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Assessing salinity impacts on crop yield and economic returns in the Central Valley

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ABSTRACT

This study aimed to assess the impact of salinity in the root zone on crop yields and profitability in the Central Valley. A comprehensive biophysical model was developed by integrating soil variables, climate conditions, irrigation inputs, and economic data. The model considered four key crops (alfalfa, almonds, table grapes, and processing tomatoes), five levels of irrigation water salinity (ranging from 0.5 to 5.5 dS/m), and daily irrigation water amounts (ranging from 0 to 12 mm). The results indicated strong predictive capabilities of the model, with R^2 values for predicted yields of 0.82, 0.77, 0.78, and 0.64 for alfalfa, almonds, grapes, and tomatoes, respectively. The corresponding RMSE values were 9%, 8%, 23%, and 11% for the same crops. Profit predictions showed an R^2 value of 0.99 for alfalfa, almonds, and processing tomatoes, and 0.74 for grapes. The RMSE values were 48, 211, 2461, and 68 $/ha for alfalfa, almonds, grapes, and processing tomatoes, respectively. Furthermore, the model incorporated a spatial component, revealing variations in yield and profitability based on soil type and groundwater salinity across the Central Valley. Results indicated that at daily irrigation rates of 3 mm, no profits were predicted for any of the crops. However, a daily irrigation rate of 6 mm produced profits of up to $1000/ha for alfalfa and processing tomatoes, while almonds and grapes required more than 8 mm/day to achieve profitable outcomes. This integrated modeling framework provides valuable insights for policymakers to identify areas unsuitable for sustainable and profitable irrigated agriculture. It can help prioritize such areas for multi-benefit land repurposing, reducing agricultural water demand, and achieving groundwater sustainability. Additionally, the model serves as a decision-aid tool for growers in arid regions, enabling them to anticipate potential losses in crop yield and profitability due to irrigation water salinity.

1. Introduction

High concentrations of soluble salts such as sodium chloride, sulfates, calcium, magnesium, and bicarbonates in soil and water threaten irrigated and rainfed agriculture worldwide (Hopmans et al., 2021). More than 954 million hectares (ha) of land worldwide are salt-affected, and between 25% and 30% of irrigated lands are rendered unproductive due to salinity (Shahid et al., 2018). The increase in the world population is expected to expand salinization further through an array of processes, including an increase in treated wastewater reuse for irrigation (Farid et al., 2020; Ogunmokun and Wallach, 2021; Pedrero et al., 2020; Tanji, 1997), groundwater contamination due to percolated salts from irrigated lands (Foster et al., 2018; Merchán et al., 2020; Quinn, 2020), and an increase in the use of brackish or saline water for irrigation (Baath et al., 2020; Wang et al., 2020; Yuan et al., 2019). The consolidative nature of these processes suggests that salinity issues are inherent to crop production and agricultural water management strategies in many water-constrained regions. Methods to quantify and reduce economic losses due to salinity should be incorporated into policies at regional and local scales.

In semi-arid and arid regions like California, where rainfall is insufficient to meet crop water needs, irrigation is necessary. About 40%

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of global irrigated land is located in arid/semi-arid zones, and irrigation is often associated with salinization (Hopmans et al., 2021; Smedema and Shiati, 2002). Intensive irrigation has allowed the Central Valley of California to become one of the world's most productive farming regions (Olmstead and Rhode, 2017). Long-term sustainability of irrigated agriculture is threatened due to decreased irrigation water quality and increased salt build-up in the soil and groundwater, particularly in the southern part of the Valley (Schoups et al., 2005; Welle and Mauter, 2017). Various factors, such as drought, climate change, water shortages, and land-use changes, exacerbate salinity problems and severely affect the Central Valley's agricultural productivity and sustainability.

In the San Joaquin Valley (Southern part of the Central Valley), more than 2 million ha of irrigated cropland are salt-affected through saline irrigation water or saline soils, and tens of thousands of ha of arable land were reported to be at high-risk (Letey, 2000). Over 30% of the agricultural salt-affected land is highly saline (Scudiero et al., 2017). Salt build-up caused about 100,000 ha to be taken out of agricultural production, and another 600,000 ha were considered damaged by salinity. In contrast, only 15% of the annual salt load is being addressed by current management activities (CV-SALTS, 2019). The high levels of salt concentrations in the Central Valley can be directly correlated with irrigation with a combination of agricultural, industrial, and municipal water. The amount of salt brought into the Valley has been increased through dams and imported water supplies. More than six million tons of salt are imported and accumulated yearly in the San Joaquin Valley (CV-SALTS, 2019; Quinn, 2020). Using remote sensing methods, Welle and Mauter (2017) reported that salinity reduced California's agricultural revenues by $3.7 billion. Long-term management strategies are needed to address the remaining 85% of salt load. Under current conditions, informed predictions about future salt build-up are required to optimize agronomic practices to reduce economic loss due to salinity and improve irrigation sustainability.

California's Central Valley agricultural production relies on surface water imports from a massive network of reservoirs, waterways, and groundwater over-drafted due to irrigation (Quinn, 2020). In recent decades, the Valley has turned to perennial (tree and vine) crops, which has triggered increased water demand amidst a cycle of multiple-year droughts and new regulations on groundwater pumping (Mall and Herman, 2019). Moreover, the Central Valley faces the challenge of protecting water quality due to inadequate dilution from rainfall. Such conditions, inherent to semi-arid agricultural regions, have led to alternative solutions, including using marginal-quality water such as recycled wastewater and brackish groundwater for irrigation (Gile et al., 2020; Kisekka et al., 2023; Qin and Horvath, 2020). However, such non-conventional irrigation water sources are likely to contain dissolved salts that can accumulate in the root zone, affecting crop productivity and leaching to groundwater and surface water resulting in severe environmental degradation (Chittick and Srebotnjak, 2017; Foster et al., 2018). The use of water high in salts requires best management practices that entail screening biological-physical system concerns and the production's economics (Kaner et al., 2019). Under constrained soil and water systems protection measures, water management strategies are challenged to maximize productivity. In addition to the evaluation of adverse effects of water containing excess salts on crop yield (relative to crop salt tolerance) and the ecosystems, decisions related to the use of marginal quality irrigation water for crop production can further consider the assessment of economic parameters such as production inputs and potential benefits.

Numerical and analytical modeling approaches to estimate crop yield for a specific soil as a function of saline water and irrigation amounts have been widely described and compared in previous research (Oster et al., 2012; Shani et al., 2009; Skaggs et al., 2014). Integrated models coupling agronomic, hydrological, and environmental aspects of irrigation-salinity water systems to economic models have also been developed and assessed in literature (Booker et al., 2012; Slater et al., 2020). However, coupling robust economic information with biophysical models and their spatial correlation has been limited. Shani et al., (2007, 2009) evaluated the impact of water stress and irrigation water salinity on crop yield and discussed the potential use of the model as an economic decision-support tool. Kaner et al. (2019) later integrated the model with economic information and implemented it as an agronomic-economic coupled decision support system for irrigation water salinity. However, these model applications were implemented considering one or two soil types without considering the spatial distribution of crop yield and profitability in terms of irrigation water salinity and quantity.

This study aimed to develop a framework that integrates the analytical biophysical model with economic and geospatial data and to assess the impact of irrigation water quality and quantity on crop productivity and economic outcomes for selected crops in the Central Valley of California.

2. Materials and methods

2.1. Biophysical model description

The ANalytical Salt-WatER (ANSWER) model contains crop parameters, hydraulic properties, and a meteorological variable (Shani et al., 2007, 2009). Four assumptions underlie the model. First, ambient conditions in the root zone affecting crop root water uptake and growth are represented by parameters, including electrical conductivity (EC), defined by water content (θ) and soil solution salinity (Schoups and Hopmans, 2002). Second, steady-state conditions of water and salt status (Tripler et al., 2012) are assumed. Third, the environmental conditions, including weather, are considered static, so the average seasonal transpiration ($T_{p)}$ value is considered as potential transpiration for the growth period. Fourth, there is a proportional relationship between the ratio of given yield to the potential yield and the ratio of transpiration to potential transpiration (Ben-Gal and Shani, 2003; Ben-Gal et al., 2008; Shani et al., 1987). The relative yield is expressed as follows:

$$Y_r = \frac{Y}{Y_p} = \frac{T}{T_p} = T_r \tag{1}$$

where Y is yield or biomass production and T is transpiration. Y_r and Y_p are the relative yield and potential yield, respectively. T_r and T_p represent the relative transpiration and potential transpiration, respectively.

The model combines salt and water balance by calculating the soil moisture of the root-zone and soil hydraulic conductivity according to the soil hydraulic model of Brooks-Corey (Brooks and Corey, 1966):

$$K(\psi) = \min\left\{K_{s,}K_{s,}\left(\psi_w{*}\psi^{-1}\right)^{\eta}\right\}, \theta(\psi) = \min\ \left\{\theta_s, (\theta_s - \theta_r)\left(\psi_w{*}\psi^{-1}\right)^{\beta} + \theta_r\right\} \tag{2}$$

where K is the soil hydraulic conductivity, K_S is the saturated hydraulic conductivity, θ_S is the saturated volumetric soil moisture content, and θ_r represents residual volumetric soil moisture content; ψ is the soil matric head, ψ_w is the air-entry head, and η and β are empirical soil characteristic parameters.

Maas and Hoffman (1977a) (1977b) modeled a piece-wise linear model (Mass-Hoffman model) in which crop salt tolerance is described by a salinity threshold and a slope describing yield loss beyond that threshold. The EC_{e50} designates the EC_e (dS/m) for which the relative yield decreases by 50%, and p is a crop parameter describing the function's steepness. The EC_{e50} values were estimated through a rearranged Eq. (3) from Maas and Hoffman (1977a) (1977b).

$$EC_{e50} = \frac{(1 - Y)}{S + EC_{eT}} \tag{3}$$

where EC_{eT} is the salinity threshold (dS/m), Y is the yield (set to 50%), and S is the slope (% yield decline per dS/m).

The logistic curve characterizes the plant-specific reduction function with an initial plateau followed by a decreasing section (Eq. 4)

$$f_{EC} = \frac{1}{1 + \left(\frac{EC_e}{EC_{e50}}\right)^p} \tag{4}$$

where f_{EC} is the relative yield reduction function due to increasing salt concentration levels and EC_e is the average saturated soil extract of the root zone. The parameter p is responsible for the steepness of the S-shape function. Recent experiments in alfalfa (Benes et al., 2018) have allowed the update of the threshold and slope for a more accurate EC_{e50}.

Shani et al., (2007, 2009) developed the transpiration function expressed as Eq. 5:

$$T = \frac{\min\left\{T_p, \left[\left(\psi_{root-\frac{\psi_w}{\left(\frac{(I-T)}{K_s}\right)^{1/\eta}}}\right) \quad (I-T)^{*}b\right]\right\}}{1 + \left(\frac{EC_I{}^{*}I^{*}\left(\theta_r + (\theta_s - \theta_r) \quad \left(\frac{(I-T)}{K_s}\right)^{1/\delta}\right)}{EC_{e50}{}^{*}(I-T)\theta_s}\right)^p} \tag{5}$$

where I represent the different irrigation water amounts and EC_{iw} the water salinity levels. The model simulated crop performance under different irrigation management and water quality (salinity levels). Eq. (5) includes management factors (I and EC_I), physical properties (T_p, K_s, δ, θ_r and θ_s) or biophysical processes (EC_{e50} and ψ_{root}). The physical and biological parameters are site and plant-specific and are determined independently. The parameter p that governs the steepness of the curve was set to 3 (unitless) (Shani et al., 2007; van Genuchten and Gupta, 1993), and the parameter b, used to characterize the flow length from the soil to the crop roots was set to 10 mm under all likely conditions (Nimah and Hanks, 1973; Shani et al., 2007). Relative yield with the initial soil water content (Y_{r0}) was assumed to be zero for all four crops. Tables 1 and 2 provide the soil and crop parameter, respectively, for the model.

