1	Climate change impacts on water demand and salinity in California's irrigated
2	agriculture
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4	G. Schoups ¹ , E.P. Maurer ² , and J.W. Hopmans ^{3*}
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7	¹ Department of Water Management, Delft University of Technology, Stevinweg 1, P.O.
8	Box 5048, 2600 GA Delft, The Netherlands, phone: +31-15-2784909, email:
9	g.h.w.schoups@tudelft.nl
10	
11	² Civil Engineering Department, Santa Clara University, 500 El Camino Real, Santa
12	Clara, CA 95053, phone: +1-408-554-2178, email: emaurer@engr.scu.edu
13	
14	³ Department of Land, Air and Water Resources, University of California, 1 Shields Ave.,
15	Davis, CA 95616, phone: +1-530-752-3060, email: jwhopmans@ucdavis.edu
16	
17	*Corresponding author: jwhopmans@ucdavis.edu
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21 ABSTRACT

22 This paper examines potential regional-scale impacts of climate change on sustainability 23 of irrigated agriculture, focusing on the western San Joaquin Valley in California. We 24 consider potential changes in irrigation water demand and supply, and quantify impacts 25 on the hydrologic system, soil and groundwater salinity with associated crop yield 26 reductions. Our analysis is based on archived output from General Circulation Model (GCM) climate projections through 2100, which were downscaled to the 1,400 km² study 27 28 area. We account for uncertainty in GCM climate projections by considering two 29 different GCM's, each using three greenhouse gas emission scenarios. Significant 30 uncertainty in projected precipitation creates large uncertainty in surface water supply, 31 ranging from a decrease of 26% to an increase of 14% in 2080-2099. Changes in 32 projected irrigation water demand ranged from a decrease of 13% to an increase of 3% at the end of the 21st century. Greatest demand reductions were computed for the dry and 33 34 warm scenarios, because of increased land fallowing with corresponding decreased total 35 crop water requirements. A decrease in seasonal crop ET by climate warming, despite an 36 increase in evaporative demand, was attributed to faster crop development with 37 increasing temperatures. Simulations of hydrologic response to climate-induced changes 38 suggest that the salt-affected area will be slightly expanded. However, irrespective of 39 climate change, salinity is expected to increase in downslope areas, thereby limiting crop 40 production to mostly upslope areas of the simulation domain. Results show that 41 increasing irrigation efficiency may be effective in controlling salinization, by reducing 42 groundwater recharge and improving soil drainage, and in mitigating climate warming 43 effects, by reducing the need for groundwater pumping to satisfy crop water 44 requirements.

45 **1. Introduction**

Potential impacts of global climate change on food production need to be considered to ensure food security for the world's growing population (Schmidhuber and Tubiello, 2007). Impact assessment is especially important for irrigated agriculture, as it supports a large part of the world's food supply, while being vulnerable to water scarcity (Rosegrant and Cline, 2003). Specifically, irrigated lands produce more than 40% of the world's food and account for almost 90% of global water consumption (Döll and Siebert, 2002).

Climate change in the 21st century is expected to affect crop productivity 53 54 (Rosenzweig and Hillel, 1998; Cline, 2007), irrigation water demand (Döll, 2002), and 55 water supply (Kundzewicz et al., 2007). Crop yields may either increase due to 56 stimulated biomass production with higher CO₂ concentrations, i.e. CO₂ fertilization, or 57 may decrease due to rising air temperatures (Rosenzweig and Hillel, 1998). Early 58 greenhouse experiments suggested that the CO_2 fertilization effect may be significant. 59 However, more recent results from Free-Air CO₂ Enrichment (FACE) trials under field 60 conditions indicate that previous greenhouse studies over-estimated the effect of CO₂ 61 fertilization (Long et al., 2006). A recent study by Cline (2007) projects an overall 62 negative effect of climate change on global crop production, with more severe production 63 losses in the warm climates of Africa, India, and South America.

64 Climate change is expected to affect irrigation water demand through shifts in 65 precipitation, temperature, and crop transpiration. Döll (2002) projected an increase in 66 water demand for half of the world's irrigated areas, due to increased crop transpiration at 67 higher temperatures and decreased precipitation in some areas. However, two additional 68 factors that may affect water demand were not considered. First, faster crop development

at higher temperatures will shorten growing seasons (Ritchie and NeSmith, 1991), resulting in reduced *seasonal* water demand, but potentially increased *annual* water demand when shorter growing seasons allow multiple cropping. Second, higher atmospheric CO_2 concentrations lead to decreases in leaf stomatal conductance, thereby reducing crop transpiration (Kimball et al., 2002). However, this is only significant in C₄ crops, as increased leaf production in C₃ crops is expected to offset decreases in leaf stomatal conductance (Ainsworth and Rogers, 2007).

76 When evaluating climate change impacts on irrigated agriculture, one must also 77 consider irrigation water supplies from rivers and aquifers. Changes in precipitation, 78 temperature, and evaporation are expected to alter river runoff and surface water supplies 79 (Kundzewicz et al., 2007). Generally speaking, runoff is likely to decrease in semi-arid 80 regions that depend on irrigation for crop production, such as the western United States 81 and the Mediterranean basin (Milly et al., 2005). Furthermore, areas that depend on 82 snowmelt are particularly vulnerable to rising temperatures and shifts in runoff 83 seasonality (Barnett et al., 2005). Reductions in surface water supply may in turn put 84 increased pressure on limited groundwater resources, leading to risks of groundwater 85 depletion (Alley et al., 2002), land subsidence (Galloway et al., 1999), and resource 86 degradation by soil and groundwater salinization (Ghassemi et al., 1995; Moench, 2004; 87 Vlek et al., 2008). Coastal aquifers are especially vulnerable in that respect, due to risks 88 of saltwater intrusion as sea level rises (Sherif and Singh, 1999). On the other hand, a 89 climate-driven increase in groundwater use could be beneficial, by reducing dependence 90 on variable surface water supplies (Schoups et al., 2006), and by improving soil drainage 91 conditions in areas affected by shallow water tables (Belitz and Phillips, 1995).

92 The implication is that climate change assessments for irrigated agriculture should 93 not only consider changes in water demand and supply, but should also account for 94 cascading effects on the regional hydrologic system, including soils, aquifers, and rivers. 95 In this paper we present such a regional-scale analysis for an area in California's San 96 Joaquin Valley.

97 In a comprehensive review by Hayhoe et al. (2004), projections from various 98 climate models for a range of emission scenarios were downscaled to evaluate potential 99 hydrological and agricultural impacts in California. General trends for the 21st century 100 include (i) an increase in annual average temperatures, (ii) a decrease in precipitation in the Central Valley, (iii) an increase in heat wave frequency and intensity, and (iv) a 101 102 substantial reduction in snow pack in the Sierra Nevada Mountains, causing a shift to 103 earlier runoff. Such changes are already apparent in historical records in the western 104 United States, and can be linked to human-induced global warming (Barnett et al., 2008). 105 Vicuna et al. (2007) concluded that seasonal shifts in runoff could diminish water 106 deliveries from the Central Valley Project's (CVP) reservoirs to farms in the San Joaquin 107 Valley by almost 30%, but realized that variation among climate scenarios was large.

