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RESEARCH ARTICLE

An invisible water surcharge: Climate warming increases crop water demand in the San Joaquin Valley's groundwater-dependent irrigated agriculture

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Abstract

California's bountiful San Joaquin Valley (SJV), a critical region for global fruit and nut production, has withstood two severe, multi-year droughts in the past decade, exacerbated by record-breaking high temperature and evaporative demand. We employed climate data and crop coefficients to estimate the crop water demand in the SJV over the past forty years. Our approach, using crop coefficients for Penman-Montieth modeled evapotranspiration, focused on the climate effects on crop water demand, avoiding the confounding factors of changing land use and management practices that are present in actual evapotranspiration. We demonstrate that increases in crop water demand explain half of the cumulative deficits of the agricultural water balance since 1980, exacerbating water reliance on depleting groundwater supplies and fluctuating surface water imports. We call this phenomenon of climate-induced increased crop water demand an *invisible water surcharge*. We found that in the past decade, this *invisible water surcharge* on agriculture has increased the crop water demand in the SJV by 4.4% with respect to the 1980–2011 timeframe—more than 800 GL per year, a volume as large as a major reservoir in the SJV. Despite potential agronomic adaptation and crop response to climate warming, increased crop water demand adds a stressor to the sustainability of the global fruit and nut supply and calls for changes in management and policies to consider the shifting hydroclimate.

1. Introduction

California is a key contributor to the global supply of fruits, nuts, and vegetables, producing 81% of the world's almonds, 42% of the world's pistachios, and 26% of the world's processing tomatoes [1–3]. California's fruit and nut production is concentrated in the San Joaquin

Github (https://github.com/kdrechsler2/Ag-Tax) and can be run in Octave (open access) or MATLAB. Spatial analyses were restricted to California Department of Water Resources sub-basin boundaries denominated as Planning Areas 606, 607, 608, 609, 702, 703, 704, 705, 706, 708, 709, and 710 described here https://data.cnra.ca.gov/dataset/ca-gw-basin-boundary-descriptions. These largely comport with the 15 groundwater basins used by Escriva-Bou et al. 2023. Map data sources for Fig 1 are cropping from CNRA as above; California State Outline from TIGER 2016 United State Census Bureau; and Global base map from Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community.

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Valley, which has a Mediterranean climate ideal for fruit and nut production. These crops require significant irrigation provided by a combination of surface and groundwater sources, the latter of which has been overdrafted for over a century in parts of the state [4]. The amount of cumulative groundwater loss in California's Central Valley during 2003–2021 was comparable to the total surface storage of major reservoirs in the state (roughly 62,000 GL) [5]. Overallocated surface water supplies and groundwater overreliance to meet agricultural water demands have resulted in many negative impacts such as land subsidence [6], dry wells [7, 8], and land fallowing [9, 10], which highlight the unsustainable nature of current agricultural practices [11, 12]. To address groundwater overdraft impacts and increase resilience to future droughts, the California legislature enacted the Sustainable Groundwater Management Act in 2014 [13], which is meant to bring groundwater basins into balance.

While groundwater levels in the southern portion of the San Joaquin Valley (SJV) have been declining for more than a century [14], the pace of decline has accelerated in the past two decades [5]. This acceleration of groundwater depletion coincided with multi-year to multi-decadal droughts that have been among the most extreme in a millennium [15–17]. These recent droughts have been characterized as hot droughts where below-normal precipitation is accompanied by also higher evaporative demand that exacerbates drought impacts [18]. While there are no significant long-term trends in precipitation in California, the state has warmed by 1.6˚C since 1900 and annual evaporative demand has increased by approximately 100 mm during the past four decades [19] contributing to increased aridity and impacts on water resources. A critical, yet understudied, aspect of the water budget is the role of increased evaporative demand on crop water demand and consumptive use in the Central Valley's irrigated agriculture.

Sustainable water management is of particular importance in the southwestern US given the dual stressors of climate change and overallocation of water resources [20]. Prior studies have examined climate-induced changes in water supplies from precipitation [21] and snowpack [22], and their collective influence on the seasonal availability of water for irrigated agriculture [23]. Likewise, the demand side of the water budget through changing evaporative demand with climate change will impact ecosystem disturbance [24, 25], water resources [26], and drought [27, 28]. Earlier studies at various scales have examined projected changes in irrigation requirements due to climate change [29–34], yet their applicability to California characterized by rather diverse set of crops including specialty perennial crops is limited. Similar studies for California [35] overlay projected cropping patterns, climate projections, supplemental pumping to fully offset interannual shortage, soil salinization, and potential phenological response in the western SJV, which merits revisiting in light of new groundwater regulation and better understanding of the water balance elements for planning. Other studies have coupled this increased demand with other anthropogenic drivers such as increasing human population [36]. More often, however, climate warming-induced increases in crop water demand and evapotranspiration loss are embedded within larger hydroclimatic modeling exercises that couple climate projection-perturbed crop water demands and cropping factors [37]. Plant physiological responses to increased air temperature and elevated carbon dioxide as related to water use efficiency have been studied [38], but fewer studies have examined the climate change-induced increases in crop water demand. Given the complexities of agronomic and ecological feedbacks, including but not limited to phenology, disease, and agricultural practice, this area of research remains understudied and carries high uncertainty [39].