2.2. Model input data

Input parameters included the amount and salinity of the applied water, 50%-yield soil salinity (ECe_{50}) and water stress, and potential evapotranspiration (T_p). Irrigation water amounts ranged from 0.4 to 12 mm/day, and six salinity levels: 0.5, 1.5, 2.5, 3.5, 4.5, and 5.5 dS/m were considered. Historical crop yield and prices, costs to establish an orchard/farm and water prices were also used as input to the model. In the spatial component of the model, salinity in irrigation water and diverse soil hydraulic properties were input to simulate spatial crop yield and profits as a function of irrigation water salinity across the Central Valley. Tables 1, 2, and 3 provide inputs for sandy loam soil and crop biophysical conditions.

2.3. Assessing biophysical model performance

A systematic review was conducted to collect experimental yield data from previous research to assess the model's performance. The criteria for selecting the studies were irrigation water salinity, crop yield, soil type, and weather data. The framework Protocol, Search, Appraisal, Synthesis, Analysis, and Reporting (PSALSAR) was applied to select the articles that fit the criteria related to the model. Details related to the PSALSAR framework are provided by Mengist et al. (2020). The searching string was "((Salinity OR saline water) AND (crop yield OR yield)) AND (almonds OR alfalfa OR tomatoes OR grapes)." The search was done for each crop separately. Databases Web of Science and CAB-Abstracts were the primary search engines considered in this study.

The R package "metagear"(Lajeunesse, 2016) was used to screen the abstracts, retrieve the articles, and delegate tasks. The package, coupled with a GUI, was also used to extract data from the figures of the selected papers. A total of 996 articles were downloaded from the databases, and 15 were selected after screening and full-text assessment (Fig. 1). R^2 and RMSE (Eqs. 6 and 7) were calculated to assess the model performance in predicting crop yield in different biophysical environments, such as soil type, irrigation regime, and other management practices.Fig. 2.

$$R^2 = 1 - \frac{\sum (O_i - S_i)^2}{\sum (O_i - \overline{O_i} \quad)^2} \tag{6}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2\right]^{1/2} \tag{7}$$

where S_i and O_i are the predicted and observed variables, respectively; $\overline{O_i}$ is the observed mean value, and i is each observation.

Table 1
Threshold (dS/m) and slope (%) for almonds, alfalfa, processing tomatoes, and table grape.

Crop	Threshold (dS/m)	Slope (%)	ECe50 (dS/m)	p	References
Alfalfa	2	5	12	3	Benes et al. (2018)
Almond	1.5	19	4.13	3	Maas and Grattan
Grape	1.5	9.6	6.7	3	(1999);
					Maas and Hoffman
Tomato	2.5	9.9	7.55	3	(1977a) (1977b)

Table 2
Parameters of a sandy loam soil used to compute the site-specific transpiration. K_S is the saturated hydraulic conductivity; θ_s is the saturated soil water content; θ_r is residual soil water content; ψ_w is air entry head; η, β and δ are soil physical parameters of the Brooks-Correy soil hydraulic model.

Parameters	Values[a]
K_S (mm/day)	3600
δ	4.91
β	0.55
η	2.7
θ_s (cm^3/cm^3)	0.41
θ_r (cm^3/cm^3)	0.06
ψ_w(mm)	-200

[a] (http://app.agri.gov.il/answerapp/

Table 3
Crop parameters considered in the study.

Crop	T_p (mm/day)[b]	ψ_{root} (mm)[c]
Alfalfa	6.5	-6000
Almond	8	-8000
Grape	6.5	-6000
Tomato	5.5	-6000

[c] (Šimůnek and van Genuchten, 2002)
[b] https://openetdata.org/

Table 4
Final selected papers from literature review after PSALSAR method application.

EC_{iw} (dS/m)	Crop	References
0.1 – 16.5	Alfalfa	(Lunin et al., 1964; Hussain et al., 1995; Shani and Dudley, 2001; Ayars et al., 2009; Díaz et al., 2018; Al-Farsi et al., 2020; Qiu et al., 2021)
1 – 4	Almond	(Sanden et al., 2014)
1.5 – 4.8	Grape	(Ben-Asher et al., 2006; Hepaksoy et al., 2006; Stevens and Partington, 2013)
1 – 10.2	Tomato	(Kamaluldeen et al., 2014; Prazeres et al., 2016; Wang et al., 2020)

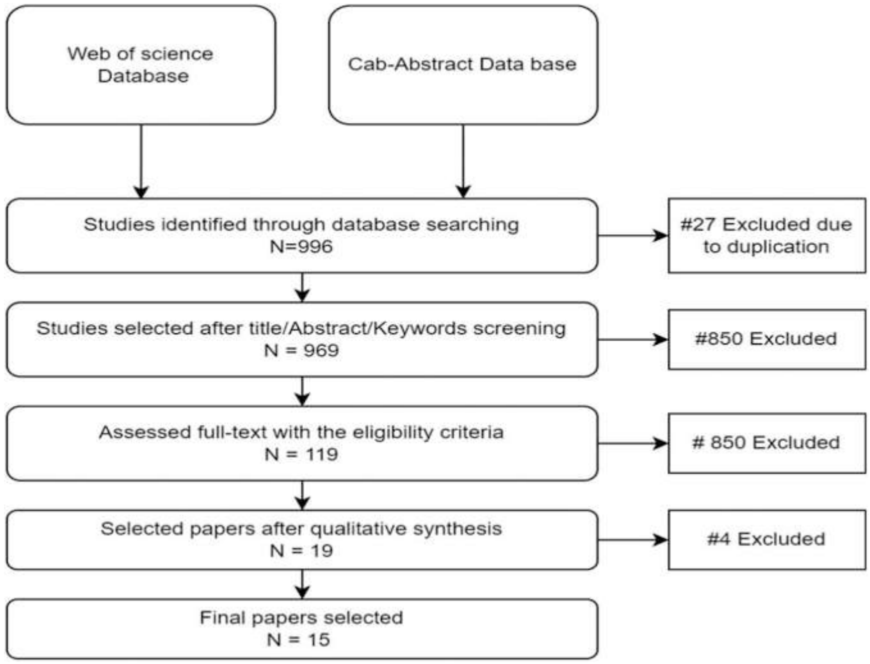

Fig. 1. Systematic literature review framework used for identification, screening, eligibility, and selection of final papers fitting the established criteria of salinity impacts on crop yield.

2.4. Economic considerations

Five economic variables, including revenue per ton ($/ton), return per ha ($/ha), yield-dependent costs ($/ha), fixed cost ($/ha), and maximum yield (ton/ha) were used to compute the potential profits (Eq. 8). All investments, including overhead and establishment costs (including the cost of old orchard removal and machinery), were incorporated into fixed costs. The fixed costs were assumed to encompass all costs of owning a field or establishing a farm (alfalfa, almond, grape, and tomato), including production, harvesting, and packaging costs. The fixed costs include operating, cash, and non-cash overhead. The irrigation water cost (water price) was considered an independent variable of interest to simulate different profits. The maximum yield was averaged over five years of historical market prices for each crop/tree considered in this study.

The profits represent the net revenue from crop yield (influenced by soil salinity and irrigation water quality) and crop prices ($/ton) (Eq. 8). The actual revenue ($/ha) is based on the relative yield, the maximum yield, amounts of land in production and the revenue per ton per ha (Eq. 9). The total costs ($/ha) encompassing fixed costs and irrigation water costs are computed using Eq. 10.

$$Profits(\$/ha) = Revenue \quad actual(\$/ha) - Costs(\$/ha) \tag{8}$$

$$Revenue \quad actual(\$/ha) = (\text{Adj } \text{Y}_\text{r} {*} 1(ha) {*} MY(ton/ha) {*} RpT(\$/ton))/HA(ha) \tag{9}$$

where $AdjY_r$ is the adjusted relative yield (unitless), *HA* is the hectare amounts (ha), *MY* is the maximum yield (ton/ha), and *RpT* is the revenue per ton($/ton).

$$Costs \ (\$/ha) = Water \ cost((\$/ha-mm) {*} (1\text{ha}-\text{mm/ha})) + Fixed \ costs(\$/ha) \tag{10}$$

Costs of establishing an orchard/farm (producing, harvesting, and orchard removal) are all incorporated into fixed costs. Expenses of non-cash overhead for an alfalfa farm include costs for establishing the field, amortized over the three-year stand life (Clark et al., 2016). The non-cash overhead includes the establishment cost of the almond orchard for the first three years, distributed evenly across the remaining 20 years of the orchard's productive lifespan. An almond orchard's yield usually varies every year before reaching 8 years (Duncan et al., 2019). For grapes, establishment costs reflect three years of investment in planting and maintaining the crop before the start of production. The total cost from the 3 years is divided into an equal cost over the remaining 22 years of the grapes' production lifespan (Fidelibus et al., 2018). The total fixed costs for producing processing tomatoes amounted to $9454/ha (Turini et al., 2018). The average maximum seasonal yield was 143 tons/ha. Economic data for alfalfa, almonds, grapes, and processing tomatoes are summarized in Table 5.

2.5. Water prices and economic returns

The cost of water is a major factor in the Central Valley's ability to produce crops. Most regions' water districts' prices are still less than $200 per acre-foot ($1.62 per ha-mm), while in certain places, it has risen to above $500 per acre-foot ($4.1 per ha-mm). Water rates in the northern half of the state are below $50 per acre-foot ($0.4 per ha-mm) and, in some districts, are around $1.00 per acre-foot (0.008 ha-mm). Rates in the southern end of the Central Valley are the highest, ranging from $1.62 to more than $4.1 ha-mm in drought years as groundwater pumping is restricted through regulations such as SGMA (https://aquaoso.com/blog/california-agricultural-water-prices/). This study considered four different water prices ($0.41 per ha-mm, $0.61 per ha-mm, $0.81 per ha-mm, and $1.22 per ha-mm) for the model simulations. Historical profits ($/ha) and crop market prices ($/tons) reported for 2013–2017 were used in the model. Considering a potential increase in the crop market price, the market price from 2017 was increased by 150%. Table 6.