108 Though it is generally believed that warming will increase crop transpiration (CA-109 DWR, 2006; CA-EPA, 2006; Lobell et al., 2006), few studies have quantified climate 110 change impacts on water demand for California's irrigated agriculture within a broad 111 hydrologic context, considering soil and groundwater salinity and groundwater pumping 112 effects to balance expected reduced surface water supplies. This paper presents a quantitative analysis of the potential effects of 21st century climate change on the 113 114 sustainability of irrigated agriculture in California's Central Valley, focusing on a 1,400 km² study area located in the western San Joaquin Valley (Figure 1). We calculate 115

116 changes in irrigation water demand, water supply, and groundwater pumping, and 117 evaluate hydrologic responses such as groundwater levels and salinity, with implications 118 for land subsidence and reduced crop yields due to increased soil salinity. Uncertainty in 119 our projections is accounted for by considering a range of climate change scenarios.

120

121 **2. Methodology**

122 To quantify potential climate change impacts, we consider three greenhouse gas 123 (GHG) emission scenarios, namely SRES B1 (low), A2 (mid-to-high) and A1fi (high). 124 These scenarios largely bracket the range of IPCC's nonintervention future emissions 125 projections, with atmospheric CO₂ concentrations for B1, A2, and A1fi reaching 550, 126 850, and 970 ppm, respectively by 2100 (IPCC, 2007). Following Hayhoe et al. (2004), 127 we used the output of two General Circulation Models (GCMs), i.e. the National Center 128 for Atmospheric Research-Department of Energy Parallel Climate Model (PCM, 129 Washington et al., 2000), and the U.K. Met Office Hadley Centre Climate Model version 130 three (HadCM3, Gordon et al., 2002). Archived output from these two GCMs for each of 131 the three GHG emission scenarios is used to extract precipitation and air temperature 132 projections for California at a spatial resolution of about 300 km.

Because the spatial resolution of GCM output is large relative to the study area (~30 km across, Figure 1), we employ a downscaling method to develop irrigation district scale climate projections. We applied the empirical statistical downscaling method of Wood et al. (2002; 2004), which has been tested and widely applied (e.g. Barnett et al., 2008; Cayan et al., 2008; Maurer, 2007; Van Rheenen et al., 2004) to downscale climate variables to a 1/8 degree (~12 km) spatial scale. The method comprises two steps. The first step is a bias-correction that uses quantile mapping (Panofsky and Brier, 1968) to

140 adjust monthly GCM simulated precipitation and temperature to statistically match (i.e. 141 yielding identical probability density functions) observations for 1960-1999 aggregated to the GCM scale. The same quantile mapping was applied to 21st century GCM projections, 142 143 so that while the statistics of observations are reproduced for the late 20th century, both 144 the mean and variability of future climate can evolve according to GCM projections. 145 Second, a spatial downscaling step interpolates monthly anomalies at the GCM scale onto 146 a 1/8 degree grid, and these are applied to observations to produce fine-scale GCM 147 projections of temperature and precipitation.

148 Starting from these climate scenarios, our regional impact study analyzes future 149 changes in (1) irrigation water demand and (2) irrigation water supply, and (3) evaluates 150 impacts of these changes on the regional hydrology.

151

152 **2.1. Irrigation water demand**

153 Annual irrigation water demand or requirement *IR* can be expressed as the sum of 154 water needs for all crops,

155
$$IR = \sum_{c} A_c \frac{ET_c - P_c}{IE_c}$$
(1)

where *c* is a crop index, ET_c is crop evapotranspiration (ET), P_c is effective precipitation, IE_c is irrigation efficiency, which accounts for conveyance and leaching losses, and A_c is areal crop fraction. Effective precipitation (P_c) was computed from biascorrected/downscaled GCM precipitation projections, whereas we considered two irrigation efficiency (IE_c) scenarios. Most crops are irrigated by gravity-systems, with IE_c values between 65 and 80%, depending on water table depth (Belitz and Phillips, 1995). As potential cuts in surface water supply may stimulate adoption of more efficient irrigation technology, we consider two scenarios, namely (i) no change in irrigation
efficiency, and (ii) a uniform increase to 90% irrigation efficiency through technological
adaptation.

166 Climate directly and indirectly affects crop ET (ET_c) . First, evaporative demand 167 changes as a function of atmospheric conditions such as temperature, relative humidity, 168 net radiation, and wind speed. We quantify this by estimating reference ET (ET_{ref}). based on the ASCE-EWRI standardized equation (ASCE-EWRI, 2004), which is an adaptation 169 170 of the Penman-Monteith equation for a short reference crop. Climate data used in this 171 equation are based on downscaled GCM projections of temperature and precipitation for 172 California, from which we obtained estimates of relative humidity and radiation. Wind 173 speed is estimated from the NCEP/NCAR reanalysis (Kalnay et al., 1996). A similar 174 approach was developed by Thornton et al. (2000), and successfully applied by Maurer et 175 al. (2002) and Cayan et al. (2008). Figure 2 shows that reference ET in the study area can 176 be correctly estimated with this method using only data on precipitation and temperature.

177 Climate also indirectly affects crop development by changing growing conditions, 178 of ambient CO_2 levels and air temperature. Effects of increased CO_2 levels on ET_c will 179 depend on photosynthetic pathway. For C₃ crops, an increase in biomass production will 180 offset a decrease in stomatal leaf conductance with increasing atmospheric CO₂ 181 (Ainsworth and Rogers, 2007), resulting in no or small effect on crop ET. The response 182 of C_4 crops is dominated by a reduction in stomatal conductance, resulting in larger ET 183 reductions (Kimball et al., 2002). However, C₄ crops (sorghum and corn) only make up 184 about 1% of all crops in the study area, so that we can assume no effect of CO₂ on crop 185 development, and used daily crop coefficients from Snyder et al. (1989) to calculate ET_c 186 as a function of projected ET_{ref} . In addition, GCM-based temperature projections were 187 used to evaluate temperature effects on crop development and ET_c . This was done by 188 expressing length of crop development stages in degree-days (DD) instead of days 189 (Ritchie and NeSmith, 1991), with DD computed as a piecewise linear function of 190 average daily temperature (Boote et al., 1998). In this model, no crop development takes 191 place, and DD = 0, below a lower threshold temperature T_l and above a high threshold T_u 192 due to heat stress. Maximum crop development is occurring between temperatures T_{opt1} and T_{opt2} , with linear crop growth or DD between temperature ranges of T_l and T_{opt1} and 193 between T_{opt2} and T_u . Threshold temperatures $T_l = 7^{\circ}$ C, $T_{opt1} = 30^{\circ}$ C, $T_{opt2} = 35^{\circ}$ C, and T_u 194 = 45°C were obtained by Boote et al. (1998) for a soybean crop, and were used for all 195 crops in the study area as they corresponded well with values of $T_l = 8^{\circ}$ C and $T_{optl} = 32^{\circ}$ C 196 reported by Ritchie and NeSmith (1991), and used by Schlenker et al. (2007) for crops in 197 198 California. Similarly, Crafts-Brandner and Salvucci (2000) observed heat stress in cotton, 199 a major crop in the study area, at leaf temperatures above 35°C.

