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The Future of Agriculture in the San Joaquin Valley

Technical Appendix

CONTENTS

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Introduction

The San Joaquin Valley is California's largest agricultural region and an important contributor to the nation's food supply. But much of the valley's agriculture relies on irrigation during its long, dry growing season, and it faces a future with less water supply. The transition to groundwater sustainability under the Sustainable Groundwater Management Act (SGMA) may significantly reduce farm water availability. These shortages could be compounded by changing precipitation patterns and increasing evaporative demands caused by climate change, alongside a likely increase in water releases for environmental flows (or "e-flows").[1] By 2040, the combined reduction in available water supplies for irrigation may total as much as 20 percent.

Attaining groundwater sustainability and adapting to these other changes are essential for the valley's future. But it is also important to recognize that this large decline in a key production input will be costly to the sector and to the regional economy, where agriculture and related activities loom large. Hundreds of thousands of acres of land will likely be fallowed, and both agricultural GDP and jobs will decline. One important asset in transitioning to a future with less water is the long history of innovation and adaptation by the valley's farmers and water managers. Some water management options—like allowing for more flexible water trading and expanding water supplies—could reduce the costs of achieving groundwater sustainability and adapting to changing climatic conditions and environmental regulations. Also, the increase of agricultural productivity over past decades has significantly raised yields and economic returns for many crops grown in the valley, and continued productivity growth could help soften the economic impacts of these other stressors.

In PPIC's 2019 report, *Water and the Future of the San Joaquin Valley* (Hanak et al. 2019), we assessed the socioeconomic consequences of the transition to groundwater sustainability and other potential water supply constraints (for details, see Medellín-Azuara, Escriva-Bou, and Jezdimirovic 2019; Escriva-Bou 2019a). We found that at least 500,000 acres of cropland could go fallow in the next 20 years, but we also highlighted that new supplies and water trading could significantly reduce the costs of transitioning to sustainability. That study relied on our own estimates of water availability and overdraft for the San Joaquin Valley as a whole; we used Central Valley hydrologic models to assign overdraft to sub-areas within the valley (Escriva-Bou 2019b). Since that study's publication, new data have become available that enable us to provide a more up-to-date, granular look at the water availability and overdraft picture across the region. For this new study, we used data from the initial groundwater sustainability plans (GSPs) produced by the valley's groundwater sustainability agencies (GSAs), along with other data, to assemble consistent valley-wide datasets on surface water availability, groundwater overdraft, cropland characteristics, and potential climate change impacts for the valley's 15 groundwater basins and 49 local areas ("subunits") within them.

The objective of this study is to assess the socioeconomic consequences of the transition to groundwater sustainability in the San Joaquin Valley at a much more detailed scale than any previous study. We also consider other future water supply constraints—including the impacts of climate change and stricter environmental regulations. And we explore the potential benefits of different types of adaptations—including water trading and expanded water supplies. We also consider the role of continued growth in agricultural productivity, which could soften the impacts of irrigation water cutbacks.

Highlights of our findings appear in the accompanying *Policy Brief: The Future of Agriculture in the San Joaquin Valley*. This appendix provides more detailed information on the analysis. We first summarize the current agricultural landscape of the San Joaquin Valley. Then we present the main water-related challenges that the valley's agriculture will face in the coming decades, as well as some opportunities to adapt to these challenges.

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[1] In most of the charts and tables we use "e-flows" when referring to environmental flows.

We conclude by assessing the socioeconomic consequences of all potential future scenarios considered in the region, and we discuss how the findings compare with our 2019 analysis. An accompanying dataset, *PPIC Water Supply Constraints at the Local Scale in the San Joaquin Valley*, provides key information at the level of basins and subunits.

The Current Agricultural Landscape in the San Joaquin Valley

Agriculture has been the leading sector of the San Joaquin Valley economy since the late 19th century, when the region's farmers raised cattle, wheat, and other field crops. During the 20th century, the regional economy evolved to include an array of agricultural commodities, including fruits and vegetables, cotton, alfalfa, dairy, and orchard crops. Today, the valley produces roughly half of California's agricultural output. Its diverse range of crops and animal products serve state, national, and international markets.

Farming and related food and beverage manufacturing are far more important in the regional economy than in the state as a whole. While agriculture in California represents 2 percent of GDP and 3 percent of employment and revenues, in the San Joaquin Valley this sector accounts for 14 percent of GDP, 17 percent of employment, and 19 percent of revenues.[2] The foundation that agriculture provides for the valley's economy is even larger if one considers the related economic activities in transportation, farm inputs, and finance, along with broader spillover (or "multiplier") effects on the overall economy (see Box A1). In light of this importance, significant challenges to agriculture will impact a broad array of valley residents.

In the following subsections, we define the geographic coverage of our analysis, and present some key statistics on the current agricultural landscape in the valley.

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[2] Estimates are for direct economic effects of farm-related GDP, defined here as crop and animal production (including support services to agriculture) and food and beverage processing. Employment includes full-time, part-time, and seasonal jobs. Data is updated for 2019, based on the methodology defined in Hanak et al. (2017).

Box A1: Measures of Economic Value

In this report, we use several measures of economic activity to track the value of the valley's economy and assess the impacts of policy change.

- "Revenue" is the total income from sales of goods and services. The economic value of a business or industry is often characterized by its sales because that is the easiest information to obtain. Revenue is not an indicator of profitability, however, because it does not consider how sales compare with costs.
- "Profit" is revenues minus costs. It is the income that remains after subtracting all expenses and taxes. Farms, like other businesses, generally seek to maximize profits by increasing revenues and reducing costs.
- "Value added" is the contribution of a business or industry to the overall gross domestic product (GDP) of a region. It includes profit, compensation to employees, and taxes paid. It excludes the cost of goods and services purchased from other vendors or sectors, which have their own value added. This is the best measure of a sector's contribution to the overall economy, because the sum of value added from each sector equals the total GDP for the region.
- "Employment" is another useful measure of economic activity. Here we use estimates that include both full- and part-time work, and both year-round and seasonal jobs. These are the best measures available for agricultural employment.