2.6. Spatial component

Spatial soil hydraulic parameters were collected from the POLARIS soil series (https://gee-community-catalog.org/projects/polaris/) (Chaney et al., 2019) and cropland land use from the California Department of Water Resources (https://data.cnra.ca.gov/dataset/-statewide-crop-mapping). Total dissolved solutes (mg/l) in monitoring

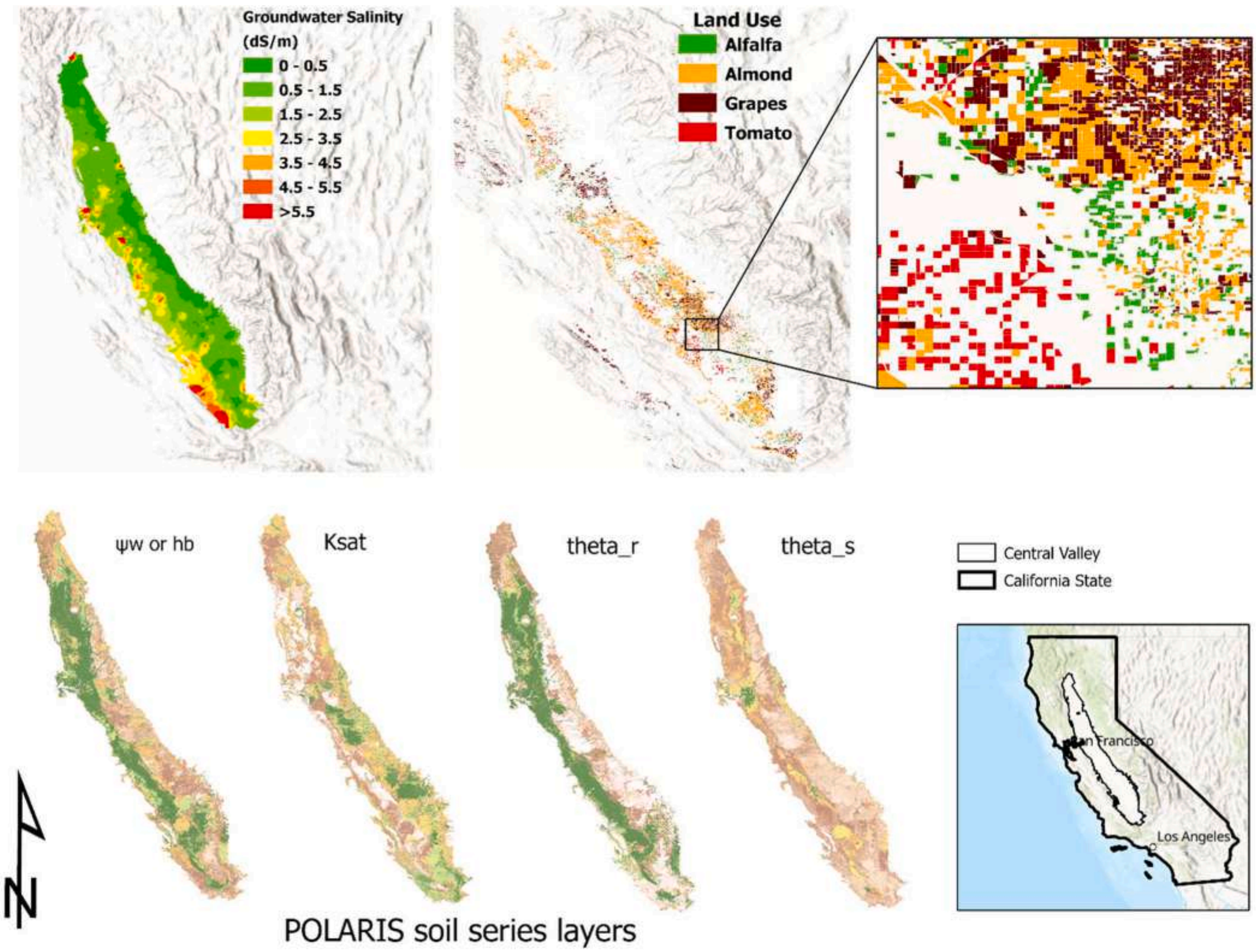

Fig. 2. Input rasters for spatial simulation of the model. At the top left, the groundwater salinity map is the spatial distribution of electrical conductivity in water in the groundwater wells. The land use of the four crops used in this study is shown at the top-right. At the bottom left, the raster layers of the soil physical parameters used to predict the spatial yield and profits are represented.

Table 5
Economics variables such as Revenue per ton ($/ton), Fixed cost ($/ha), and Maximum yield (ton/ha).

Crops	Revenue per ton ($/ton)	Fixed cost ($/ha)	Maximum yield (ton/ha)	References
Alfalfa	250	1716	24.7	Clark et al. (2016)
Almonds	4500	5096	3.7	Duncan et al. (2019)
Grapes	1789.5	21,335	30.6	Fidelibus et al. (2018)
Processing tomatoes	70.5	3826	143.3	Turini et al. (2018)

and irrigation wells (https://data.cnra.ca.gov/dataset/-statewide-crop-mapping) were used as irrigation water salinity. Four levels of daily irrigation water, such as 3, 6, 9, and 12 mm, were simulated to evaluate crop response to salinity across the entire Valley. All geospatial processing was performed using the R terra package, google earth engine and ArcGIS Pro.

3. Results

3.1. Piece-wise and s-shape salinity function

The EC_{e50} for the four crops was computed using the threshold EC (dS/m) and the slope (% per dS/m) parameters (Table 1). Almonds had the lowest $EC_{e50,}$ followed by grapes, processing tomatoes, and alfalfa. Fig. 3 shows piece-wise and s-shape plots describing the degree of salt tolerance for alfalfa, almonds, grapes, and processing tomatoes,

Table 6
Historical prices ($/tons) for alfalfa, almonds, grapes, and processing tomatoes.

Crop	2013	2014	2015	2016	2017	1.5 * (2017)	References
Alfalfa	208	225	160	155	130	195	(*https://usda.library.cornell.edu/?locale=en*)
Almond	6420	8000	6260	4780	5060	7590	(*https://usda.library.cornell.edu/?locale=en*)
Grapes	1617.5	1660	1810	1520	1480	2220	(*https://usda.library.cornell.edu/?locale=en*)
Tomatoes	70.5	83	80	72.5	70.5	105.5	(*https://www.ctga.org/Statistics*)

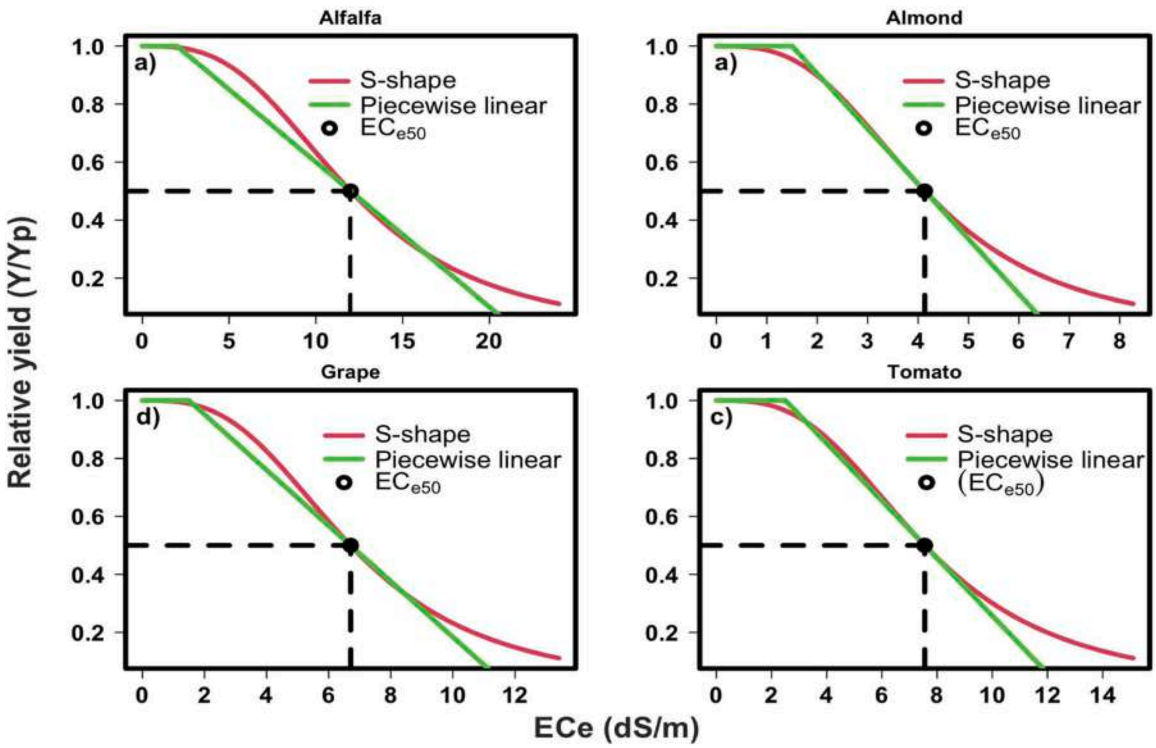

Fig. 3. S-Shape and piece-wise linear models for a) almonds, b) alfalfa, c) processing tomatoes, and d) table grapes. Soil type and ET related to environmental conditions for which the ECe50 were computed are found in Tables 3 and 4.

respectively.

3.2. Crop yield response to salinity

All four crops were affected by increasing salinity levels in the root zone in a sandy loam soil. The model predicted that an EC_{iw} level of 5.5 dS/m could decrease relative yield by up to 10%, 45%, 18%, and 12% for alfalfa, almonds, grapes, and processing tomatoes, respectively, considering irrigation water application up to 12 mm/day. The model predicted 99% of the relative yield for alfalfa, almond, grape, and processing tomato using 6.5, 8.5, 7, and 5.5 mm/day, respectively, using irrigation water with low salinity level (0.5 dS/m). However, the same daily irrigation amount with an $EC_{iw\,=}$ 5.5 dS/m showed just 76%, 50%, 70%, and 72% of the relative yield is attainable for alfalfa, almond, grape, and processing tomato, respectively (Fig. 4).

3.3. Model performance in predicting yield

Considering the model's simplicity and the associated estimated parameters (soil properties and EC_{iw}), the model predictions for yield were excellent and within acceptable limits (Fig. 5). Comparison of experimental data from different studies conducted under different conditions against the model's prediction resulted an R^2 of 0.82, 0.77, 0.78, and 0.64, with an RMSE of the relative yield of about 9%, 8%, 23%, and 11% for alfalfa, almonds, grapes, and tomatoes, respectively. (Shani et al., 2007) found R^2 of 0.94 and 0.96 for tomatoes and grapevines but did not use RMSE as a performance indicator of the model.

3.4. Salinity impacts on expected profits from crop production

Decreasing yield due to salinity affects expected economic returns. In arid and semi-arid climates, where agricultural production relies heavily on irrigation, water cost is critical to profitable crop production. At the current water price of $0.57 per ha-mm, daily irrigation with 7 mm of water ensured profit with Alfalfa, irrespective of the irrigation water salinity. For almond production, profit is only obtained with at least 9 mm/day of irrigation with water with salinity less than 2.5 dS/m (Fig. 6). Similarly, grapes production was still profitable with at least 8.6 mm/day and EC_{iw} not greater than 2.5 dS/m. As the ECiw increased from 0.5 dS/m for both almonds and grapes, more irrigation is required to maintain profitability. However, above the salinity level of 2.5 dS/m, irrigation with additional water did not generate profit even though it increased yield (Fig. 6). Processing tomatoes produced $186 per ha using 6.4 mm/day of water with EC_{iw} not greater than 0.5 dS/m, and losses occurred beyond EC_{iw} of 1.5 dS/m (Fig. 6).

