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Agricultural Losses from Salinity in California's Sacramento–San Joaquin Delta

Josué Medellín–Azuara*[1], Richard E. Howitt[2], Ellen Hanak[3], Jay R. Lund[1], and William Fleenor[1]

ABSTRACT

Sea level rise, large-scale flooding, and new conveyance arrangements for water exports may increase future water salinity for local agricultural production in California's Sacramento–San Joaquin Delta. Increasing salinity in crop root zones often decreases crop yields and crop revenues. Salinity effects are nonlinear, and vary with crop choice and other factors including drainage and residence time of irrigation water. Here, we explore changes in agricultural production in the Delta under various combinations of water management, large-scale flooding, and future sea level rise. Water management alternatives include through-Delta water exports (current conditions), dual conveyance (through-Delta and a 6,700 Mm^3 yr^{-1} [or 7500 cfs] capacity peripheral canal or tunnel) and the flooding of five western islands with and without peripheral exports. We employ results from previous hydrodynamic simulations of likely changes in salinity for irrigation water at points in the Delta. We connect these irrigation water salinity values into a detailed agro-economic model of Delta agriculture to estimate local crop yield and farm revenue losses. Previous hydrodynamic modeling work shows that sea level rise is likely to increase salinity from 4% to 130% in this century, depending on the increase in sea level and location. Changes in water management under dual conveyance increase salinity mostly in the western Delta, and to a lesser extent in the north, where current salinity levels are now quite low. Because locations likely to experience the largest salinity increases already have a lower-value crop mix, the worst-case losses are less than 1% of total Delta crop revenues. This result also holds for salinity increases from permanent flooding of western islands that serve as a salinity barrier. Our results suggest that salinity increases could have much smaller economic effects on Delta farming than other likely changes in the Delta such as retirement of agricultural lands after large-scale flooding and habitat development. Integrating hydrodynamic, water salinity, and economic models can provide insights into controversial management issues.

KEY WORDS

Sacramento–San Joaquin Delta; salinity; positive mathematical programming; calibration; California; hydro-economic models; agricultural production; drought analysis; economic effects; climate change, sea level rise, large area flooding

* Corresponding author: *jmedellin@ucdavis.edu*

1 University of California, Davis, Department of Civil and Environmental Engineering, Davis, CA USA

2 University of California, Davis, Agricultural and Resource Economics, Davis, CA USA

3 Public Policy Institute of California, San Francisco, CA USA

INTRODUCTION

Salinity-driven reductions in agricultural production have long been a policy concern for California's Sacramento–San Joaquin Delta (CDPW 1931; Lund et al. 2007; DPC 2012; Medellín–Azuara et al. 2012a). In this study we quantify the economic effects on local agriculture of changes in localized Delta water salinity for a range of sea level and water management conditions during the irrigation season. We employ the Delta Agricultural Production model (DAP, after Lund et al. 2007; Howitt et al. 2012), an agro-economic model for crops in the Delta that accounts for crop yield response to changes in irrigation water salinity. This work demonstrates the combined application of hydrodynamic, water salinity, and agro-economic modeling to provide policy and management insights for a major water resources problem in California.

The economic effects of changes in irrigation water salinity vary in magnitude by crop, location, and the initial level of water salinity. By connecting hydrodynamic simulations with the crop production model, we find that small changes in salinity generally cause little change in Delta crop yields and revenues. Land use surveys indicate that higher-value and generally less salt-tolerant crops tend to be grown in areas of the Delta that currently have lower-irrigation water salinity; these areas do not experience major salinity changes in the simulated scenarios. These conditions allow lower-cost adaptation of cropping patterns, irrigated areas and the intensity of production factors per unit area within the Delta in response to the modeled salinity changes.

Salt accumulation has affected agriculture since ancient times in Mesopotamia and Egypt, and modeling of crop salinity response has been in the literature for some decades. Crop production response to salinity also has a history in the economics modeling literature at various temporal (short and long run) and spatial scales (from crop to farm and regional levels) (Feinerman 2000). Models usually involve optimization to maximize profits or minimize costs in farming under different salinity scenarios. Also, Cardon and Letey (1992) applied Darcy's law on "flow through a porous medium" to model plant water uptake under salinity conditions. Knapp and Wichelns (1990) review dynamic optimization methods, finding that initial conditions matter and that large enough drainage disposal costs make water recycling more attractive.

This paper uses results from Delta hydrodynamic and salinity transport modeling to provide irrigation water salinity levels for various locations in California's Sacramento–San Joaquin Delta under a variety of sea level and water management conditions; we use these values as inputs to an agro-economic model of crop production that includes the effects of soil salinity (Figure 1). Our modeling framework, presented in Figure 1, shows the flow of information among models. The hydrodynamic models (Water Analysis Module [WAM] and Resource Management Associates [RMA] 2-D model) provide water salinity data for different locations in the Delta. The DAP model takes crop production information from the Statewide Agricultural Production model (SWAP, Howitt et al. 2012), crop response to salinity models (Hoffman 2010), and land use information from the Department of Water Resources for each water salinity scenario to produce economically optimal cropping patterns for each Delta island. Sensitivity analyses for more recent Delta export periods and fixed salinity scenarios are also part of the modeling framework.

Several underlying assumptions are worth discussing. First, our approach assumes that soil salinity in the root zone is the same as that of irrigation water applied in the surface. Second, following Hoffman (2010), we assume sufficient drainage exists in irrigated areas to avoid salt accumulation in the root zone (a problem in the southern Central Valley studied by Medellín–Azuara et al. [2008] and Howitt et al. [2009]). Hoffman (2010) concluded that many factors influencing soil salinization in general, including leaching requirements, crop salt tolerance at growth stages, shallow groundwater table, effective rainfall, irrigation efficiency and uniformity, climate, soil