Economic sectors are interconnected. Farm revenues usually consist of sales of crop and animal products. Food and beverage processing industries also would be affected by reduced farm output.

When a policy reduces farm output, there can be additional effects on sectors that supply farms—such as transportation, fertilizer, and irrigation services—as well as spillovers to the broader economy because people have less money to spend. These "multiplier" effects are much more difficult to estimate accurately. They often overstate the impacts of policy change, because they assume that businesses will not adapt to changing economic conditions.

We focus on the direct economic effects of reducing water use on crops, livestock, and related food and beverage processing industries. We do not include other multiplier effects, given the greater uncertainties in these measures.

Geographic Coverage

Our analysis focuses on cropland use and an array of socioeconomic indicators (revenues, GDP, and jobs) for irrigated agriculture and related activity (downstream beef, dairy, and food and beverage processing) in the San Joaquin Valley. This region lies primarily within two watersheds—the San Joaquin River and the Tulare Lake hydrologic regions—spreading over eight counties: Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, and Tulare. Given that most irrigated agriculture is on the valley floor, we removed from our analysis the lands at higher elevations, which are largely covered by rangelands and headwater forests.

Figure A1 shows the geographic coverage of our analysis. We include 15 groundwater basins and 49 local areas—or subunits—within these basins.[3] We defined these subunits by combining adjacent water districts with similar amounts of surface water per acre of cropland. This allows us to represent the potential water management challenges in the valley with considerable local nuance, as lands within subunits also face similar groundwater overdraft conditions.

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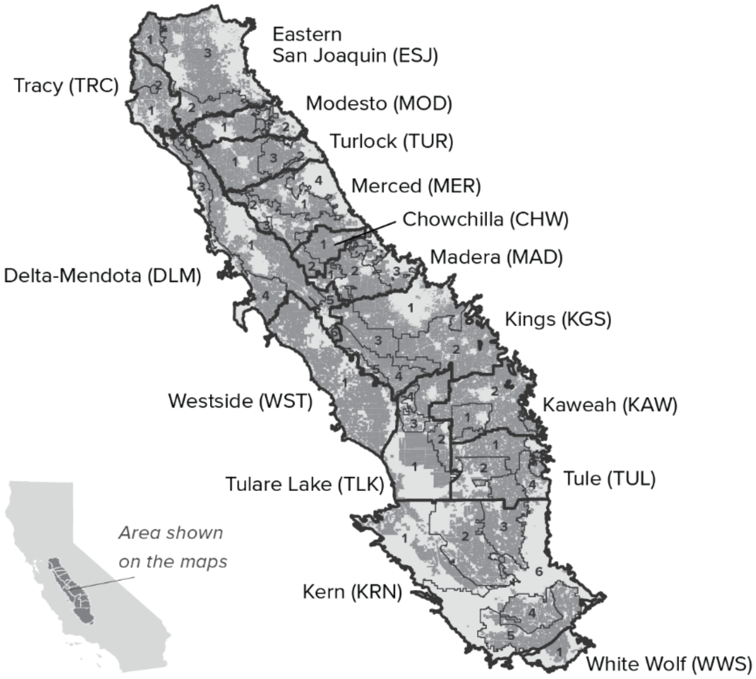
[3] The basins are the geographic units subject to SGMA. DWR officially defines these as subbasins, since many are part of much larger aquifer systems.

The 15 groundwater basins almost completely cover the valley floor of the two hydrologic regions, with around 8.3 million acres of land and around 4.5 million acres of irrigated cropland.[4]

FIGURE A1

Our geographic coverage of the San Joaquin Valley includes 49 subunits within 15 groundwater basins



SOURCE: Basin outlines are from the Department of Water Resources; subunits are defined by the authors.

NOTE: Darker grey shows irrigated cropland in 2018, and the numbers indicate the different subunits in each basin. For shapefiles, see the accompanying dataset: *PPIC Water Supply Constraints at the Local Scale in the San Joaquin Valley*.

Agricultural Acreage, Water, and Revenues

In 2018—a year with average water supplies—the valley's 4.5 million acres of cropland were irrigated with roughly 16.1 million acre-feet (maf) of applied water (Table A1). Gross crop revenues totaled about $24 billion. Of this total, 81 percent comes from trees and vines (perennial crops), which use 61 and 69 percent of total irrigated land and water, respectively. Among these, almonds stand out with almost 1.2 million acres, over a quarter of the total irrigated acreage in the valley. Other perennials—including pistachios, grapes, citrus, and other subtropical crops—also have an important presence. Field and grain crops are the category with the second-largest acreage (12%), using 8 percent of the water and generating 3 percent of revenues. Vegetables and non-tree fruits occupy 8 percent of irrigated acreage and 5 percent of farm water, with 11 percent of revenues. And finally, two categories are dedicated mostly to feed animals: corn and other silage, with half a million acres (11%), 7 percent of water, and 2.5 percent of revenues; and alfalfa and irrigated pasture, with around 350,000 acres (8%),

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[4] In *Water and the Future of the San Joaquin Valley* (Hanak et al. 2019), we reported around 5 million acres of irrigated cropland, using data from the California Agricultural Commissioners' Reports and the National Agricultural Statistics Service (NASS). That dataset includes acreage at the county scale and includes double cropping—fields that might be planted with wheat or other crops in the winter, and tomatoes or other vegetables in the summer of the same year. In this study, we use acreage data from LandIQ, made available by the Department of Water Resources. This data is available at the plot level, allowing for more precise delineation than the county-level data. It does not, however, take into account double-cropping. The differences in the reported acreage between these two sources might come from the inclusion of double cropping in the NASS data, as well as some cropped acreage at elevations above the valley floor.