Crop output depends on water quality and cost. Fig. 7 shows that alfalfa, almonds, grapes, and processing tomatoes lose profit margins as water prices increase. At $1.22 per ha-mm, alfalfa and tomatoes become unprofitable. Alfalfa production generated profits ($1,297-$356 per ha) irrespective of EC_{iw} values, with the price of water at $0.41 per ha-mm. However, profits were possible only with EC_{iw} of 0.5 dS/m, at $1.22 per ha-mm of water (Fig. 7a). Processing tomato production was only profitable when the EC_{iw} was not above 1.5 dS/m and water price of $0.41 per ha-mm. Above $0.41 per ha-mm, tomato production was barely profitable only when irrigated with EC_{iw} of 0.5 dS/m. At water price of $1.22 per ha-mm, tomato becomes unprofitable regardless of the water quality (Fig. 7d). On the other hand, high market value crops like grapes and almonds were still profitable at higher water prices. Provided that the EC_{iw} was not greater than 2.5 dS/m, almond production was still profitable even at $0.81 per ha-mm water. However, at $1.22 per ha-mm water, profits were possible only with EC_{iw} not greater than 1.5 dS/m (Fig. 7b). Similarly, Grape's production was profitable when EC_{iw} levels were not greater than 2.5 dS/m and water prices of were less than $0.41 per ha-mm. At higher water prices, profit was only possible with irrigation water EC_{iw} of 0.5 dS/m (Fig. 7c).

3.5. Assessing the model performance in predicting profits

According to the R^2 and RMSE obtained from the model predicted crop profit using five years of observed profits versus the reported

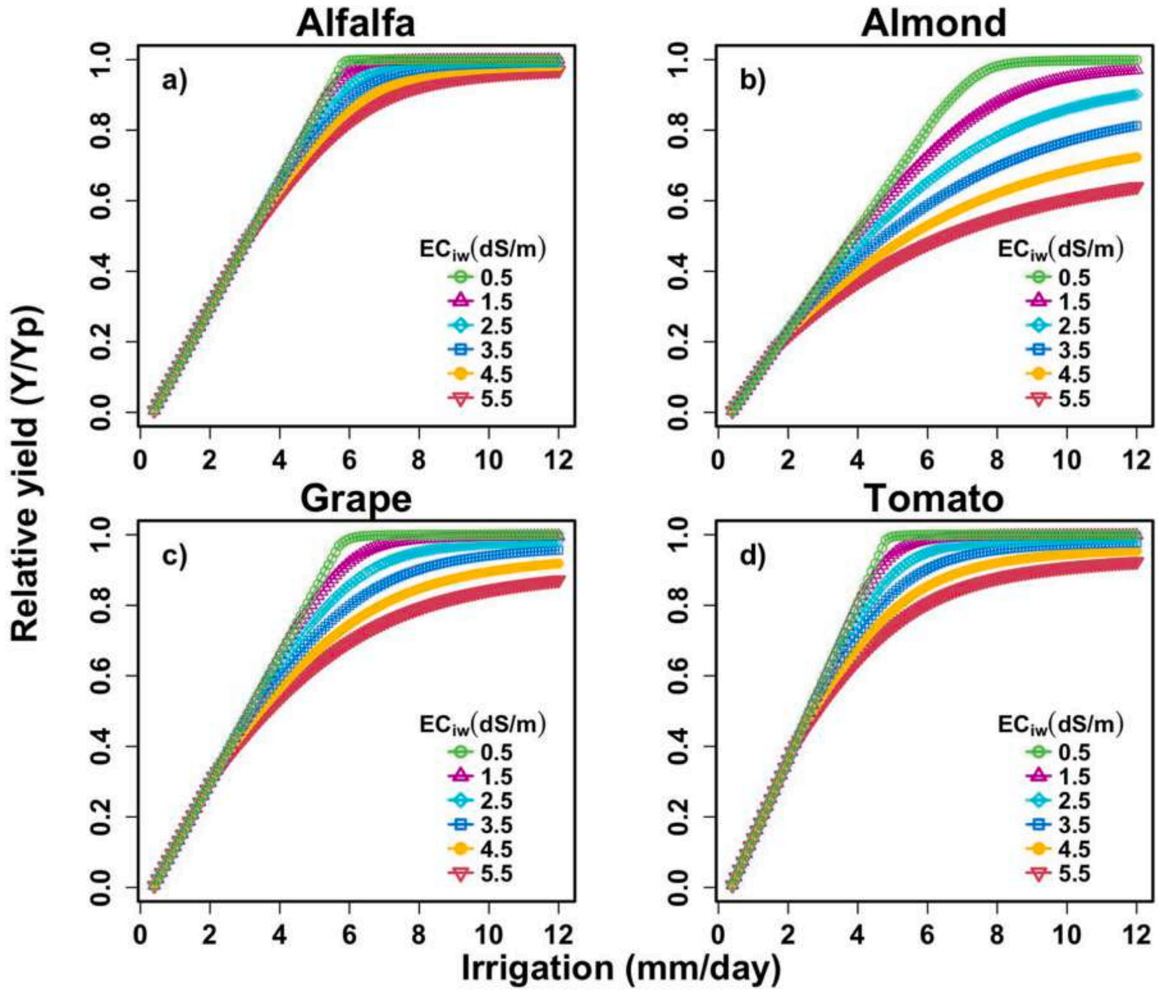

Fig. 4. Relative yield as a function of daily irrigation amount (mm/day) at different levels of irrigation water salinity EC_{wi} (dS/m) for a) alfalfa, b) almonds, c) grapes, and d) processing tomatoes. Different colors represent different salinity (EC) levels from 0.5 to 5.5 dS/m.

profits, the model has a very strong goodness-of-fit. The R^2 for alfalfa, almonds, grapes, and processing tomatoes were 0.99, 0.99, 0.74, and 0.99, respectively, while the RMSE for the simulated profits were 48, 211.39, 2461, and 68 $/ha for alfalfa, almonds, grapes, and processing tomatoes, respectively (Fig. 8).

3.6. Influence of crop market price and salinity on profitability

Crop market price determines the revenue generated from crop production and is critical to the amount of profit that can be generated. Fig. 9 shows the historical market price and profit for alfalfa, almonds, grapes, and processing tomatoes from 2013–2017 and 1.5 times the 2017 market price at various EC_{iw}. Alfalfa's market value showed a declining trend with losses recorded from 2015 irrespective of the water EC_{iw}. As water prices increased, losses were recorded even with high quality irrigation water. For almonds, production was profitable irrespective of water price, except in 2016 and 2017 when the market value of almonds was low. Even then, almond cultivation was still profitable, provided that EC_{iw} was not higher than 3.5 dS/m. Profits were possible for grapes with the market price reported in 2015 when the EC_{iw} was not greater than 2.5 dS/m. Regardless of water quality and cost, all other years resulted in net loss, except for the projected market value of 1.5 times the 2017 price. Lastly, the model indicated profit for processing tomatoes when the market value was above $80/tons (2014, 2015 and 1.5 *2017) for salinity levels between 0.5 and 5.5 dS/m, regardless of the water price per ha-mm. Other years with poor crop market values (2013, 2016 & 2017) resulted in losses, especially if irrigated with EC_{iw} greater than 1.5 dS/m. Market prices reported in 2013 and 2017 triggered profitability losses with high saline water and water prices.

3.7. Spatial distribution of predicted yields and profits

Considering groundwater salinity, the model estimated adequate yields in the Central Valley. The relative yields were less impacted in the northern and eastern portions of the Valley compared to the western and southern parts. The relative yield for alfalfa, almonds, grapes, and processing tomatoes with 3 mm of daily irrigation range from 0.20 to 0.54, 0.00–0.42, 0.18–0.54, and 0.17–0.65, respectively. However, with 6 mm/day of irrigation water, the relative yield ranged from 0.24 to 0.99, 0.00–0.82, 0.23–0.99, and 0.22–0.99 for alfalfa, almonds, grapes, and processing tomatoes, respectively. Simulations with daily irrigation amount of 6 mm allowed alfalfa and processing tomatoes to reach up to 99% of their relative yield, while almonds and grapes required at least 9 mm/day to reach that same yield level (Fig. 10).

The model prediction indicated that no profit was possible from all four crops with 3 mm/day irrigation. At 6 mm/day of irrigation, maximum profits was obtained for alfalfa and processing tomatoes. However, at higher irrigation amounts, such as 9 and 12 mm/day, the profits decreased due to the cost of the extra water and the relative yield obtained per mm of water used. Maximum profits with almonds and grapes cultivation were obtained with 9 mm/day irrigation. Similarly, application of higher amounts of water resulted in a decline in the profit

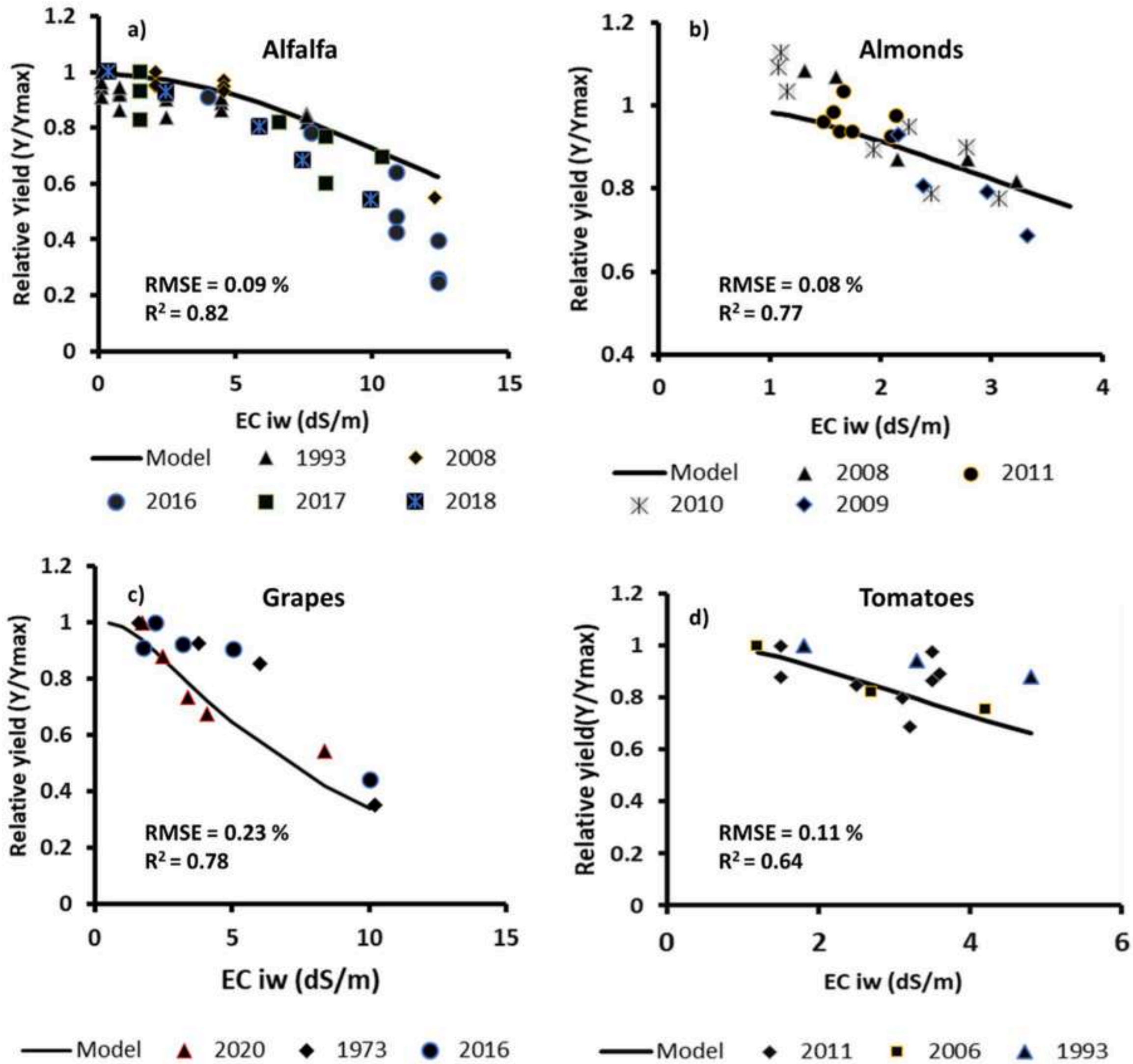

Fig. 5. Relative yield response to irrigation water salinity (EC_{iw}) for a) alfalfa, b) almonds, c) grapes, and d)tomatoes. The data points are measured yield data collected from selected papers of the systematic literature review.

margin (Fig. 11).