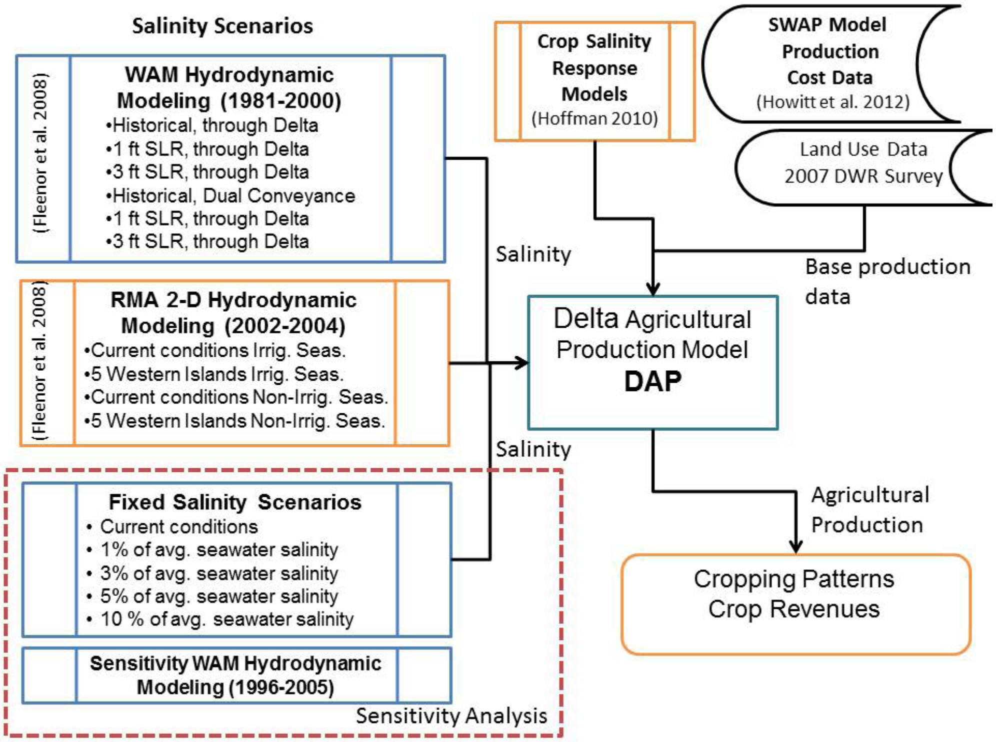

Figure 1 Modeling framework

bypass flow, salt precipitation and dissolution, are not major factors for salt accumulation in soils in the southern Delta. In Delta locations where drainage is a concern for crop productivity, subsurface drainage has been already installed.

Third, we use a sigmoidal approach (Van Genuchten 1983) for crop salinity response, as it is the best developed and well-suited for non-linear cropping optimization models like the one employed in this paper. In addition, the sigmoidal response-function approach showed good performance compared to the threshold-linear and exponential approaches (Van Genuchten and Hoffman 1984).

Mass and Hoffman (1977) pioneered comprehensive assessment of crop response to soil salinity. Mass (1990) provided a threshold approach in which different crop types (within a range of tolerant and sensitive) have relative yields constant up to thresholds in soil salinity. Beyond a threshold, relative yields decline at a constant rate. Another approach (Van Genuchten 1983; Hillel 2000) describes crop response to soil salinity in the root zone using a sigmoidal function that calibrates to a soil salinity at which crop yields are reduced by 50 percent.

Other factors that may affect crops include drainage and irrigation water salinity. Drainage salinity is closely related to soil salinization, because poor soil drainage conditions retain salts. A rising groundwater table with brackish or saline water can degrade soil at the root zone with prolonged exposures. Salinity in irrigation water decreases yields for many crops. However, brackish or slightly saline irrigation water may not affect yields for some crops if the appropriate drainage exists, in which case salts do not accumulate in the root zone.

Below, we present the DAP model structure and data sets, the water salinity scenarios and hydrodynamic modeling work, and model results for the water salinity scenarios (Figure 1). We conclude with a summary of the findings and some suggestions for further research.

DELTA AGRICULTURAL PRODUCTION MODEL

The Delta Agricultural Production Model (DAP) estimates the irrigated crop area and the crop mix that maximizes total net revenues on land areas within the Delta, taking into account production costs, crop prices, water use, and yield changes from irrigation water salinity (Lund et al. 2007, Appendix D). DAP is a customized version of the SWAP agro-economic model of California agriculture, augmented to examine the effects of irrigation water salinity. SWAP uses positive mathematical programming (PMP, after Howitt 1995) to calibrate a base case to observed values of input use, namely land, water, labor and supplies. SWAP has been used for numerous agricultural modeling applications in California including water markets, soil salinity in the Central Valley (Howitt et al. 2009; Medellín–Azuara et al. 2008), climate change (Medellín–Azuara et al. 2012b), and regional economic impacts of water markets and drought in the Central Valley (Howitt et al. 2012).

Model Formulation

DAP expands the SWAP model to incorporate crop yield changes from varying irrigation salinity following Van Genuchten and Hoffman (1984) and Hoffman (2010). PMP calibration for SWAP is presented in detail elsewhere (Howitt et al. 2012). PMP is a multi-stage calibration method developed by Howitt (1995) to represent agricultural production, land and water. It calibrates to a base data set of production costs, production volume and factor use. PMP takes the opportunity cost of land and water and a linear profit maximization program and uses these values and the first-order condition identities to parameterize a non-linear cost function. In a last stage, these PMP cost functions and the resource constraints conform to the base case, which calibrates exactly to observed values of crop production inputs such as land, water, labor and supplies. PMP (Howitt 1995) is one of the most common approaches in optimization models of agricultural production. Here we describe the steps in the last stage of optimization, relevant for assessing irrigation water salinity effects on crop yields. The DAP objective function is to maximize net financial returns of land and management using the following equation:

$$Maximize\ Z = \sum_g \sum_i v_{gi} \left[Y_{red} \tau_{gi} \sum_j X_{gij}^{\rho} \right]^{1/\rho} - \sum_g \sum_i \sum_j \left(\alpha_{gij} X_{gij} + \gamma X_{gij}^2 \right) \tag{1}$$

In this formulation, v_{gi} is the price for crop i on Delta island g; Y_{red} is the relative yield under each water salinity scenario following Van Genuchten and Hoffman (1984), τ_{gi} is the CES scale parameter for a constant elasticity of substitution production function. X_{gij} is the quantity of production factor j (land, water, labor and supplies) allocated to crop i, and α_{gij} and γ_{gij} are the parameters of a PMP cost function (Howitt 1995).