200 We considered three types of land use (A_c) change, namely (i) changes in 201 cropping patterns, (ii) land fallowing, and (iii) land retirement. For California, Howitt et 202 al. (2003) projected a general shift in cropping pattern by 2100 for a range of climate 203 change scenarios, from cotton and grain crops to high-value crops such as vegetables and 204 fruit. This shift was attributed to increased demand for high-value crops, caused by 205 anticipated population growth. To allow for cropping changes, we calculated irrigation 206 water requirements for two cropping scenarios: (i) a gradual demand-driven shift to high-207 value crops, as suggested by Howitt et al. (2003), and (ii) no change in current cropping 208 patterns. Farmers may respond to cuts in surface water supplies by temporarily taking 209 land out of production by land fallowing, for example when groundwater is unavailable. 210 For each water district in the study area, we used a linear regression relation between land 211 fallowing acreage and surface water supplies for the 1988-1997 period, to project future 212 land fallowing for the range of climate change scenarios, assuming no future investment 213 in additional groundwater pumping capacity. Lastly, land degradation by soil salinization 214 may result in permanent land retirement, as almost 100,000 acres of agricultural land was 215 retired in 2006 in the western SJV (Figure 1; Russ Freeman, Westlands Water District, 216 pers. comm., 2007). We computed future soil salinization under various climate change 217 scenarios and identified additional land acreage that may be retired by 2100.

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2.2. Irrigation water supply

220 Irrigation water requirement or demand, IR, can be met by two main sources, 221 namely (i) imported surface water supply SW, and (ii) local groundwater supply GW, 222 such that IR = SW + GW. Given projections in surface water supply (see next 223 paragraph), annual groundwater supply (GW) was computed from this water budget. 224 Possible implications of excessive groundwater pumping, such as land subsidence and 225 soil salinization were assessed by simulating hydrologic system responses (section 2.3.).

226 Surface water supplies were estimated based on the results of Vicuna et al. (2007). 227 For each climate scenario, we generated annual surface water supply time series that 228 account for long-term water supply trends due to climate change, and that preserve 229 historical short-term statistics, such as variance, auto-correlation, and cross-correlation of 230 historical water supply records for each water district within the study area. We 231 calculated annual surface water supply as the sum of a long-term average, which evolves 232 according to climate change projections in each scenario, and a random fluctuation, 233 which reflects short-term deviations from the mean. or

$$SW_y = \mu_y + d_y \tag{2}$$

where SW_y is water supply in year y, μ_y is a low-frequency term, and d_y is a high frequency term. The low-frequency term is calculated based on average precipitation *P* from the previous *n* (= 30) years,

238
$$\mu_{y} = f\left(\sum_{i=0}^{n-1} \frac{P_{y-i}}{n}\right)$$
(3)

where *f* is based on a correlation between projected changes in precipitation for the study area and surface water supplies projected by Vicuna et al. (2007). Deviations d_y from the mean μ_y are simulated using a first-order (lag one) auto-regressive model for each of the 14 irrigation districts of the study area (Figure 1), or,

243
$$d_{y} = \rho d_{y-1} + \varepsilon_{y} \tag{4}$$

where ρ is a first-order (lag-one) auto-correlation coefficient, estimated from the historical record, and ε_y is the observed deviation from the mean for a randomly selected year from the historical record (1973-1997). This resampling procedure ensures that cross-correlations of water supply between districts were preserved in the future supply scenarios. For example, water supply during droughts often depends on the strength of a district's water right, leaving districts with weak water rights typically more affected by water cuts compared to districts with strong water rights.

251

252 **2.3. Hydrologic response**

253 Schoups et al. (2005) developed and calibrated a hydro-salinity model for the 254 study area using historical data from 1940 to 1997. The model extent is depicted in 255 Figure 1 which is discretized horizontally into a regular spatial grid with a resolution of 256 800 m, and vertically into 17 layers. The model solves three-dimensional variable 257 saturated subsurface flow and salt transport, and accounts for chemical reactions, in 258 particular gypsum dissolution-precipitation, affecting salt concentrations. Numerical 259 solutions are obtained with the MODHMS code. Please refer to Schoups et al. (2005) for 260 more details. We used their final simulation results of 1997 to perform simulations for 261 each climate change scenario during 1998-2099, with a focus on changes in groundwater 262 levels, soil and groundwater salinity, and impacts on crop yield and land subsidence. 263 Following Schoups et al. (2005), boundary conditions (irrigation, crop ET, precipitation) 264 and stresses (groundwater pumping) were specified annually for each numerical grid cell. 265 Groundwater flow across the north-eastern boundary was simulated using a general head 266 boundary condition, such that flow depends on hydraulic gradients between simulated 267 groundwater levels in the model domain and specified groundwater levels just east, and 268 outside, of the model domain. Since it is not clear how groundwater levels east of the 269 model domain will evolve in the future, we set them equal to historically observed values. 270 Finally, in order to simulate effects of pumping on groundwater levels, we extended the 271 original model of Schoups et al. (2005) to include the Corcoran clay and the confined 272 aquifer beneath it, from which most groundwater is extracted. Following Belitz and 273 Phillips (1995), no flow is assumed to occur between the confined aquifer and geological 274 layers below it, at a depth of around 500 m. The extended model was partially 275 recalibrated by adjusting hydraulic conductivities to match historically observed 276 groundwater levels and soil salinity over the period 1941-1997.

277

278 **3. Results**

Table 1 gives an overview of the climate scenarios and projected atmospheric conditions for the period 2080-2099. For comparison, we have included historical climate data

281 (denoted "H" in Table 1), and a scenario that assumes no climate change ("N"). The 282 latter was obtained using statistical resampling of historical values, and resulting climate 283 conditions differ slightly from historical conditions due to natural climate variability. The seven remaining scenarios represent different combinations of GHG emission scenarios, 284 285 GCMs, and adaptation, with increased projected temperatures by the end of the 21st 286 century. Climate change projections were differentiated between wet (W1 and W2) and 287 dry (D1 through D4) scenarios We note that level of dryness correlates well with 288 magnitude of projected warming (Figure 3a), though other studies with different GCM 289 selections have not consistently showed this correlation (Cayan et al., 2008). The last 290 scenario in Table 1 ("D4-IE") was included to assess consequences by increasing 291 irrigation efficiency.