In this study, we quantify the role of observed changes in climate on crop water demand in California's SJV, independent of changes in land use and management practices. We present the climate change-induced change in crop water demand in the context of the agricultural water budget during the past four decades. We conclude by characterizing these results as an *invisible water surcharge* on our global food system, joining other pervasive human-induced impacts to the Earth where many effects are pervasive but not immediately visible, including groundwater depletion [40], ocean acidification [41], soil degradation [42], and biodiversity loss [43].

2. Materials and methods

2.1 Study area

The SJV study area is bounded by the San Joaquin River and Tulare Lake Basin hydrologic regions, which have the subject of research on water balance studies [14, 44, 45]. The SJV region in this study covers 3.6 million hectares of land and around 1.8 million ha of irrigated cropland [44] and is home to seven of California's top ten producing counties in a state generating over $54.5B in gross agricultural receipts, the highest in the US and accounting for 11% of the national share [46]. Within the SJV, Fresno, Kern, and Tulare Counties are three of the US's leading counties in agricultural sales [47]. As of 2018, the SJV's farmland was 28% almonds (437,516 ha), 11% pistachios (169,163 ha), 10% vineyards (164,914 ha), 6% citrus (98,906 ha), 6% cotton (97,691 ha), 5% alfalfa (84,840 ha), 4% processing tomatoes (60,545 ha), and 30% (466,419 ha) all other crops, respectively (Fig 1). The SJV is an important focus region for several reasons, not least of which is its importance to the global food supply, where

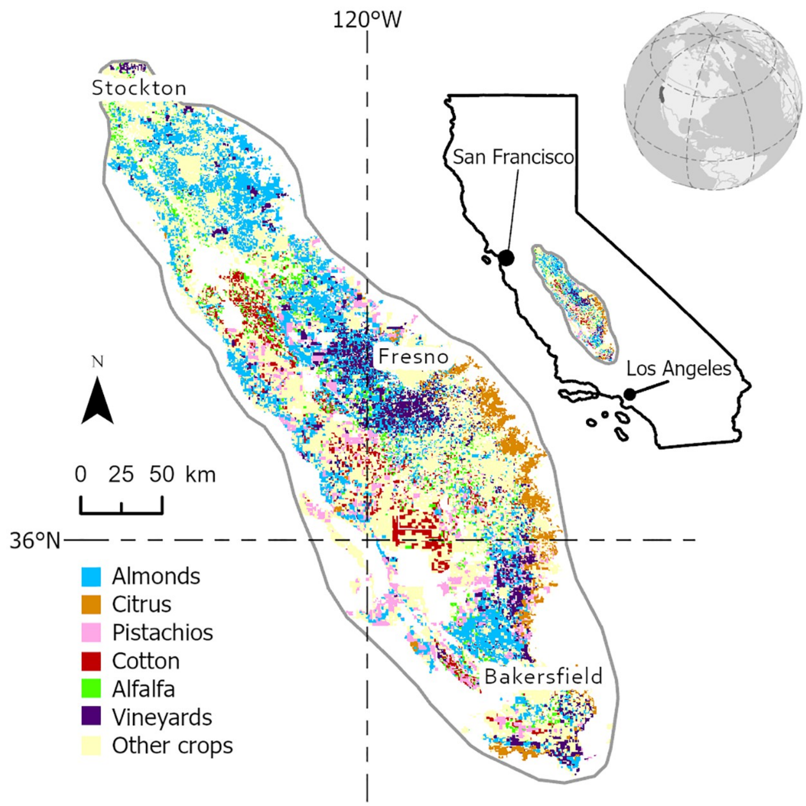

Fig 1. Map of the crop area of the San Joaquin Valley, showing the areas of almonds (blue), citrus (orange), pistachios (pink), cotton (red), alfalfa (green), vineyards (purple), and all other crops (yellow). Map data sources are Cropping from California Natural Resources Agency; California State Outline from TIGER 2016 United State Census Bureau; and Global base map from Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community.

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California's export crop trade accounts for \$6.3B to Asia and \$3.5B to Europe [48]. None of this agricultural productivity would be possible without the irrigation supply provided by a vast and intricate statewide water supply capture, storage, and delivery system network. Agriculture in the SJV consumes an annual average of 17,880 GL, with water imports to the SJV averaging 4000 GL and an additional 2200 GL in groundwater overdraft [14]. Given this water imbalance, climate warming is expected to affect both water availability and demand by agriculture in this region [44].

2.2 Estimation of crop evapotranspiration

We followed the crop coefficient approach described by the FAO-56 irrigation and drainage paper [49] for calculating the potential crop evapotranspiration (ET_c) which we will summarize in this section. First, it is important to clarify that we define ET_c as the evapotranspiration that would occur under standard optimal growing conditions and full production [49]. ET_c differs from actual evapotranspiration (ET_a) which is modulated by crop management (e.g., irrigation practices). We acknowledge that ET_c differs from ET_a, and we are not suggesting that they are equal, but rather that ET_c represents potential ET under well-watered conditions. By focusing on ET_c, we isolate the climate change effects on the agricultural water budget without concern about variations in crop management over the study period from 1980 to 2023. We chose not to look at ET_a for two reasons: (1) lack of long-term ET_a data from the last four decades in the SJV, and (2) irrigation management practices have changed in the last four decades, making it difficult to differentiate the climate change effects from changes in management practices effects on ET_a. While SJV agricultural landscapes have changed substantially in cropping mix in recent decades (e.g., perennial crop acreage expansion over annual crops [50]), we focus on climate contributors using a static 2018 agricultural land use for our ET_c baseline calculations.