Y_{red}, the relative yields, are given by:

$$Y_{red} = \frac{1}{1 + \left(C/C_{50} \right)^{\rho}} \tag{2}$$

Where C is the reference salinity and C_{50} is the salinity at which the crop yields are reduced by 50% of the base yield. The parameters C_{50} and *rho* were obtained empirically by Van Genuchten and Hoffman (1984). *Rho* was estimated using a maximum entropy approach (Shannon 1948) detailed below. Land and water are the limiting resources such that:

$$\sum_i X_{gij} \le b_{gj} \quad \forall g, j \in \{land, water\} \tag{3}$$

DAP Projections for Year 2030

To estimate a 2030 case for farming in the Delta, we scaled down 2050 projections for California agriculture in Medellín–Azuara et al. (2012b) through interpolation. These projections include yield increases from improved technology (Brunke et al. 2005) and changes in market conditions and crop demands that increase prices of most crops. For prices we assumed that:

1. The Delta does not have market power; commodity prices elsewhere in the state are not affected by production in the Delta, thus the Delta is a commodity price taker;
2. California will maintain market power for specialty crops (e.g., fruits, nuts, vegetables) but will be a price taker for global crops such as rice, corn, and wheat; and
3. Shifts in demands—and consequently prices—for the specialty crops, are linked to income and population growth projections, whereas global crops are influenced by future world demand trends.

Crop Yield Response to Salinity

Figure 2 shows the relative yield as a function of salt concentration in the root zone for different parameter values. Root zone salinity is assumed to be the same as the irrigation water salinity.

We estimated the value of the *rho* parameter in Equation 2 using a compilation of studies by Hoffman (2010) for crops in the southern Delta. We employed a maximum entropy algorithm that used the experimental relative yield observations in Figure 2 to obtain *rho*. With a maximum entropy approach it is possible to obtain a parameter probability distribution even with small data sets. From there, *rho* was used in Equation 2 to obtain the entropy-adjusted relative yield curve (Figure 2). As in Hoffman's study, we assume that irrigation efficiency in the Delta is 85%, with a 15% leaching fraction. We assume no long-term salinity accumulation in Delta soils, because Delta farmers can drain their soils to avoid long-term salinity build-up. This contrasts with closed basins such as the Tulare Basin, where imported salts accumulate because salts cannot be exported (Medellín–Azuara et al. 2008).

We used a maximum entropy estimation to obtain a probability distribution and the expected value of the *rho* parameter in the nonlinear response function shown in Lund et al. (2007). With respect to the entropy-estimated *rho* parameter, we grouped the Delta crops into three categories: "sensitive" to salinity in the root zone, "moderately sensitive," and all other crops. The sensitive group includes almonds and pistachios, some vegetables (truck crops), and subtropical fruits. The moderately sensitive group includes alfalfa, irrigated and non-irrigated pasture, tomatoes, other deciduous, cucurbits, and vine crops. For all other DAP crop groups (corn, grain, other field, rice, and sugar beet) we used parameter information for the relative yield equation above from Lund et al. (2007).

Model Data Sets

The DAP model requires a base data set that includes average land and water use, labor and supplies, crop prices, yields and production costs using these factors. The DAP model has been revised from

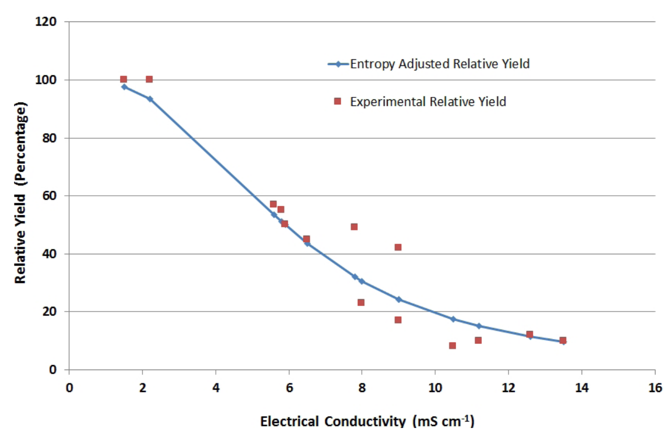

Figure 2 Empirical data on relative yield response to changes in electrical conductivity for dry beans in the South Sacramento–San Joaquin Delta. (Adapted from Medellín–Azuara et al. 2012a.)

previous versions (Lund et al. 2007), with more recent land use information, salinity response functions and production costs. DAP base model information on prices and other factors is for the average of 2005 through 2008, which we applied to 2007 land use as described below.

Land Use

This latest version of DAP employs preliminary land use estimates from the California Department of Water Resources (CDWR) 2007 field survey of the Delta (Medellín–Azuara et al. 2012a). We disaggregate production in the area defined as the "Legal Delta" into 70 different Delta islands and mainland areas, which are treated as individual farming units. The DAP model includes about 57% of the total Legal Delta area (nearly 299,000 ha). Thus total area in the modeled DAP area is 169,159 ha (418,000 ac), of which nearly 106,432 ha (263,000 ac) are farmed.

Figure 3 illustrates the study area, showing the salinity sampling stations, and breaking the Delta into sub-regions to describe the salinity results for the 70 modeled land units (detailed results by island are shown in Appendix Tables 1-4[1]). The Far West (dark red) is an area where salinity is already too high to support farming. The Delta's core agricultural areas are in the North (purple), South (orange), East (dark green), Central (light green), and West (light red). As discussed below, baseline salinity levels (and cropping patterns) vary considerably across these sub regions, as do the salinity effects of the scenarios examined here. The hatched blue area within the Western sub-region represents the five western islands flooded in the 2-D hydrodynamic modeling (hatched area in Figure 3). These five islands were chosen for an analysis of the effects of flooding in the state's Delta Risk Management Strategy study because of their role as a salinity barrier (Fleenor et al. 2008; Medellín–Azuara et al. 2012a).