In the following, we discuss results for computed changes in irrigation water demand, irrigation water supply, and hydrologic response (Table 2, Figures 3 to 6). All scenarios account for retired land, i.e. land permanently taken out of production, as shown in Figure 1.

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297 **3.1. Irrigation water demand**

Results in Table 2 (row 5) and Figure 3d indicate that total irrigation water demand is projected to decrease for the dry scenarios (D1 to D4) and increase for wet scenarios (W1 and W2), relative to the scenario without climate change (N). These results are counter-intuitive in that one would expect a greater need for irrigation water when rainfall is less, and vice versa. However, one must realize that all rainfall occurs in the off-season and annual irrigation water supply is inversely proportional to rainfall, thereby dictating cropped acreage and crop water requirements. Specifically, for the dry scenarios

the reduced surface water supplies favor increased acreage of land fallowing, thereby reducing irrigation water demand (Table 2, Figure 3b), and a decreases in ET_c , despite a consistent increases in reference ET (Table 2, Figure 3c). Hence, the relationship between precipitation, surface water supply, and land fallowing drives irrigation water demand. This relationship is intuitive and is based on inverse correlations between precipitation and surface water supply projections of Vicuna et al. (2007), and between historical land fallowing and water supply for the water districts in the study area.

312 The projected decrease in ET_c (Figure 3c) contradicts the general belief that global 313 warming will lead to an increase in crop transpiration in California (e.g., CA-DWR, 314 2006). The annual decrease in ET_c is a result of the accelerated crop development by the 315 projected increased air temperatures (section 2.1). Since historical average daily 316 temperatures were below the optimal range of 30-35°C, most crops will benefit from a 317 modest temperature increases $(2-5^{\circ}C)$, resulting in faster crop development, thereby 318 shortening the growing seasons and reducing annual crop water requirements. We note 319 that we ignored the possibility of multiple cropping. As projected temperatures continue 320 to rise, crop ET will increase due to an increase in ET_{ref} , as evidenced by the results for 321 the warmest scenario D4 (Table 2, Figure 3c).

In addition to the projected climate change impacts, we note that irrigation water demands are already reduced by ongoing land retirement (Figure 3b), removing the most salt-affected areas from cultivation. Specifically, recent land retirement in our study area of about 60,000 acres caused a 16% decrease in irrigation water demand for our study area, irrespective of climate change (compare water demand entries for N with H scenarios in Table 2). The water supplies from these areas were transferred to the remaining agricultural lands in the district, outside our study area. 329

330 **3.2. Irrigation water supply**

Projections of surface water and groundwater supply also differentiate between wet and dry scenarios, and are largely determined by the inverse correlation between annual precipitation and surface water supplies (Vicuna et al. , 2007). Projected surface water supplies range from an increase of 14% for the wettest scenario (W2), to a decrease of -26% for the driest scenario (D4), relative to a no-climate-change scenario (Table 2; Figure 3d). Because of recent land retirements, surface water supplies are significantly reduced for all scenarios, including the no-climate-change scenario (Figure 3d).

338 Groundwater use for irrigation follows the opposite trend of surface water 339 supplies (Figure 3d), as most pumping will occur in the driest scenarios (D4), to 340 compensate for reduced surface water supplies. The model assumes that farmers will 341 avoid water stress of all cropped lands, thereby supplementing available surface water 342 supplies with groundwater pumping to satisfy all water demands. As one would expect, 343 improvements in irrigation efficiency reduced the need for groundwater pumping (D4-IE 344 scenario, Table 2 and Figure 3d). The reduced groundwater pumping (Table 2) for the 345 wet scenarios is caused by the higher predicted rainfall amounts for those scenarios as 346 compared to the no-climate change benchmark.

347

348 **3.3. Hydrologic response**

We evaluate climate change impacts of water and land use changes on the hydrologic system by simulating shallow water table extent (section 3.3.1), soil salinity (section 3.3.2), salt-affected crop yields (section 3.3.3), groundwater salinity (section 3.3.4), and land subsidence (section 3.3.5). Using the modified hydro-salinity model of Schoups et al. (2005), we first reconstructed historical changes starting in 1940, and extended simulations through the 21st century for each climate change scenario. Whereas aggregate study area results are summarized in Table 2, time-series and spatial maps are presented in Figs. 4-6.

357

358 **3.3.1. Shallow water tables**

Figure 4 shows historical and projected changes in the area affected by shallow 359 360 water tables, less than 2 m below land surface. As irrigated area increased during mid-361 century and imported surface water replaced locally-pumped groundwater as the main irrigation water source, groundwater levels rose throughout the 20th century (Figure 4, 362 363 and Schoups et al., 2005). Shallow water tables mainly developed in downslope, low-364 lying areas (see Figure 1). Results in Table 2 and Figure 4 show significant variations 365 between scenarios. Wet scenario (W1, W2) projections show an increase in shallow water 366 table extent by 2100, whereas dry scenario simulations (D1 to D4) predict a decrease in 367 shallow water table extent. The dry scenario results are caused by the decrease in surface 368 water supplies, thereby causing increased groundwater pumping and lower groundwater 369 levels by induced downward hydraulic gradients. The shallow groundwater level extent 370 for the D4-IE scenario (fractional area of 0.16 in Figure 4) was much smaller than any of 371 the others because of the assumed high irrigation efficiency of 90% and the relatively 372 high pumping rate (Table 2). Shallow groundwater table is one of the most important 373 hydrologic variables, as it enhances the contribution of capillary rise to soil evaporation, 374 leading to soil and groundwater salinization in downslope areas.

375

377 **3.3.2. Soil salinity**

Historical and projected changes in the area of salt-affected soils, as defined by electrical conductivity (EC) values greater than 4 dS/m. Historical simulations by Schoups et al. (2005) showed the large decrease in soil salinity in the San Joaquin Valley, with saline soils decreasing from a fractional area of about 0.5 to about 0.3 (Figure 5), as the alluvial soils contained high salt content originally and were reclaimed by irrigation. Soil salinization increased in the late 1990's because of excess application of surface water, leading to rising water tables and drainage problems.

385 When comparing soil salinity with shallow groundwater level extent, salinity 386 projections are much less variable between climate scenarios. There appears to be an 387 upper limit of the areal extent of salt-affected soils, geographically constrained to the 388 low-lying areas with clayey deposits in the north-eastern part of the study area (Figure 5), 389 leading to poorly drained conditions. Additional areas of shallow water table extent 390 (Figure 4) are not salinized, because of adequate drainage to deeper groundwater. 391 Alternatively, part of the retired areas (Figure 1) remains salinized, as caused by regional 392 shallow groundwater flow from upslope areas towards the retired agricultural lands. The 393 largest decrease in salt-affected area was predicted for scenario D4-IE, as it exhibits the 394 least shallow groundwater extent. Hence, source control through improvements in 395 irrigation efficiency can be an effective management approach to reduce groundwater 396 levels and soil salinity.