Here, we go into detail about the approach for calculating ET_c. The first step to using this method is to calculate the grass-based reference evapotranspiration (ET_o) using the American Society of Civil Engineers (ASCE) standardized Penman-Monteith (PM) equation [51] (shown by Eq 1).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{(T+273)} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o is the reference evapotranspiration [mm day^{-1}], R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [˚C], u_2 is the wind speed at 2 m [m s^{-1}], e_s is the saturation vapor pressure [kPa], e_a is the actual vapor pressure [kPa], $e_s - e_a$ is the saturation vapor pressure deficit [kPa], Δ is the slope of the vapor pressure curve [kPa ˚C^{-1}], and γ is the psychometric constant [kPa ˚C^{-1}]. This version of the Penman-Monteith equation defines the reference crop as a hypothetical crop with a height of 0.12 m, a surface resistance of 70 s m^{-1}, and an albedo of 0.23, which resembles a well-watered smooth green grass of uniform height [49].

The data for calculating ET_o using Eq 1 was from gridMET. The gridMET gridded dataset includes daily surface meteorological data at ~4 km resolution (1/24th degree) across the contiguous United States, starting from 1979 [52]. The primary climate variables include maximum daily air temperature, minimum daily air temperature, precipitation accumulation, downward surface shortwave radiation, wind velocity, specific humidity, maximum daily relative humidity, and minimum daily relative humidity. These climate variables are used to derive the grass reference evapotranspiration (ET_o) using [49] Eq 1, also included in the gridMET dataset. While gridMET is one of several datasets for estimating gridded ET_o, others have shown largely similar variability and trends in the SJV region [19].

The next step of the crop coefficient method for determining ET_c is to employ a five-point crop coefficient model (K_c), which simulates the four major crop development stages, initial (constant K_c), rapid growth (increasing K_c), mid-season (constant K_c), and late season (decreasing K_c), for 17 major crop categories in the San Joaquin Valley, namely grain, rice, cotton, corn, dry beans, safflower, alfalfa, processing tomatoes, cucurbits, onions and garlic, potatoes, truck crops, other field crops, almonds, and pistachios, other deciduous trees, citrus and subtropical, and vineyard. The K_c values and typical dates of development stages were obtained from the California Department of Water Resources [53]. Static typical dates of development stages were used instead of dates based on year-to-year variability. We note that changing crop phenology associated with climate variability and change may complicate this assumption. Warming may in some cases hasten crop maturation [54] and reduce the number of days irrigation is needed [55]. Likewise, warmer and longer growing periods may enable management strategies such as double cropping that may increase irrigation needs [56], or increasing cropped acreage and subsequent water demand [57]. Herein, we constrain our focus to static crop phenology to avoid confounding phenological and management influences on changing crop water demand. The daily K_c values for each crop development stage of each crop category are reported by California Detailed Analysis Units (DAU), which are sub-boundaries within the SJV. The K_c values for rice, alfalfa, processing tomatoes, corn, onions, almonds and pistachios, vineyard, and citrus and subtropical were developed by measuring ET using eddy covariance or surface renewal methods at sites in California (personal communication with DWR staff). The K_c values for all other crops were obtained from FAO-56 [49].

We employed main season summer crop land use data from the 2018 Land IQ land use survey [58], which claims a 95% accuracy by combining remote sensing, statistical, and temporal analysis techniques. Land use from 2018 was used instead of dynamic land use as other spatial data (e.g., Cropland Data Layer [59]) are unreliable for California because of high proportions of specialty crops [60], and the 2018 snapshot is a conservative estimate [9]. By keeping land use constant, we controlled for the effects of the land use changes on ET_c and focused on the climate change effects on ET_c.

Crop evapotranspiration (ET_c) under well-watered, optimal management conditions were simulated using the FAO-56 single crop coefficient equation, by multiplying total ET_o (in mm) from gridMET and the single crop coefficient K_c [49]. To obtain a single K_c coefficient, we first calculated a monthly K_c, by averaging the daily K_c values by month for each crop category, to account for crop phenology. We then calculated a weighted mean K_c based on weights of the area of each crop category i (w_i) in each DAU, using Eq (2):

$$w_i = \frac{Crop\ Area_i}{DAU\ Area} \tag{2}$$

For every DAU and each month, a w_i weighted mean K_{cw} was calculated and the $K_{c,i}$ for each crop category i over the total of crops n:

$$K_{cw} = \frac{\sum_{i=1}^{n} \left(K_{c,i} \times w_i\right)}{\sum_{i=1}^{n} w_i} \tag{3}$$

Gridded monthly totals of ET_o from gridMET were clipped and averaged by the study area boundary. Monthly total ET_c was calculated using average SJV monthly K_{cw}, average SJV monthly total ET_o, and the single crop coefficient approach using Eq (4) [49]:

$$ET_c = K_{cw} \times ET_o \tag{4}$$

The total ET_c was summed on an annual water-year basis (running from October 1 of the previous calendar year through September 30). For example, water-year 1980 is from October 1, 1979, to September 30, 1980. Gridded monthly totals of precipitation (P) from gridMET were clipped by the study area boundary and then summed on an annual water-year basis to produce annual water-year total P.

2.3 Selection of the baseline period

We identified 2012 as the starting point for recent observations using a breakpoint analysis of ET_c timeseries [61]. This date also corresponded with the start of the first multi-year drought of the past decade. The period preceding 2012 (water-years 1980–2011) was used to define the baseline. The mean annual water-year total ET_c and P between 1980 and 2011 were calculated to produce the baselines. The baselines averaged across the extent of the SJV were 1,014 mm/year for ET_c and 262 mm/year for P.