11 percent of water, and 2 percent of revenues. As shown below, perennials are relatively more present in areas with higher groundwater overdraft.

TABLE A1

Irrigated acreage, water use, and revenues by commodity group in the San Joaquin Valley in 2018

Crop Commodity Group	Irrigated Cropland (thousands of acres)	Applied Water (thousands of acre-feet per year)	Revenues (2019 $ millions)
Alfalfa and pasture	347 (8%)	1,724 (11%)	454 (2%)
Corn and other silage	493 (11%)	1,143 (7%)	604 (3%)
Other field and grain	547 (12%)	1,219 (8%)	714 (3%)
Trees and vines	2,736 (61%)	11,145 (69%)	19,519 (81%)
Vegetables and non-tree fruits	368 (8%)	858 (5%)	2,733 (11%)
Total San Joaquin Valley	**4,491**	**16,090**	**24,025**

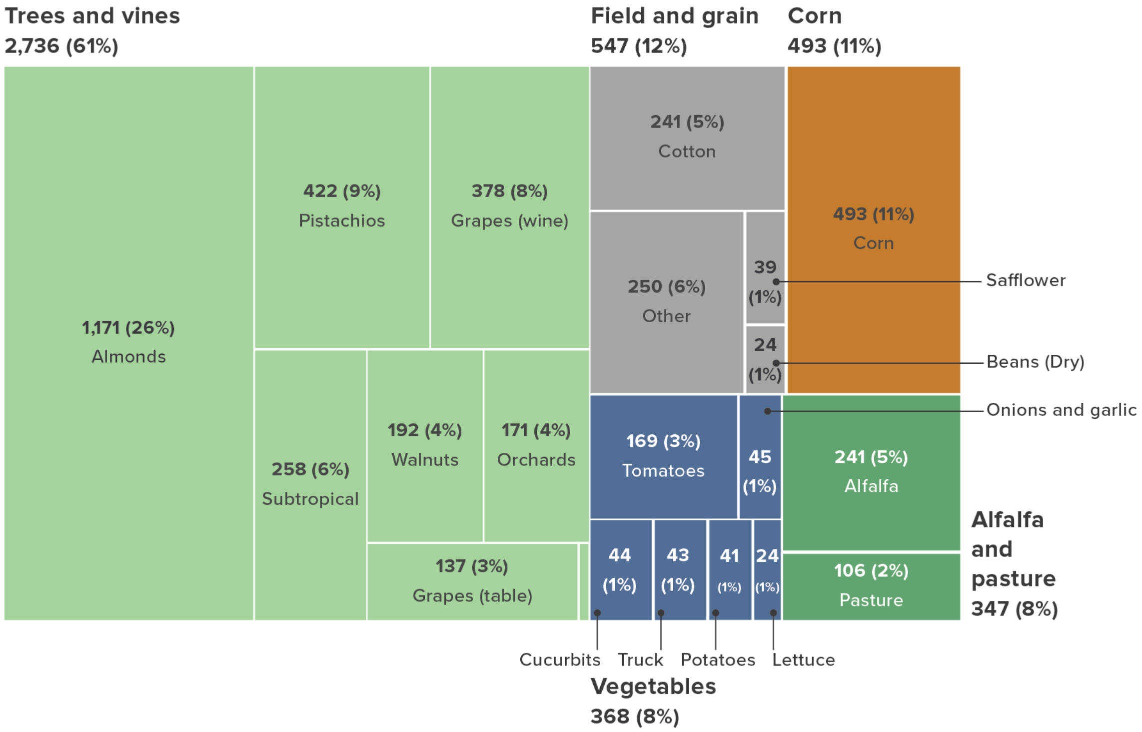
SOURCES: Irrigated cropland is from the California Department of Water Resources (LandIQ). Applied water use and revenues are derived from the openAG model (see text).

NOTES: Land use data is for 2018; revenues are based on average crop prices for 2017–19, adjusted to 2019 dollars. Applied water use was estimated by the authors using Department of Water Resources applied water use dataset for 2011–13, applied to 2018 land use (see note 9). For detailed acreage breakdowns within these five crop categories, see Figure A2. Some totals do not add up exactly to the sum of crop categories because of rounding.

Since the early 1980s, irrigated acreage has remained relatively stable (Hanak et al. 2017 and 2019). But as farmers seek to increase productivity and expand their markets, the crop mix is evolving constantly. The potential for high crop returns has fueled significant growth in perennials—up from just 21 percent of total acreage in the 1980s to 61 percent in 2018. There has also been growth in corn and other silages—used primarily for dairies. These trends mirror comparable declines in field and grain crops—especially cotton. Once the most important crop in the valley—with over a million acres planted in the early 1990s—only 240,000 acres of cotton remained in 2018.

FIGURE A2

The San Joaquin Valley has a diverse crop mix, but perennials constitute more than 60 percent of acreage



SOURCES: Irrigated crop acreage from the California Department of Water Resources (LandIQ), adapted by the authors.

NOTES: Numbers in boxes show acreage cultivated in 2018. Some crop categories were adjusted by the authors. For instance, young perennial acreage (which is not broken out by crop in the LandIQ data) was included in each perennial crop category proportionally to current acreage. Grapes were divided into table and raisins (fresh) and wine grapes (processed), using ratios at the hydrologic region provided by NASS county-level data. Pasture only includes irrigated pasture. Other field and grain crops include wheat, other grain and hay, and other miscellaneous grain crops.

Dairy and Beef Production

Animal products, particularly in the dairy and beef sectors, produce a substantial portion of agricultural revenues in the San Joaquin Valley and are intertwined with crop production. Dairies and beef produce about $6.4 billion and $3.2 billion, respectively, in total revenues. Poultry products and egg production contribute an additional $1.5 billion annually.[5] Beyond the consumption of irrigated feed crops (such as corn, alfalfa, and irrigated pasture), livestock operations in the valley use relatively little additional water, and the operations themselves do not have large footprints. Some seasonal grazing is done on non-irrigated lands.

