 4 shows the production surface for alfalfa in the central San Joaquin Valley when simplified to two inputs, water and labor (all other inputs held constant at the optimized values). The figure shows how the marginal productivity of each input changes, as does the ability to substitute labor for water at the intensive margin.

The CES production function specification allows for evaluating the effect of crop stressing as a response to water shortages. As the surface in figure 4 shows, the farmer is able to reduce water use, thereby shifting along the surface, and still realize positive crop yields. This is a likely response among many farmers, especially among perennial crops, and the ability to capture this effect is unique to the SWAP model.

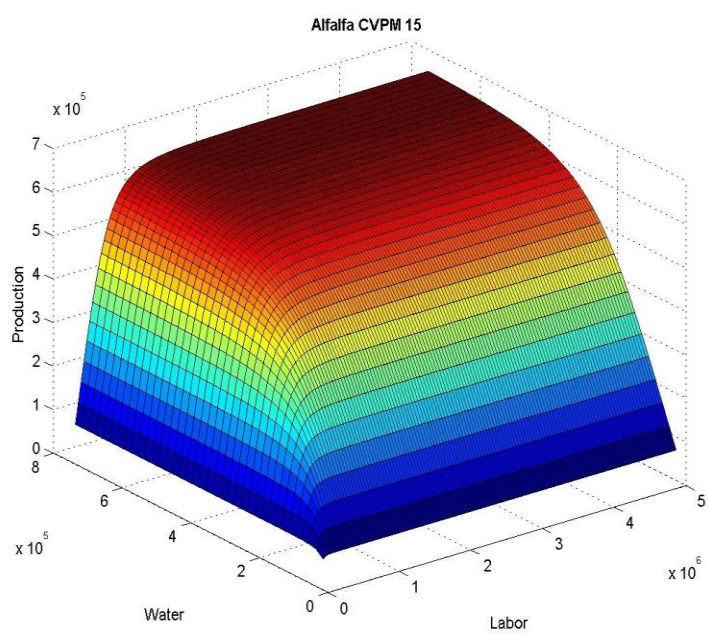

Figure 4. CES Production Surface

CALIBRATED NON-LINEAR OPTIMIZATION PROGRAM

The last step in PMP is to solve the problem defined by equations 6 to 9, below, for the base case (i.e. before specifying any policy constraints) and then again after a policy is defined.

In order to more accurately reflect the fact that California is a large exporter of some commodities and a small proportion of the world supply of others, SWAP has a built in endogenous price calculation routine. This is defined in equations 12-19, after the initial model definition.

$$Max_{EX\geq 0}TB = \sum_{g}\left(Int_i TP_i + 0.5\varphi_i TP_i^2\right) + \sum_{g}\sum_{i} RMC_{gi}Y_{gi}^1 - \sum_{g}\sum_{i}(\delta_{gi}e^{\gamma_{gi}X_{gi,land}}) - \sum_{g}\sum_{i}\sum_{j\neq land}\omega_{gij}X_{gij} \tag{6}$$

subject to:

$$TP_i = \sum_{g} Y_{gi}^1 \tag{7}$$

$$\sum_{i} x_{gij} \leq b_{gj} \quad \forall g,j \tag{8}$$

$$\sum_{i} x_{gij} \leq b_{ws,g} \quad \forall\ g \tag{9}$$

$$\sum_{g} x_{g,corn,j} \geq silage_g \quad \forall g \tag{10}$$

$$\sum_{g} x_{g,peren,j} \geq peren_g \quad \forall g \tag{11}$$

Equation(6) defines total producer and consumer surplus for all regions net of PMP costs and other input costs. The decision variable in the program is X_{gij}; that is, the input use of factor *j*, in crop *i* in region *g*. The decision variable X_{gij} is implicit in the regional output Y_{gi} and its production function in equation (5). The objective function above reflects a situation where California production levels have an effect on crop prices, thus making crop prices respond endogenously to some policy changes. Several important California crops determine national price levels.

Equations 7 thru 11 represent the constraint sets. Equation (7) is an accounting identity used in the endogenous price routine where total production of crop i is TP_i. Equation 8 is the constraint on inputs supply and labor where b_{gj} is amount available in region *g*. The constraint set in equation 9 is for regional water supply for the irrigation season, where $b_{ws,g}$ is the *observed* water use for region *g* across all sources *ws*. The constraint set assumes yearly water is available in a limited amount for every region and every source. Less realistically, it also implies that water is not re-traded across groups or regions under the basic calibration assumptions; however SWAP has been used to generate results when water transfers are possible, discussed later

(Howitt 2009). Equations 10 and 11 represent a lower bound on fallowing of corn and perennial crop acres due to dairy herd feed requirements and maximum annual expected perennial retirement, respectively (Howitt et al 2009).

There are three fundamental underlying assumptions. First, water is assumed to be interchangeable among crops in the region. Second, a representative regional farmer is assumed to maximize annual expected profits, equalizing marginal revenue of water to its marginal cost. Third, a region selects the crop mix that maximizes profits within that region given the interaction among regions through endogenous prices. This assumes sufficient levels of water storage and internal water distribution capacity and flexibility. However, some of these assumptions are relaxed in subsequent applications of the SWAP model.