2.4 Wilcoxon rank sum test

A Wilcoxon rank-sum test was conducted for determining whether the ET_c was significantly higher in 2012–2023 compared to the baseline period. The same test was also applied for P and vapor pressure deficit (VPD). The ET_c, P, and VPD were separated into the baseline period (1980–2011) and the 2012–2023 period. The non-parametric Wilcoxon rank-sum statistic tests the null hypothesis that two samples belong to the same distribution (i.e., no significant difference in ET_c between the baseline period and the 2012–2023 period). The alternate hypothesis is that the values in one sample group have a higher probability to be greater than the values in the other sample (i.e., there is a significant difference in ET_c between the baseline period and the 2012–2023 period). The p-value was calculated for each Wilcoxon rank-sum statistic and was considered statistically significant if less than 0.05 (5% significance level).

2.5 Linear regression analysis

A linear regression analysis was performed to determine the interannual relationship between ET_c and P in the SJV. The motivation behind this analysis was to quantify any shift in the relationship between ET_c and P between the two periods. The land-surface coupling between surface temperatures–a key driver of ET_c–and P is widely recognized. We examined this relationship over the two periods (1980–2011 and 2012–2023) to assess whether changes in P alone account for changes in ET_c. The regression model is shown in Eq 5.

$$ET_c(t) = \beta_0 + \beta_1 P(t) + \beta_2 BP_{WY2011} + \varepsilon_i \tag{5}$$

where β_0 and β_1 are the parameters estimated through the least-squares method, representing the baseline relationship between ET_c and P. The term t denotes the water-year. The coefficient β_2 captures the shift in ET_c associated with the post-2011 period, as indicated by the breakpoint variable BP_{WY2011}. This term factors for changes in ET_c attributable to the transition across the breakpoint. The random error term is represented by ε_i. Notably, tests for variable interaction within this model indicated no significant differences in the slope coefficients (i.e., β_1) between these periods, suggesting a consistent effect of P over time.

2.7. Anomalies calculations

Anomalies in the annual water-year total (P—ET_c) were calculated as the difference between annual water-year total (P—ET_c) and the mean annual water-year total (P—ET_c) between 1980 and 2011. The cumulative annual anomalies in climate variables can be helpful to describe the chronic spells of anomalous moisture deficits and surpluses [62]. The cumulative annual anomalies of (P—ET_c) were calculated for the water-years of the analysis period with the summation starting at water-year 1980.

3. Results

Fig 2 shows time series of water-year total ET_c and mean VPD during the last four decades. As expected by the Penman-Monteith equation, the annual total ET_c mimicked the same temporal pattern as the annual mean VPD. Drier conditions and warmer temperatures have occurred since the turn of the 21^{st} century. This climate data shows that the aridification process that happened in the last four decades corresponded to a trend toward increasing ET_c.

Water-year ET_c increased by 44 mm, P decreased by 31 mm, and VPD increased by 0.20 kPa between the baseline and the 2012–2023 period. We additionally found that both ET_c and VPD were significantly higher in the 2012–2023 period compared to the baseline (p-value of 0.0061 and 0.0004, respectively). By contrast, water year P was not significantly different in the last decade compared to the baseline (p-value = 0.2).

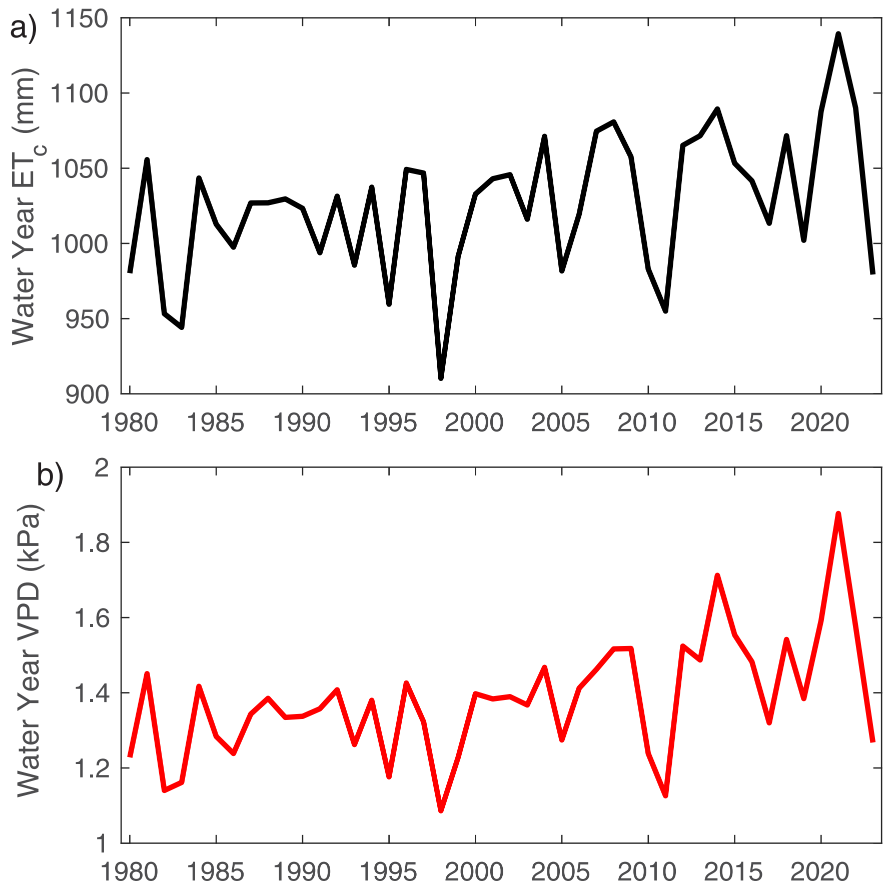

Fig 2. (a) Time series of the annual total crop evapotranspiration (ET_c) in mm, (b) time series of the mean vapor pressure deficit (VPD) in kPa in the San Joaquin Valley during water-years 1980 to 2023.