Irrigated feed crops are essential inputs for dairy and beef production processes. Feeding strategies for cattle typically include a mixture of grazing and feedlots and can evolve over time, depending on the age of the herd. In feedlots, cattle consume dry feeds (such as alfalfa and other hays) and wet roughage consisting primarily of silage corn. Whereas hay can be imported from other parts of the state or country, wet feeds are expensive to transport long distances and must be produced locally. This constraint explains the lesser decline of silage corn as compared with other annual crops in the region, as silage corn is required as an input for dairy farms and cattle ranches and is often grown onsite by dairies. Silage acreage is also an important part of nutrient management for dairies, as this land is typically fertilized with manure.

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[5] Data reported in this paragraph are from USDA NASS for 2018.

In our analysis, we assume that silage corn and irrigated pasture reductions affect the output of dairy and beef, respectively, but that producers substitute local alfalfa with alfalfa purchased from elsewhere at the same cost (see note 43).

Food and Beverage Processing Sectors

Many crop and animal products in the valley serve as inputs to processing sectors that incorporate these raw products into foods and beverages. Revenues from these processing sectors total roughly $34 billion, but they must account for the purchase of upstream agricultural products and other inputs, so the regional value added is substantially lower— $7.4 billion.

With the exception of fresh fruits and vegetables, many crop products are incorporated into processing streams for canned goods and other foodstuffs that are ultimately sold to consumers. The dairy and beef sectors are also relatively important contributors to the downstream processing of food and beverages in the region.[6]

When raw inputs from local crop and animal sectors are not available, processing plants may adjust by reducing production or purchasing alternative inputs from elsewhere. In our analysis, we assume that they reduce production.

Valley-Wide Economic Effects of the Agricultural Sector

When we aggregate all the economic effects of crop production, animal products, and processing sectors, the agricultural sector generates $67 billion in annual revenues; this adds $28 billion to the GDP of the valley, and supports nearly 340,000 jobs—including both direct employees and contract labor. This represents 19 percent of the valley's revenues, 14 percent of GDP, and 17 percent of employment (Table A2).

TABLE A2

Base case revenues, value added, and employment in the San Joaquin Valley

Agriculture-related sectors	Revenues ($ millions)	Value added ($ millions)	Employment
Crops	24,025	17,038*	233,897*
Dairy and beef	8,373	3,163*	35,860*
Food and beverage industries	34,359	7,427	67,766
Agricultural sector total	**66,757**	**27,628**	**337,523**
Economy-wide total	**344,997**	**193,442**	**2,024,543**

SOURCES: IMPLAN database for the eight-county region in 2019. Revenues for crops are from openAG (see note 29).

NOTES: Employment includes full- and part-time jobs. "*" Denotes measures that were adjusted to include agricultural support services (mainly contract labor), which are an important input into San Joaquin Valley crop and animal production. This may overstate the total sector size. For revenues, we only include direct crop and animal product revenues to avoid double-counting the costs of contract labor. (Revenues for the support services sector are payroll costs that must be covered by the proceeds of farm sales.)

When a policy reduces farm output, there can be additional effects on sectors that supply farms—such as transportation, fertilizer, and irrigation services—as well as spillovers to the broader economy because people have less money to spend. These "multiplier" effects are much more difficult to estimate accurately. They often overstate the impacts of policy change because they assume that businesses will not adapt to changing economic conditions. By including both crops and the downstream livestock and food and beverage processing industries,

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[6] Whereas crops provide 62 percent of agricultural value added and 69 percent of agricultural jobs (see Table A2), they account for just 40 percent of the local agricultural production inputs into the valley's food and beverage processing industries. Dairy accounts for 11 percent of agriculture's value added and jobs, but 17 percent of local agricultural production inputs into processing. For beef, the corresponding numbers are 27 percent of value added, 20 percent of jobs, and 40 percent of production inputs.

we capture the effects of water use reductions on the main sectors that depend on crop production. We do not include other multiplier effects, given the greater uncertainties in these measures.

Assessing Future Water Scenarios in the San Joaquin Valley

Changes in water availability will constrain the San Joaquin Valley's agricultural sector in the coming decades. In particular, the water reductions required to achieve groundwater sustainability will likely cause irrigated agriculture to shrink in size. Climate change is also expected to affect both water availability and demand, and there is the potential for additional supply reductions with new environmental water requirements. Some adaptations, including water trading and expanding water supplies, could mitigate some of the expected economic losses, and continued increases in farm productivity could also soften the impacts of reduced water availability. Still other factors—such as changing labor, input, and product markets—are also important for agriculture's future in this region, but beyond the scope of this analysis.

In this section, we define and assess the effects of some of the most pressing water-related challenges and opportunities that could impact the valley's agriculture. We look first at potential water constraints by: i) estimating the reductions in groundwater pumping needed to achieve sustainability under SGMA; ii) assessing the combined effects of climate change by calculating the reductions in surface water deliveries and the increase in crop water demands; and iii) assessing the potential reductions in farm water availability from proposed increases in environmental flows. Then, we estimate potential benefits to agriculture from: i) increased flexibility from different water trading approaches; ii) expanded water supplies; and iii) increased farm productivity.

In the following subsections, we detail our calculations and assumptions.

Reductions in Groundwater Pumping to Achieve Sustainability

After the passage of SGMA in 2014, estimating the amount of groundwater overdraft that must be eliminated to bring basins into balance has been a key question in the San Joaquin Valley, a region that is ground zero for SGMA implementation. These estimates are essential for defining and implementing the supply and demand management actions that are needed, and for assessing the socioeconomic and land use implications of different pathways to achieve sustainability.

