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Timely drought impact assessment for agriculture using a water–food systems approach

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Abstract

We present an integrated drought impact assessment framework to capture the cascading effects of drought on water supply, agriculture, and the broader economy, using California's 2020–2022 drought as a case study. The assessment was conducted as the drought unfolded, applying a top-down methodology to estimate changes in agricultural water supply, cropland adaptation responses, and spillover effects across downstream sectors. Despite data limitations, we demonstrate a replicable framework for predicting land fallowing and estimating economic impacts, relevant for timely drought assessments in California and other semi-arid irrigated regions worldwide. The framework leverages diverse, readily available datasets, including remote sensing based evapotranspiration estimates, records of reservoir storage and allocations, crop insurance claims, and regional economic statistics, combined with economic modeling tools. Our results indicate that in both 2021 and 2022, surface water deliveries in the Central Valley declined by about 43%, with varying spatial footprints. To partially offset these reductions, groundwater pumping rose by 51% in 2021 and 41% in 2022, with the largest increases occurring in the Tulare Lake region. These shifts resulted in an estimated 212 thousand hectares (8.2% reduction) of fallowed land in 2021 and 282 thousand hectares (10.9% reduction) in 2022, with direct crop revenue losses of \$1.2 and \$1.5 billion dollars, and 8.9 and 10.2 thousand jobs lost. Regional value added declined by \$1.3 billion in 2021 and \$1.9 billion in 2022 from both crop production and downstream food processing industries. Ex-post validation using newly released state water balance and crop mapping datasets shows that aggregate fallowing and water supply impacts were captured within -13% to $+2\%$ at the Central Valley scale, with more variable performance across individual crops and hydrologic regions. We highlight both the strengths and limitations of the framework while demonstrating its usefulness for timely drought impact assessment and mitigation planning.

1. Introduction

Assessing the impacts of drought is inherently challenging due to its multidimensional nature and the cascading effects it generates across water systems, agriculture, communities, and ecosystems. In regions with sizable agriculture-related economic activity, timely estimation of drought impacts is crucial for enabling effective adaptation and mitigation strategies. Early identification of potential consequences can guide more targeted governmental responses and effective resource allocation. One of the primary obstacles is limited data accessibility, particularly land use changes and economic impacts, which are not monitored in real time and require analytical approaches capable of capturing these dynamics using available data on other factors (AghaKouchak *et al* 2023).

Agricultural regions worldwide are experiencing drought impacts, leading to land use shifts, idling, and land abandonment (Richter *et al* 2023, Peterson *et al* 2024, Xie *et al* 2024, Perez-Quesada *et al* 2025). Drought disruptions extend far beyond individual farms, rippling through local and regional economies and influencing global food markets and security (Wheeler and von Braun 2013, Leah Jones-Crank *et al* 2024, Gomez and Mejia 2025). Beyond direct economic losses from diminished water access and crop yields, prolonged droughts disrupt entire industries that rely on agriculture, including food processing, transportation, and retail (Mishra *et al* 2021). Drought disruptions may also trigger widespread job losses and economic instability, disproportionately affecting rural and agricultural communities which also can fuel broader social challenges, including rising unemployment, poverty, migration, and even increased crime rates (Greene 2018, Fleming-Muñoz *et al* 2023, Cohen 2025). Additionally, declining agricultural activity and shifts in land use patterns can contribute to public health concerns, such as increased exposure to dust and air pollution from fallowed fields (Ayres *et al* 2022, Jalalzadeh Fard *et al* 2024, Adebiyi *et al* 2025).

The rapid onset of climate change, with warmer temperatures, coupled with more extreme precipitation swings alternating drought and floods (Swain *et al* 2018), often demands governmental response at multiple levels. Yet, inadequate planning frequently leads to costly emergency response measures, undesirable social and environmental impacts, and missed opportunities to enhance long-term adaptation and resilience (Wilhite *et al* 2014, Tortajada *et al* 2017, Gailey *et al* 2022). These challenges highlight the need for proactive, science-informed strategies that enhance system-wide resilience across agriculture, ecosystems, communities, and groundwater resources (Dunlop *et al* 2024). Addressing the growing and interconnected impacts of drought requires adaptive land and water management, long-term planning, and increased capacity. This also presents a valuable opportunity to drive innovation in how planners prepare for and respond to drought (Grafton *et al* 2013, Mount *et al* 2016). Such strategies are crucial for protecting vulnerable communities, groundwater reserves, and ecosystems at greatest risk from prolonged drought conditions.

Central to this issue is the comprehensive assessment of drought impacts. Understanding how drought affects different sectors and at what scales is essential for informing effective drought adaptation strategies. Droughts are a multidimensional phenomenon that unfolds across space, time, and sectors, and is characterized by a 'memory' effect, where past conditions and adaptations influence system responses (Van Loon *et al* 2024). For example, agricultural regions that have experienced recurrent droughts may have developed more robust infrastructure (e.g. irrigation wells), greater adaptive capacity, and stronger governance to respond effectively. Learning from past droughts can also act as catalysts for systemwide reforms, prompting investments in preparedness and governance that help balance the growing competition for water among agriculture, communities, and ecosystems (Lund *et al* 2018).

A systems-based approach enables the identification of key drivers and feedback loops that amplify or buffer drought impacts, forming a foundation for comprehensive drought impact assessments. These assessments not only reveal where impacts are occurring, but also can elucidate the broader social and economic dimensions of drought impacts. This knowledge is critical for guiding long-term planning efforts and policies that move beyond crisis response.

In this study, we introduce a water–food systems framework to analyze the multidimensional impacts of drought, using the 2020–2022 drought in California's Central Valley as a case study. Previous studies have examined drought impacts in California, providing important insights into agricultural economic losses and water availability (Howitt *et al* 2015, Medellín-Azuara *et al* 2016, Lund *et al* 2018), but these analyses generally rely on retrospective datasets that become available months to years after drought conditions occur. Here, we demonstrate how publicly accessible datasets on land use, water supplies, satellite-based evapotranspiration (ET), and groundwater indicators, can support timely drought impact assessment.

While prior studies incorporate economic and hydrological water balance analyses similar to those used here, they primarily focus on individual system components. In contrast, we adopt an integrated systems-based framework that jointly assesses surface water supplies, groundwater pumping and depletion, agricultural production responses, and regional economic impacts, allowing us to identify systemic vulnerabilities and cross-sectoral interdependencies that are not captured in sector-specific assessments.

1.1. California's Central Valley and the 2020–2022 drought

California's Central Valley (figure 1) is one of the most agriculturally productive regions in the world and the United States' most valuable. The contemporary agricultural landscape reflects a long history

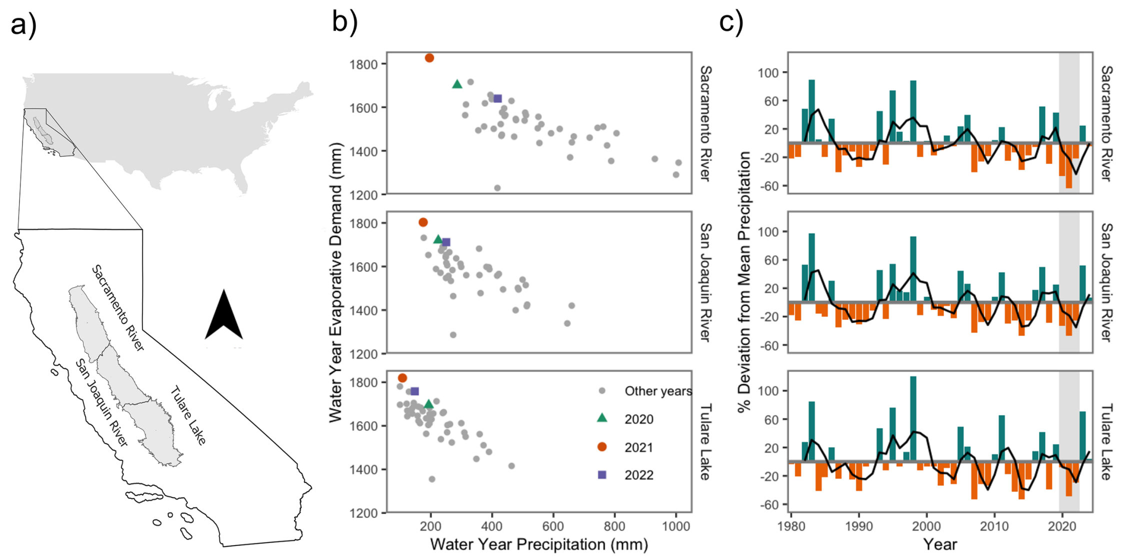

Figure 1. (a) California's Central Valley and its three hydrological regions (Sacramento River, San Joaquin River and Tulare Lake), (b) total water year evaporative demand and precipitation from 1980 to 2024 and (c) percent deviation of total water year precipitation from historical average, 3 year moving average (solid line), and drought period (2020–2022) shaded. Data was downloaded from gridMET (Abatzoglou 2013).

of land transformation, beginning with Indigenous land stewardship practices, followed by colonization and settler-driven expansion of agriculture (Anderson 2005). Early agricultural development converted extensive rangelands and wetlands into irrigated cropland (Garone 2020), initially dominated by wheat and barley, followed by hay and cotton, and later transitioning toward perennial tree orchards, vineyards, forage crops, and rice (Olmstead and Rhode 2020). The widespread adoption of micro/drip irrigation has increased field-scale application efficiency; however, it has not reduced basin-scale net water use because efficiency gains have been offset by intensification and expansion, including into crops and locations that would otherwise be less viable (Tindula *et al* 2013, Taylor and Zilberman 2017).

As of 2023, irrigated agriculture occupies approximately 2.7 million hectares across the Central Valley, including more than one million hectares of perennial tree orchards, primarily almonds, which alone exceed 600 000 hectares. Field crops account for over 300 000 hectares, largely forage crops such as corn concentrated in the southern Central Valley, while rice cultivation exceeds 200 000 hectares and is predominantly located in the northern Central Valley (DWR 2025c). While the region's Mediterranean climate and fertile alluvial soils provide favorable conditions for high agricultural productivity, this system has become increasingly dependent on additive inputs, including fertilizers, pesticides, and, most critically, irrigation water.