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The increasing ET_c in the last four decades without a significant increase in P has implications on the overall agricultural water budget. Although annual total ET_c always exceeded P in the SJV during 1980–2023 (Fig 3), this climate shifted during the 1980–2023 study period to higher ET_c. Specifically, the annual total ET_c was on average 3.9 times higher than on-farm P in water-years 1980–2011 but shifted to 4.6 times higher in water-years 2012–2023. This increase in ET_c relative to P in the past decade coincided with two historical warm droughts in 2012–2016, and 2020–2022, further amplifying climate driven pressures on the SJV agricultural water balance. These observations hold despite the very wet conditions of the 2023 water-year.

Aggregated across the agricultural area of the SJV, the increase in ET_c translates to an annual increase of 717.9 GL (582 thousand-acre-feet, TAF) in crop evaporative demand during 2012–2023 compared to the 1980–2011 baseline. We call this increase in climate change induced ET_c an *invisible water surcharge*. We want to emphasize that this *"surcharge"* is not an economic phenomenon, but rather a climate change phenomenon and demonstrates both the hidden nature and the additional burden of the increased water demand due to climate change. The *invisible water surcharge* is equivalent to a 4.4% increase in ET_c with respect to precedent decades, and it is equivalent to more than two thirds (67%) of the annual urban water use of the 4.3 million human population of the SJV, assuming 681 L (180 gal) per capita

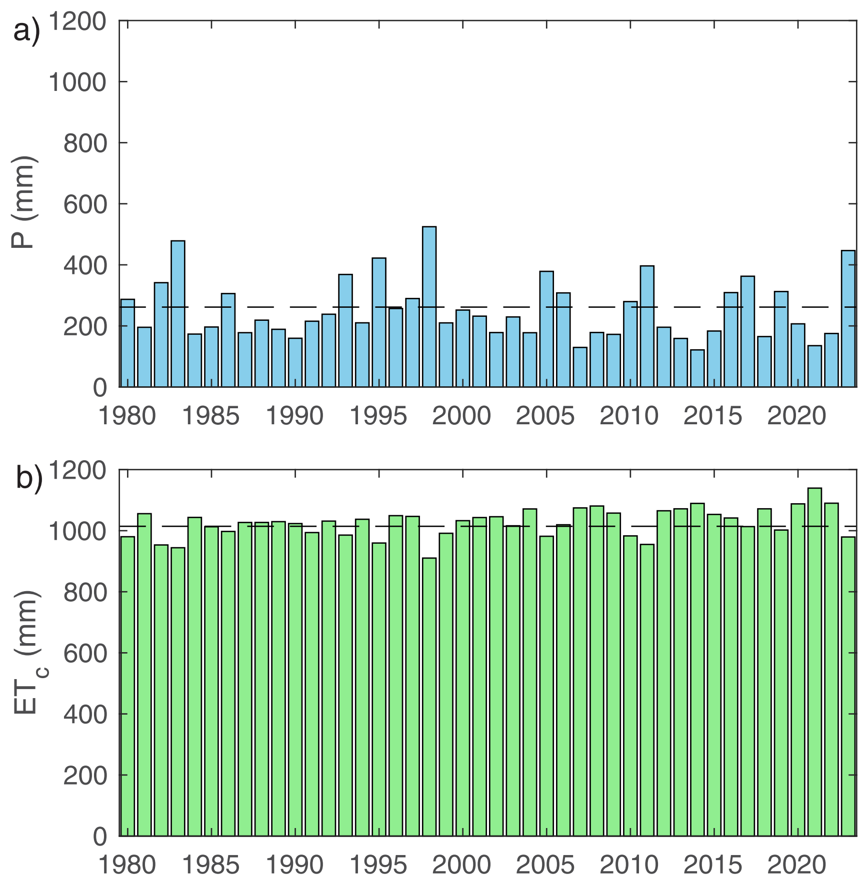

Fig 3. (a) Time series bar chart of the average San Joaquin Valley water-year annual total precipitation (P) and the baseline for a 1980–2011 baseline shown by horizontal dashed line, and (b) time series bar chart of the average San Joaquin Valley water-year annual total potential crop evapotranspiration (ET_c) and the baseline for a 1980–2011 baseline shown by horizontal dashed line.

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per day [63, 64]). The average annual increase in ET_c not only exceeds the capacity of the SJV's Millerton Lake Reservoir (690 GL or 520 TAF), but when integrated over the 12-year study period, it exceeds the combined storage capacity of SJV's five largest reservoirs (8,560 GL or 6,938 TAF [65]).