In 2019, we estimated the annual water balances in the San Joaquin Valley for the 1988–2017 water years, and obtained groundwater overdraft for the region as a whole, as well as for a set of subregions defined in Central Valley hydrologic models (Escriva-Bou 2019b). While our regional estimates are consistent with more recently reported data (Hanak et al. 2020), they were spatially coarse, as it was challenging to find reliable local data.

Since the publication of our 2019 report, valuable new information has become available that can improve these estimates. Among the most important new sources of data are the GSPs submitted to the state's SGMA Portal. In most of these plans, there is substantial detail about annual water budgets at the basin level.[7] At PPIC, we have also been developing datasets that provide consistent and comprehensive information for the valley (see link). Two datasets in particular were essential to refine our estimates of local groundwater overdraft: PPIC San Joaquin Valley GSP Water Budgets (Jezdimirovic et al. 2020a), which reviews GSP water budgets using a consistent 2003–10 historical baseline, and PPIC San Joaquin Valley Surface Water Availability (Jezdimirovic et al. 2020b),

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[7] For basins with multiple GSPs, all GSPs had to use common accounting for the basin. Plans for different basins were not required to use the same set of years for historical baselines, however, and there was considerable variation in the set of years used. See Hanak et al. (2020).

which compiles surface water availability at the local level for the whole valley.[8] We estimated water use at the subunit level using LandIQ spatial cropping data and estimates of crop water use from the Department of Water Resources.[9]

In this subsection, we explain how we estimated groundwater overdraft and derived pumping reductions required to end overdraft at the local level. First, we describe how we obtained estimates of basin-level overdraft, then surface water deliveries, and finally the groundwater supply cuts needed at the subunit level to achieve sustainability.

Overdraft at the basin level

Estimates of overdraft at the basin level build on research outlined in Hanak et al. (2020), which drew on the values reported in the GSPs. We updated this analysis to include the Modesto, Turlock, Tracy, and White Wolf groundwater basins, which had not published plans at the time of the previous review.

From this basin-level data, we obtained annual measures for the major components of the water budgets: surface water deliveries, groundwater pumping, and change in groundwater storage. SGMA regulations require GSPs to include three types of water budgets—historical, current, and projected—but allow substantial flexibility on the specifics. Historical budgets only need to include a minimum of 10 continuous years of data, including the most recent years available for that basin (see Hanak et al. 2020 for a review of the GSPs). Current budgets need to show present-day conditions, and projected budgets need to look ahead 50 years and consider anticipated changes in population, climate, and other factors that could affect water supplies and demands. The plans can then choose which budget to emphasize for addressing overdraft (the “preferred” estimates shown in Figure A3a).

Hanak et al. (2020) showed that timeframes used to estimate overdraft vary widely across basins, because there is no requirement for consistency across neighboring basins. Since the plans cover different timeframes, it is misleading to simply compare their preferred estimates of overdraft. To compare apples to apples, we looked at the eight years that are included in all of the budgets: 2003–10. As shown in Figure A3b, the plans estimate around 1.84 maf of annual overdraft in these years—fairly close to our 2019 valley-wide estimate of 1.9 maf for the same period (and 1.85 maf for the 30-year period from 1988–2017) (Escriva-Bou 2019b). Overdraft is more significant in the Tulare Lake hydrologic region (orange bars in Figure A3) with roughly two-thirds of the valley’s total overdraft, but some basins on the east side of the San Joaquin River hydrologic region also report substantial overdraft.

The 2003–10 period is instructive, because it includes both wet and dry years. However, it is also a short timeframe that might not fully reflect more recent trends in the San Joaquin Valley. In Escriva-Bou (2019b), we showed that while total average water use remained relatively constant over the first and second half of the 30 years analyzed (1988–2017), the shares of different water sources shifted considerably. From 1988–2002, local supplies and Delta imports provided an average of 71 and 21 percent of supplies, respectively. Those shares fell to 68 and 17 percent in 2003–17, reflecting a combination of drier hydrology, increased regulatory constraints on Delta imports (especially since the late 2000s), and increased use of Delta imports in Southern California. To complement this decline, groundwater overdraft increased from 8 percent in the first 15-year period, to 15 percent in the second 15-year period. For the most part, the GSPs do not emphasize these more recent changes in their

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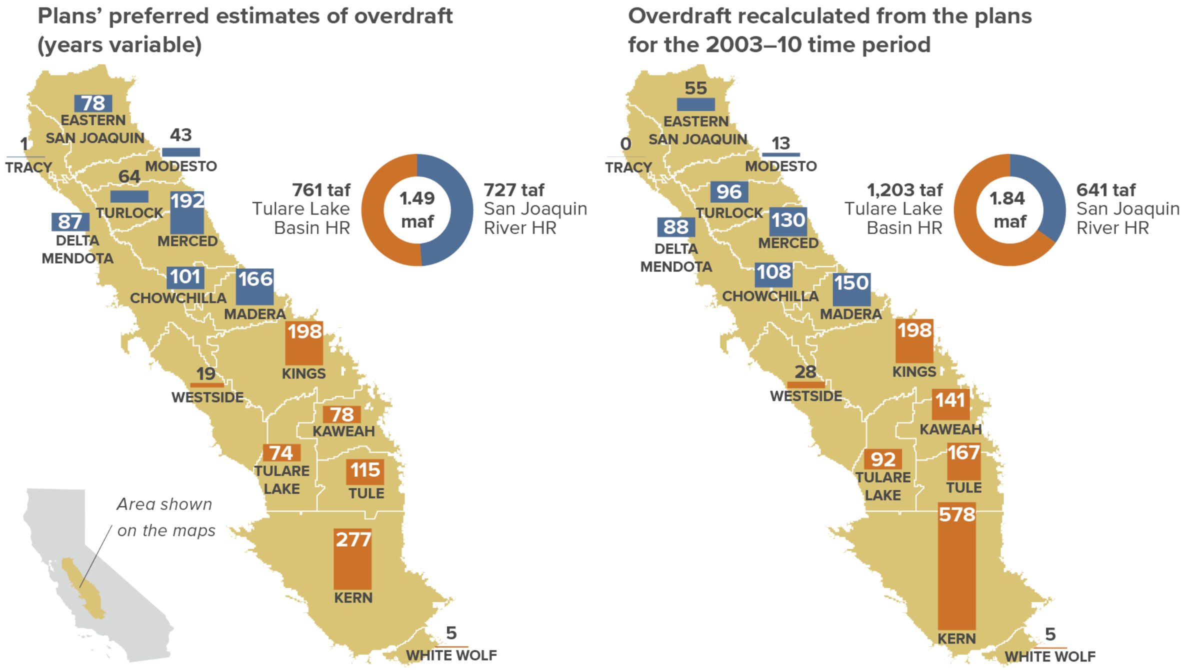
[8] In 2021, the PPIC Sacramento Valley and Delta Surface Water Availability (Ehrens et al. 2021) was published; it includes data for several San Joaquin Valley basins for which information was incomplete at the time of the publication of the San Joaquin Valley dataset in 2020.