Agriculture is one of the economic pillars of the Central Valley and a major source of employment, particularly for farmworkers and communities whose livelihoods are directly tied to agricultural production and processing. The sector employs more than 400 thousand people each year (EED 2025) and underpins local and regional economies through associated industries such as food processing, transportation, equipment manufacturing and agricultural input providers. This economic reliance on agriculture also creates structural vulnerabilities, as fluctuations in water availability and crop production directly affect labor demand, household income, and regional economic stability, disproportionately impacting low-income and disadvantaged communities.

Agriculture in the Central Valley relies heavily on an extensive surface water storage and conveyance system. Large reservoirs and interbasin transfer infrastructure capture runoff from the Sierra Nevada and northern parts of the state and convey water to agricultural regions in the southern Central Valley, as well as urbanized areas. Despite this infrastructure, surface water supplies are often insufficient to meet agricultural demand in most years, leading to chronic reliance on groundwater pumping. Decades of groundwater extraction in excess of recharge have resulted in widespread groundwater depletion, land subsidence, water quality degradation, and declining agricultural and domestic well reliability, rendering the region particularly vulnerable during drought periods (Faunt *et al* 2016, Hanak *et al* 2019). In response to these conditions, California enacted the Sustainable Groundwater Management Act (SGMA) in 2014, which mandates locally led, integrated groundwater management to address chronic overdraft and its associated impacts. Although implementation remains in its early stages, at the time of this study many local agencies had begun adopting key management actions, including groundwater pumping caps aligned with sustainable yield targets, incentive programs for land fallowing and cropland transitions, and investments in groundwater recharge infrastructure.

Provision of environmental flows and habitat protections for native species further widens the gap between water available for consumptive use and total systemwide demands. Exports from wetter northern regions, reservoir releases, and stream diversions are increasingly constrained by a multilayered framework of California state and federal regulations, including water quality standards, endangered species protections, and operational rules for major conveyance facilities (Grantham and Viers 2014, Chang and Bonnette 2016, Durand *et al* 2020). Collectively, these regulatory requirements limit operational flexibility in surface water systems, particularly during dry and critically dry years, intensifying competition among agricultural, urban, and environmental water uses (Medellín-Azuara *et al* 2008, Hanak and Lund 2012).

Multi-year droughts have long shaped California's hydroclimatic variability (figure 1(c)), and recent research suggests that warming temperatures are increasing drought severity through enhanced evaporative demand (Mann and Gleick 2015). The 2020–2022 water years constitute one of the driest consecutive three-year periods in the modern instrumented record. These years were characterized by both sustained precipitation deficits, anomalously high temperatures, and extreme atmospheric evaporative demand across the state (figure 1(b)). All three Central Valley hydrologic regions, the Sacramento River Basin, San Joaquin River Basin, and Tulare Lake Basin, experienced hot and dry conditions, though differences in baseline precipitation and water storage capacity produced regionally distinct drought dynamics.

The Sacramento River Basin, typically the wettest of the three regions and the primary contributor to surface water storage and conveyance systems, experienced concurrent precipitation deficits and elevated evaporative demand during 2020–2022 (figure 1(c)). These conditions reduced water availability to levels more commonly associated with drier southern regions, illustrating how extreme hydroclimatic anomalies can stress even historically water-abundant basins.

The 2020–2022 drought provides an example of how compound climate extremes interact with water allocation systems, groundwater dependence, and agricultural production patterns to generate cascading impacts. These impacts included increased land fallowing, shifts in groundwater extraction, reduced agricultural output, labor disruptions, and widespread well failures affecting rural communities reliant on groundwater. This case illustrates how drought impacts propagate across interconnected water, food, and economic systems, underscoring the need for integrated and timely assessment frameworks.

2. Data sources and methodological approach

The analysis presented here was conducted during the 2020–2022 drought and contributed to a published report aimed at informing state drought response efforts. Drawing from the experience of conducting this assessment and previous drought impact assessments (Howitt *et al* 2015, Medellín-Azuara *et al* 2016, Lund *et al* 2018), we present a framework to conduct drought assessments by incorporating multiple layers of analysis to better capture the interconnectedness among drought effects in water supply, agricultural production, and the economy. We use 2019 as a baseline year to represent pre-drought land use and economic conditions. This allows us to assess how the multi-year drought from 2020 to 2022 affected surface water availability, groundwater conditions, agricultural production, and economic activity, focusing particularly on 2021 and 2022, when reduced surface water deliveries intensified impacts on agriculture and the downstream economy.

In the original analysis (Medellín-Azuara *et al* 2022), constraints on land use data, and net water use to all agricultural water areas precluded us from a more comprehensive assessment of what can be considered drought land idling. In this paper, we underscore the value of undertaking such preliminary analyses with limited data and also the benefits from validation for improving future drought impact predictions. As of early 2025, newly released crop mapping and water balance data for the years of the original study, from the California Department of Water Resources (DWRs) provided an opportunity to retrospectively evaluate the accuracy of our methods to project land fallowing and refine our understanding of the drought's broader impacts.

2.1. Systems approach for drought impact assessment

Water–food systems are inherently interconnected, with strong spatial, temporal, and sectoral linkages between water availability, agricultural production, groundwater resources, and regional economies (Niggli *et al* 2022, Shah and Gao 2025). In irrigated regions worldwide, drought events expose these linkages by simultaneously reducing surface water supplies, increasing crop evaporative demand,

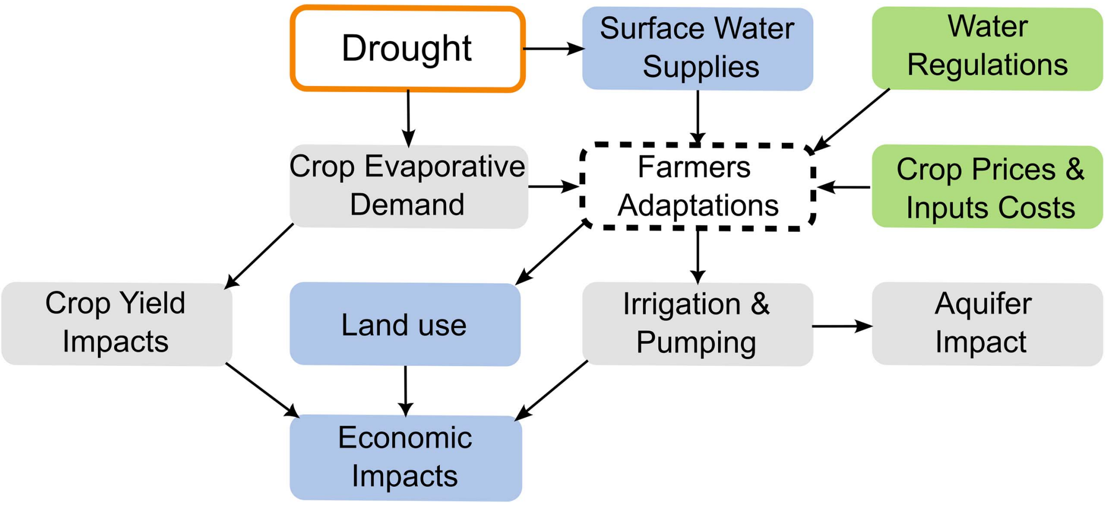

Figure 2. Drought impact assessment framework used in this study. Blue boxes show key drought-impacted factors, highlighted in this study, gray boxes denote additional outcomes, and green boxes represent economic and regulatory drivers influencing farmers' adaptation and economic impacts.

cascading in economic losses to agriculture and supply chains, as well as rural communities and the environment (Madruga de Brito *et al* 2020, Shyrokaya *et al* 2023). These dynamics require adaptive responses from agricultural producers and water managers, often mediated through allocation systems, regulatory mechanisms, and water markets.

California's Central Valley provides a well-documented example of such an engineered water–food system. Declines in precipitation, rising temperatures, and increased evaporative demand jointly reduce annual water availability and surface water deliveries. In allocation-based systems such as California's, regulatory agencies may impose curtailments on surface water diversions during extreme drought to protect environmental flows and water quality, further constraining supply.

When surface water availability declines, agricultural producers and urban users increase reliance on groundwater. Sustained extraction under drought conditions can accelerate aquifer depletion, particularly in historically overdrafted basins. Falling groundwater levels raise pumping costs due to increased energy requirements and infrastructure needs (Gailey 2023), while tighter supplies may increase the cost of acquiring water through transfer markets (Ayres *et al* 2021).

Higher evaporative demand under warmer and drier atmospheric conditions intensifies crop water requirements and can reduce yields when irrigation is constrained (Moyers *et al* 2024). In irrigated systems dominated by perennial crops, such as tree and vine crops that require water annually to remain viable, producers often prioritize irrigation for these long-lived investments, increasing the likelihood that annual crops are idled during water shortages (Lund *et al* 2018). Land idling, crop shifting, irrigation and nutrient management therefore become primary adjustment mechanisms under drought. While these impacts originate at the farm scale, they propagate through upstream and downstream supply chains, affecting labor markets, food industries, and broader regional economic activity.

The conceptual framework in figure 2 illustrates these interconnections and the cascading impacts of drought on water resources, agriculture, and the economy. Although developed using California as a case study, the framework is designed to be transferable to other irrigated regions where comparable hydrologic, agricultural, and economic datasets are available.

2.2. Surface water supply impacts

The Central Valley is supplied by a highly engineered water system consisting of reservoirs, dams, canals, and aqueducts that deliver surface water to agricultural users. Surface water supplies are primarily managed through California's State Water Project (SWP), operated by DWR, and the federal Central Valley Project (CVP), operated by the U.S. Bureau of Reclamation. Together with local surface water systems and groundwater pumping, these projects form the backbone of irrigation supply in the region. Both the SWP and CVP operate under an allocation-based framework, in which actual water deliveries represent a fraction of contracted amounts and vary annually in response to hydroclimatic conditions.