The model forecasted a decrease in relative yield and a reduction in the areas that can generate profits. However, 9 mm/day irrigation is projected to result in sufficient profits across the Valley, although some areas may still experience losses. Figs. 12 and 13 present the stacked data on relative yield and profits for the four crops to better visualize the distribution of salinity impacts on crop production. This allows for a more comprehensive understanding of the impact of salinity on crop production across the Valley. It is important to note that while some areas may still suffer losses, the overall profitability is expected to be satisfactory with 9 mm/day irrigation. This information can be highly valuable for farmers and decision-makers in making informed choices regarding irrigation practices and crop selection. By considering the potential salinity impacts on crop production and the corresponding profit margins, farmers can optimize their yields and minimize losses.

4. Discussion

4.1. Crop yield response to irrigation water salinity

Crops are tolerant to different salinity levels, and simplistic models have been developed to characterize crop salt response and predict their relative yield as a function of the root zone's average saturated soil extract (EC_e). Woody and vine crops such as almonds and grapes are less tolerant and demonstrate stronger response functions to salinity than agronomic crops such as alfalfa and tomatoes (Grieve et al., 2012). Crop response to salt can be effectively measured using a threshold value, denoting the maximum tolerable root zone EC_e above which yields decline and with a slope describing the rate of yield decline due to increased soil salinity beyond the threshold (Maas and Hoffman, 1977a, 1977b). The list of crop-specific parameters for the threshold and slopes was updated by Grieve et al. (2012). Steppuhn et al. (2005) assessed six non-empirical models, including both piece-wise and the discount (S-shape) models, and concluded with similar EC_{e50} values found in the studies. However, some alfalfa varieties are more salt tolerant, and recent experiments showed that a relative yield reduction of 50% can be reached at EC_e from 11 to 14 dS/m (Benes et al., 2018). With this model, we predicted the EC_{e50} to be 12 dS/m by modifying the slope and the threshold. Low salinity tolerance of almonds and grapes has been reported to adversely affect their productivity (Sandhu and Acharya, 2019; Suarez et al., 2019; Zhou-Tsang et al., 2021; Zrig et al., 2011) which is in agreement with the modeling results of this study. Tree crop salinity response can be complicated because of the influence of specific salt constituents (Christie, 1987), and woody perennials can accumulate specific ions in their tissues leading to specific ion toxicity, e.g., sodium and boron. Semiz and Suarez (2019) found tomato yield loss of up to

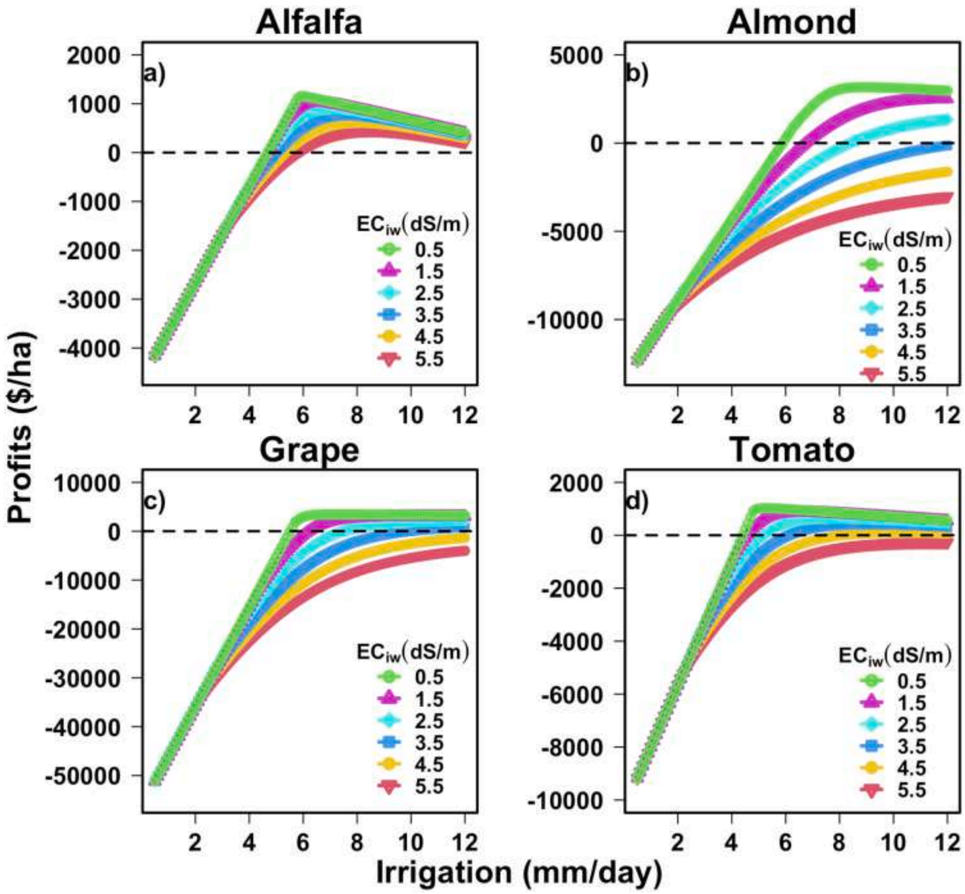

Fig. 6. Potential profits regarding irrigation water applied and irrigation water salinity (EC_{iw}). The colors represent salinity levels from 0.5 to 5.5 dS/m. An assumed average water cost in California ($70 per ac-ft $0.57 per ha-mm) was considered for computing the profits in the graphic.

50% at 5.7 dS/m, which is very similar to the one calculated by the model in this study (EC_{e50} = 5.5 dS/m).

The standard errors pertained to the threshold (EC_{e50}) range from 50 to over 100%, denoting the enormous uncertainty of these values primarily due to a lack of physiological justification (Grieve et al., 2012). The debate about a real threshold value has led to the development of s-shape models (van Genuchten and Gupta, 1993; van Genuchten and Hoffman, 1984) that are more agronomically plausible, although they have found less extensive application as the threshold model due to less intuitive appeal of the s-shape model parameters (van Straten et al., 2019). A more robust and agronomically sound threshold crop salt-tolerance parameter (EC_{e90}: soil salinity that decreases the relative yield up to 90%) was suggested as an alternative to the threshold EC_e (van Straten et al., 2019, 2021).

Alfalfa is classified as moderately sensitive to salinity beyond an ECe of 2.0 dS/m. A unit increase in salinity beyond this threshold would reduce alfalfa yield by 9.6% (Grieve et al., 2012; Maas and Grattan, 1999; Maas and Hoffman, 1977a, 1977b). Recent studies such as Cornacchione and Suarez (2017) found that alfalfa could produce high biomass (up to 77%) in high saline conditions (EC_e = 5.8 dS/m). However, this salinity tolerance might be due to a specific gene, as salinity response varies greatly among alfalfa genotypes (Sandhu et al., 2017). Alfalfa yields using irrigation water with high salinity levels (EC_{iw} of 8–11 dS/m) were found to be economically viable in the Southern part of the Central Valley (21.5 tons/ha) (Putnam et al., 2019). Such findings refute literature values estimating alfalfa yield decline at low root zone salinity (EC_e = 2 dS/m).

Almonds are sensitive to salinity, which is reflected by their low threshold EC of the soil saturation extract (ECe) of 1.5 dS/m and a growth reduction rate of 19% per unit increase in salinity beyond the threshold (Maas and Hoffman, 1977a, 1977b). Several almond orchards are damaged under conditions caused by salinity, even under the published threshold value (Sanden et al., 2014). Irrigation with high saline water (4.6 dS/m) was reported to decrease almond kernel yield by 46% compared to low saline water (0.8) dS/m) (Franco et al., 2000). Although almonds are drought-resistant, their peak performance is extremely sensitive to irrigation water quality (Prgomet et al., 2020).

Grape is considered moderately sensitive to salinity beyond an EC threshold of 1.5 dS/m and 9.9% of the yield decline rate with 1 dS/m EC increase (Grieve et al., 2012; Maas and Grattan, 1999; Maas and Hoffman, 1977a, 1977b). Paranychianakis et al. (2004) reported 50% grape yield loss when irrigated with salty water (EC_{iw} 1.9/m) as compared to freshwater (EC_{iw} 0.6 dS/m). However, long-term studies of grape yield-salinity relationships have shown the pre-eminence of particular rootstocks that allow salinity tolerance (Zhang et al., 2002). A confounding issue arises because grapevines can have a catastrophic response to long-term salt exposure as salts build up to threshold levels in woody tissues of the plants resulting in physiological damages, including vine mortality (Dag et al., 2015; Shani and Ben-Gal, 2005; Simhayov et al., 2023).