1 *https://watershed.ucdavis.edu/project/water-quality-and-hydrodynamics*

Table 1 Annual revenues per acre (2008 $USD) in the base year and projected for 2030[a]

Crop group	2005–08	2030	Increase (%)
Perennial fruits and nuts			
Almond and pistachio	5,054	5,533	9
Other deciduous	4,401	5,084	16
Subtropical	5,983	6,825	14
Vine	4,632	5,479	18
Vegetables and other truck farming			
Tomato[b]	1,940	2,668	38
Other truck	4,120	6,234	51
Field crops and pasture			
Alfalfa	1,004	1,207	20
Corn	853	1,242	46
Grain	464	470	1
Irrigated pasture	597	691	16
Non-irrigated grain and pasture	464	470	1
Other field crops	1,000	1,135	13
Rice	1,333	1,486	11
Sugar beet	1,891	2,043	8

a. Sources: author estimates using SWAP; Howitt et al. 2012; adapted from Medellín–Azuara et al. 2012a
b. Price is based on processing tomato, which constitutes 95% of the value.

Crop Prices, Yields, and Production Costs

Both DAP and SWAP use a 20-crop group classification established by CDWR (Howitt et al. 2012). Within the Delta, only 14 of these groups are present in large acreages (Table 1).

Cost information is from SWAP for Central Valley Production Model (CVPM) Region 9, which corresponds to the Sacramento–San Joaquin Delta. Information on CVPM regions is detailed in Howitt et al. (2012) and on the SWAP website (*http://swap.ucdavis.edu*).

SWAP crop production budgets are updated regularly using University of California–Davis' cost studies (*http://coststudies.ucdavis.edu/*). The SWAP crop prices and yields and resulting revenues per acre for the baseline period (2005–2008 average) are from a

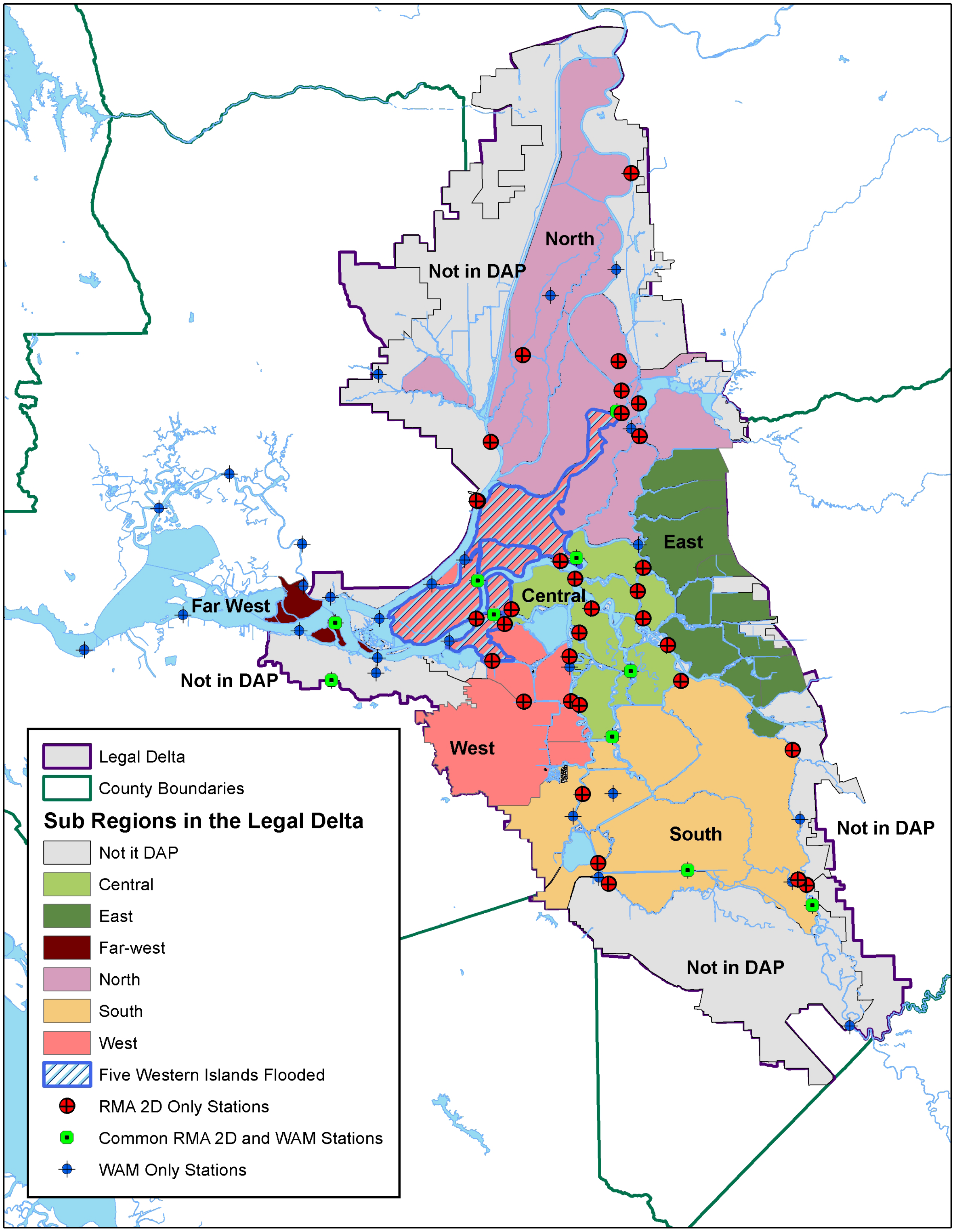

Figure 3 Land use coverage in the Delta Agricultural Production model and location of water salinity model output stations in the legal Delta. (Adapted from Medellín–Azuara et al. 2012a.)

recent analysis by CH2M Hill, which used USDA–NASS County Agricultural Commissioners' reports, adjusted in some cases to ensure positive returns to land and management. Whereas land use and applied water in SWAP can be represented at relatively fine scale, SWAP compiles production costs for each of the 20 CDWR crop groups at a regional scale, because this information is not available for all commodities for all counties and years.