We estimated drought-related reductions in SWP and CVP irrigation supplies by comparing reported deliveries in 2021 and 2022 to the mean deliveries over a historical baseline period (2000–2020), which represents average hydroclimatic conditions. At the time of analysis (Fall 2022), observed delivery data were available for the full 2021 water year and early 2022 water year. Where delivery data for was not available, we forecasted deliveries using published allocation announcements and delivery records.

The SWP delivers water under long-term contracts that specify maximum annual delivery volumes, known as *Table A* amounts. Each year, the DWR announces allocation percentages that determine what fraction of these contracted volumes will be delivered, with allocations varying widely in response to hydrologic conditions. In addition to Table A deliveries, SWP contractors may receive supplemental water through mechanisms such as carryover storage from prior years, which occur when surplus water is available beyond approved allocations. During drought years, however, allocations are typically low and supplemental deliveries are limited, resulting in substantial reductions in total surface water availability relative to average conditions. We used the final announced allocation of 5% for Table A agricultural deliveries and assumed that non–Table A deliveries were comparable to those observed during 2016, a previous severe drought year.

The CVP includes multiple contractor types with distinct allocation rules. For settlement contractors, deliveries were estimated using reported deliveries from January through May and proportional scaling based on contract amounts, assuming similar supply conditions for the remainder of the year. Exchange contractors were assumed to receive 75% of their contracted supply, consistent with critically dry year provisions. Friant Division contractors and other CVP agricultural users were estimated to receive 30% and 0% of their contract amounts, respectively, consistent with final allocation announcements.

For local surface water supplies outside the SWP and CVP systems, we estimated drought-related reductions using an empirical relationship between historical water storage and deliveries. Specifically, we regressed historical deliveries against combined reservoir storage and snow water equivalent for each hydrologic region using data from the California Data Exchange Center. We then used observed storage conditions as of April 1, when seasonal precipitation accumulation is largely complete in California, to forecast local reservoir deliveries for 2021 and 2022. In addition, we incorporated information from the State Water Resources Control Board's Electronic Water Rights Information Management System to account for water rights curtailments in affected watersheds.

2.3. Groundwater use increase

Groundwater plays a critical role in sustaining irrigated agriculture in the Central Valley, particularly during drought periods when surface water deliveries decline. Historical estimates of groundwater pumping for irrigation were obtained from DWR's regional water balance dataset (DWR 2025d; see figure SI.1). To estimate drought-induced changes in groundwater extraction in 2021 and 2022, we applied a basin-scale water balance in which groundwater pumping was inferred as the residual necessary to satisfy irrigation demand after accounting for available surface water supplies.

Basin wide irrigation demand was approximated using remotely sensed ET from OpenET (Melton *et al* 2022), aggregated by region and irrigation season. Surface water deliveries were independently estimated from reported project allocations, historical delivery records, and reservoir and snowpack storage conditions. Because ET reflects consumptive crop water use, proportional differences in seasonal basin-wide ET between drought years and selected historical drought analog years were used to adjust groundwater pumping estimates relative to observed pumping in those analog years. Complete accounting of all water balance components is not consistently available (e.g. percolation, recharge and return flows) at the spatial and temporal resolution required for this analysis. We therefore rely on the two components that can be robustly quantified in near real time, surface water deliveries (section 2.2) and basin-wide agricultural ET, and use observed pumping from analog drought years as an empirical anchor. This approach provides a pragmatic, data-constrained means of maintaining consistency between surface water availability, irrigation demand, and inferred groundwater extraction.

For the Sacramento River region, 2015 was selected as the closest analog for 2021 based on comparable surface water delivery constraints. Surface water availability for 2021 and 2022 was estimated as described in section 2.2. In 2022, surface deliveries reached historic lows while state constraints (e.g. Sacramento-San Joaquin Delta outflow) increased, reducing irrigation water availability relative to 2021 by approximately 30%. Applying the water balance framework, ET-derived irrigation demand indicated that groundwater pumping in 2022 exceeded the previous peak observed in 2016 by approximately 14%, corresponding to a 65% increase relative to 2019 baseline conditions.

In the San Joaquin River region, 2021 conditions most closely resembled those of the 2013–2014 drought years. Observed groundwater pumping from those years was used as the baseline estimate and then scaled using proportional differences in basin-wide cropland ET. Because seasonal ET in 2021 was 3% lower than in the selected analog years, groundwater pumping was reduced by 3% relative to the analog baseline. For 2022, a similar approach was applied, with ET indicating irrigation demand was 4% lower than in the reference years, resulting in a 4% downward adjustment in inferred pumping.

In the Tulare Lake region, 2021 conditions were most comparable to the 2015 water year. Groundwater pumping was initialized using observed pumping from that year and adjusted using ET-derived irrigation demand. Basin-wide cropland ET in 2021 was 22% lower than in 2015, leading to a 22% reduction in pumping relative to the analog baseline. In 2022, improved surface water availability relative to 2021 led us to use 2013 as the analog year; cropland ET was 26% lower than in 2013, and pumping was adjusted proportionally.

We estimated the economic implications of increased groundwater pumping by calculating the electricity costs of pumping additional groundwater from the median groundwater level as of 2021. Groundwater level data was obtained from monitoring wells (DWR 2025a), and increased energy requirements per unit of water pumped were obtained using standard hydraulic relationships, assuming a 70% efficiency (Peacock 1996). Electricity prices were based on regional agricultural electric rates data from PG&E, using an average value of \$0.24 kWh^{-1} for both years.

2.4. Land fallowing

Fallowing of cropland is a key agricultural response to water scarcity during drought and constitutes the primary driver of downstream water, production, and economic impacts in this analysis. To estimate drought-induced land fallowing at the field scale, we employed a parcel-level ET based approach using remote sensing data. This enables consistent spatial coverage and near-real-time assessment during ongoing drought conditions, when detailed crop classification datasets are typically unavailable.

We used two primary data sources: (i) parcel-level cropland mapping for the baseline year 2019 from the (DWR 2022), and (ii) daily field-scale ET estimates from the OpenET SSEBop model (Savoca *et al* 2013, Morton *et al* 2022). ET was selected as the primary indicator of field activity because it directly reflects crop water use, crop vegetation conditions and irrigation management. This assumption is particularly well suited to semi-arid irrigated regions such as the Central Valley, where ET during the irrigation season provides a strong and physically meaningful signal for detecting production cessation under water-limited conditions.

Parcel-specific mean daily ET was calculated for the irrigation season (May–September) for 2019, 2021, and 2022. We evaluated ET distributions by crop type and hydrologic region (Sacramento River, San Joaquin River, and Tulare Lake basins) to establish crop- and region-specific thresholds distinguishing active production from fallow conditions. Because ET distributions vary substantially across crop types and regions, even under active management (as shown in figure SI.3), a single absolute ET threshold would risk systematic misclassification of low-water-use crops while failing to detect partial or late-season fallowing in higher-water-use crops. To account for this heterogeneity, we tested percentile-based thresholds using the 2019 baseline ET distribution. Percentile thresholds define fallowing relative to each crop's observed ET distribution in a reference year, thereby preserving physically meaningful differences in crop water use while enabling consistent classification across different crops.

Based on sensitivity and calibration analyses (figures SI.5 and SI.6), we adopted the 2nd percentile of mean daily ET for each crop-region combination in 2019 as the baseline fallow threshold. This percentile represents a conservative cutoff corresponding to the lowest observed ET values for cropped parcels in a wetter year. To account for interannual changes in atmospheric demand, thresholds were scaled for 2021 and 2022 using relative changes in the 75th percentile of the ET distribution for each crop and region, thereby preserving crop-specific water use patterns while adjusting for climatic and water management conditions.

Threshold selection was evaluated using USDA Farm Service Agency (FSA) prevented planting data for rice (Sacramento River region) and cotton (San Joaquin River and Tulare Lake regions). The FSA is a U.S. federal agency that administers agricultural insurance and disaster assistance programs and reports county-level of insured cropland that could not be planted due to weather-related conditions such as drought. A separate analysis using the historical FSA reports is shown in supplemental information (SI) section 3, where rice and cotton historically account for more than 95% of prevented acreage in the Sacramento River and Tulare Lake regions respectively. These crops also represent substantial baseline production shares, rice accounted for 26.5% of total cropland in the Sacramento River region, while cotton accounted for 5.6% and 3.5% of total cropland in the Tulare Lake and San Joaquin River regions, respectively, in 2019.

At the 2nd percentile, ET-based estimates differ from FSA reported prevented area by 20% on average across crop–year combinations. However, higher percentile thresholds systematically increased total fallowed area at both the crop and regional levels, producing magnitudes that diverged substantially from FSA-reported acreage and other independent checks. Sensitivity analysis further shows that regional totals increase disproportionately at thresholds above the 2nd percentile, exceeding levels consistent with observed land use patterns during the previous droughts (see SI section 3). In addition to quantitative comparisons, the spatial distribution of fallowing at the 2nd percentile aligns with reported regional drought impacts and commodity-level responses documented in conversations with state and local officials, commodity groups and researchers.

Fields with seasonal mean daily ET below the adjusted threshold were classified as fallow (as shown in figure SI.2). Because some cropped parcels in the 2019 baseline year exhibited low ET values due to management differences or field heterogeneity, drought-induced fallowing in 2021 and 2022 was quantified as the net increase relative to baseline area that would have been classified as fallow in the baseline rather than absolute fallow extent. This net change was propagated through economic analysis.

A limitation of this approach is that it focuses on identifying parcels that transition from cropped to fallow relative to the 2019 baseline and does not explicitly model other land-use dynamics that may occur, including fallow-to-crop and crop switching. For these cases, there is a lack of real-time information on what specific crop type should be assigned to these fields which is necessary for the economic impact estimates. However, the ET-based method reliably detected crop to fallow dynamics; refer to supplemental information section 6 for more information.