[9] Applied water use for crop categories were primarily obtained from DWR Agricultural Land and Water Use Estimates using average 2011–13 data and were adjusted using a combination of data from OpenET and PRISM for crops that aren’t explicitly reported in DWR categories. These applied water use estimates were higher than the values used in Hanak et al (2019), but given the reduction in acreage considered, overall applied water use at the valley scale is similar (16.2 maf of applied water use in the 2019 study, and 16.3 maf in this study).

preferred estimates of overdraft. Indeed, some select much lower estimates of overdraft than the ones we use here—resulting in a lower overall estimate of overdraft for the region (compare panels a and b in Figure A3). To the extent that recent conditions more accurately reflect the baseline for attaining sustainability in some basins, irrigation water cutbacks could be greater than those analyzed here.

FIGURE A3

Estimates of groundwater overdraft by basin from the groundwater sustainability plans



Plans' preferred estimates of overdraft (years variable)

Overdraft recalculated from the plans for the 2003–10 time period

SOURCE: PPIC estimates using data from the groundwater sustainability plans.

NOTES: In this analysis, we use the 2003–10 overdraft estimates (right-hand panel) to ensure consistency across basins. For more details on the estimates by basin, see Hanak et al. (2020), Figure 2 and related discussion.

Surface water at the local scale

To estimate surface water availability at the local scale (i.e., the 49 subunits within the 15 groundwater basins), we based our approach on the one used in PPIC San Joaquin Valley Surface Water Availability (Jezdimirovic et al. 2020b). This dataset summarizes land uses within water districts and assigns annual surface water deliveries for the period 2001–15 to irrigated cropland. This dataset was compiled from a variety of sources, including agricultural water management plans submitted to the California Department of Water Resources (DWR) and the US Bureau of Reclamation (USBR), reports on district deliveries, reports on river diversions, and data provided in GSP appendices.

We took water availability for the years 2003–10 from this dataset as our measure of baseline supplies.[10] For the basins not covered in that assessment (Tracy and Eastern San Joaquin), we drew on averages of surface water availability for 2010–19 as described in the PPIC Sacramento Valley and Delta Surface Water Availability (Ehrens et al. 2021). Then, we obtained subunit surface deliveries by adding up the surface deliveries in each of the districts within a subunit. For districts with boundaries that extend beyond the subunit boundaries, we assumed that surface deliveries are allocated proportionally to acreage.

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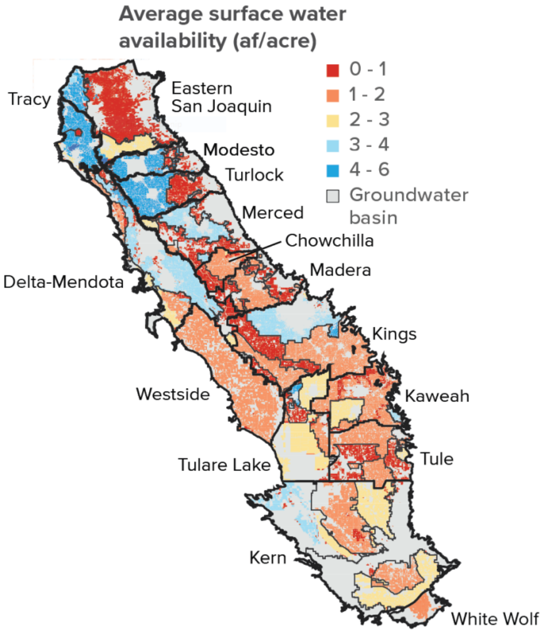
[10] The same limitations described in the previous section about the 2003–10 timeframe apply here.

We compared resulting surface deliveries for districts, subunits, and basins using PPIC datasets with agricultural demands and surface water from a variety of sources, including GSP data, agricultural water management plans, DWR farm gate deliveries, and miscellaneous reports.[11] In some basins we found discrepancies between these other sources and estimates from our surface water deliveries data; we adjusted these by assuming that 2003–10 annual data on agricultural surface deliveries provided in GSP appendices represented the best estimate of baseline availability.[12] Based on irrigation district deliveries and crop acreages within subunits, we partitioned this water from the basin level to the subunit level.

With these adjustments, the final surface water availability estimates are those shown in Figure A4. These are available by subunit in the dataset: *PPIC Water Supply Constraints at the Local Scale in the San Joaquin Valley*.

FIGURE A4

Surface water availability varies within and across basins



SOURCE: PPIC estimates (see text for description).