The extremely dry water-year 2021 featured a 12.3% increase in ET_c relative to the baseline —equivalent to 2,036 GL (1,651 TAF), which represents almost twice the total annual urban water use, and three times the capacity of SJV's Millerton Lake Reservoir (641 GL or 520 TAF), which diverts most of the San Joaquin River for irrigation.

There is a strong negative interannual correlation between water-year P and ET_c that compounds drought impacts in the SJV (Fig 4). The linear regression analysis resulted in a constant relationship ($ET_c = -0.368 \times P$), but statistically different ET_c intercepts between baseline (1110.7 mm) and the 2012–2023 period (1143.8 mm), suggesting a potential shift in the hydroclimate. The divergence between the regression lines for these two periods likely suggests that the low precipitation years during 2012–2022 cannot fully explain the notably upward shift in ET_c. Notably, 8 of the 10 warmest summers in the state since 1895 occurred during 2012–2023 [66] highlighting a shift to hot-dry compound extremes.

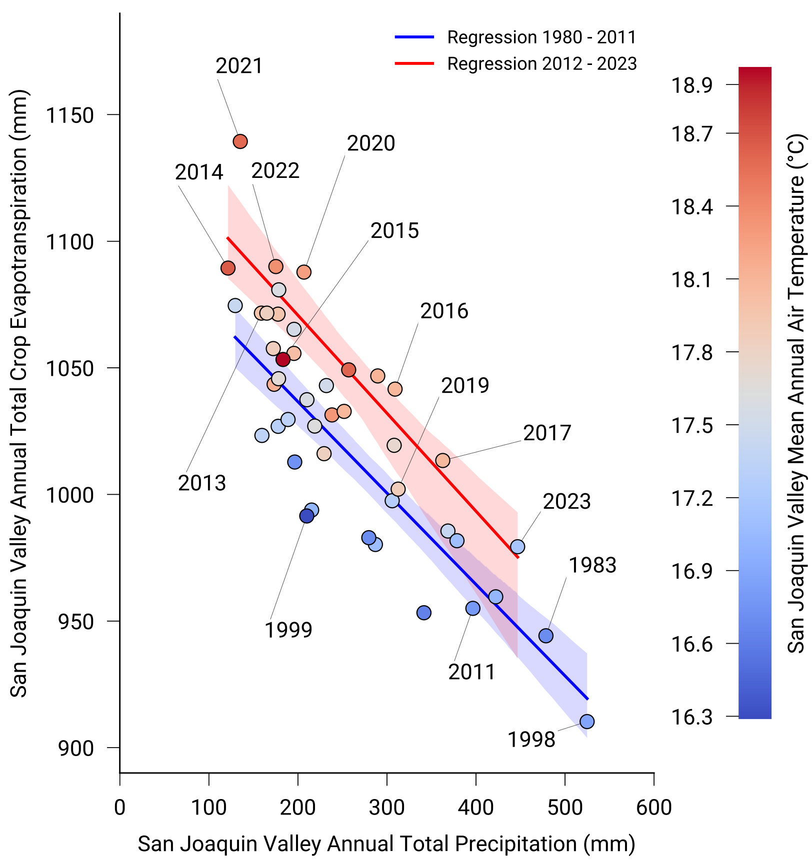

Fig 4. A scattergram of the average San Joaquin Valley total water-year (October 1 to September 30) annual potential crop evapotranspiration (ET_c) in mm versus average San Joaquin Valley total annual precipitation (P) in mm with linear regression lines for 1980–2011 (blue) (n = 32) and 2012–2023 (red) (n = 12). Bands around the regression lines are 95% confidence intervals. The colors of the scatterplot points indicate the average San Joaquin Valley annual water-year mean air temperature ranging from 16.3 to 19.0˚C using the blue-red color bar. Labels of the scatterplot points are water-years.

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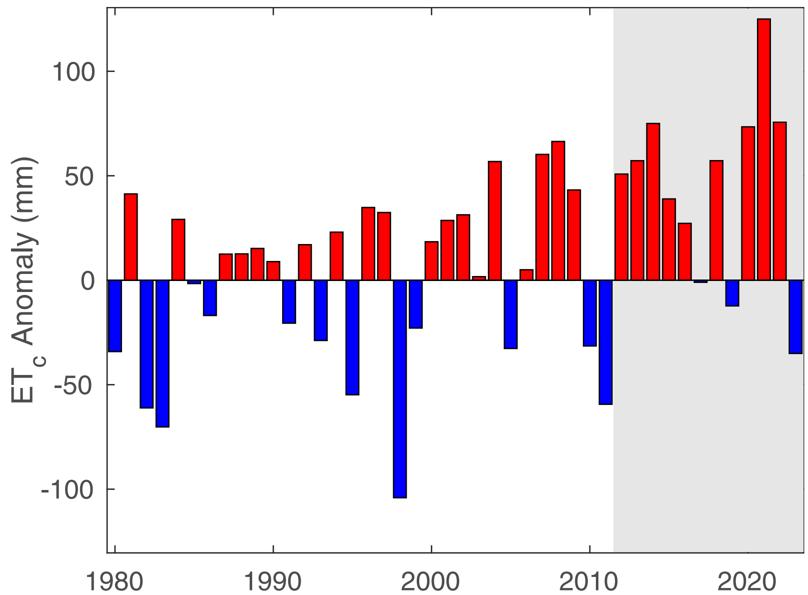

Fig 5. Annual water-year anomalies of ET_c relative to the from the mean ET_c of the period 1980–2011.