2.5. Economic impacts

After estimating drought-induced land fallowing, we quantified direct crop revenue losses using baseline economic data from the USDA California Agricultural Commissioners' reports (2016–2019), which provide crop-specific yields and prices per acre. This range was chosen to avoid skewing due to acute shifts in these values that can occur from year-to-year. These baseline averages were applied to estimated net fallowed acreage by crop category to calculate foregone gross production value. For major perennial crops (almonds, pistachios, and walnuts), production trends at the time of analysis were reviewed using data from the California Almond Board, the Administrative Committee for Pistachios, and the USDA Objective Measurement Reports, refer to supplemental information section 4 for more details on how this information was incorporated in our analysis.

To evaluate broader economic consequences beyond direct farm-level losses, we employed a regional input-output modeling framework. Input-output models quantify how changes in economic output in one sector propagate through interlinked industries via services and supply chain transactions and household spending. Changes in agricultural output due to fallowing represent direct effects. These direct losses generate indirect effects through reduced purchases from upstream industries (e.g. agricultural services, financial services, input suppliers), downstream industries (e.g. food, beverage and packing industries) and induced effects through reduced household spending associated with declines in labor income. The sum of direct, indirect, and induced effects represents the total regional economic impact.

We implemented this analysis using the IMPLAN (Impact Analysis for Planning) input-output model (IMPLAN Group LLC 2019), which is widely used for regional economic impact analysis. IMPLAN is based on the North American Industry Classification System (NAICS) and integrates data from the U.S. Department of Agriculture, U.S. Census Bureau, Bureau of Labor Statistics, and Bureau of Economic Analysis to construct region-specific multipliers that describe intersectoral linkages. We used the 2019 IMPLAN dataset to match the baseline year of agricultural production and constructed separate regional models for the Sacramento River, San Joaquin River, and Tulare Lake regions using county-level data aggregated to each region.

Crop categories from the fallowing analysis were mapped to corresponding NAICS agricultural sectors within IMPLAN categories (field and grain, alfalfa and pasture, trees and vines, and vegetables and non-tree fruits). Estimated direct revenue losses were used as direct output shocks to the corresponding sectors in IMPLAN where multipliers were then used to calculate total impacts on downstream food and beverage industries, value added (GDP), and employment.

2.6. Ex-post assessment of aquifer response and well impacts

Given the cascading nature of drought impacts across water, agricultural, and community water supply systems, evaluating aquifer response and well vulnerability is essential for understanding broader system consequences in California, which insights can support other heavily irrigated regions worldwide (Udmale *et al* 2016, Perrone and Jasechko 2017, MacDonald *et al* 2019).

Although the analytical framework developed in this study is designed for rapid drought assessment, we use groundwater level observations, well completion and domestic dry wells records here in an ex-post capacity to evaluate the cumulative aftermath of the drought. While the new agricultural wells and well monitoring datasets were incorporated to calculate the groundwater augmentation costs. The objective of this assessment is to evaluate whether observed aquifer responses, well construction patterns, and domestic well failures are consistent with the magnitude and spatial distribution of estimated land fallowing and surface water shortages. This ex-post analysis therefore complements the real-time approach by examining broader and longer-term cascading effects on groundwater systems and community water infrastructure.

Data on newly drilled irrigation wells were obtained from DWR Well Completion Reports and compiled datasets (Cole 2024, DWR 2025e). Wells classified for agricultural production with completion dates between January 2020 and December 2022 were extracted and spatially assigned to each region. For comparison, well construction totals were also summarized for previous years, including other drought periods for reference. Reported domestic well failures were obtained from the DWR Dry Well Reporting System (DWR 2025b). Records were filtered for 2020–2022 and summarized by region. New domestic and public supply wells were identified from Well Completion Reports over the same period and similarly aggregated by region. This analysis evaluates regional-level patterns of net impacts of domestic groundwater access using well failures and new domestic well construction.

Groundwater level observations were obtained from DWR monitoring well datasets (DWR 2025a). Wells with consistent measurements spanning early 2020 through late 2022 were selected. Groundwater level change was calculated as the difference between water levels measured at the beginning and end of the period and summarized by region. Spatial patterns of drawdown were mapped to evaluate spatial heterogeneity in aquifer response.

This ex-post assessment provides insights of the cascading impacts identified in the water system. While these datasets were not available for real-time modeling, they illustrate how reductions in surface water supply and increased reliance on groundwater can propagate into well construction activity, domestic well failures, and measurable groundwater declines.

3. Results

3.1. Drought-induced declines in water supply

Shortages were driven by reductions across the three major sources of surface water, SWP, CVP, and local supplies. SWP agricultural deliveries declined by approximately 40% in 2021 and 60% in 2022 relative to historical averages, with the Tulare Lake region bearing the largest impact. CVP agricultural deliveries fell by 55% in 2021 and nearly 70% in 2022, with shortages concentrated in the Tulare Lake and San Joaquin River regions. Our estimates show, local surface water deliveries declined by 35% in 2021 and 20% in 2022 relative to 2019 conditions, with more pronounced reductions in the Sacramento River region in 2022. Total surface water supplies across the Central Valley decreased by 43% in both 2021 and 2022 (table 1). Reductions were observed across all three hydrologic regions, with the largest losses in the Tulare Lake region in 2021 (-4052 Mm^3) and in the Sacramento River region in 2022 (-3223 Mm^3).

To offset these surface water deficits, groundwater pumping increased substantially. Groundwater extraction rose by 5106 Mm^3 (51%) in 2021 and 4109 Mm^3 (41%) in 2022 relative to baseline conditions, with the largest increases in the Tulare Lake region. Despite this substitution, total water supplies (surface plus groundwater) still declined by 2253 Mm^3 (8.3%) in 2021 and 3163 Mm^3 (11.7%) in 2022 relative to the 2019 baseline.

Using the Water Plan Water Balance dataset (DWR 2025d), we estimated the precision of our estimates (summarized in table SI.1). We underestimated total supplies in 2021 by 5%, and overestimated total supplies by 2% in 2022, therefore overestimating the drought effects in 2021 and underestimating the effects in 2022. The precision of the estimates is good ($<$6% of error) at the aggregate regional level which shows the validity of the water balance approach. For individual hydrologic regions and water source estimates we found a relatively good precision ($<$10% of error in average) except in three cases: (1) we overestimated the pumping in 2022 for the Sacramento Region; (2) we also overestimated the surface deliveries in the Tulare Basin in 2022, that were compensated by (3) the underestimation of the groundwater pumping in this same region. Note that the remainder of this article focuses on our estimated water balance values, as these were the information available at the time of study and were used to support other elements of analysis.

3.2. Estimated land fallowing

Using our ET analysis and information available at the time the analysis was performed, we estimated a total of 212 000 and 282 000 hectares for 2021 and 2022 respectively in the Central Valley (table 2). In 2021, the Sacramento River region had the greatest land fallowing with 82 000 hectares followed by Tulare Lake with 108 000 hectares and San Joaquin River experiencing only 22 000 hectares of fallowing. In 2022, the estimated fallow increased by 72 000 hectares in Sacramento River yet remained similar in

Table 1. Surface and groundwater supply impacts summary for the Central Valley's hydrologic regions for 2021 and 2022.

Type of water supplies	Baseline (Mm^3)	Change in 2021 (Mm^3)	Change in 2022 (Mm^3)
Surface Water	17 103	−7361 (−43%)	−7273 (−43%)
Sacramento River	6555	−1795	−3223
San Joaquin River	4711	−1515	−1515
Tulare Lake	5837	−4052	−2535
Groundwater	10 048	5106 (+51%)	4109 (+41%)
Sacramento River	2087	852	1358
San Joaquin River	2787	1252	1210
Tulare Lake	5174	3002	1541
Total water supplies	27 151	−2253 (−8%)	−3163 (−12%)

Table 2. 2021 and 2022 total projected fallowed land compared to 2019 baseline land use (thousand hectares).

Hydrologic region	Baseline cropland 2019	Land fallowing 2021	Land fallowing 2022
Sacramento River	699	82 (−11.7%)	154 (−22.0%)
San Joaquin River	787	22 (−2.8%)	26 (−3.3%)
Tulare Lake Basin	1,111	108 (−9.7%)	101 (−9.1%)
Central valley total	2597	212 (−8.2)	282 (−10.9%)

other regions. This region experienced the most drastic reduction in surface water deliveries and experienced water transfers from rice and other field crops to urban coastal areas and high-value crops in the San Joaquin Valley. Additionally, this region has less developed groundwater pumping infrastructure compared to the San Joaquin Valley, constraining the ability to pump groundwater to make up for lost surface supplies.

These regional hotspots reflect the varying levels of groundwater reliance, water transfer dynamics, and overall regional water shortages across California's major agricultural regions. Farmers in some areas, particularly in the San Joaquin River and Tulare Lake regions, have adapted historically to drought conditions through a combination of increased groundwater supply infrastructure and other investments. Previous droughts (e.g. 2012–2016) influenced these local adaptations, shaping the capacity to mitigate the extent of drought impacts (Lund *et al* 2018), as the case of the studied drought. On the other hand, regions with more limited groundwater access or greater dependence on surface water deliveries, such as the Sacramento River region, experienced higher rates of fallowing, highlighting the uneven capacity to cope with surface water shortages.

Figure 3 shows the cropland distribution of our baseline (figure 3(a)) and fallowing patterns in California's Central Valley for 2021 and 2022 (figures 3(b) and (c)). These figures highlight notable fallowing hotspots in the Sacramento River region, particularly in rice-growing areas, and in the western part of the San Joaquin River and Tulare Lake regions, where field and grain crops and processing vegetables are common. As observed, the extent of fallowing increased in 2022, particularly in the Sacramento River region, with 2021 seeing similar hotspots for land fallowing in the southern part of the Central Valley.

Our fallow land estimation method enables a comparison of results summarized by major crop categories (figure 4). For a higher resolution view of the results, refer to figure SI.4 in the supplementary information. In both years of analysis, the most impacted commodity group was field and grain crops, particularly rice in the Sacramento River region, with 59 000 hectares in 2021 and 125 000 hectares in 2022. This was followed by field and grain crops (mainly cotton) in the Tulare Lake region, with 48 000 hectares in 2021 and 47 000 hectares in 2022, and followed by corn in the same region, with 24 000 hectares in 2021 and 21 000 hectares in 2022. The fallowing behavior observed in rice in the Sacramento River region, and cotton and corn in the San Joaquin River and Tulare Lake regions, reflects a common adaptation by farmers, who typically fallow these annual crops (Gebremichael *et al* 2021, Rodriguez-Flores *et al* 2021).