NOTES: The map shows data by irrigation district. Data by subunit (which may include multiple irrigation districts with similar surface water allocations) are provided in the dataset *PPIC Water Supply Constraints at the Local Scale in the San Joaquin Valley*.

Groundwater cutbacks at the local scale

To obtain the amount of water available when sustainable groundwater management is implemented at the local scale (our 49 subunits), we used estimates of groundwater overdraft at the basin scale, surface deliveries at the subunit scale, and the crop acreage and applied water demand for each subunit. (See Box A2 for definitions of applied and net water and other essential terms for this water accounting.)

First, we calculated sustainable groundwater pumping at the basin scale using the following equations:

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[11] Farm gate deliveries reported to DWR are available only for 2013–21 and were used only as a frame of reference. Reports considered include district reports on operations and Local Agency Formation Commission (LAFCO) documents detailing regional water suppliers.

[12] The discrepancies were found in Eastern San Joaquin, Merced, Modesto, Tracy, Turlock, Kings, and Tulare Lake basins. Some of these discrepancies are due to differences in total water supplied to districts versus farmgate deliveries, and differences in the way the water is accounted for. More details are provided in the notes accompanying the dataset *PPIC Water Supply Constraints at the Local Scale in the San Joaquin Valley*.

$$GW_{total_b} = Applied\ Demand_b - Surface\ Deliveries_b = GW_{sustainable_b} + GW_{unsustainable_b}$$

then,

$$GW_{sustainable_b} = Applied\ Demand_b - Surface\ Deliveries_b - GW_{unsustainable_b}$$

Unsustainable groundwater pumping was calculated as the estimated overdraft, factoring in water losses due to irrigation practices. The reduction in applied groundwater use—or groundwater pumping—is greater than the amount of overdraft, because farmers need to apply more irrigation water to their fields than the amount crops consume.[13]

Once unsustainable groundwater pumping is established for each basin, we next calculated each subunit's responsibility for cutting groundwater pumping. We made the simplifying assumption that the reduction is proportional to the irrigated acreage in each of the subunits, relative to total basin acreage. This method results in several subunits with large surface water allocations having "excess" groundwater; we assumed they share a portion of this with other subunits in their basins, and retain part of the surplus for drought management.[14]

$$GW_{unsustainable_s} = GW_{unsustainable_b} \times \frac{Acreage_s}{Acreage_b}$$

Here, the subindex b indicates values at the basin scale, and the subindex s indicates values at the subunit level.

With estimates of unsustainable groundwater pumping for each subunit, along with our datasets on surface deliveries and crop water demands, we can obtain all the relevant components of the water budget at the local scale.

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[13] We have also updated the estimates of irrigation efficiency using DWR Statewide Irrigation Systems Methods Survey for 2010, obtaining estimates at the subunit level. On average, these estimates are higher than those used in the Hanak et al. (2019)—73 percent irrigation efficiency in the 2019 study, versus 79 percent in the current study. These estimates have a significant effect: the higher the irrigation efficiency, the lower the reductions in applied water use needed to end a given level of overdraft. Higher irrigation efficiency also reduces excess water that recharges the basin (less return flow). See also Box A2 for more details on water accounting measures.

[14] The assumption of proportional allocations of overdraft across the basin differs from the approach followed in some basins, where different levels of overdraft are assigned to GSAs depending on the relative volumes of surface and groundwater use in overall water use. It was beyond the scope of our exercise to develop more finely tuned estimates. We did, however, allow for adjustments in cases where the amount of groundwater pumping cuts needed in a subunit was negative, which occurred in subunits with large amounts of surface water. In these cases, we assumed that this "excess groundwater" can be partially shared—we assumed a 50 percent share—with other subunits in the same groundwater basin, thereby reducing groundwater cuts needed in these other subunits. These subunits are shown as having "surplus groundwater" in Figure A6, panel a. More details about these calculations are provided in Box A2.

Box A2: Water Accounting Measures

Water accounting systems usually need to distinguish between two types of uses: "applied" or "gross" use—the amount initially used for a given purpose—and "net" or "consumptive" use—the amount that is actually consumed at the place of use. The difference is called "return flows"—the water that returns to rivers, streams, or aquifers and is available for reuse. In agricultural areas, return flows come mainly from irrigation water not consumed by crops (in urban areas, wastewater discharges are also important). These flows are often substantial, and depending on the irrigation technology, irrigated agriculture may return 10 to 60 percent of applied water to the system.

For agriculture, the difference between applied water and consumptive use is given by the "irrigation efficiency ratio." This ratio is the percentage of the water consumed by crops through evapotranspiration ("consumptive use") relative to the total amount of water delivered by the water system ("applied use").

In this study, the correct use of these measures is very important. For instance, the estimated historical overdraft at the valley scale is 1.84 maf. This value represents the "consumptive" use that has to be reduced to bring basins into balance. But the "applied" water cutback will be higher, because some of the applied water will go back to the aquifer as return flows. To obtain the amount of applied water cutback reductions, we divide the amount of overdraft by the irrigation efficiency ratio.

This is also important when considering the effects of climate change or new supplies on surface deliveries; both will affect return flows. When considering a reduction in surface deliveries by climate change, the ultimate reduction in water availability is larger because less water is recharging the aquifers or available for downstream users. Conversely, when new supplies are brought to the region, more water is recharging the aquifer or available for downstream users, increasing water availability beyond the initial increase in surface supplies.

In our analysis, an additional complexity arises because we estimated that some areas (subunits) have "excess" groundwater (totaling 693 taf). This arises in some areas that have ample surface deliveries, on average, relative to the acreage currently in production (see Figure A6, panel a). We assume that these areas will share part of their groundwater surplus (50 percent) with other areas within their basin, while retaining the rest for drought management. This assumption affects the applied water reduction needed to attain sustainability region-wide. We use a total of 2.68 maf, which includes the applied water needed to bring basins into balance with the estimated regional overdraft of 1.84 maf (2.33 maf) plus half of the excess groundwater in these subunits (0.35 maf).