Table 1 also compares of baseline revenues per acre from 2005 through 2008 and in 2030 in the Delta for its 14 crop groups, taking into account farmers' responses to prices, yields, and baseline salinity conditions, as discussed earlier in this section. As a result of yield and price changes, some crops maintain about the same irrigated land area (e.g., alfalfa and corn). Most vegetable and fruit crops (orchards, tomatoes, other vegetables, sugar beet, and vine crops) experience a slight increase (1% to 7%) in irrigated area. Lastly, almonds and pistachios, some grains, some field crops, irrigated pasture, and rice and subtropical crop groups have acreage reductions from 2% to 10%.

HYDRODYNAMIC MODELING AND WATER SALINITY INFORMATION FOR DAP

The hydrodynamic modeling used to estimate salinity changes of Delta waters is based on two models developed by Resource Management Associates, Inc. for the state-commissioned Delta Risk Management Strategies (DRMS) study and reported in Fleenor et al. (2008). Development, verification, calibration and validation of both models can be found in Fleenor et al. (2008), Bombardelli et al. (2010) and (2011), and Fleenor and Bombardelli (2013).

First, the one-dimensional Water Analysis Module (WAM) is used to estimate salinity changes with the introduction of dual conveyance of water exports and sea level rise. Fleenor et al. (2008) performed simulations with WAM over water years 1981 through 2000. Second, a two-dimensional RMA Bay-Delta model (referred to here as the "RMA 2-D" model) was used to estimate salinity changes from the permanent flooding of five western islands that serve as a salinity barrier at the Delta's western edge (hatched in Figure 3). RMA performed these 2-D simulations that spanned the April 2002 through December 2004 hydrologic period for the DRMS study. Permanent flooding represents conditions where the islands have either been flooded for some time or during winter months when considerable freshwater flows are available, but not the near-term results of a "Big Gulp" of salt water flowing into the Delta that might occur with catastrophic island failures during the summer or fall. We summarize these modeling results and show the model output water salinity sampling locations (Figure 3). To assign irrigation water salinity for each island and water salinity scenario we located the two closest sampling locations (Figure 3 and Medellín–Azuara et al. 2012a) and then selected the sampling station with the highest monthly average salinity during the irrigation season. (This choice was made to avoid under-estimating the salinity effects farmers might experience.) The supplementary tables in the project website (Appendices 1-4[2]) provide detailed information on the sampling stations used and simulated monthly average salinity levels by island and hydrodynamic modeling scenario.

To account for the largest possible monthly average salinity levels, we explored salinity conditions within a relatively long irrigation season (April 1 to September 30). This choice also likely overstates the average salinity conditions most farmers face when irrigating their crops, because salinity tends to be highest in the late summer and fall, when most irrigation is finished except for pasture and hay crops.

Salinity Scenarios

WAM simulations contrast 1981–2000 salinity conditions for three sea levels (current conditions, and for 1 and 3 feet of sea level rise). The sea level rise projections are within the range the California Ocean Protection Council (2011) recommends for long-term planning purposes, based on recent model projections for the mid- and late-21st century

2 *https://watershed.ucdavis.edu/project/water-quality-and-hydrodynamics*

(Vermeer and Rahmstorf 2009). Some projections anticipate the potential for higher sea level rise (55 in) by the end of the century, and these would likely generate higher salinity levels than those shown here. WAM simulations also include two Delta export configurations (current through-Delta exports and a dual conveyance system in which a 212.4 $m^3 s^{-1}$ [7,500 $ft^3 s^{-1}$] capacity peripheral facility is added that draws water from the Sacramento River at a point upstream of the Delta). RMA 2-D simulations contrast a 2002–2004 base salinity case with all islands intact and a scenario with five western islands flooded (Bradford, Brannan–Andrus, Jersey, Sherman, and Twitchell), the hatched area in Figure 3. RMA 2-D runs do not consider sea level rise. For WAM, we also contrast a base case (through-Delta exports with no sea level rise) and a dual conveyance case for critically dry years within the modeled time period (1987–1991 and 1994). For both WAM and RMA 2-D runs, all cases assume the same daily hydrology and water system operations (reservoir releases, Delta export volumes) as those which actually occurred during the modeled periods. In the case of dual conveyance, the model draws exports through the new conveyance system unless these exports would cause Sacramento River flows to fall below a minimum environmental flow of 283.2 $m^3 s^{-1}$ (10,000 $ft^3 s^{-1}$). This environmental constraint is introduced to avoid reverse flows at the intake points that could harm fish (Burau 2007). Average export levels during the 1981–2000 reference period used for WAM were 5.96 billion $m^3 yr^{-1}$ (4.83 million ac-ft yr^{-1}) (and 5.74 billion $m^3 yr^{-1}$ or 4.65 million ac-ft yr^{-1} for the dry and critical years), and 7.14 million ac-ft yr^{-1}(5.79 million ac-ft yr^{-1}) for the 2002–2004 reference period used for RMA 2-D. Reference salinity for each hydrodynamic model run are shown in supplementary tables in the project website (*https://watershed.ucdavis.edu/project/water-quality-and-hydrodynamics*, hydrodynamic modeling results used in DAP).

Figure 4 shows salinity as electrical conductivity during the irrigation season for the five agricultural sub regions within the Delta under different export conveyance and sea level rise cases. Baseline salinity (the solid blue "current conditions" bar) is highest in the western Delta and lowest in the northern Delta. At current sea level, dual conveyance would increase salinity in most regions (particularly in the west), though not necessarily in the eastern and central parts of the Delta (hatched blue bar). Sea level rise increases salinity in most cases (again, particularly in the west). However, dual conveyance operations combined with sea level rise may not increase salinity in the eastern and central Delta (hatched green and red bars). During dry years, salinity is generally higher than during other years in the modeled time period, and dual conveyance increases average salinity at least marginally in all regions in both the irrigation (April to September) and non-irrigation (October to March) seasons, as shown in Figure 5.