397

398 **3.3.3. Crop yields**

Apart from changes in salt-affected areas, we also considered the impact of soil
 salinity on crop production, as crop salt tolerance varies among crops and is not limited to

401 4 dS/m. Here, we present simulated yields for cotton (salt tolerant) and tomato (salt-402 sensitive), as affected by soil salinity, using the Maas-Hoffman function that relates 403 relative yield to average root zone salinity (Maas, 1990). Whereas cotton yields were 404 historically not affected by soil salinity (Table 2, Figure 6a), projected results for all 405 climate scenarios indicate that soil salinity levels in salt-affected areas are expected to 406 increase, reducing yield to 50% or more for about 20% of the study area by 2100. As 407 expected, the wet scenarios with limited groundwater pumping predict the widest extend 408 of yield reduction, and the scenario with technological adaptation projects (D4-IE) is the 409 least affected (see also Figure 5). Our simulation results confirm that soil salinization will 410 continue unless higher irrigation water efficiency management practices are widely used. 411 Figure 6 also shows that the yield-reducing areas are mainly concentrated in the southern 412 part of the study area, coinciding with the northern portion of Westlands Water District 413 with shallow water tables and poor drainage. Though this area has already partly been 414 retired from agricultural production (Figure 1), our results suggest that future land 415 retirement may be necessary for areas further upslope as well.

416 Because of the increasing sensitivity to salinity stress, the area affected by tomato 417 yield reduction is much larger (up to 30%), and is almost twice as big (Table 2 and Figure 418 6b) as for cotton. Results suggest that in some high saline areas, initial reclamation of 419 soils by irrigation was likely necessary to allow tomato production. Furthermore, renewed soil salinization after the availability of surface water supply in the mid 20th century has 420 421 affected tomato yields from the 1970's-1980's onwards, confirming anecdotal evidence 422 by local farmers who indicated that tomato production has shifted upslope (towards the 423 west). As many high-valued crops such as vegetables and fruit (melons, in particular) are 424 also salt sensitive, the anticipated increase in future demand for such crops may require425 improved water and salt management practices in the study area.

426

427 **3.3.4. Groundwater salinity**

428 As determined by Schoups et al. (2005), the degradation of groundwater quality in 429 the long-term may eventually jeopardize groundwater-based irrigated agriculture. 430 Therefore, in addition to considering soil salinity, we also quantified salt loadings below 431 the root-zone (Table 2). Differences in salt loading to groundwater between climate 432 scenarios are related to groundwater pumping, with the highest salt loadings projected for 433 the driest climate change scenario, D4. This is caused by (i) higher salinity of pumped 434 groundwater compared to imported high quality surface water, and (ii) lower water tables 435 induced by downward hydraulic gradients by groundwater pumping. Most of the salt 436 leaching will occur for the well-drained soils in the western half of the study area 437 (upslope), where soils are well drained. In the long-term, this leaching process, combined 438 with the continued dissolution and transport of soil gypsum, will continue to increase 439 groundwater salinity of underlying aquifers (Schoups et al., 2005). Excessive soil 440 salinization in downslope areas in the eastern part of the study area is caused by 441 groundwater discharge by regional lateral flow, resulting in upward salt fluxes from 442 deeper groundwater into the root-zone.

443

444 **3.3.5. Land subsidence**

We included an estimate of potential land subsidence as part of the climate change analysis, considering inelastic compaction of sediments. For each climate change scenario, the simulation model computed hydraulic head values in the confined aquifer,

448 in response to projected changes in groundwater pumping. Future occurrence of inelastic 449 land subsidence was recorded when simulated confined heads fell below previously 450 simulated minimum levels. This definition of inelastic compaction is only approximate, 451 as it ignores the presence of residual pore pressure (Larson et al., 2001; Alley et al., 452 2002), potentially underestimating total subsidence. We use an inelastic storage 453 coefficient of 10% (Domenico and Schwartz, 1998), i.e. 1 m of subsidence for each 10 m 454 drop in head, to estimate total land subsidence in each grid cell over the period 2010-455 2099. Results show that land subsidence is projected to be very limited, with no 456 subsidence for the wet and no-climate-change scenarios (Table 2). The driest D4 scenario 457 with the largest groundwater pumping value projects subsidence in less than 1% of the 458 irrigated area, for a total simulated subsidence of less than 30 cm.

459

460 **4. Concluding Remarks**

The sensitivity results presented provide insights into impacts of climate change on irrigated agriculture. Our analysis does not only apply to California, but can be extended to other irrigated regions in the world, as many have similar constraints regarding water supply and land degradation. Our conclusions about potential impacts of climate change on irrigated agriculture can be summarized as follows:

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<u>Water demand:</u> Demand projections for the 1,400 km² study region in the western
San Joaquin Valley range from a decrease of 13% to an increase of 3% by the end
of the 21st century. Reductions are largest in dry and warm scenarios, for which
increased fallowing and decreased crop transpiration was projected, both leading
to reductions in irrigation water demand. Our simulations showed that an increase

472 in ET_{ref} for a warming climate is offset by a decrease in seasonal crop ET due to 473 faster crop development. Though climate warming unexpectedly projected 474 reduced seasonal crop water requirements, the resulting shorter growing seasons 475 could make multiple cropping possible, thereby increasing annual irrigation water 476 demand, perhaps beyond what can be supplied.

<u>Water supply</u>: The impact of climate change on water supply ranges from a decrease of 26% to an increase of 14% towards the end of the 21st century. We assumed that groundwater pumping supplemented surface water supplies to meet total water demand, thereby resulting in a large range (factor of 5) in projected groundwater use values, among scenarios. It is important to realize that the uncertainty in surface water supply projections is very high, due to large variations in projected precipitation among climate scenarios.

<u>Shallow water tables and soil salinity:</u> Despite the large variation in the spatial
 extent of projected shallow water tables, the total salt-affected area is predicted to
 remain fairly constant in the 21st century, irrespective of climate scenario. High
 soil salinity is limited to the eastern half of the study area that is flat and poorly
 drained. The western half of the study area contains topographic gradients and
 coarse alluvial soil deposits, which is why salinization due to rising water tables is
 unlikely to occur in those areas, irrespective of climate scenario.