We validated the ET-based fallowing estimates using statewide cropland mapping for 2021 and 2022 released by (DWR 2025c). To maintain methodological consistency, we preserved the 2019 parcel boundaries used in our fallowing analysis and rasterized the 2021 and 2022 crop maps onto those same field polygons. For each 2019 field, the dominant (majority) crop category was assigned based on the crop classification. Fallowing in the validation dataset was defined as parcels that were classified as irrigated cropland in 2019 but were either fallowed or transitioned to a non-agricultural land use in 2021 or 2022.

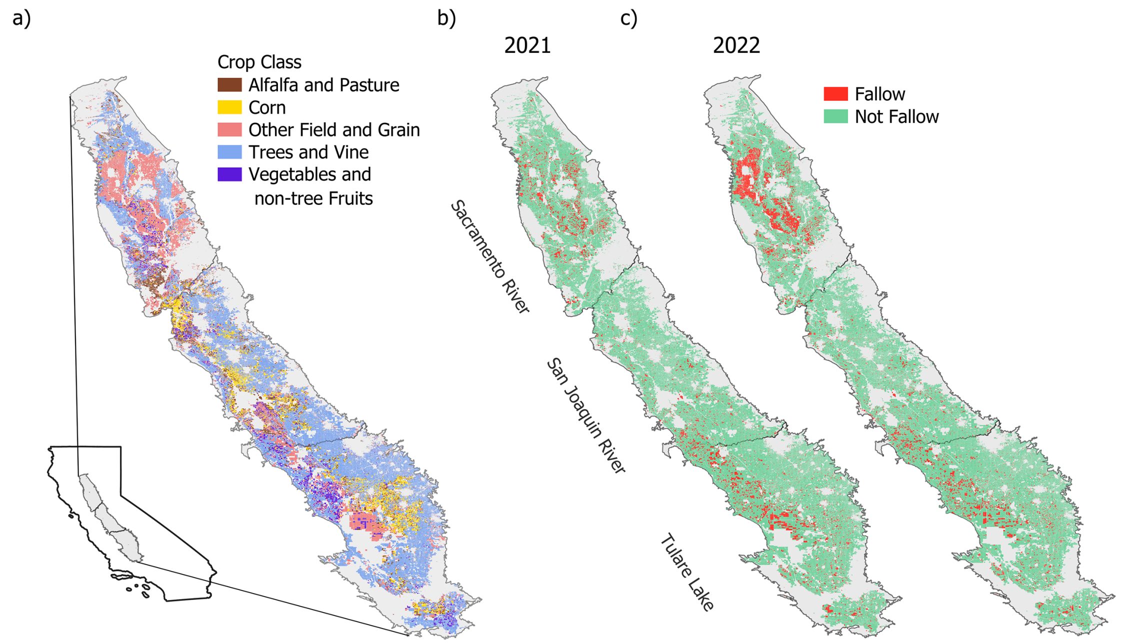

Figure 3. (a) 2019 cropland in Central Valley used as baseline (DWR 2022) and projected fallowed in (b) 2021 and (c) 2022.

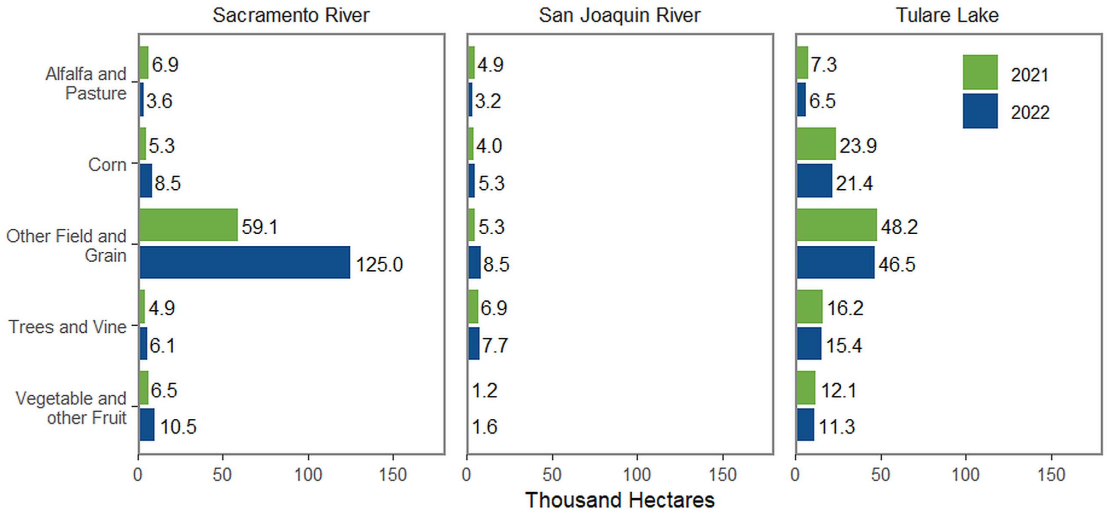

Figure 4. Estimated fallow land by crop category in 2021 and 2022 compared to baseline.

Acres were then aggregated by hydrologic region and crop category (table SI.2) to allow direct comparison with our ET-based estimates. Some parcels that transitioned from irrigated cropland to fallow during the drought may have done so as part of a planned rotational cycle that was unrelated to the ongoing drought.

The validation indicates that the ET-based method captures total drought-induced fallowing with good accuracy at the regional scale, differing from validated totals by −13% in 2021 and +2% in 2022 across the Central Valley. Hidrologic region totals show deviations of +3% to +14% in the Sacramento River and −18% to −8% in Tulare Lake, for 2021 and 2022 respectively, with larger deviations in the San Joaquin River region (−11% to −33%). The ET-based approach performs most robustly at the regional and Central Valley-wide scale, which underpins the economic impact estimates. The validation analysis further allows us to quantify broader land-use dynamics beyond drought-induced fallowing (table SI.3). Across the Central Valley, cropped-to-fallow transitions accounted for 9% of parcel area in 2021 and 10% in 2022 relative to the 2019 baseline field boundaries. In contrast, fallow-to-cropped, outside of the scope and capacity of our methodology, transitions represented 2% and 3% of total area,

Table 3. Employment and value added direct impacts from crop production. Values in parenthesis give the reduction from baseline (2019) direct revenue.

Hydrologic region	Direct revenue ($M) 2021	Direct revenue ($M) 2022	Employment (Jobs) 2021	Employment (Jobs) 2022	Value added ($M) 2021	Value added ($M) 2022
Sacramento river	358 (−8%)	659 (−15%)	2312	3698	213	438
San Joaquin river	157 (−2%)	184 (−2%)	1562	1793	102	139
Tulare lake	667 (−4%)	621 (−4%)	4992	4685	418	449
Total	1182 (−4%)	1464 (−5%)	8867	10 176	733	1026

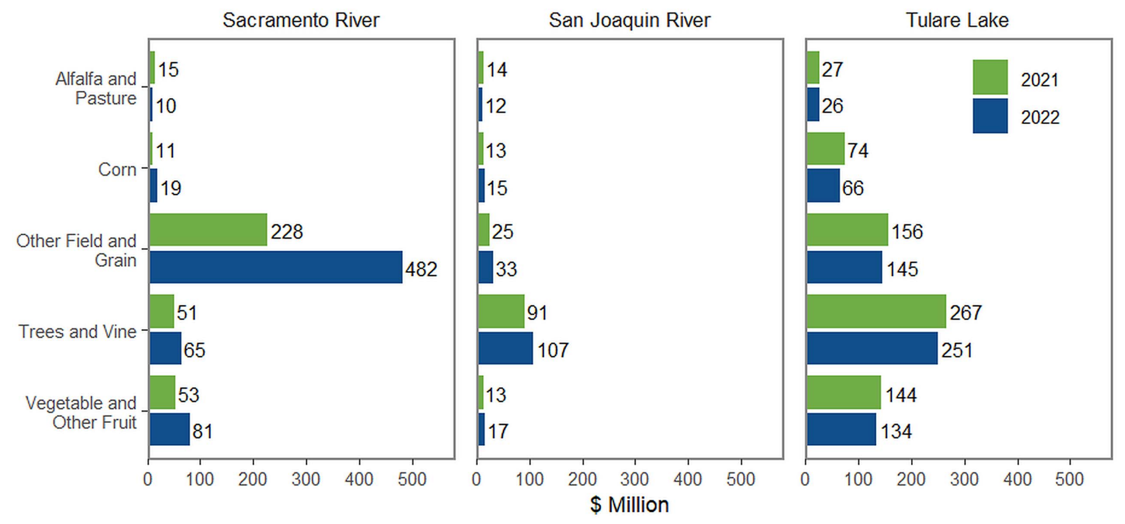

Figure 5. Direct economic impact as gross revenues (millions of dollars) by crop category in 2021 and 2022.

respectively, and may encompass lands transitioning as part of a normal rotation that includes periods of fallowing.

3.3. Economic impacts

3.3.1. Direct economic impacts

Using fallow land estimates, we assessed direct economic impacts by incorporating crop yields and prices. The results reveal significant variations across regions and crop classes. As shown in table 3, total agricultural revenue losses across the Sacramento River, San Joaquin River, and Tulare Lake regions increased from $1.18 billion in 2021 (a 4% reduction from 2019) to $1.46 billion in 2022 (a 5% reduction from 2019). Among the regions, the Sacramento River experienced the largest total direct revenue loss, rising from $358 million in 2021 (an 8% reduction from 2019) to $659 million in 2022 (a 15% reduction from 2019).