The endogenous price calculation routine is as follows and is directly integrated into the objective function (6) through the first term which specifies the demand function for each crop in each region.

$$Price_i = Int_i - \varphi_i X_i \tag{12}$$

Int_i and φ_i are respectively the intercept and slope parameters of the inverse demand function for crop *i*.

A global price for crop *i*, is calculated by weighting the average observed prices v_{ig} by the fraction of region *g* in the statewide production ($prodprop_{gi}$). Formally:

$$prodprop_{gi} = \frac{yb_{gi} X_{gi,land}}{\sum_g yb_{gi} X_{gi,land}} \tag{13}$$

$$wp_i = \sum_g v_{gi} prodprop_{gi} \tag{14}$$

$$RMC_{gi} = v_{gi} - wp_{gi} \tag{15}$$

For empirically given price flexibilities the parameters φ and the intercept *int* are calculated using equations 16 and 17 below:

$$\varphi_i = \frac{Flex_i wp_{gi}}{\sum_g yb_{gi} X_{gi,land}} \tag{16}$$

$$\text{int}_i^o = wp_i - \delta_i \sum_g yb_{gi} X_{gi,land} \tag{17}$$

Historical price flexibility of crop i, is given by the parameter $Flex_i$. Finally, SWAP allows for incorporating shifts in demand for crops due to exogenous changes such as population growth or changes in taste. If these are included in the model they are given by the following two equations:

$$shift_i = 1 + shiftdem_i \tag{18}$$

$$\text{int}_i = \text{int}_i^o \, shift_i \tag{19}$$

Where $shift_i$ is the change in the slope of the demand curve; int^o is the initially calculated intercept of the demand curve (equation 17); and $shiftdem_i$ is given and corresponds to expected changes in demand as a result of income and population projections (assuming constant imports/exports ratio for selected crops in California).

SPECIFYING POLICIES AND GENERATING RESULTS

Up to this point the program has completely self-calibrated and calculated all of the necessary parameters. Next, a relevant policy is specified in an exogenous routine. The program defined by equations 6 thru 19 is re-run, possibly incorporating additional policy constraints. Results are summarized and compared to the results for the base CES program to determine the effects of the policy. Typical output of the SWAP model includes revenues by regions and crop, land use, water use, crop stress percent, and marginal value of water. these will be discussed more in the applications in the following sections.

APPLICATION: SOUTH OF DELTA WATER TRANSFERS

Agricultural water markets have been considered as a drought impact mitigation strategy but often face significant political opposition. Towards the end of the last major drought in California, in 1991, DWR implemented a water bank to facilitate water transfers between agricultural users. The bank was largely successful, transferring over 800 kaf through over 350 contracts. A similar situation has been forming in recent years, 2009 was the third consecutive below average water year and preliminary indications are that 2010 will be more of the same. As such, an interesting question is what is the current economic gradient for water transfers and are they feasible to implement.

Since the water deliveries in any given year are constantly subject to updating from USBR and DWR we present a generic "moderate" drought scenario of 45 percent reductions in supply to all regions. Previous reports published by DWR and elsewhere[4] focus on policy specific cuts and, as such, represent more detailed and specific results. A 45 percent reduction across all regions can be seen to incorporate a moderate drought (weather induced or legal) and account for increases in groundwater pumping while abstracting from region specific differences.

The Department of Civil and Environmental Engineering at UC Davis conducted a study of the capacity of existing water infrastructure to determine how much water was feasible to move (physically). Additionally, they recorded the distance between agricultural regions to incorporate into SWAP as a proxy for water conveyance costs. As such, we were able to accurately model conveyance costs and physical transfer capacities. However, in addition to physical constraints there are significant legal and political constraints to water transfers. To capture the effect of legal constraints, any region exporting water was not allowed to pump additional groundwater. To capture political constraints, only within county transfers were allowed since an argument against selling water is that profits shift out of the county.

The most commonly cited effect of drought, with the exception of job losses, is total fallowed acres. This represents the most common extensive margin adjustment of farmers captured in the SWAP model. Introducing water markets for within country transfers in regions South of the Delta significantly reduces the losses associated with drought. Figure 5, below, shows the percent change in acres (increase in fallowing) under a no water markets compared to a situation where water markets are allowed.