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The anomalies in ET_c from the baseline tended to increase during the last four decades (Fig 5). In the 2012–2023 period, the ET_c was higher than the baseline in nine out of twelve of those years, indicating that the crop water demand was usually higher than average in recent years.

The difference between P and ET_c is a simplified metric of the crop irrigation demand that must be supplied from reservoir storage, imports from the upper watersheds of the Sierra Nevada, and groundwater reserves. We calculated the cumulative crop water balance departures in (P—ET_c) from baseline conditions to quantify changes in agricultural water deficits. Anomalies or differences between each water-year annual total (P—ET_c) from the baseline indicate whether each water-year had excess (P—ET_c) or a deficit in (P—ET_c) compared to the baseline (Fig 6). The cumulative anomalies show a net increased deficit in (P—ET_c) since the turn of the 21st century. We additionally demonstrate that increased ET_c explains half of the cumulative departure in P—ET_c in the last decade. This result means that ET_c should be considered alongside interannual variations in P to comprehensively assess the agricultural water budget.

4. Discussion

The key finding in this study was that the *invisible water surcharge* was equivalent to a 4.4% increase in crop water demand in the last decade compared to precedent decades. Agricultural droughts are not only caused by precipitation deficits, but more and more by increased crop demands. We want to emphasize that crop water demand normally exceeds precipitation in the SJV, requiring surface water imports and groundwater supplies to fulfill the deficit, with greater reliance on groundwater extraction during drought water-years with diminished snowpack [14]. Thus, it is important to understand that the 4.4% increase in crop water demand in the last decade due to the *invisible water surcharge* is on top of the challenges of irrigation-dependent agriculture in the SJV due to the normal Mediterranean climate. The magnitude of the invisible water surcharge calculated here is similar to the acceleration of groundwater

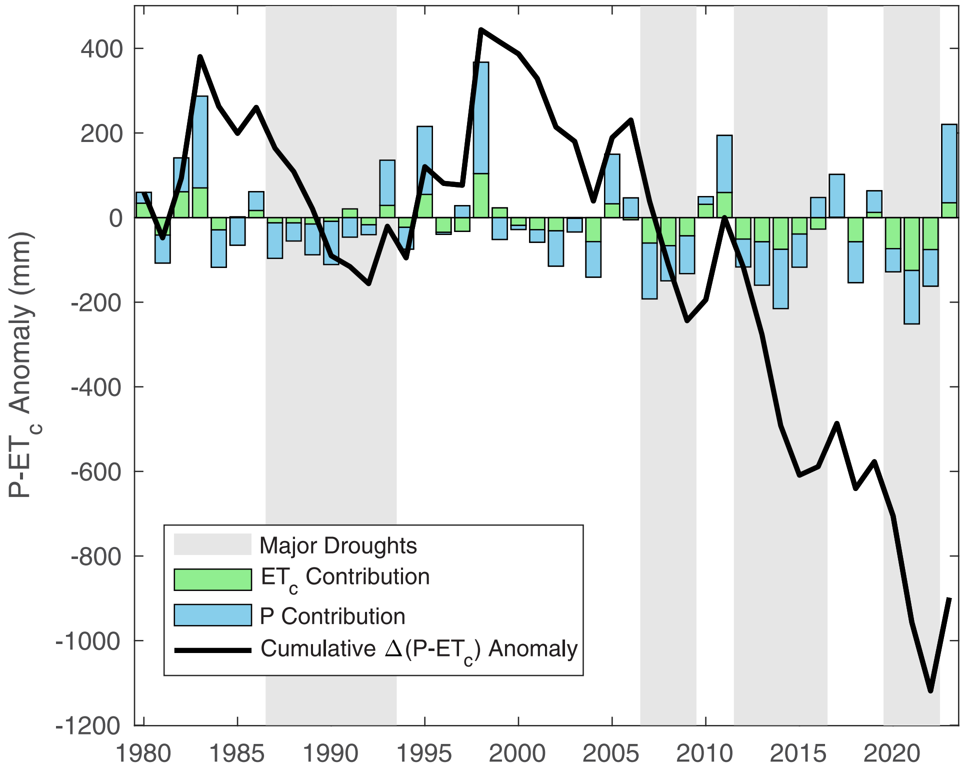

Fig 6. Annual water-year anomalies of P—ET$_c$ (the difference between precipitation and crop evapotranspiration on the San Joaquin Valley floor) from the mean P—ET$_c$ of the period 1980–2011, shown by the bar chart. Annual water-year cumulative anomalies of P—ET$_c$ from the mean P—ET$_c$ of the period 1980–2011, starting in 1980, are shown by the black line. The green and blue bars isolate the ET$_c$ and P portions of the (P—ET$_c$) anomaly, respectively. The California major drought years [9, 67] are shown in grey.

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overdraft reported for the Central Valley [5] emphasizes the importance of groundwater regulations such as SGMA [13]. Further research should focus on confirming whether the *invisible water surcharge* has contributed to the acceleration of groundwater overdraft that was reported in recent years [5]. Any contribution of the *invisible water surcharge* to the acceleration of groundwater overdraft should be factored into long-term groundwater sustainability management plans.