The permanent flooding of western islands does not result in large increases in salinity over the base case during the irrigation season, although it does increase salinity somewhat more in the non-irrigation season (Figure 6). The lack of major effects in either season reflect the nature of the modeling scenario: recall that these islands are treated as "pre-flooded"—with salinity levels set the same as the surrounding channels; this corresponds to long-term conditions or near-term flooding under high river-flow conditions within the Delta, not the near-term effect of a "Big Gulp" of saltwater that might occur if the islands flood in the summer or fall or a very dry winter or spring. The contrast between the irrigation and non-irrigation seasons may reflect the effects of the D-1641 regulations (adopted in the mid-1990s), which include requirements to maintain low "X2" salinity standards in the western Delta from February until June. As a result, water exporters responded by increasing pumping in the fall for storage and urban uses, drawing more saline water toward the pumps. Permanent flooding of western islands greatly increases the volume of flood tide inflows and reduces the ability of the out-flowing water to restrain salinity intrusion.

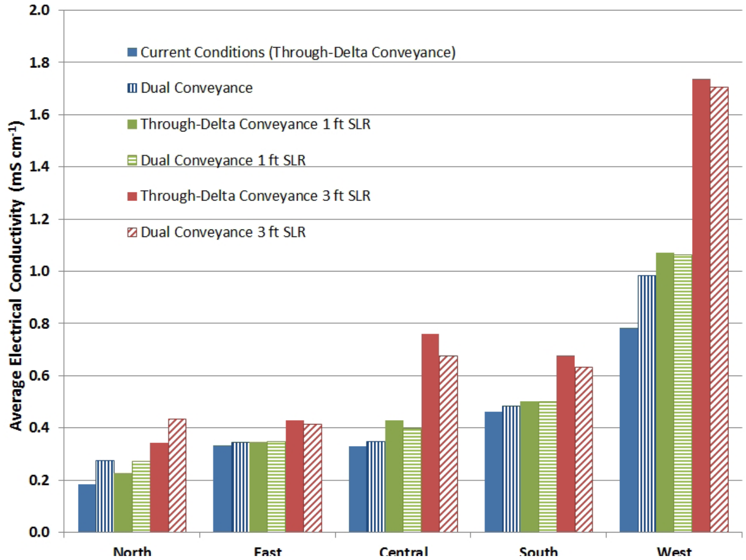

Figure 4 Electrical conductivity during the irrigation season (April to September) by WAM modeling scenario for five Delta sub-regions. Solid bars indicate through-Delta conveyance and hatched bars refer to dual conveyance.

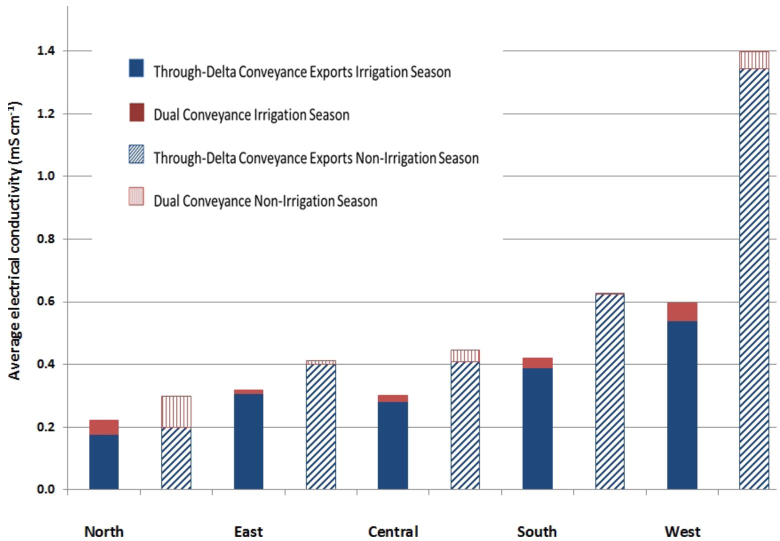

Figure 5 Electrical conductivity during dry years for through-Delta exports and dual conveyance configurations (current sea level)

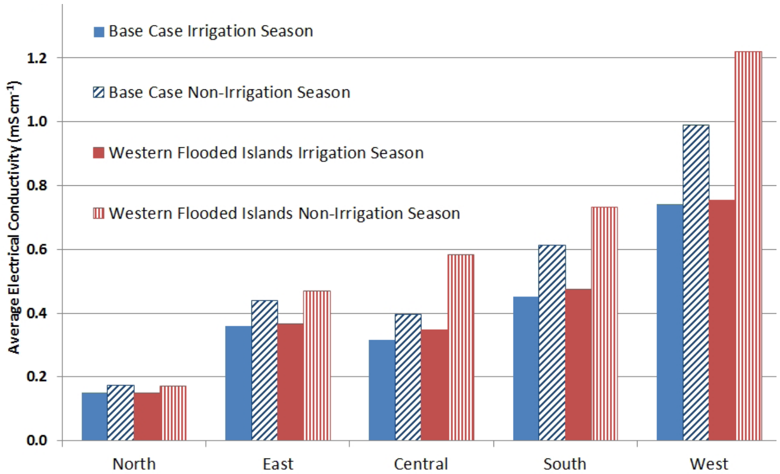

Figure 6 Electrical conductivity from the RMA 2-D hydrodynamic model for a base case and five western islands flooded during the irrigation season (solid bars) and non-irrigation season (hatched bars)

DAP MODELING RESULTS

In general, higher salinity reduces the relative yield of crops in the Delta. However, a large enough change to cause major yield losses throughout the Delta seems unlikely even under three feet of sea level rise or the flooding of the five western islands. Similarly, we do not find major changes in baseline cropping patterns or crop revenues with any of the hydrodynamic modeling salinity scenarios analyzed.

Hydrodynamic-Based Salinity Model Simulations of Revenue Losses

Sea level rise leads to limited crop revenue losses in the Delta, both with dual conveyance and through-Delta exports (Figure 7). Dual conveyance for Delta exports generally increases total revenue losses somewhat relative to through-Delta exports, but these losses remain well under 1% of total revenues. During dry years, when Delta waters are more saline, dual export conveyance gives the highest revenue losses, slightly above 0.7% (third bar from the left in Figure 7), roughly \$4.5 million yr^{-1}, with most losses occurring in the western Delta.