Among crop categories, field and grain crops experienced the largest increase in revenue losses (figure 5), rising from $409 million in 2021 to $660 million in 2022. This trend was primarily driven by a sharp rise in water supply losses in the Sacramento River region, where revenue losses increased from $228 million to $482 million, largely due to reductions in rice production. The second largest revenue losses occurred in the Tulare Lake region where field and grain crops (mainly cotton) constitute most of the $156 million in 2021 and $145 million in 2022. Similarly, revenue losses for trees and vine increased from $409 million to $423 million, with the most notable decline occurring in the Tulare Lake region.

Land fallowing had economic impacts across regions, disrupting not only on-farm revenues but also employment and value added. Employment losses totaled 10 176 jobs in 2022, reflecting a loss of critical livelihoods in rural communities. The Sacramento River region experienced 3698 job losses, an increase of 1386 compared to 2021, highlighting the region's reliance on farm labor. In contrast, the San Joaquin River and Tulare Lake regions experienced 6478 job losses, a slight decline from the previous year.

Value-added losses from crop production (table 3), or measure of contribution to the economy, reached $1.03 billion in 2022, with the Sacramento River region contributing $438 million, twice as much as in 2021. The San Joaquin River and Tulare Lake regions accounted for $520 million and $588 million in 2021 and 2022, respectively. These results highlight the regional disparities in how

Table 4. Estimated impact of fallow land on food and beverage processing industries.

	Employment		Gross revenue		Value added	
	(Jobs)		(Million $)		(Million $)	
Hydrologic region	2021	2022	2021	2022	2021	2022
Sacramento river	2499	4794	1172	2223	294	549
San Joaquin river	465	536	259	265	60	63
Tulare lake	1892	2036	978	979	235	235
Central valley total	4856	7366	2409	3467	589	846

Table 5. Estimated increase in groundwater pumping and pumping costs in the central valley in 2021 and 2022. Reproduced with permission from Medellín-Azuara *et al* (2022).

	Groundwater pumping augmentation (Mm^3)		Additional energy costs (million $)	
Hydrologic region	2021	2022	2021	2022
Sacramento river	852	1358	14.9	23.8
San Joaquin river	1252	1210	28.2	27.3
Tulare lake	3002	1541	140.4	72.1
Central valley total	5106	4109	183.6	123.1

drought-related crop production losses impact local economies, with the Sacramento River region bearing a more pronounced burden. Such differences reflect the uneven vulnerability of agricultural systems to water shortages. Understanding these indirect economic impacts of drought is essential for informing targeted and equitable strategies that support farm-dependent communities and guide adaptive approaches to land and water management.

3.3.2. Food and beverage processing industry economic impacts

Crop production losses cascade into both upstream sectors (those providing goods and services to agriculture) and downstream sectors including dairies, beef, and food processing. Economic losses include job losses in processing, transportation, and other sectors that depend on agricultural production. Additionally, reduced agricultural activity leads to declines in value-added contributions, which represent the overall economic output generated by processing, and supply chain activities.

Gross revenue losses (table 4) in the food industry sectors increased from $2.41 billion in 2021 to $3.47 billion in 2022, driven primarily by the Sacramento River region, where losses nearly doubled from $1.17 billion in 2021 to $2.22 billion in 2022. In contrast, the San Joaquin River and Tulare Lake regions saw an increase, from $1.24 billion to $1.25 billion. These findings underscore the cascading economic effects of agricultural land fallowing, highlighting the need for targeted policies and support mechanisms to mitigate impacts on rural economies and farm-dependent communities.

The total employment impact rose from 4856 jobs in 2021 to 7366 jobs in 2022, with the Sacramento River region experiencing the largest increase, from 2499 jobs in 2021 to 4794 jobs in 2022. This trend aligns with the sharp rise in agricultural revenue losses in the region, particularly in Other Field and Grain crops (rice in Sacramento). Similarly, value-added losses escalated from $589 million in 2021 to $846 million in 2022, with the Sacramento River region seeing the most significant rise, increasing from $294 million to $549 million. Meanwhile, the Tulare Lake region experienced $235 million value added losses in both years.

3.3.3. Increase in groundwater pumping costs

We estimated incremental groundwater pumping of 5106 Mm^3 in 2021 and 4108 Mm^3 in 2022 for the Central Valley. The increased pumping costs were estimated based on the energy required to lift water from median groundwater levels, as reported by the DWR periodic groundwater level measurements (DWR 2024). The estimated augmentation costs were $183.6 million in 2021 and decreased to $123.1 million in 2022 (table 5). This reduction in 2022 is attributed to improved surface water conditions in the Tulare Lake basin, where groundwater levels are usually deeper. Additionally, increased pumping in the Sacramento Valley incurs lower costs due to shallower groundwater depths.

It is important to note that these water supply costs may be partially offset by reduced surface water expenses. However, in many California irrigation districts, surface water supplies have fixed costs based on land assessments. Beyond the direct costs associated with increased groundwater extraction during droughts, growers may encounter additional, often overlooked expenses. One significant cost arises

Figure 6. Total regional economic impacts from the 2020–2022 drought.

from the necessity to activate unused wells, deepen existing wells or drill new ones as groundwater levels decline. Statewide, approximately 930 new agricultural wells are drilled annually under typical conditions. During drought periods, this number increases substantially. For example, 1447 new agricultural wells were constructed statewide in 2021. Across the 2020–2022 drought period, approximately 4200 new agricultural wells were drilled within the Central Valley alone (see section 3.4), indicating sustained infrastructure expansion in response to surface water shortages.

3.3.4. Total economic impacts

The regional-wide economic consequences of the drought, including losses from crop production, food processing, and increased pumping costs, are depicted in figure 6. These estimates highlight the varying economic burdens across California's agricultural regions. In 2021, the San Joaquin River & Tulare Lake region experienced the most significant economic impact, with $2.2 billion in revenue losses and 8920 jobs lost. The Sacramento River region, while affected, faced a lower total economic loss of $1.5 billion and 4810 jobs lost. Overall, Central Valley faced a total of $3.8 billion in gross revenue losses, $1.3 billion in value added losses, and 13 720 jobs lost due to drought impacts in 2021.

The economic impacts shifted in 2022, with the Sacramento River region experiencing the highest losses at $2.9 billion, leading to 8490 job losses. Meanwhile, the San Joaquin River & Tulare Lake region saw an estimated $2.1 billion in total revenue losses and 9050 job losses. These findings underscore the shifting economic impact of drought across regions, with increased impacts in 2022, particularly in the Sacramento River Valley. Overall, the 2022 drought impacts in the Central Valley led to $5.1 billion in gross revenue losses, $1.9 billion in value-added losses, and 17 540 job losses.

3.4. Ex-post assessment of agricultural wells, domestic wells, and groundwater depletion

This ex-post assessment results, using publicly released data from recent years, helps to identify hotspots of drought impacts, including farmer adaptation strategies, community water shortages, and groundwater level changes. A common form of farmer drought adaptation is the drilling of new wells, reflecting how growers responded to reduced surface water (Medellín-Azuara *et al* 2015, Gailey 2023). For communities, the failure of domestic wells represents one of the most critical consequences of drought, with significant socio-economic and water access (Gailey *et al* 2022, Rodríguez-Flores *et al* 2024). Finally, changes in groundwater levels provide a broader view of the drought's cumulative effects on aquifers.

As described in our water supply analysis, groundwater pumping increased substantially (by an estimated 40%–50%) during the drought to compensate for reduced surface water supplies. This expansion was achieved through greater use of active wells, reactivation of previously idle wells, and the construction of new wells across the Central Valley (figure 7). The extent of these responses depended on existing infrastructure and prior water conditions. In many cases, farmers needed to install additional pumping capacity, while in others, well failures caused by declining water levels required replacement.

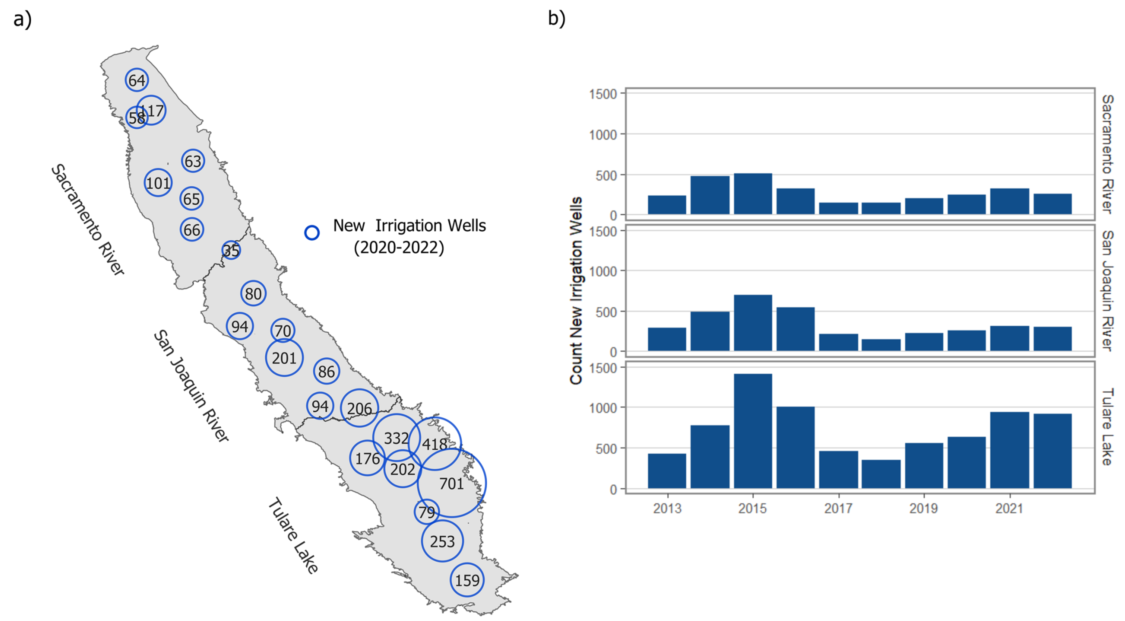

Figure 7. New irrigation wells drilled between 2020 and 2022. Data adapted from Cole (2024) and DWR (2025e).