[4] http://swap.ucdavis.edu

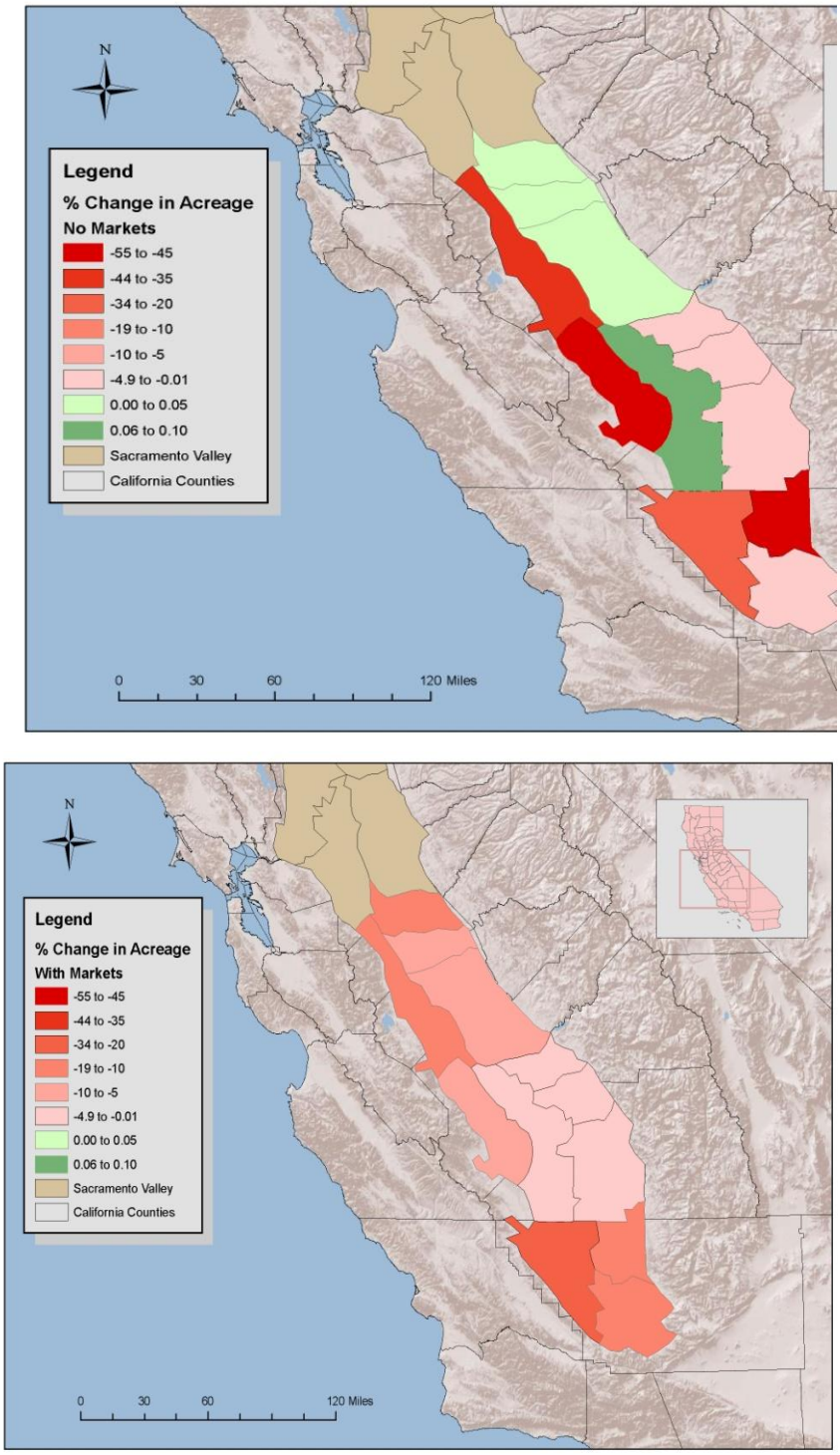

Figure 5. Comparison of Crop Acreage Change with and without Water Markets

It should be emphasized that constraining markets to be within county, without additional groundwater pumping, and within the cost and physical capacity of existing infrastructure impose significant constraints on the model. However, there is still a steep economic gradient during drought with the most

significantly affected regions willing to pay over $600 per acre foot (according to model runs). Table 1, below, shows the anticipated transfers between regions under the scenario outlined above.

Table 1. Water Transfers Summary (in af)

		Export Regions							
		V11	V12	V13	V14B	V15A	V17	V21A	Total Imports (AF)
Import Regions	V10	17,587	53,186	22,109	0	0	0	0	92,882
	V14A	0	0	0	13,665	70,000	0	0	83,665
	V15B	0	0	0	0	16,270	0	0	16,270
	V19A	0	0	0	0	0	0	68,121	68,121
	V20	0	0	0	0	0	0	0	0
	V21B	0	0	0	0	0	0	15,747	15,747
	V21C	0	0	0	0	0	0	6,513	6,513
	Total Exports	17,587	53,186	22,109	13,665	86,270	0	90,381	283,197

Finally, table 2 summarizes the changes in acres and revenues by model region with and without water transfers. Export regions show moderate increases in drought impacts which are offset monetarily by payments for water transfers from import regions and economically by gains from import regions.

Table 2. Percent change relative to drought without water transfers.