Results using the RMA 2-D hydrodynamic modeling for salinity with permanently flooded western islands (Figure 6) also show little revenue loss during the irrigation season. Some areas in the north of the Delta may even see slight decreases in water salinity and corresponding increases in crop revenues. Because most salinity changes occur outside the main irrigation season, crop yield and revenue effects are largely confined to acreage planted to winter crops such as wheat; thus the absolute revenue losses are very small because the acreage of winter plantings is itself small (less than 0.2% in the affected areas in the western and southern Delta).

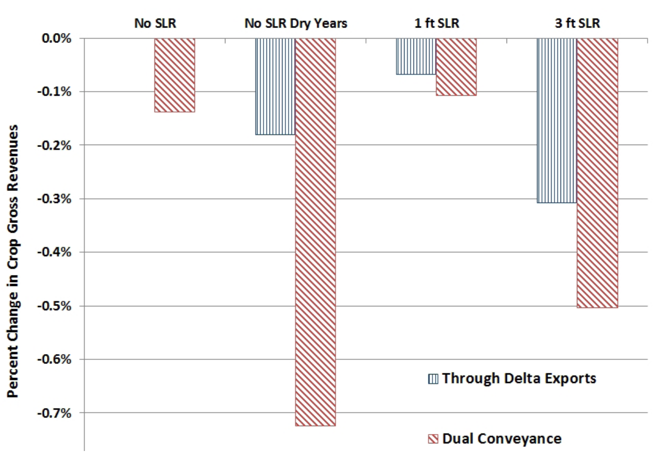

Figure 7 Percent change in agricultural crop revenues across WAM water salinity scenarios

Of course, beyond their effects on water salinity in the Delta, the permanent flooding of the five western islands would also lead to losses from flooded land being taken out of production. Elsewhere, we used DAP to show that farm revenue losses from the permanent flooding of 19 western and central Delta islands would far exceed the salinity-related losses shown here—roughly \$66 to \$90 million yr^{-1}—10% or more of baseline crop revenues (Medellín–Azuara et al. 2012a). (Suddeth et al. [2010] had earlier shown that these 19 islands would not merit repair after flooding based on the costs of repair and the value of agricultural production and other assets on the islands.) Changes of this magnitude would also ripple through the regional economy (multiplier effects), causing additional losses in revenues and value added. Large conversions of farmland to habitat could also have more substantial local and regional economic effects than the salinity changes modeled here (Medellín–Azuara et al. 2012a).

Sensitivity Analysis

To test the robustness of both the hydrodynamic and salinity transport simulations and the crop yield response model (DAP), we conducted two separate sensitivity analyses. The first tests for changes in water salinity in more recent levels of water exports in the Delta. The second tests the sensitivity of the crop production model to higher levels of irrigation water salinity than those obtained from hydrodynamic and salt transport modeling with WAM and RMA2/RMA11.

Because the historical 1981–2000 water year, average export of 5.96 billion $m^3\ yr^{-1}$ (4.83 million ac-ft yr^{-1}) might not be representative of more recent, higher export levels, we replicated Fleenor et al. (2008) WAM hydrodynamic modeling runs using the 1996–2005 water years, when average exports were 7.28 billion $m^3\ yr^{-1}$ (5.9 million ac-ft yr^{-1}). We found no major increase in salinity for any of the 52 sampling stations considered during the irrigation season. The largest increase was 2% at the Mokelumne River station near Terminous Tract, and the average electrical conductivity across all stations in the Delta was generally lower than during the 1981–2000 period. This is because the 1996–2005 period was fully covered in the D-1641 requirements in operation from the mid-1990s; under these requirements, the isohaline line of 2 ppt must be maintained in the far western Delta (around Chipps Island) from February to June to support delta smelt. During the non-irrigation season of the 1981–2000 time period, however, dual conveyance may increase salinity in some areas, including those near Old and Middle Rivers, which are intake points to supply Delta water for urban uses in Contra Costa Water District. The change in salinity in these locations is about 15%, which would increase water treatment costs for the Contra Costa Water District service area if the utility were unable to store water during lower salinity periods for later use.

To test the sensitivity of the DAP agro-economic model, we also examine cases with uniform values of irrigation water salinity for all islands at 1%, 3%, 5% and 10% of seawater salinity (set at 33 practical salinity units, psu: 50.4 mS cm^{-1} in surface at 25 °C (77 °F) or 33 ppt. DAP responds more abruptly to electrical conductivity levels beyond one percent of seawater. This analysis supports conclusions from earlier modeling (Medellín–Azuara et al. 2012a): crop revenue losses from salinity increases caused by dual conveyance and sea level rise are relatively low because most higher value crops are not located in parts of the Delta that experience the highest salinity increases.

When identical, higher levels of irrigation water salinity are assumed for all Delta islands and sub regions, DAP reports generally higher agricultural revenue losses than those shown in the previous section. This results from two factors: first, the proportional salinity increases are much higher on islands and sub regions in the Delta where salinity is currently low; second, these areas also tend to have greater concentrations of higher-value crops. Thus, increased salinity conditions and losses of higher value crops increase revenue losses substantially (Figure 8). The absolute revenue losses are highest in the northern and southern Delta, where such higher value crops predominate (Figure 9).

CONCLUSIONS

In the coming decades, the Sacramento–San Joaquin Delta is likely to experience changing land and water conditions as a result of a variety of natural and anthropogenic forces (Lund et al. 2010). Sea level rise, permanent flooding of some islands that lie below sea level, and altered water export operations are likely to affect water salinity and crop farming in the Delta.

In this paper, we quantified changes in agricultural crop revenues in the Delta for a range of water salinity changes using the DAP model. We used geo-referenced land use and water salinity information from field data and existing hydrodynamic modeling was employed to assess agricultural production under the different water salinity scenarios. We also tested the sensitivity of the model using more recent, higher export levels and a set of fixed scenarios with higher salinity levels, based on percentages of seawater salinity.

Several conclusions arise from this work:

1. Salinity changes from sea level rise, estimated by hydrodynamic modeling, reduce total agricultural crop revenues in the Delta by less than 1% of current revenues.