491 - Crop productivity: All scenarios project an increase in soil salinity in downslope
 492 areas (eastern portion of the study area), resulting in reduction of both tomato and
 493 cotton yields. Although already a significant fraction of the low-lying areas has
 494 been retired from agricultural production, model simulations indicated that
 495 additional upslope areas could be affected. Therefore, if these additional lands

will not be drained in the future, additional land retirement may be required.
Model results show that salinization will continue to occur, regardless of climate
change. This is especially significant, realizing that economic analysis has shown
that farmers will likely switch from salt tolerant crops (such as cotton) to highvalue, salt-sensitive crops (such as tomato and melons), in the future.

501 _ Groundwater salinity: Salt leaching to deeper groundwater is most significant for 502 the dry climate change scenarios, for which groundwater use is greatest. 503 Groundwater irrigation generates the highest groundwater salinity, as salinity 504 increases by recycling of already salinized groundwater, combined with gypsum 505 dissolution. Hence, although groundwater pumping may reduce shallow 506 groundwater extent, thereby preventing excessive soil salinization, irrigation with 507 saline groundwater accelerates groundwater salinization. We realize that the time 508 scales of these two processes are different, with soil salinization being controlled 509 and managed over time scales of years and decades, whereas deep groundwater 510 salinization occurs over time scales of decades to hundreds of years.

<u>Land subsidence</u>: Land subsidence is projected to be very limited, even for the
 driest climate scenario, using historical subsidence and groundwater pumping
 simulations. However, we realize that direct modeling of pore pressures and
 subsidence calculations are needed to more accurately assess the future
 occurrence of land subsidence if groundwater pumping is increased.

<u>Technological adaptation</u>: Among the simulated scenarios, we considered a
 technological adaptation by improving irrigation efficiency to 90%. Such an
 adaptation could effectively mitigate many projected adverse effects. Increasing
 irrigation efficiency would reduce groundwater pumping, irrigation water

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- demand, groundwater recharge, and soil salinity (both extent and level of salinity), thereby decreasing the need for land retirement.
- 522

523 In conclusion, the greatest threat to agricultural sustainability in the study area 524 appears to be the continued salinization of downslope areas, jeopardizing crop production 525 and requiring future land retirement. Technological adaptations, such as increasing 526 irrigation efficiency, may mitigate these effects. Future work should consider additional 527 scenarios, and evaluate the vulnerability of the system to increased groundwater 528 pumping. This would require addressing economic profitability of irrigated agriculture, 529 for example, to include pumping costs and crop yield reduction by salinity. Also, more 530 work is needed on quantifying the uncertainties of the projected impacts, including 531 climate projections and the hydro-salinity model. We also conclude that many of the 532 simulated adverse effects, such as soil salinization, are caused by regional groundwater 533 dynamics of the hydrologic system in the study area, irrespective of climate change. It is 534 therefore important to include such hydrologic dynamics in any impact assessment, as 535 they may be as important as potential climate impacts.

536

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541 **6. References**

- Ainsworth, E.A., and A. Rogers (2007), The response of photosynthesis and stomatal
 conductance to rising CO₂: mechanisms and environmental interactions, Plant, Cell
 and Environment, 30:258–27.
- Alley, W.A., R.W. Healy, J.W. LaBaugh, and T.E. Reilly (2002), Flow and storage in
 groundwater systems, Science, 296, 1985-1990.
- 547 ASCE-EWRI (2004), The ASCE standardized reference evapotranspiration equation,
- 548 Technical Committee report to the Environmental and Water Resources Institute of
- 549 the American Society of Civil Engineers from the Task Committee on
- 550 Standardization of Reference Evapotranspiration, Reston, VA, USA. 173 pp.
- Barnett, T.P., J.C. Adam, and D.P. Lettenmaier, 2005, Potential impacts of a warming
 climate on water availability in snow-dominated regions, Nature, 438, 303-309.
- 553 Barnett, T.P., et al. (2008), Human-induced changes in the hydrology of the western
- 554 United States, Science, 319, 1080-1083.
- 555 Belitz, K., and S.P. Phillips (1995), Alternative to agricultural drains in California's San
- Joaquin Valley: results of a regional-scale hydrogeologic approach. Water Resour.
 Res. 31 (8), 1845–1862.
- 558 Boote, K.J., J.W. Jones, and G. Hoogenboom (1998), Simulation of crop growth:
- 559 CROPGRO model, p.651–692. In: R. M. Peart and R. B. Curry (eds.), Agricultural
- 560 systems modeling and simulation. Marcel Dekker, NewYork.
- 561 CA-DWR (2006), Progress on incorporating climate change into planning and
 562 management of California's water resources, Technical Memorandum Report,
- 563 California Department of Water Resources, Sacramento, CA, July 2006, 339 pp.

- 564 CA-EPA (2006), Climate action team report to Governor Schwarzenegger and the
 565 Legislature, California Environmental Protection Agency, Sacramento, CA, March
 566 2006, 110 pp.
- 567 Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree and K. Hayhoe, 2008, Climate
- change scenarios for the California region, *Climatic Change*, Vol. 87, Suppl. 1, 21-42
- 569 doi: 10.1007/s10584-007-9377-6.
- 570 Cline, W.R. (2007), Global warming and agriculture: impact estimates by country,
- 571 Peterson Institute for International Economics, July 2007, 250 pp.
- 572 Crafts-Brandner, S.J., and M.E. Salvucci (2000), Rubisco activase constrains the
- photosynthetic potential of leaves at high temperature and CO₂, PNAS, 97(24),
 13430-13435.
- 575 Döll, P. (2002), Impact of climate change and variability on irrigation requirements: a
 576 global perspective, Climatic Change, 54, 269-293.
- 577 Döll and Siebert, 2002., Global modeling of irrigation water requirements, Water Resour
- 578 Res. 38:8, DOI 10.1029/2001WR000355
- 579 Domenico, P.A., and W. Schwartz (1998), Physical and chemical hydrogeology, second 580 edition, Wiley.
- Galloway, D., D.R. Jones, and S.E. Ingebritsen (1999), Land Subsidence in the United
 States, United States Geological Survey, Circular 1182, 177 pp.
- 583 Ghassemi F., A.J. Jakeman, and H.A. Nix. 1995. Salinization of Land and Water
- 584 Resources: Human Causes, Extent, Management & Case Studies. Univ. of New South
- 585 Wales Press Ltd. Sydney, Australia.
- 586 Gordon, C., C. Cooper, C.A. Senior, H.T. Banks, J.M. Gregory, T.C. Johns, J.F.B.
- 587 Mitchell, and R.A. Wood (2002), The simulation of SST, sea ice extents and ocean