Additionally, constructing new wells is a burdensome expense for growers and construction timeframes were reportedly exacerbated during the recent drought by drilling companies being overwhelmed by a surge of customers.

Across the Central Valley, about 4200 new wells were constructed during the 2020–2022 drought, compared to roughly 6900 during the 2013–2015 drought, indicating a decline in drilling activity in the more recent period. Across regions, over 860 wells were drilled in the Sacramento River region, 910 in the San Joaquin River region, and 2600 in the Tulare Lake region. Spatial hotspots, shown in figure 7(a), indicate that the west side of the Tulare Lake basin was the primary area of new well construction. Although drilling activity remained substantial, it may have been partially curtailed due to new permitting requirements that align new wells with local drought preparedness and groundwater sustainability planning.

One of the most severe consequences of drought in the Central Valley is the effect on drinking water wells in small communities (figure 8(a)). Using data released after our initial analysis, we note that during the 2020–2022 drought more than 2400 domestic wells were reported dry (figure 8(b)), exceeding the number reported during the 2013–2015 drought by 501 wells. Regional patterns show over 560 dry wells in the Sacramento River region, more than 770 in the San Joaquin River region, and over 1090 in the Tulare Lake region. Similar to agricultural well drilling, most domestic well failures were concentrated on the west side of the Tulare Lake basin (figure 8(b)), where the overlap between new irrigation wells and dry drinking wells suggests localized pumping pressures. Because domestic wells are typically shallower, they are more vulnerable to groundwater declines driven both by drought-related recharge reductions and by intensive pumping from agricultural wells (Perrone and Jasechko 2017, Pauloo *et al* 2020).

A common adaptation for affected households and communities dependent on wells is drilling deeper replacement wells. However, for many small and disadvantaged communities, this represents a financial burden, given capital, operating and maintenance costs. During the 2020–2022 drought, over 9400 new drinking water wells were constructed, including over 3500 in the Sacramento River region, 2900 in the San Joaquin River region, and 2900 in the Tulare Lake region. However, new drinking well construction is not limited to drought years. In the 2017–2019 period, there were close to 6300 new drinking wells in the Central Valley (figure 8(b)). Although the number of new wells drilled during the drought exceeded reported well failures, this does not mean that household water insecurity was resolved. The disparity reflects the unequal ability to invest in costly well infrastructure, with many low-income households and disadvantaged communities unable to build deeper wells. In addition to drilling, many communities often rely on emergency measures such as bottled water, water hauling, or temporary storage tanks (London *et al* 2018). These responses underscore the structural vulnerability of domestic and community water systems, which are often underfunded and lack the capacity to withstand

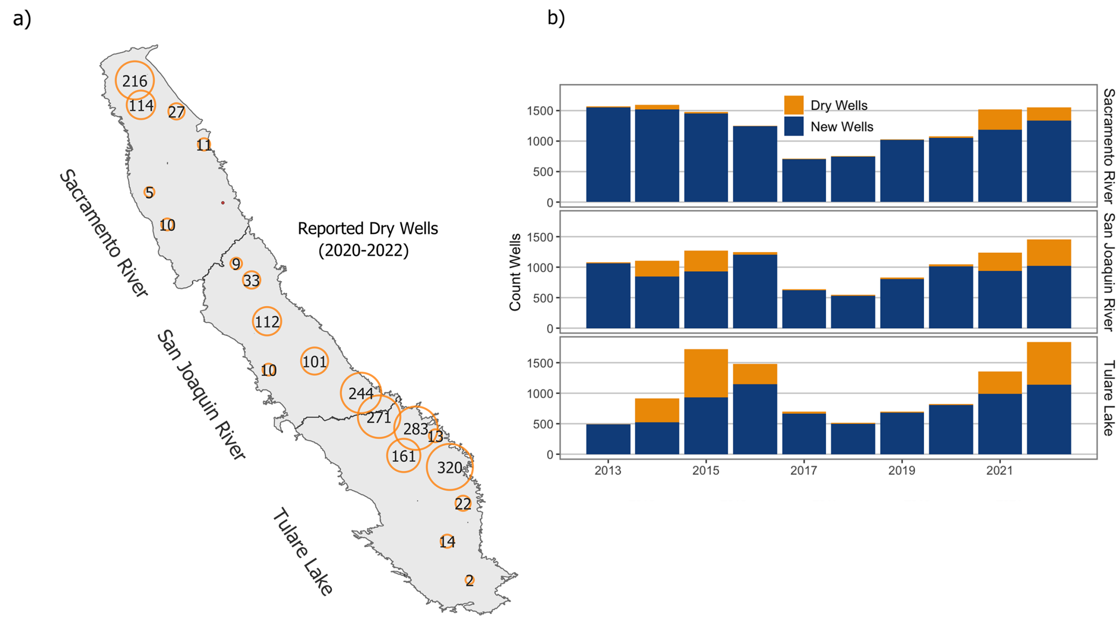

Figure 8. Reported dry and new drinking wells. Data from DWR Dry Well Reporting System and Well Completion Reports (DWR 2025b, 2025e and Cole 2024).

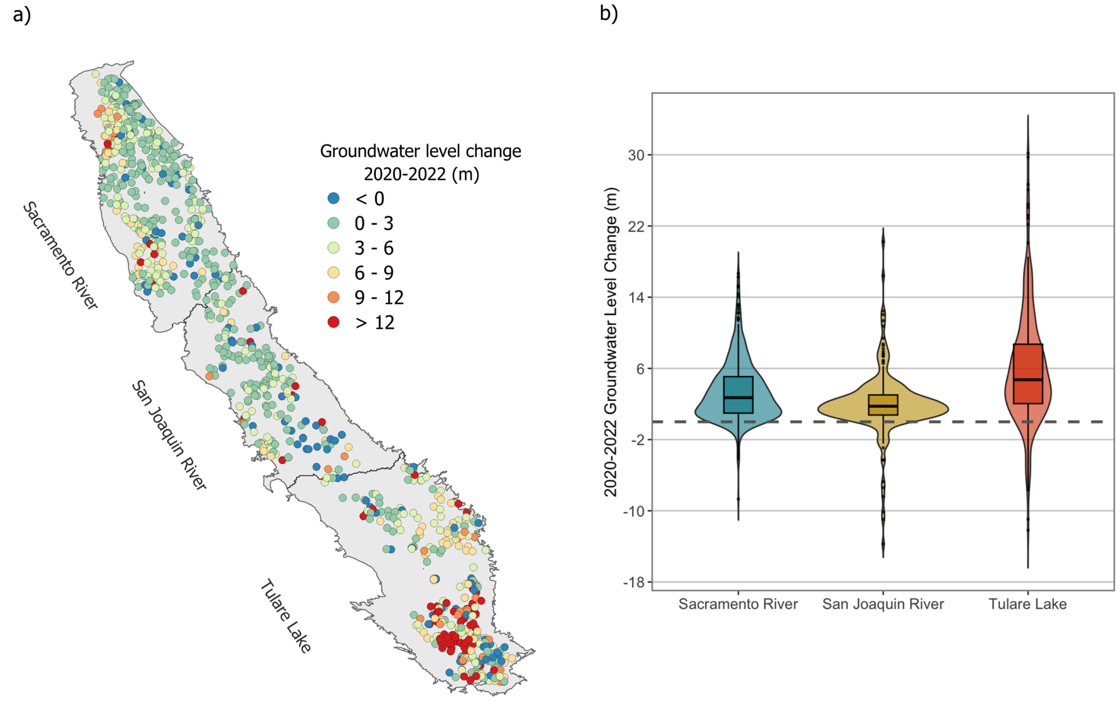

Figure 9. (a) Groundwater level change from selected monitoring wells from 2020–2022, (b) distribution of groundwater levels changes between 2020 and 2022 from selected monitoring wells. The dashed line in panel b) is 0 m or no change. Data was obtained from SGMA monitoring wells (DWR 2025a).

sustained shortages (Klasic *et al* 2022). The burden falls disproportionately on low-income rural communities, compounding existing socio-environmental vulnerabilities and worsening water access challenges and public health risks (Dobbin *et al* 2023, McNeeley *et al* 2025).

Groundwater level changes during the 2020–2022 drought reveal both the uneven spatial distribution of impacts and the risks posed by sustained declines across the Central Valley (figure 9). Figure 9(a) shows total changes in groundwater levels from early 2020 to late 2022, indicating that most monitoring wells recorded total declines of less than 3 m, across the Central Valley, while several areas experienced much greater drawdowns. In particular, large portions of the southern Tulare Lake region (Kern County) exhibited declines exceeding 12 m, and parts of the west side (Tulare County) showed moderate declines of up to 9 m. Localized declines were also observed in the northwestern and southwestern Sacramento Valley. Figure 9(b) summarizes the distribution of changes by hydrologic region, highlighting deeper declines and greater variability in the Tulare Lake region compared to the Sacramento and San Joaquin Valleys.

Groundwater level declines can have multiple implications. Lower water tables can cause well failures, as shallow wells may be unable to access deeper groundwater and may require costly rehabilitation. Deeper pumping also increases energy demands and operational costs for water extraction. Persistent groundwater depletion raises additional concerns about land subsidence: prolonged or intensive pumping can compact fine-grained aquifer materials, leading to irreversible reductions in groundwater storage and damage to critical infrastructure such as canals, levees, and roads. These subsidence impacts, which have historically been concentrated in the southern regions, remain a significant risk during droughts when reliance on groundwater increases. Additionally, given the increase of agricultural wells activity there were subsidence hotspots in the Sacramento River region that may have impacted federal and local water conveyance canals as shown in supplementary information section 9.

4. Discussion

4.1. Advancing timely drought impact assessments

Although the analysis presented here was completed in Fall 2022 using the best publicly available data streams at that time, it was later validated in 2025 using newly released state-reported datasets (including crop mapping and water balance data). The framework presented here can be transferred to other irrigated regions where comparable hydrologic, remote sensing, and economic datasets exist. For example, outside California, nationally consistent crop products such as the USDA Cropland Data Layer, could serve as the baseline crop classification input for applying this framework, while the OpenET data are available across the contiguous United States. Similarly, publicly available reservoir storage records, water allocation reports, and crop statistics are increasingly accessible.