Region	Percent Change in Acres	Percent Change in Revenues
V10	8.16%	2.27%
V11	-2.25%	-0.35%
V12	-6.60%	-1.43%
V13	-2.21%	-0.38%
V14A	16.18%	8.28%
V14B	-9.06%	-5.15%
V15A	-7.74%	-2.07%
V15B	55.29%	39.11%
V16	0.00%	0.00%
V17	0.00%	0.00%
V18	0.00%	0.00%
V19A	52.04%	33.00%
V19B	0.00%	0.00%
V20	0.00%	0.00%
V21A	-16.78%	-9.91%
V21B	7.74%	2.99%
V21C	4.26%	1.65%

APPLICATION: ECONOMICS OF SOIL SALINIZATION

Increasing salinity in the San Joaquin Valley is a significant challenge for the future of agriculture in affected regions. Salinity reduces crop yields which directly affects farmer revenues, additionally farmers may shift to more salt tolerant crop rotations which are generally lower values crops. The current levels of shallow groundwater salinity are summarized in figure 6. Figure 6 shows significant concentrations along the west-side of the Valley, regions that are additionally more susceptible to drought.

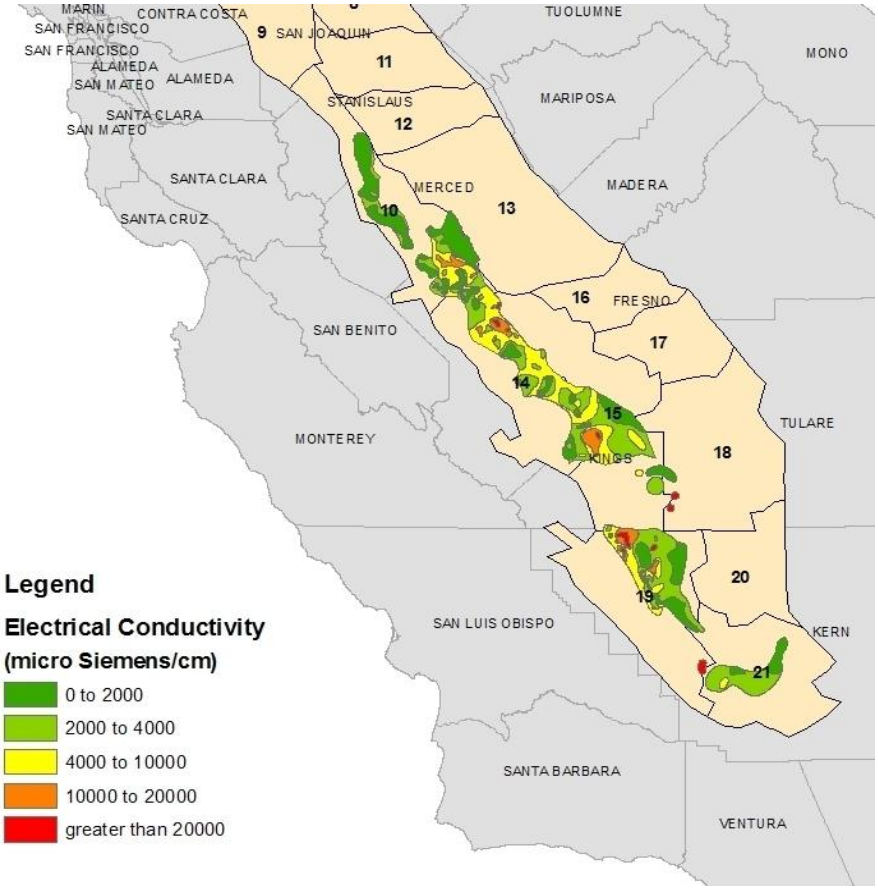

Figure 6. Salinity Affected Areas in the San Joaquin Valley (from Howitt et. al. 2009)

Water quality can be incorporated into SWAP by modeling its effect on agricultural yields. Two applications of SWAP, one for the Sacramento San Joaquin Delta (Appendix D in Lund et al. 2007) and one for agriculture in California's western Central Valley in California (Medellin-Azuara et al. 2008) consider yield reductions in agricultural production due to salinity in the root zone and in shallow groundwater. For these models, the yield reduction model developed by Van Genuchten and Hoffman (1984) is used. The effect of salinity on agricultural production is represented by the relative yield variable $yred_{gj}$, for crop i in region g, is given by:

$$yred_{gi} = \frac{1}{1 + \left(C_g / C50_i\right)^2}$$

In this formulation, C_g is the root zone salinity in region g and $C50_i$ is the root zone salinity at which the yield of crop i is reduced by half. Figure 7 shows this relationship graphically for various values of curvature parameters. A value of 2 (the empirical average) is used for SWAP model applications. For the SWAP applications shown here, aggregate empirical measures suggest that the yield effect of shallow groundwater salinity was half that of equivalent root zone levels.