- heat transports in a version of the Hadley Centre coupled model without fluxadjustments, Climate Dynamics, 16, 147-168.
- 590 Hayhoe, K., D.R. Cayan, C.B. Field, P.C. Frumhoff, E.M. Maurer, N. Miller, S. Moser,
- 591 S. Schneider, K. Cahill, E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.
- 592 Kalkstein, J. Lenihan, C. Lunch, R. Neilson, S. Sheridan, and J. Verville (2004),
- 593 Emissions pathways, climate change, and impacts on California, Proceedings of the
- 594 National Academy of Sciences, 101(34), 12422–12427.
- 595 IPCC (2007), Climate Change 2007: Synthesis Report, Contribution of Working Groups
- 596 I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on
- 597 Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)], *IPCC*,
- 598 Geneva, Switzerland, 104 pp.
- Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, Bull. Amer.
 Meteor. Soc., 77, 437-471.
- 601 Kimball, B.A., K. Kobayashi, and M. Bindi (2002), Responses of agricultural crops to
- free-air CO_2 enrichment, Advances in Agronomy, 77, 293-368.
- 603 Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller,
- T. Oki, Z. Sen and I.A. Shiklomanov, 2007, Freshwater resources and their
 management. Climate Change 2007: Impacts, Adaptation and Vulnerability.
 Contribution of Working Group II to the Fourth Assessment Report of the
 Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P.
 Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press,
- 609 Cambridge, UK, 173-210.
- Larson, K.J., H. Basagaoglu, and M.A. Marino (2001), Prediction of optimal safe
 groundwater yield and land subsidence in the Los Banos-Kettleman City area,

- 612 California, using a calibrated numerical simulation model, Journal of Hydrology,
 613 242(1-2), 79–102.
- Lobell, D.B., C.B. Field, K.N. Cahill, and C. Bonfils (2006), Impacts of future climate
 change on California perennial crop yields: Model projections with climate and crop
- 616 uncertainties, Agricultural and Forest Meteorology, 141, 208–218.
- 617 Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nösberger, and D.R. Ort. 2006. Food for
- Thought: Lower-than-expected crop yield stimulation with rising CO2 concentrations.Science 312:1918-1921.
- 620 Maas, E.V. (1990), Crop salt tolerance, In: K.K. Tanji (ed.), Agricultural salinity
- assessment and management, ASCE Manuals and Reports on Engineering Practiceno. 71, Am. Soc. Civil Eng., New York.
- 623 Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen (2002), A long-
- term hydrologically-based dataset of land surface fluxes and states for the
 conterminous United States, J. Climate 15(22), 3237-3251.
- 626 Maurer, E.P., 2007, Uncertainty in hydrologic impacts of climate change in the Sierra
- 627 Nevada, California under two emissions scenarios, Climatic Change, Vol. 82, No. 3-
- 628 4, 309-325, doi: 10.1007/s10584-006-9180-9.
- Milly, P.C.D., K.A. Dunne, and A.V. Vecchia, 2005, Global pattern of trends in
 streamflow and water availability in a changing climate, Nature, 438, 347-350.
- 631 Moench, M. (2004), Groundwater: the challenge of monitoring and management, In: P.
- 632 Gleick. (Ed.), The World's Water 2004-2005, The Biennial Report on Freshwater
- 633 Resources, Island Press, Washington D.C., USA, pp. 79-100.
- 634 Panofsky, H. A. and G. W. Brier: Some Applications of Statistics to Meteorology. The
- 635 Pennsylvania State University, 224 pp, 1968

- 636 Ritchie, J. T., and D. S. NeSmith (1991), Temperature and crop development, p.5–29. In:
- 637 J. Hanks and J. T. Ritchie (eds.), Modeling plant and soil systems. Agron. Monogr.
- 638 31, ASA, CSSA, and SSSA. Madison, WI.
- 639 Rosegrant, M.W., and S.A. Cline (2003), Global food security: challenges and policies,
- 640 Science, 302, 1917-1919.
- 641 Rozenzweig, C. and D. Hillel. 1998. Climate change and the global harvest Potential
- 642 impacts of the greenhouse effect on agriculture. Oxford University Press.
- 643 Schlenker, W., W. Hanemann, and A. Fisher (2007), Water availability, degree days, and
- the potential impact of climate change on irrigated agriculture in California. Climatic
- 645 Change, 81(1):19-38.
- 646 Schoups, G., J.W. Hopmans, C.A. Young, J.A. Vrugt, W.W. Wallender, K.K. Tanji, and
- 647 S. Panday (2005), Sustainability of irrigated agriculture in the San Joaquin Valley,
 648 California, PNAS, 102(43), 15352-15356.
- 649 Schoups, G., C.L. Addams, J.L. Minjares, and S.M. Gorelick (2006), Sustainable
- 650 conjunctive water management in irrigated agriculture: Model formulation and
- application to the Yaqui Valley, Mexico, Water Resour. Res., 42, W10417,
- 652 doi:10.1029/2006WR004922.
- 653 Schmidhuber, J., and F.N. Tubiello, 2007, Global food security under climate change,
- 654 Proc. Nat. Ac. Sci., 104(50), 19703-19708.
- Sherif, M., and V. Singh, 1999, Effect of climate change on sea water intrusion in coastal
 aquifers, Hydrol. Proc., 13, 1277-1287.
- 657 Snyder, R.L., B.J. Lanini, D.A. Shaw, and W.O. Pruitt (1989), Using reference 658 evapotranspiration and crop coefficients to estimate crop evapotranspiration for

- agronomic crops, grasses, and vegetable crops. California Department of Water
 Resources, Leaflet 21427, Sacramento, CA, pp. 1-12.

662

Thornton, P.E., H. Hasenauer, and M.A. White (2000), Simultaneous estimation of daily

solar radiation and humidity from observed temperature and precipitation: an

- application over complex terrain in Austria, Agric. For. Meteor., 104, 255-271.
- Van Rheenen, N.T., Wood, A.W., Palmer, R.N., and Lettenmaier, D.P.: 2004, Potential
- 665 implications of PCM climate change scenarios for California hydrology and water
 666 resources, *Climatic Change* 62, 257-281.
- Vicuna, S., E.P. Maurer, B. Joyce, J.A. Dracup, and D. Purkey (2007), The sensitivity of
- 668 California water resources to climate change scenarios, Journal of the American
 669 Water Resources Association, 43(2): 482-498.
- 670 Vlek, P.L.G., D. Hillel, and A.K. Braimoh (2008), Soil degradation under irrigation, In:
- A.K. Braimoh and P.L.G. Vlek (eds.), Land use and soil resources, Springer, p. 101119.
- 673 Washington, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, T.W. Bettge, A.P. Craig,
- W.G. Strand, J. Arblaster, V.B. Wayland, R. James, and Y. Zhang (2000), Parallel
 climate model (PCM) control and transient simulations, Climate Dynamics,
 16(10/11), 755-774.
- Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier (2002), Long range
 experimental hydrologic forecasting for the eastern U.S., J. Geophys. Res. 107 (D20):
 4429.
- Wood, A.W., Leung, L.R., Sridhar, V., and Lettenmaier, D.P.: 2004, 'Hydrologic
 implications of dynamical and statistical approaches to downscaling climate model
 outputs', *Climatic Change* 62, 189-216.