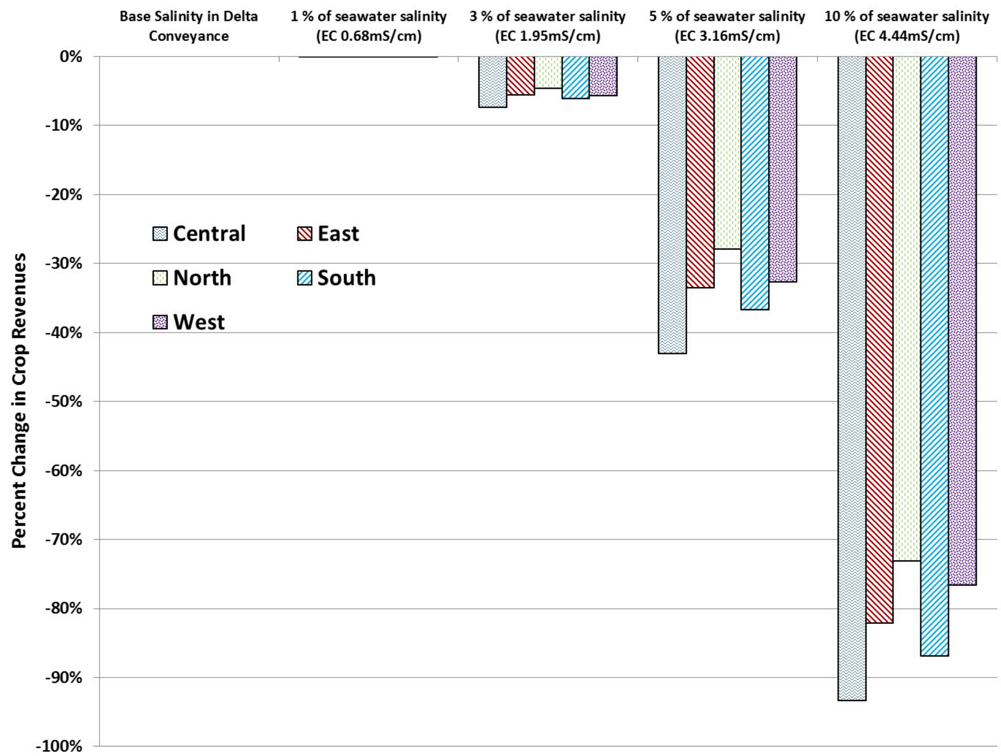

Figure 8 Change in crop revenues by percent of seawater salinity level (sensitivity analysis)

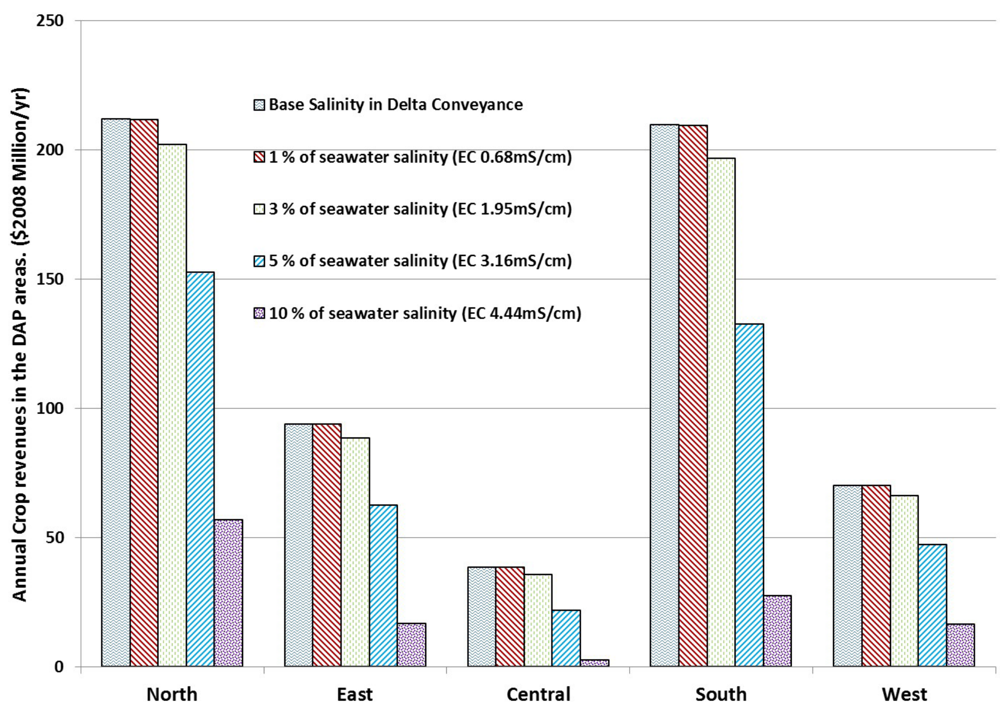

Figure 9 Sub-regional breakdown of total crop revenue in the Sacramento–San Joaquin Delta at different salinity levels (sensitivity analysis)

2. Water export operations with dual conveyance (including a peripheral canal or tunnel intake in the northern Delta) would slightly decrease crop revenue, especially during dry years, but these losses would remain within 1% of total projected Delta crop revenues under current salinity conditions.

3. Similar conclusions also hold for salinity losses arising from the permanent flooding of the five western islands that serve as a salinity barrier; salinity increases more during the non-irrigation season. Direct agricultural revenue losses from island flooding are much greater.

4. Total crop revenue losses from these salinity increases generally remain small because areas in the Delta with the greatest salinity effects now mostly grow lower-value crops. Farmers' ability to vary crop mix in response to salinity increases also reduces crop revenue losses. Economic losses from the permanent removal of agricultural lands because of island flooding or habitat conversions shown elsewhere (Medellín–Azuara et al. 2012a) are potentially much higher than the salinity effects found here.

5. Sensitivity analyses show that large increases in salinity for all Delta islands, beyond 3% of seawater, would greatly reduce Delta crop revenues. The greatest losses would be in areas that currently grow more salt-sensitive, higher-value crops; these areas are further inland from San Francisco Bay.

6. A better understanding of the hydrodynamics of Delta water salinity is needed through the aid of 3-D models, both to assess the combined effects of island flooding and sea level rise and to assess additional water operation alternatives. However, this study demonstrates the insights and potential from more detailed integrated analysis of crop production, adaptation, and revenue losses from salinity for a wide range of salinity and management conditions.

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