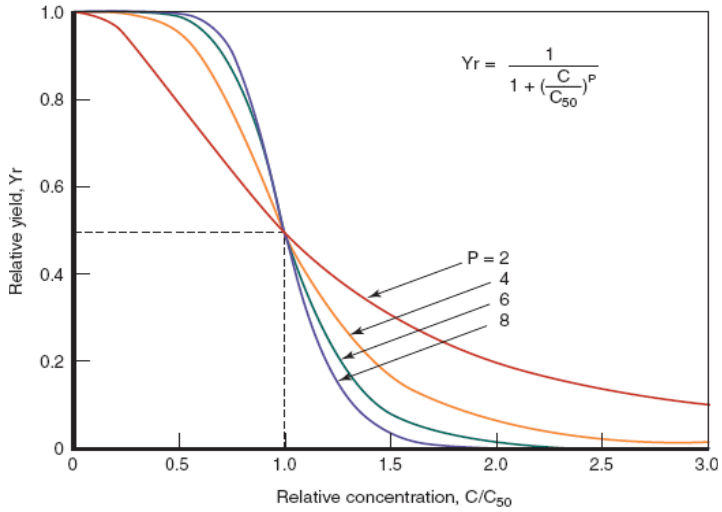

Figure 7. Van-Genuchten Salinity Yield Reduction Functions

Results of the study are summarized in table 3 below. For this study, only areas in regions 10, 14, 15, 19 and 21 (on the west side of the southern Central Valley) are affected by salinity. Six potential salinity zones are defined in each CVPM region. The first zone is the irrigated area unaffected by salinity. The remaining five zones have salinity in shallow groundwater ranging from zero to more than 20,000 µS/cm.

For base conditions it was assumed that, on average, 3.7 million acre-feet of irrigation water are imported from the Delta-Mendota Canal and the California Aqueduct, with an average salinity of about 300 mg/L measured by TDS. It was projected that current conditions will gradually increase the area affected by a saline shallow groundwater table, based on a regression equation fitted to data over a subset of the salinity area (417,000 acres) (Schoups 2004). Given historical rates of change in saline affected areas, it was expected that by 2030, the saline affected area will increase by 12% to 15%. Salinity in shallow groundwater and the root zone are closely correlated (Schoups et al. 2005). Here it is assumed that the total saline area within each CVPM region grows by 13% by 2030 under base conditions. Revenue losses by crop are summarized in table 3.

Table 3. Revenue Loss (thousands) by Crop Due to Salinity

CVPM	Alfalfa	Citrus	Cotton	Field Crops	Grains	Orchard	Pasture	Sugar Beet	Grapes	Truck Crops
10	-979	-15	-25,733	17,599	-3,061	-1,010	-744	28	-35	-618
14	-3,439	0	-35,869	-4,727	-15,918	-9,717	55	-1,318	-2,408	-17,616
15	-13,109	-8	-35,782	3,671	4,494	-2,481	-406	-180	-1,149	-180
19	-1,229	-8	-1,372	-2,562	-15,542	-1,027	-314	-63	-343	-215
21	175	-65	-3,959	-311	-6,896	-90	2	-	-105	-136

APPLICATION: CLIMATE CHANGE EFFECTS ON AGRICULTURE

Uncertainty about the future of the climate has significant implications for agriculture in California. Agricultural yields may be adversely affected by climate warming, resulting in increased production costs per unit. this would have adverse effects on farmer revenues. However, 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. Due to the longer time horizon of climate change effects it is expected that technological progress will continue to increase yields which may be another mitigating factor. Furthermore, changes in demand for certain crops will have uncertain implications on crop prices. In general, there are significant changes happening simultaneously which affect the future of California agriculture under climate change.

The effect of climate change on California agriculture was studied in a 2009 report for the PPIC which used the SWAP model to evaluate the effects of climate change on agriculture across the state out to the year 2050 (Howitt et al. 2009c). This report considered the rates of change in technology, urbanization, crop demand, and yield changes due to both climate change (largely negative) and technological progress (largely positive). Additionally, the CALVIN model was used to feedback into the SWAP model and generate expected water availability under the climate change scenario.

2050 was selected as suitable for projections of climate change effects to be consistent with most of the technical work of the California Climate Change Biennial Assessment (Cayan et al. 2008). Land conversion from agriculture to urban uses by 2050 are taken into account based on projections from Landis and Reilly (2002) (**Error! Reference source not found.**). The pale pink areas represent the 1998 levels of urbanization, and the red shades surrounding it show urban growth. There is potential for significant shifting of agriculture to urban land.