Table 1. Overview of climate change scenarios. Projected temperature and precipitation are average values for the end of the 21st century (2080-2099), based on bias-corrected and spatially downscaled GCM output. Historical data are for the period 1976-1995.

Scenario label	GCM	SRES emission	Technological adaptation	Atmospheric CO ₂ (ppm)	Air temperature	Precipitation (m)
		scenario			(°C)	
Η	Historical		-	347	17.1	0.21
Ν	No climate	e change	-	347	17.6	0.20
W1	PCM	B1	-	544	19.2	0.24
W2	PCM	A2	-	775	20.2	0.24
D1	PCM	A1fi	-	885	20.8	0.18
D2	HadCM3	B1	-	544	20.9	0.18
D3	HadCM3	A2	-	775	22.2	0.17
D4	HadCM3	A1fi	-	885	23.5	0.13
D4-IE	HadCM3	A1fi	IE^*	885	23.5	0.13

* Uniform increase in irrigation efficiency to 90%, from current efficiencies ranging from 65 to 80%.

Table 2. Climate change impacts on water supply, water demand, and hydrology. Values represent averages or totals over the entire study area and over a 20-year period. Refer to Table 1 for scenario labels and climate characteristics. Minimum and maximum values

for each variable are underlined.

Scenario	Н	Ν	W1	W2	D1	D2	D3	D4	D4-IE
Time period	1976-1995	2080-2099	2080-2099	2080-2099	2080-2099	2080-2099	2080-2099	2080-2099	2080-2099
Water demand									
Reference ET (m)	1.49	1.53	<u>1.52</u>	1.57	1.60	1.62	1.65	1.73	<u>1.73</u>
Crop ET (m) ^(a) , scenario 1	0.58	0.58	0.54	0.54	<u>0.53</u>	0.55	0.55	0.60	<u>0.60</u>
Crop ET (m) ^(a) , scenario 2	0.58	0.60	0.56	0.55	<u>0.54</u>	0.57	0.56	0.60	<u>0.60</u>
Non-cultivated land ^(c, d)	0.15	0.31	<u>0.30</u>	0.31	0.33	0.34	0.34	0.34	0.34
Water demand (MCM) ^(b)	831	694	702	<u>717</u>	617	620	634	664	<u>601</u>
Water supply									
Surface water use (MCM) ^(b)	744	588	652	<u>673</u>	498	462	469	433	<u>433</u>
Groundwater use (MCM) ^(b)	87	105	50	<u>44</u>	119	158	165	<u>232</u>	168
Hydrologic response									
Shallow water tables ^(c)	0.40	0.39	0.53	<u>0.55</u>	0.29	0.24	0.25	0.23	<u>0.11</u>
Salt-affected soils (c)	0.32	0.47	0.47	<u>0.49</u>	0.46	0.46	0.46	0.47	0.37
Cotton yield $< 50\%$ ^(c)	0.00	0.18	0.19	0.22	0.17	0.16	0.15	0.15	<u>0.10</u>
Tomato yield $< 50\%$ ^(c)	0.08	0.31	0.32	<u>0.34</u>	0.29	0.29	0.27	0.27	<u>0.18</u>
Salt loading to groundwater	5.47	2.37	2.37	<u>1.12</u>	2.77	3.39	3.55	<u>4.74</u>	4.67
(million tons)									
Renewed land subsidence (c)	N/A	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

^a This is a weighted average over all crops, with weights proportional to crop acreages. Results are shown for two scenarios. Scenario 1 corresponds to an assumption of no change in cropping patterns. Scenario 2 assumes a demand-driven shift to high-value crops, such as vegetables and fruits (Howitt et al., 2003). Results for water demand, supply and hydrologic responses are for scenario 1.

^b Total water volume in Million Cubic Meter (MCM).

^c Fraction of total land area. Shallow water table are less than 2 m below land surface. Salt-affected soils have an EC_e greater than 4 dS/m. ^d Includes non-agricultural areas (4% of total land area) and, for future years, retired agricultural land (18% of total land area).

Figure Captions

- Figure 1 (a) Location of study area and model domain in the western San Joaquin Valley, California; (b) Detailed view of model domain, showing irrigation districts (as jagged lines) and two dark areas where land is retired from agricultural production as of 2006. Grey shades indicate land elevation, with lighter shades having higher elevation. Regional groundwater flow follows topographic gradients, i.e. south-west to north-east.
- Figure 2 Validation results for reference ET estimation. "Diamonds" are data for temperature, precipitation, and reference ET measured at a local CIMIS weather station in the study area. "Squares" are (i) gridded data of precipitation and temperature from Maurer et al. (2002) for the grid point at the center of the study area, and (ii) calculated values of reference ET based on these temperature and precipitation data, using the method of Thornton et al. (2000).
- Figure 3 (a) Precipitation and temperature for various climate scenarios listed in Table 1, and resulting projections in land use (b), reference ET and crop ET (c), and irrigation water demand and supply (d). Reported values are totals for the entire study area and averaged in time for the period 2080-2099 (except for historical conditions denoted by "H", which represents the period 1976-1995). BCM = Billion Cubic Meter.
- Figure 4 Historical and projected extent of shallow groundwater areas: time-series and spatial maps for three scenarios, i.e. N (no climate change), W2 (wettest scenario), and D4-IE (driest scenario). Shallow water tables are less than 2 m below land surface. Solid lines are simulations, and open symbols are observations in May (squares), July (diamonds), or October (triangles).
- Figure 5 Historical and projected extent of salt-affected areas: time-series and spatial maps for three scenarios, i.e. N (no climate change), W2 (wettest scenario), and D4-IE (driest scenario). Salt-affected soils have an EC_e greater than 4 dS/m. Solid lines are simulations, and open symbols (triangles) are observations.
- Figure 6 Historical and projected extent of areas where (a) cotton and (b) tomato yield is reduced by 50% or more due to salt accumulation: time-series and spatial maps for three scenarios, i.e. N (no climate change), W2 (wettest scenario), and D4-IE (driest scenario). Yield reductions are more severe for darker shades.



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Figure 5 Historical and projected extent of salt-affected areas: time-series and spatial maps for three scenarios, i.e. N (no climate change), W2 (wettest scenario), and D4-IE (driest scenario). Salt-affected soils have an EC_e greater than 4 dS/m. Solid lines are simulations, and open symbols (triangles) are observations.



Figure 6 Historical and projected extent of areas where (a) cotton and (b) tomato yield is reduced by 50% or more due to salt accumulation: time-series and spatial maps for three scenarios, i.e. N (no climate change), W2 (wettest scenario), and D4-IE (driest scenario). Yield reductions are more severe for darker shades.