Processing tomatoes are considered moderately sensitive to salinity, with a 9.6% yield decline with one unit of increased salinity beyond the

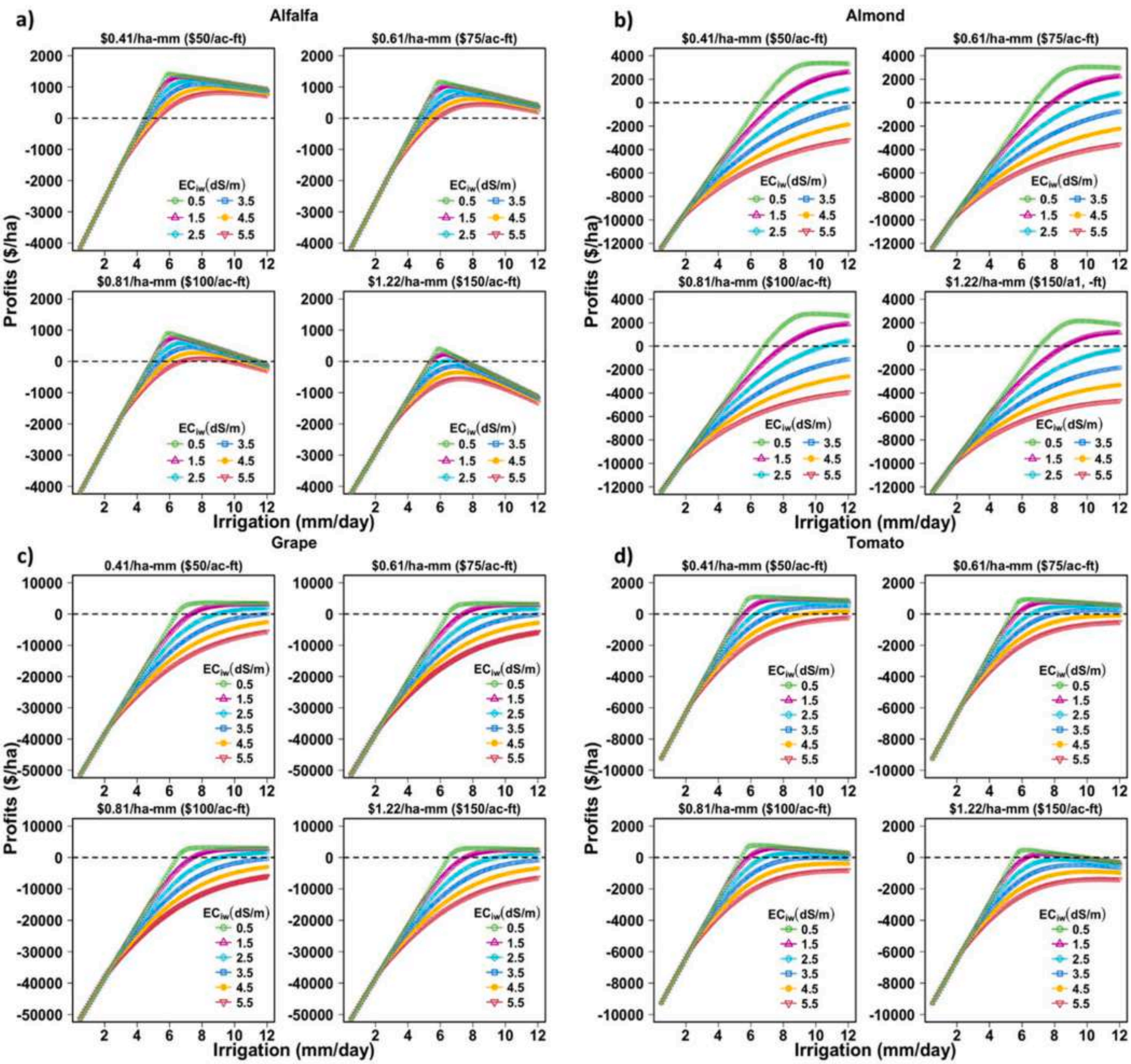

Fig. 7. Profits ($/ha) as a function of water amount at different water prices for alfalfa, almonds, grapes, and processing tomatoes. The water prices were $0.41/ha-mm, 0.61/ha-mm, $0.81/ha-mm, and 1.22/ha-mm. The colors represent the irrigation water's different electrical conductivity (ECiw) levels from 0.5 to 5.5 dS/m.

threshold EC of 2.5 dS/m (Grieve et al., 2012; Maas and Grattan, 1999; Maas and Hoffman, 1977a, 1977b). Salinity can significantly affect tomato yield by reducing vegetative growth (Tzortzakis et al., 2022). Tomato yield is reduced at ECe of 2.5 dS/m or higher, and an increase of 1 dS/m would trigger a yield reduction of up to 10% (Cuartero and Fernández-Muñoz, 1998), similar to our results. However, a salinity level (ECe) of 4.8 dS/m was found to have no significant impact on tomatoes' fruit yield and improved the quality of the nutrients contained in the fruit (Stamatakis et al., 2003).

4.2. Combined impacts of salinity, crop market prices, and water prices on economic returns

Water scarcity in California has led to the adoption of high-value crops such as fruits and nuts (Ayars et al., 2015). Under irrigation water with higher salinity values, the model predicted higher profits from crops with high market value, such as almonds and grapes. In contrast, both alfalfa and tomatoes were likely more affected by increased water prices than salinity due to their relatively low market value. The slope of the profits from alfalfa and processing tomatoes decreased slowly with the salinity increase. However, processing tomatoes profits were much more affected than alfalfa at higher salinity levels, such as 5.5 dS/m. The profits from almonds and grapes decreased substantially with the salinity levels. However, water prices and salinity levels affected almond profits less than grapes (Figs. 9 and 10). This might be due to the almond sale prices. Almond's revenue overtook processing tomatoes by providing much more profits in many Counties of the State of California (Smith, 2018). Gebremichael et al. (2021) investigated cropping patterns in California's Central Valley in response to droughts. They concluded that the shift in cropping patterns was probably due to increasing crop prices and changes in pumping costs. These findings agree with our study results predicting higher profits

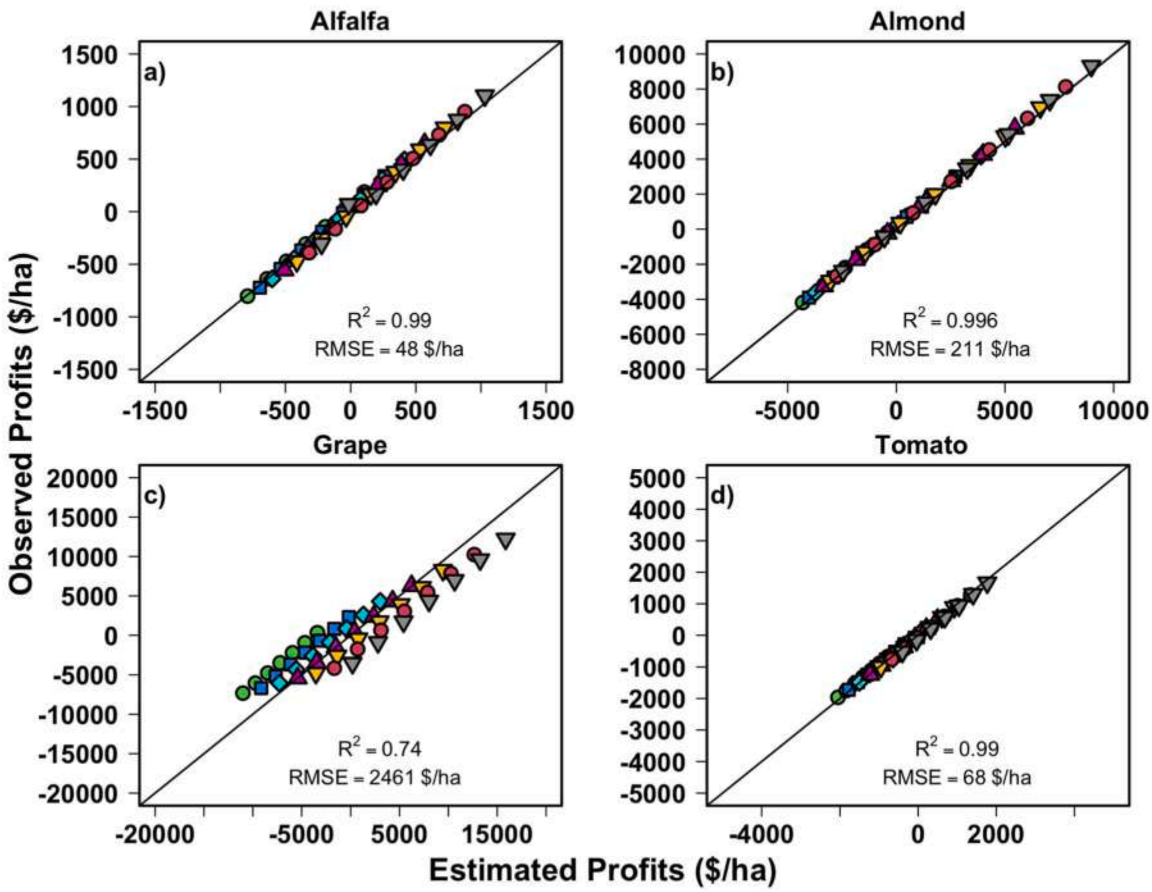

Fig. 8. Assessing model performance against observed data for a) alfalfa, b) almonds, c) grapes, and d) processing tomatoes.

from crops with high market value while predicting lower economic returns from crops with low market values, although with a relatively mild response to salinity.

Similar findings were generated by the same model for a case study evaluating the feasibility of brackish groundwater desalination for irrigation in southern Israel (Kaner et al., 2017). In that study, high-value, salinity-sensitive crops (date palms and table grapes) were found to justify the costs of desalination as an alternative to irrigation with local water high in salts.

The model predicted a decrease in revenues, similar to other studies assessing salinity impacts on economic outcomes in the Central Valley (Medellín-Azuara et al., 2014; Montazar et al., 2017; Wichelns and Oster, 2006). Integrated biophysical models with soil and irrigation water salinity and economic data can be used as decision-support tools for salinity management. Kaner et al. (2019) implemented a web-based decision support system that returns yield and economic gains from crops considering irrigation water salinity and market price scenarios with environmental considerations. Increases in water prices or salinity were predicted to significantly negatively affect farmers' incomes. Welle and Mauter (2017) estimated that salinity reduced agricultural revenues by $3.7 billion (in 2014) using a generalizable approach to estimate the agricultural yield losses due to soil salinization. When the Delta water is more saline during dry years, dual export conveyance gives the highest revenue losses, roughly $4.5 billion annually. Under the future groundwater pumping regulations in the Central Valley, water supplies may not be sufficient to meet water demands and trigger losses by up to 30% of total annual revenues in the Valley (Mall and Herman, 2019). Major crops such as almonds, alfalfa, and grapevine have a significant water footprint in the Central Valley (Fulton et al., 2019), and their economic returns can be severely affected by high water prices in drought periods. The paradox projected declines in water supplies for irrigation in the Central Valley of California would exacerbate salinity problems because there will be less water leaching salts out of the root zone.

4.3. *Significance and limitations of the model*

The success of the model is remarkable, considering its simplicity and dependence on major assumptions. The assumption of steady-state conditions may limit its validity to environments where much of the irrigation season is without significant precipitation and where advanced irrigation scheduling and water is supplied regularly as a constant function of potential evapotranspiration. Pseudo-steady state conditions were found to be the case for date palms grown in lysimeters in Israel (Tripler et al., 2012). The assumption that economic return can be predicted by simulation of vegetative growth (transpiration) is also questionable, obviously crop-specific, and not always validated in cases where vegetative and reproductive growth are not linearly related. While these may necessitate caution in using the model, its success under advanced irrigated agriculture conditions in Israel and California boosts confidence in its potential as a planning and analysis tool.