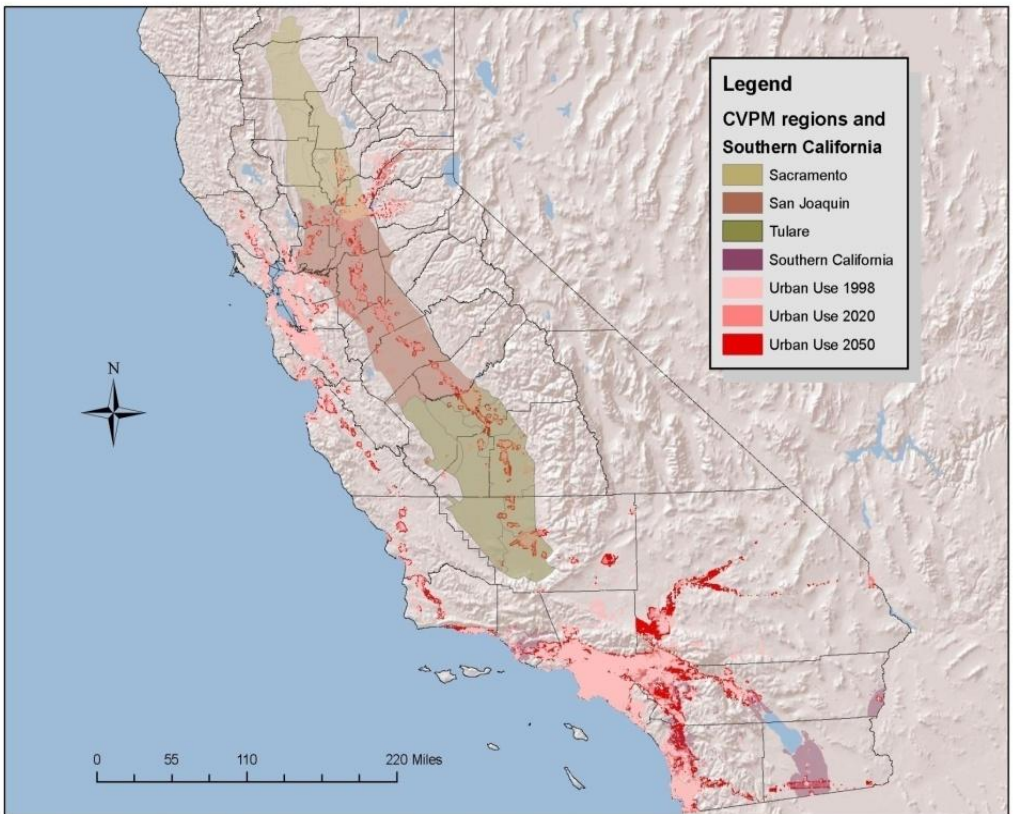

Figure 8. Urbanization by 2050

Technological change by year 2050 was represented as increasing crop yields. This was calculated based on extrapolating current trends as detailed in Brunke *et al.* (2004) with a cap on the growth rate starting in 2020. Yield related technological growth is capped at 2020 due to an inherent limit to the rate of carbon fixation through photosynthesis. Yield increases due to technological change vary by crop but average 25 percent.

The domestic demand for California crops was modeled as increasing with population and income based on relevant elasticity estimates from the literature. Specifically, effect on crop demand was captured through the income elasticity of demand for California crops, income, and population growth. The proportion of California crops exported was assumed to remain constant through 2050 and the demand for rice, grain, and corn was modeled as perfectly elastic. Rice and grain demand were decreasing in California and other crops were increasing.

The final step was to measure yield changes due to climate change. This was calculated based on Adams et al. 2003, Lee et al. 2008, and Lobell et al. 2007 with significant variation between crops. The range of percent changes in yield was between -18 percent (citrus crops) to 7.5 percent (alfalfa).

Farmer reactions to climate-related yield reductions occur at the three margins. The crop mix, production factor use intensity, and commodity prices as a result of changes in the statewide or regional crop production. Overall, climate change is expected to decrease land and water use by 20 and 26 percent, respectively, and increase agricultural revenues by 11 percent statewide. Lower value crops such as cotton, corn, pasture and some grains may face the largest reductions. This indicates adaptation on the economic side dominates climate tolerance effect of some of these low value crops. Field crops, grains and pasture are the most affected under dry-warm form of climate change.

APPLICATION: DELTA AGRICULTURAL PRODUCTION MODEL

The Delta Agricultural Production model (DAP) is a version of SWAP developed for agricultural production in the Delta islands. The model regions were defined considering land use and spatial distribution of salinity. Land use surveys from DWR in the 1990's populate the dataset. The data are disaggregated into the 72 spatial units presented in figure 9. The three categories of land use include environmental, agricultural, and urban. Agricultural uses in the model are sub-classified as pasture, alfalfa, field corn, sugar beets, grain, rice, truck crops, tomato, orchards, and vineyards. Environmental and urban uses are not part of DAP but include native riparian, water surface, and native vegetation (Lund et al. 2007).

Data on electrical conductivity (EC) for nineteen locations were obtained from the California Department of Water Resources web site. The common period of record available for all monitoring stations of interest was from August 1999 to May 2006. The historical salinity distribution was considered as the model base case. Two additional salinity scenarios were explored. The spatial distribution of salinity for these scenarios was obtained by scaling the base salinity distribution by factors of 10 and 20, respectively. Land use and revenue losses were estimated for these scenarios.