The increasing crop water demand should be considered alongside increasing inter-annual P variability [21] in water planning and management to comprehensively account for the effects of climate change. As stated earlier, the annual total ET$_c$ was on average 3.9 times higher than on-farm P in water-years 1980–2011 but shifted to 4.6 times higher in water-years 2012–2023. Furthermore, previous work showed that evaporative demand will continue increasing across the broader region of California due to climate change [24], which will further the gap between water availability and demand. Other recent studies have focused on the increasing range of extreme hydroclimate events and thus shifting baseline conditions for water budgets that may obscure near term anomalies [68]. This observed shift in the hydroclimate in the SJV calls for policy changes, such as improved water demand management (e.g., establishing groundwater pumping allocations and re-evaluating the mix of annual and perennial crops) and a reconsideration of water storage options such as the expansion of groundwater banks [69].

The *invisible water surcharge* jeopardizes the sustainability of fruit, nuts, and vegetable production in the SJV by adding an increased reliance on groundwater for irrigation under declining snowpack storage and unreliable imports [70, 71]. While this study focused on the *invisible water surcharge* in the SJV, the same analysis could be replicated in other regions with a Mediterranean climate to obtain a broader picture of the role of climate change on surcharging the sustainability of fruit and nut production. Specifically, the "Old World" Mediterranean Basin is anticipated to undergo both increased human population growth and accelerated climate change impacting both water and food security, exacerbating existing environmental problems caused by a combination of changes in land use, increasing pollution and declining biodiversity [72]. While improving irrigation efficiency [73] is seen as a potential adaptation strategy to the *invisible water surcharge*, it is unlikely to overcome the severity of climate change induced droughts in the Mediterranean Basin [74] and points to a need for more comprehensive water budget accounting [75]. In the "New World" Mediterranean, which includes Australia [76], California, Chile [77], and South Africa [78], similar evidence of increasing crop water demand due to climate change has been found. Many fruit and nut crops can only be grown in a Mediterranean climate; thus, the *invisible water surcharge* has important implications on the types of crops within our global food supply.

California's historic drought policies have focused on the multi-year major droughts in 1987–1992, 2007–2009, 2012–2016, and 2020–2022 shown in Fig 5 [9, 67]. While California's multi-year major droughts are important, they should be considered along with the long-term effects of the *invisible water surcharge* on the agricultural water balance shown by the anomalies in (P-ET_c) in Fig 5. The percentage of P and ET_c contributing to the anomalies of (P-ET_c) during major droughts shows that the P portion of (P-ET_c) has decreased while the ET_c portion of (P-ET_c) have increased during the last four decades. Specifically, the P portion of (P-ET_c) during the major droughts in California (1987–1992, 2007–2009, 2012–2016, and 2020–2022) tended to decrease (89%, 64%, 58%, and 50%, respectively) while the ET_c portion of (P-ET_c) tended to increase (11%, 36%, 42%, and 50%, respectively). Increased drought risk [28, 68] coupled with climate change induced increased ET_c suggests that water policy should treat warm and dry conditions as a long-term and worsening phenomenon rather than temporary multi-year droughts. Even after a major drought is over, the effects of climate change on the agricultural water balance continues and, thus, groundwater policy should always factor in shifts in the hydroclimate. This conclusion is reinforced by the inclusion of the historical precipitation rebound in 2023.

It is worth noting that the use of the crop coefficient method for estimating ET_c was essential for this analysis. The long-term ET_o data provided by the gridMET repository made it possible to analyze changes in the crop water demand over the last four decades using the crop coefficient approach [49]. While ET_a data exist for the San Joaquin Valley, such as OpenET [79], these data do not span a sufficiently long time series for assessing long-term climate-induced increases in crop water demand and are subject to a host of uncertainties—such as the potential shortening of the growing season due to more rapid phenological development with warming for some crops—that are beyond the scope of this study. Furthermore, ET_a is affected by management practices and changing crop mixes [49], preventing the isolation of climate-induced changes in crop water demand. Ultimately, this defends the usefulness of the crop coefficient approach for estimating crop water demand in climate change studies, despite its limitations. Lastly, the extent that crop response to increased carbon dioxide concentrations [80] might offset increased crop water demand remains unknown for the SJV.

Assuming static land use was essential for this analysis. We explicitly isolate the climate factors associated with increased crop water demand by using static 2018 cropland for the analysis period. While we show that a warmer climate has contributed to a change in crop water requirements, projecting future change in crop water demands merits assumptions on future cropping patterns including the increased share of perennials [81] and varieties with higher economic return per unit area or applied water [82]. Further research using finding from this approach may characterize the relative contributions of changing crops patterns, groundwater regulation and climate change in the *invisible water surcharge* in the SJV. Likewise, while our study held crop phenology, physiology, and management constant through time, additional work is needed to elucidate the roles these factors have on crop water demands with a warming climate.

5. Conclusions

California's recent warm droughts call for the investigation into the effects of climate change on the agricultural water balance. Although decreased precipitation is usually the focus of droughts, in this study, we demonstrate that increased crop water demand is also a flagship of California's warm droughts. Here, we quantified the increased crop water demand using a gridded meteorological dataset using a crop coefficient approach which does not depend on changing land use and management practices. The results showed that the 2012–2023 period had significantly higher crop water demand than the baseline 1980–2011 period, indicating that climate-induced changes in crop water demand should be considered with precipitation in water resources planning and management. Through an analysis of cumulative anomalies, we showed that the chronic increases in crop water demand over the last four decades explain half of the cumulative deficits in the agricultural water budget, and this trend is expected to worsen in the future. From these results, we can conclude that ignoring climate-induced increased crop water demand will impact the agricultural water balance, calling for further research to focus on the implications of this phenomenon on groundwater depletion in groundwater-dependent irrigated agriculture.

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