5. Conclusion

The findings of this study shed light on the significant impact of irrigation water salinity on the sustainability of irrigated agriculture, in the form of reduced crop yields and profitability. Salinity is a global problem with approximately 30% of irrigated lands being salt-affected due to human-induced salinization. In the Central Valley, more than 2 million hectares of irrigated cropland are affected by salinity arising from saline irrigation water or saline soil. The depletion of groundwater resources further exacerbates salinization in certain areas of the Central

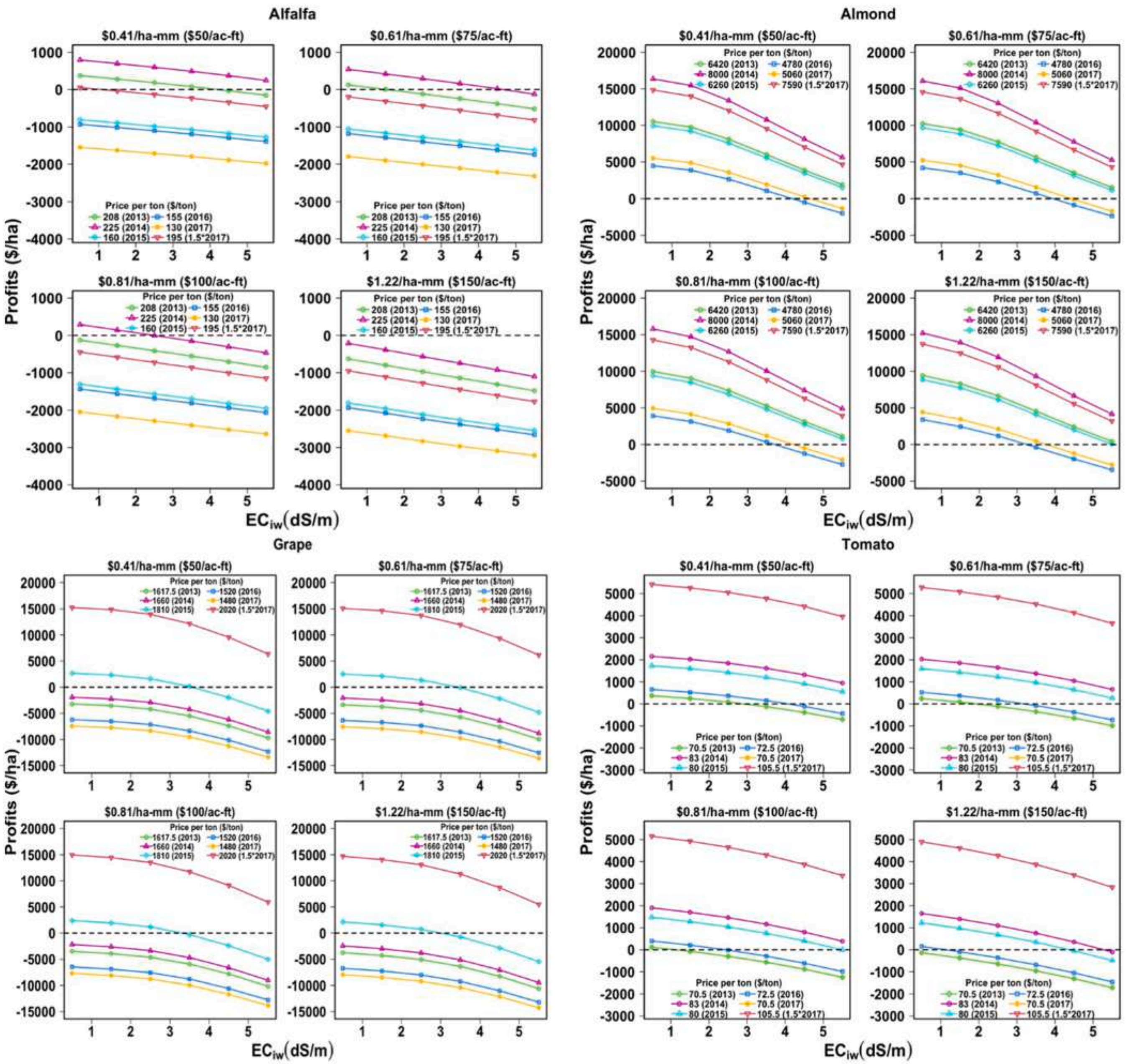

Fig. 9. Expected profits ($/ha) as a function of ECiw for alfalfa, almonds, c) grapes, and processing tomatoes under different water prices ($50 per acre-ft or $0.41 per ha-mm, $75 per acre-ft or 0.61 per ha-mm, $100 per acre-ft or $0.81 per ha-mm, and $150 per acre-ft or $1.22 per ha-mm). The colors represent the different crop prices.

Valley.

Given the influence of profitability on grower management decisions, it is crucial to establish a comprehensive integrated framework for sustainable management of irrigation water salinity. To address this challenge, the study developed a unique framework that integrates biophysical modeling, economic analysis, and geospatial modeling. This framework enables a comprehensive assessment of the impact of irrigation water salinity on crop yield and profitability.

The framework was applied to evaluate the effects of salinity on major crops cultivated in the Central Valley, including alfalfa, almonds, grapes, and processing tomatoes. A notable feature of the modeling framework was its ability to incorporate site-specific soil and groundwater quality information to assess the impacts on crop yield and profitability. This detailed assessment provided valuable insights into the sustainability of irrigated agriculture in the Central Valley, which is one of the world's most vital agricultural regions.

The study revealed that economic revenue decreases as irrigation water salinity and the cost of water increase. However, even under elevated salinity levels and increased water costs, agricultural activities can remain profitable, particularly when cultivating high-value crops such as almonds and grapes. Moreover, the framework's capability to account for spatial variations in soil properties and groundwater quality enables predictions of regional differences in salinity impacts on crop yield and profitability. Negative impacts were found to be more pronounced on the Westside of the Central Valley.

The spatial predictions derived from the modeling framework can assist in prioritizing lands for potential retirement from irrigated agriculture, especially in regions where groundwater supplies face constraints, as observed under public policies such as the Sustainable Groundwater Management Act (SGMA) in the case of California. While

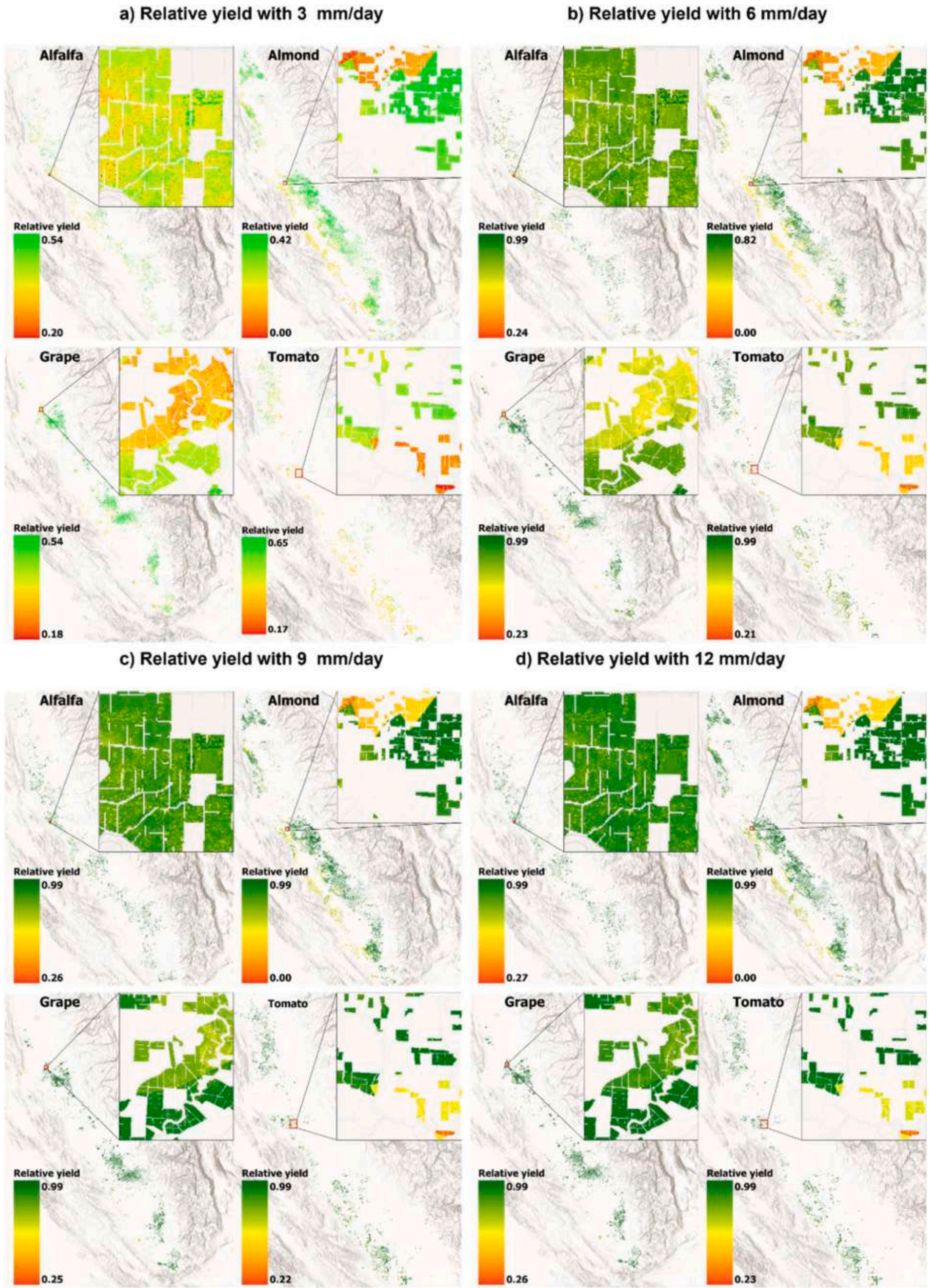

Fig. 10. Spatial distribution of relative yield across the Central Valley for alfalfa, almond, grape, and processing tomatoes considering groundwater salinity status. a-d represent irrigation amount of 3, 6, 9, and 12 mm/day, respectively.