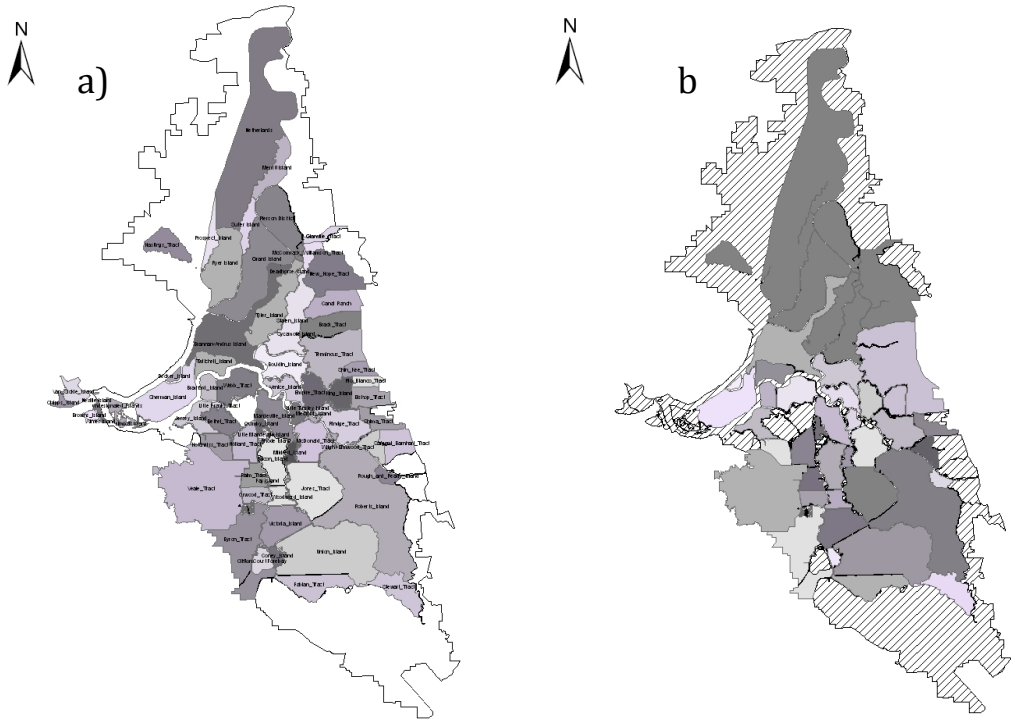

Figure 9. DAP modeling regions (after Lund et al. 2007)

For the Delta Agricultural Production model (DAP), results show that the increased salinity in the root zone adds cost to agricultural production and reduces crop yields. Current revenues of roughly $367 million per year for the Delta could be reduced to $329 per year (or 10 %) with a tenfold increase in salinity (Figure 10). These results suggest that effects on Delta agricultural production due to salinity are not catastrophic to the region. A twenty fold increase in salinity might reduce revenues by 31%. Western, central and southern areas of the Delta are more vulnerable to salt. These areas tend to have the

lowest agricultural value and are more desirable to allow salt fluctuations that have been argued beneficial for native species habitat in the Delta (Lund et al. 2008).