Drought impact analysis is constrained by several data limitations. Year to year land use classification errors can introduce uncertainty and errors in our methodology, as shown by Espinoza *et al* (2023). The selection of a baseline year may also introduce bias due to year-to-year differences in water availability, crop rotations, and climatic variability. In addition, economic impact estimates depend on baseline assumptions regarding crop prices, yields, and revenues, which reflect regional averages rather than parcel-specific conditions.

Despite these limitations, our analysis demonstrates the value of remote sensing based ET as a scalable and spatially-explicit indicator of drought response. ET enables near-real-time assessment of irrigation reductions at both field and basin scales, providing a basis for estimating incremental drought-induced fallowing and first-order irrigation demand changes within a regional water balance framework. However, remote sensing-based ET estimates vary across models and depend on input data quality. In this study, we used the OpenET ensemble product, which reduces model-specific bias and has demonstrated strong agreement with flux tower observations in cropland (Volk *et al* 2024).

Our approach highlights the challenges of interpreting validating fallow land estimates and the need for complementary ground-based or authoritative data to refine classification. Future analyses could be strengthened by showing how other data or tools could be used in this type of analysis. Systematic real-time reporting of drought impacts by federal, state, or local agencies, for example, documenting prevented acres for uninsured crops not reported to the FSA or providing higher-resolution real-time accounting of surface water curtailments, would enhance timely evaluations and help calibrate drought impact assessment frameworks. Additionally, other remote sensing based metrics can provide information to improve the robustness of drought impact assessments (AghaKouchak *et al* 2023).

Together, these elements can be understood within a water balance framework unifying structure allowing hydroclimatic, water supply, and water demand (e.g. crop ET) information to estimate region wide drought impacts. In terms of water supply, our approach considered precipitation deficits, reservoir storage, announcements of major water supply project deliveries, and water rights curtailments. Our groundwater capacity assumptions are based on historical pumping within the water supply portfolios by hydrological region. However, not having readily accessible data has many limitations and while this water balance approach provides a broad approximation of systemwide dynamics, it may miss the finer-scale variability observed locally. Further research could develop more refined drought indicators that link hydroclimatic and water supply conditions that could support improved real-time drought assessments (Escriva-Bou *et al* 2025).

Finally, ex-post assessment of groundwater levels, agricultural well construction, domestic well failures, and subsidence underscores the interconnected and cascading nature of drought impact. We show how agricultural adaptation strategies can propagate unintended consequences to the aquifer and community water systems. Though in this study, these indicators were evaluated retrospectively to understand the broader aftermath of the drought. Future research could move beyond by integrating groundwater levels, well completion data, and subsidence monitoring into operational drought indicators, allowing for earlier detection of emerging vulnerabilities. Improved data continuity, standardized reporting, and reduced lag times in groundwater monitoring levels and well datasets would enhance both drought monitoring and rapid mitigation response. In addition to physical impacts, our analysis also quantified direct and associated economic consequences, including regional GDP output losses and employment effects. Future research could further expand this framework by integrating more detailed social indicators, such as income distribution, drinking water affordability, and demographic characteristics of affected communities, to better capture uneven drought burdens.

4.2. Land use dynamic considerations

It is important to distinguish between the incremental drought-induced fallowing estimated in this study (and validation data), and total irrigated and fallow area derived from recently released crop mapping by DWR. Our approach holds 2019 parcel boundaries constant and measures fields that were irrigated in 2019 but subsequently became fallow estimated remote sensing ET. In contrast, comparing total acreage across years from DWR crop maps captures net change, which reflects not only crop fallowing but also crop rotation, crop switching, and new plantings. As a result, differences between ET based fallowing and validation estimates and aggregate DWR acreage totals may reflect structural shifts in cropping patterns. A full breakdown of ex-post land use derived directly from DWR crop mapping is provided in table SI.3 and figure SI.9. These totals reflect net changes in irrigated area and therefore incorporate both drought-induced idling and structural shifts in cropping patterns, such as substantial increases in recent tree crop acreage (Cole *et al* 2024).

Future research could explore methods to explicitly incorporate crop switching and rotational dynamics into rapid drought assessment frameworks. These methodological improvements could include long-term assessment of individual parcels to determine rotation patterns that would support distinguishing between planned and drought-induced land fallowing. However, assigning specific crop types to parcels that transition between fallow and production or parcels that switch between crops remains challenging, as it requires crop classification across many years and careful differentiation of crop phenology and irrigation regimes, the granularity for which may be lacking in currently available remote-sensing datasets.

An important dimension not fully addressed in this study is the distributional impact of drought. Adaptive capacity varies among farmers and communities, and smaller or resource-constrained producers may face greater barriers to investing in groundwater infrastructure or other adaptation measures. Broader socioeconomic determinants, including access to credit, labor conditions, and institutional support, also shape resilience. Future research should more explicitly integrate these social and economic dimensions to better evaluate how drought responses affect different groups and to inform more equitable policy design.

4.3. Drought compounding effects and other interacting factors

In addition to drought, lingering effects of the COVID-19 pandemic, inflationary pressures (especially for food and energy), disruptions in the food supply chain, global price changes, and other factors influenced crop choices for California growers (Mishra *et al* 2021). Strong commodity prices for animal products not only increased demand for irrigated feed crops including alfalfa, silage corn and irrigated pasture, but also increased their cost due to a higher opportunity cost of water. A 20 year drought in the Colorado River Basin, where at least 70% of the irrigated area is in feed crops, further increased price pressure on feed crops. Feed crops typically among the lower value crop commodities constitute a systemwide constraint for water supply often overseen in integrated water and food systems (Medellín-Azuara *et al* 2024). Record high prices for processing tomatoes, in part because of reduced cropland in 2021, motivated farmers to plant moderately, some of which suffered from late season heat wave crop damage in 2022. These dynamics illustrate that drought impacts cannot be interpreted in isolation from broader market signals, price volatility, and climate extremes. Incorporating such interacting economic and climatic factors into an operational assessment framework remains challenging but could be further studied for improving timely impact evaluation.

An additional challenge in conducting drought impact assessment is setting a representative baseline and reconciling trends in price and other production trends. For example, in this study we chose to draw comparisons to land use conditions from 2019 but used a blend of years to represent water supply and crop prices and yields in the baseline. During the drought prices for many prevalent crop commodities in the Central Valley varied dramatically from their pre-drought (2016–2019) average. Almonds and walnuts saw significant price declines in the drought years due to high stock and other factors, while prices of many other crops including oranges, alfalfa, corn, rice, and processing tomatoes were up (USDA 2025). Land use considerations also play an important role in drought study design. Comparing land use to a baseline water year with uncharacteristically wet or dry conditions may over- or understate drought-induced land use changes. Longer-term shifts in land use, including the expansion of tree crops in recent years, create additional uncertainties in estimating net impacts as these trends may offset economic losses from drought fallowing with higher revenues for lands remaining in production.

4.4. Nuances of the 2020–2022 drought impacts and comparison with previous droughts

Agricultural land fallowing in the 2012–2016 drought was estimated to be up to 225 thousand hectares per year, with some years facing shallower reductions in cropland (Howitt *et al* 2015, Medellín-Azuara *et al* 2016, Lund *et al* 2018). Fallowing during the 2021–2022 drought was estimated in this study at about 247 thousand hectares per year on average and was validated at about 260 thousand hectares with recently available land use data. In this sense, the magnitudes of California's most recent two droughts were relatively comparable. However, the spatial distribution of impacts and the particular commodities that were most affected differed markedly between the two periods. Drought impacts in the 2012–2016 drought were concentrated more in the Tulare Lake Basin and were less severe in the Sacramento Valley region, whereas in 2021–2022 the Sacramento Valley experienced the highest fallowing increases and economic impacts. This pattern underscores the extent to which regional water infrastructure, management practices, and adaptive capacity developed during previous droughts enabled many regions to better withstand the most recent event's impacts. Strengthening coordination among agencies, farmers, communities, and groundwater sustainability agencies could further enhance this adaptive capacity and improve drought resilience in future events.

5. Conclusion

Our results demonstrate that timely, spatially resolved estimation of land fallowing, water supply reductions, and associated economic impacts is feasible using publicly available datasets. This study illustrates how an integrated framework can be applied during an unfolding drought to approximate cascading impacts across water supply, agriculture, and regional economies. By linking surface water shortages, groundwater substitution, land-use change, and economic ripple effects within a unified structure, the framework reveals the interconnected nature of drought impacts across water, land, and socioeconomic systems. Early indicators, including surface water allocation reductions, changes in ET, and groundwater level declines, can provide actionable signals for anticipating localized impacts.

Integrating a water-food systems-based framework such as the one presented here into water planning could also support a coordinated approach to irrigated agriculture management in a warming and increasingly variable climate. Drought response will require irrigation systems that can adapt across cycles of water abundance and scarcity, moderating water consumption during dry periods while sustaining agricultural production, the economy and community water security. Operationalizing such an approach depends not only on technical, modeling and data tools but most importantly on institutional coordination including water agencies, agricultural institutions, and community stakeholders. Embedding drought impact indicators within planning structures can foster learning across drought events, improve alignment between supply and demand management, and strengthen anticipatory planning. In this way, drought assessment moves beyond retrospective impact quantification toward supporting adaptive irrigation and water management.

Although the statewide economic impacts of the 2020–2022 drought were not catastrophic, they were substantial at regional scales and exposed uneven resilience across hydrologic regions. Agricultural production was sustained in many areas through increased groundwater pumping, but this buffering strategy elevated pumping costs, increased risks to household water security, and contributed to aquifer decline and subsidence. Finally, basins subject to SGMA have initiated a transition toward sustainable groundwater management, yet heavy reliance on groundwater remains central to short-term drought response. Continued groundwater declines, domestic well failures, and subsidence suggest that translating long-term sustainability goals into operational drought-resilient irrigation and groundwater management remains an ongoing challenge.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. Data used in the analysis has multiple formats and the original data sources were referenced.

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