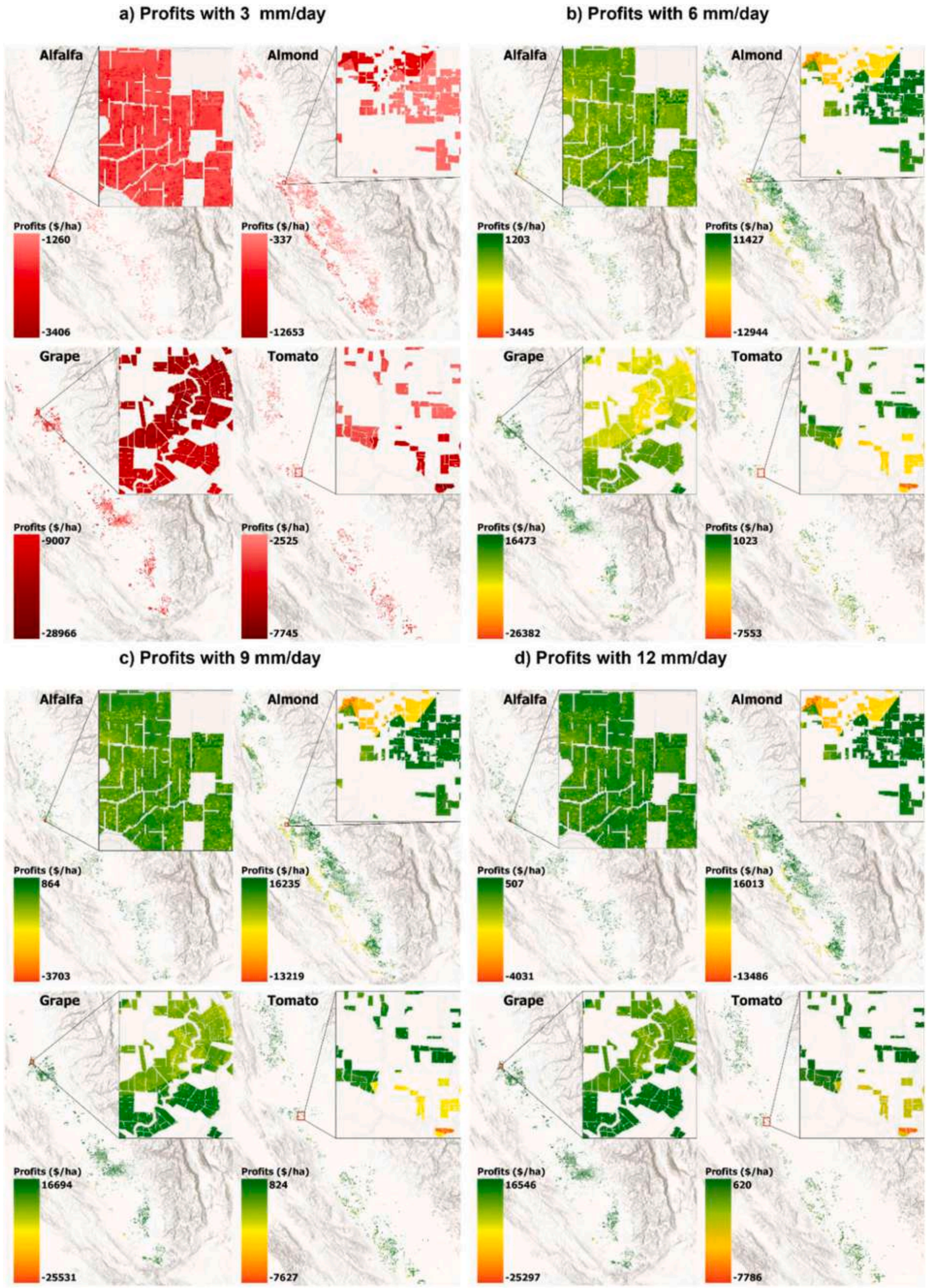

Fig. 11. Spatial distribution of profits across the Central Valley for alfalfa, almond, grape, and processing tomatoes, considering groundwater salinity status. a-d represent irrigation amount of 3, 6, 9, and 12 mm/day, respectively.

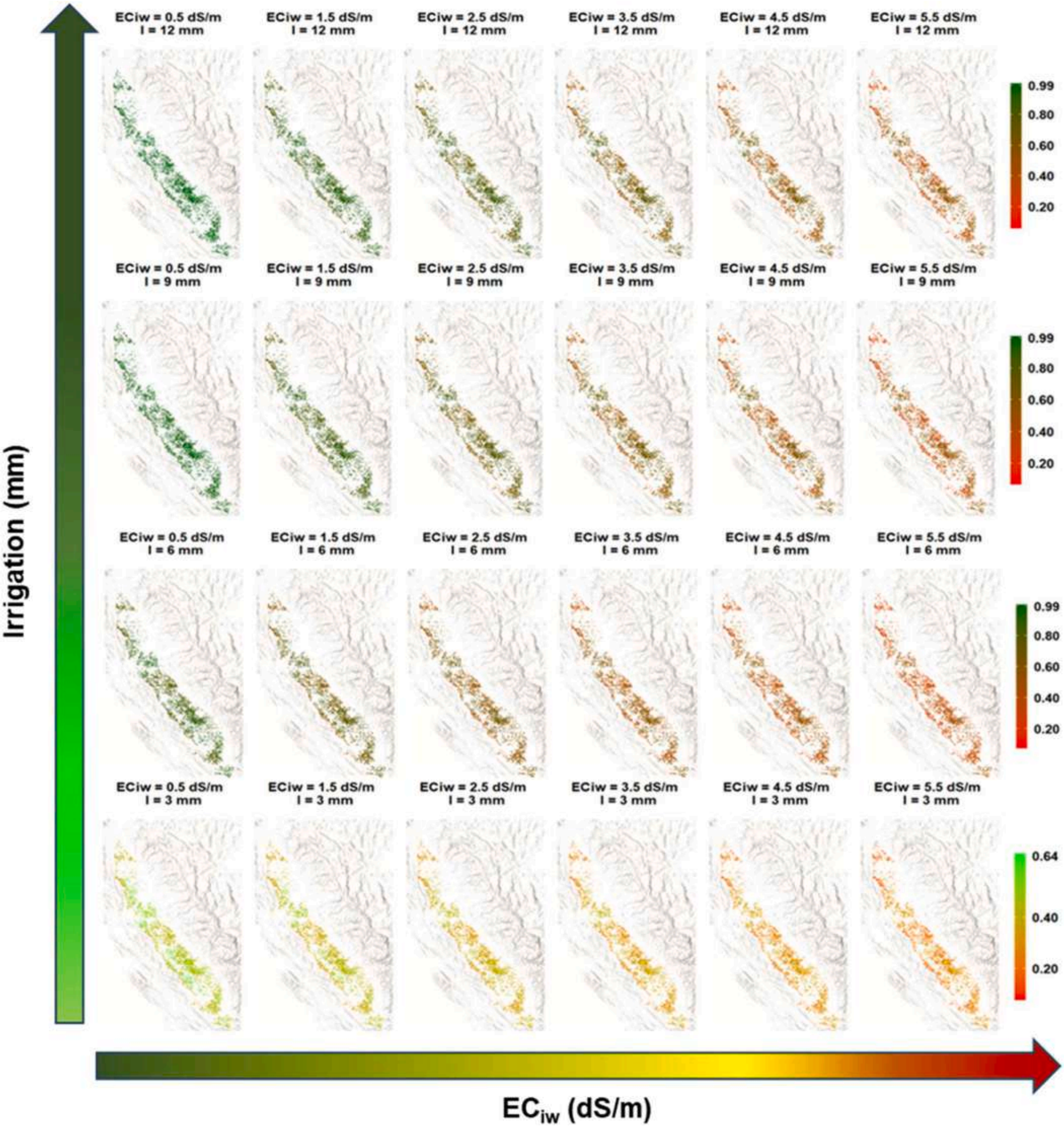

Fig. 12. Spatial distribution of the relative yield for alfalfa, almond, grape, and processing tomatoes across the Central Valley considering 3, 6, 9, and 12 mm/day irrigation. Water application doses are presented from 3 to 12 from top to bottom and increasing EC_{iw} from 0.5 to 5.5 dS/m from left to right. Crop relative yields are grouped to show the impacts of salinity and irrigation amount on crop yield across the Valley. The color bars, from green to red, illustrate decreasing relative yield as EC_{iw} increase.

this study focused on the Central Valley, the integrated modeling framework can be applied to any region worldwide grappling with salinity issues and their impact on irrigated agriculture productivity and economic outcomes.

Furthermore, the developed modeling framework, implemented in R, is publicly available and can be utilized by various stakeholders including policymakers, agricultural consultants, extension professionals, economists, agronomists, engineers, and water managers. Its availability facilitates informed decision-making and the development of sustainable strategies to address salinity-related challenges in irrigated agriculture.

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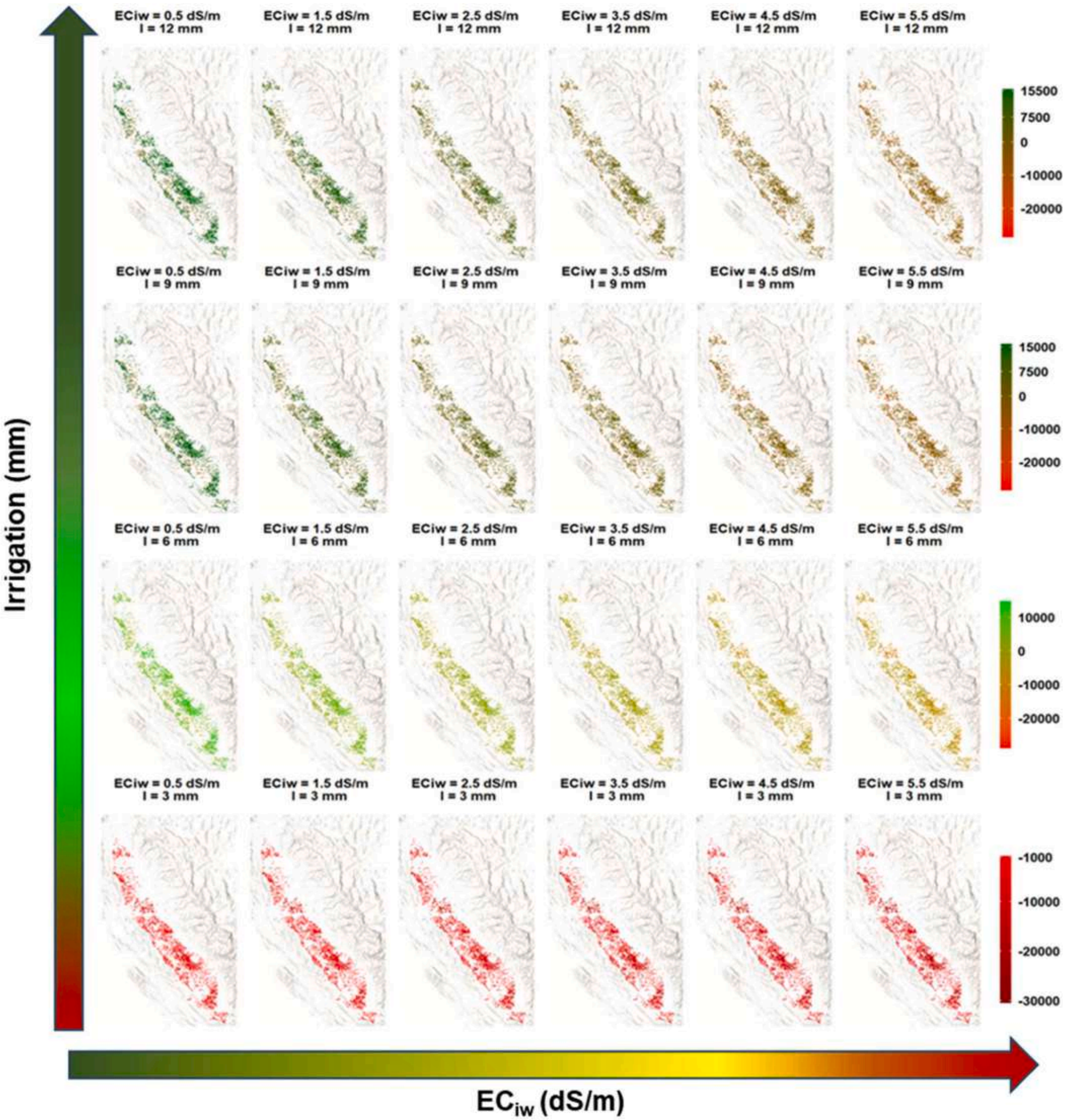

Fig. 13. Spatial distribution of the relative profits for alfalfa, almond, grape, and processing tomatoes throughout the Central Valley considering 3, 6, 9, and 12 mm/day irrigation. Water application doses are presented from 3 to 12 from top to bottom, and increasing EC_{iw} from 0.5 to 5.5 dS/m from left to right. Predicted profits for all four crops are grouped to show the impacts of salinity and irrigation amount on crop production across the Valley. The color bars, from green to red, illustrate decreasing relative yield as EC_{iw} increase.

CRediT authorship contribution statement

Floyid Nicolas: Conceptualization, Methodology, Coding, Writing – original draft, Visualization. **Tamir Kamai**: Writing – review & editing. **Alon Ben Gal**: Writing – review & editing. **Jose Ochoa-Brito:** Coding. **Andre Daccache**: Writing – review & editing. **Felix Ogunmokun**: Writing – review & editing. **Isaya Kisekka**: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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