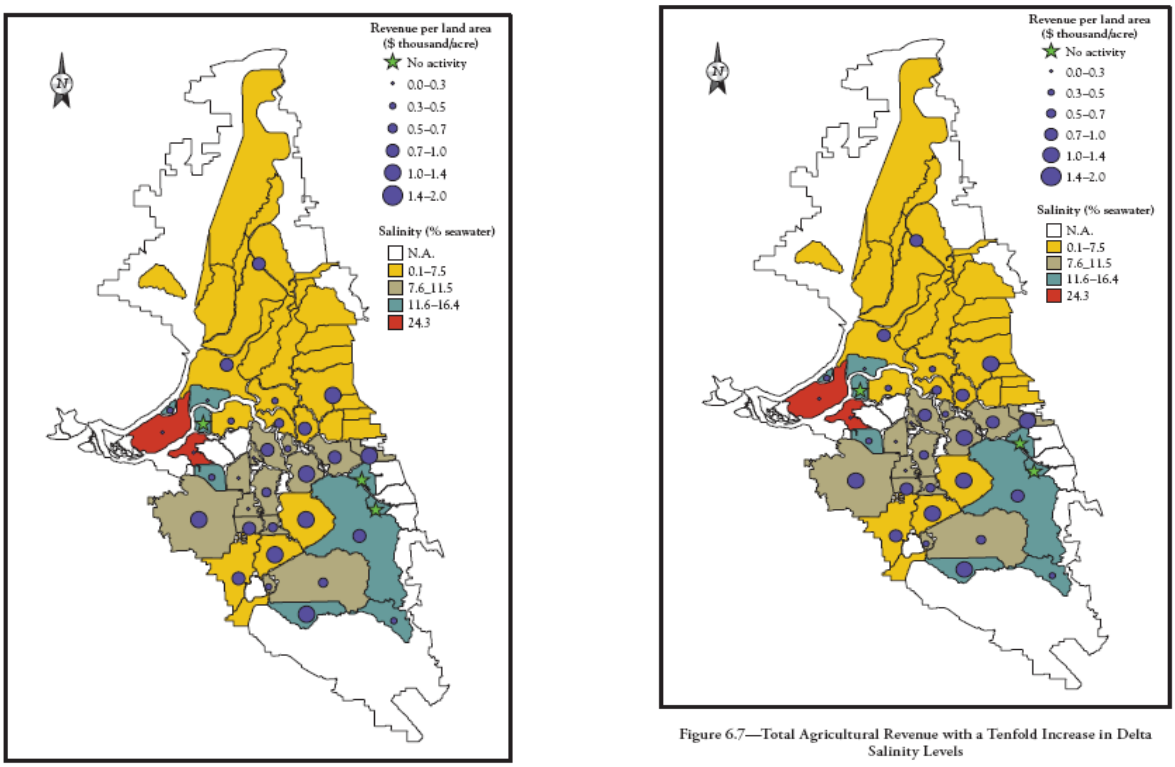

Figure 10: Left Panel: Agricultural revenues and by Delta island using DAP for typical salinity level. Right Panel: Decreases in agricultural revenue with a tenfold increase in Delta salinity levels (after Lund et al., 2007).

APPLICATION: EFFECTS OF DROUGHT

The final application of SWAP considered in this paper is to modeling the effects of the 2009 drought on agriculture revenues and, subsequently, jobs. The drought in 2009 was a result of both the biological opinion and lack of rainfall/snowpack. SWAP was used to model the expected marginal losses in revenue and acres starting in January 2009 and updated with every announcement in expected deliveries from USBR and DWR.

Since 70 percent of California's water runoff occurs north of the Bay Delta but 75 percent of California's agricultural and urban demands are to the south, the Delta is a central hub for conveying California's water. Therefore, agricultural regions south of the Delta rely on water pumped through the Delta. However, the Delta is the largest estuary in the Western U.S. and is home to a wide variety of unique wildlife. Three consecutive years of below average rainfall and an increased awareness of the effect of

water exports on key native species has put significant strain on the ability to export enough Delta water to meet urban and agricultural water demands. Further complicating the situation, recent legal decisions have clearly linked the well being of Delta fish and farmers.

The 2009 drought presents a situation that is unique relative to previous events for several reasons. During the drought of the early 1990s farmers increased groundwater wells and rates of pumping. However, wells drilled in the 1990s are still operating, and many aquifers have a limited capacity for even short run increases. Droughts always spur irrigation efficiency, but steady advances in technology over the past 15 years have made rapid improvements harder to achieve. Crop fallowing and switching were common responses in previous droughts, but this avenue of adjustment has been trimmed by increasing areas of perennial crops due to market growth. Reduced irrigation that stresses the crop is yet another short term water management strategy although it depends on the timing of application which, in turn, depends on crop and soil specific characteristics. Additional limitations as a result of recent legal rulings designed to protect endangered Delta fish have further complicated matters by restricting Delta exports. The combined effect of these factors is one of "hardening" the demand for water and making it less flexible and price responsive.

Modeling the marginal effect of the drought was done using the general SWAP model and modifying water deliveries by source according to announcements from DWR and USBR. Initial estimates, produced in January 2009 showed that potential losses were in the range of one billion dollars in gross agricultural revenues. These estimates were revised as new data became available and new delivery projections were released. The final set of estimates released in May 2009 estimated 568 million in gross agricultural revenue losses.

In addition to modeling revenue losses, employment and income losses (both direct and indirect) were modeled by coupling the output of SWAP with a regional IO model. Initial (January) estimates used the REMI model and estimated around 40,000 jobs lost. More accurate results using an in house version of the IMPLAN model combined with updated water deliveries data produced a final estimate in May 2009 of 21,100 total jobs lost. Additionally, SWAP was used to break down job and revenue losses as being attributable to pumping restrictions due to legal rulings and the natural drought. Results are summarized in table 4.

Table 4. Summary of Drought Impacts

Estimate	Drought Only	Drought and Smelt
Ag. Revenue Losses ($ Millions 2008)	586	703
Job Losses	16,000	21,100

One short coming of the analysis on drought impacts was a lack of data on transfers between agricultural users. As such, model results are likely slightly biased upward since many regions may have had access to additional water through transfers. However, to the extent that this transferred water was offset in the transferring region through fallowing this mitigates the overstatement.

CONCLUSIONS AND EXTENSIONS

This paper has summarized the technical details and supporting literature behind the Statewide Agricultural Production Model. SWAP represents the state of the art in agricultural modeling in California using a well researched methodology combined with updated data. This type of approach is ideal for investigating the implications of disaggregated constraints and region specific characteristics. The level of disaggregation is necessary for evaluating environmental policies. Additionally, this paper highlighted five recent applications of the SWAP model including water transfers, salinity, climate change, Delta agricultural production, and effects of drought. These applications represent some of the most pressing issues in California agriculture and the SWAP model works well to provide valuable insights to water managers and policy makers.

Self-calibrated programming models such as SWAP provide useful policy insights and a framework to easily accommodate changing market conditions, improved datasets and increased regional coverage. Such models provide a versatile tool for regional water management and policy as well as a framework for integrating many aspects of regional water and agricultural management.

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