Impacts of Climate Change on Water Availability

On top of water reductions caused by the transition to groundwater sustainability, the San Joaquin Valley and the rest of California are also facing water constraints brought on by climate change. Precipitation patterns are changing significantly, and a thirstier atmosphere is increasing crop water demands. We explain below how we obtained estimates of these effects using downscaled climate models and other methods.

Reduction in surface water deliveries

Changes in rainfall timing and intensity, and declines in the amount of precipitation falling as snow, are challenging water operations in California. To obtain the impact of these changing precipitation patterns on water deliveries, we obtained inflow data for the main reservoirs in the valley from seven climate models as inputs to the California's Food-Energy-Water System (CALFEWS) model (Zeff et al. 2021).

The CALFEWS model simulates surface deliveries throughout California's Central Valley under current water system operating rules. It also simulates the daily timescale operation of dams, water conveyance systems, groundwater banks, and water allocation decisions in California's Central Valley. CALFEWS includes the operation of 12 major reservoirs in north-central California. Most of the water is conveyed from northern dams such as Shasta and Oroville to central California's agricultural areas. The model mimics the operation of these dams in terms of water stored and water released for agricultural, urban, and environmental services, taking into account seasonal changes in reservoir flood storage requirements.

As our objective was to evaluate the effect of changes in surface water deliveries by 2040, when SGMA plans should be fully implemented, we obtained downscaled streamflow data for the RCP4.5 scenario from seven climate models (CANESM2, CCSM4, CNRM-CM5, GFDL-CM3, HadGEM22-CC, HadGEM2-ES and MIROC5).[15] These data were used as an input to the CALFEWS model.

We obtained average annual surface water deliveries for the 2031–50 period (climate change scenario) and compared them to average annual deliveries for the 1991–2020 period (historical scenario) for each climate model. Then, we obtained the relative change in deliveries (in %) for each subunit, and we applied this change to the observed supplies for our 2003–10 baseline period.

Using this approach, we estimated the median change in deliveries from all seven climate models for each subunit; the overall reduction of surface deliveries is 243 thousand acre-feet (taf) per year—a 2.3 percent reduction in surface deliveries, or 1.2 percent reduction in total water supplies. Despite aggregate reductions in supplies, median deliveries to some areas showed increases over historic conditions. It bears emphasizing that this result is highly uncertain, given the wide variability across the results of different climate models. The wettest model predicts that aggregate surface deliveries increase by 13.6 percent, while the driest model predicts that they fall by 8.7 percent (Figure A5). In the discussion below, we also briefly explore the economic results for the wettest and driest scenarios.

It also bears noting that our estimates assume current water system operating rules; in practice, reservoir management will likely adapt to significant changes in the timing and pattern of runoff. The effects of such adaptations on surface water deliveries are uncertain. System operators would likely seek to adjust the timing of releases to reduce losses in deliveries. But if significant changes are required to accommodate higher winter and spring flood risk (e.g., by leaving more space available in reservoirs during the wet season), this could require greater reductions in deliveries. More coordinated operation of surface and groundwater storage—getting more carryover storage into the ground—could help mitigate the water supply losses from such adaptations. Improved information and models, such as those used in forecast-informed reservoir operations (or FIRO), will be helpful (Delaney et al 2020).

Any reduction in surface deliveries would also reduce groundwater recharge coming from excess irrigation, resulting in an even larger reduction in water availability. We corrected the final reduction in availability by accounting for recharge losses considering irrigation efficiency.

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[15] Representative Concentration Pathways (RCPs) portray possible future greenhouse gas and aerosol emissions scenarios. We used data from RCP4.5 because it is described by the IPCC as an intermediate scenario, with emissions peaking around 2040 and then declining. The seven models used are among the 10 that passed the collective screening process for California water management metrics (DWR Perspectives and Guidance for Climate Change Analysis, 2015), and include the four global climate models chosen to represent a range of possible futures for California (Pierce et al. 2016).

Increase in evaporative demands

Another impact of climate change is on the demand side. Climate warming is a major contributor to "evaporative demand"—or what can be thought of as the "thirst of the atmosphere." Recent climate studies have identified major increases in evaporative demand in the western US since 2000 (Albano et al. 2022).

We estimated the increase in crop water demands due to climate change by 2040 by obtaining climate variables from six climate global circulation models (GCMs) to calculate the reference evapotranspiration (ET_0),[16] using a modified version of the Penman-Monteith equation that accounts for increased carbon concentration.[17] Then, we obtained the potential crop evapotranspiration (ETc)—the evapotranspiration that would occur under standard optimal growing conditions—by using a five-point crop coefficient model (Kc) simulated for the four major crop development stages for 17 major crop categories in the San Joaquin Valley.[18]

Similarly to the reduction in surface deliveries, we obtained the change in crop water use by obtaining the percentage change in average annual demand in the climate change scenario (using 2031–50) relative to average annual demand in the historical period (2006–18) for each crop and climate scenario. Then, we applied the percentage change to historical crop water demand.

We obtained a median increase of 0.4 percent in crops' total consumptive use by 2040 using data from six climate models, or around 70 taf of increased demand valley-wide.[19] Again, uncertainty around these estimates is high, with the warmest model forecasting a 2.7 percent increase, and the coldest model predicting a decline of 1.5 percent relative to the baseline period.[20] We focus on the median model results for each subunit, but briefly explore the implications of more extreme model projections below.

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[16] Reference evapotranspiration is a standardized measure of crop evapotranspiration for well-watered turfgrass; this measure varies under different climatic conditions (e.g., higher ET_0—and hence higher crop water demand—in areas with hotter temperatures).

[17] Increased carbon dioxide concentration will lead to reduced stomatal conductance, causing a reduction in crop water demands. See Yang et al. (2019) for more information.

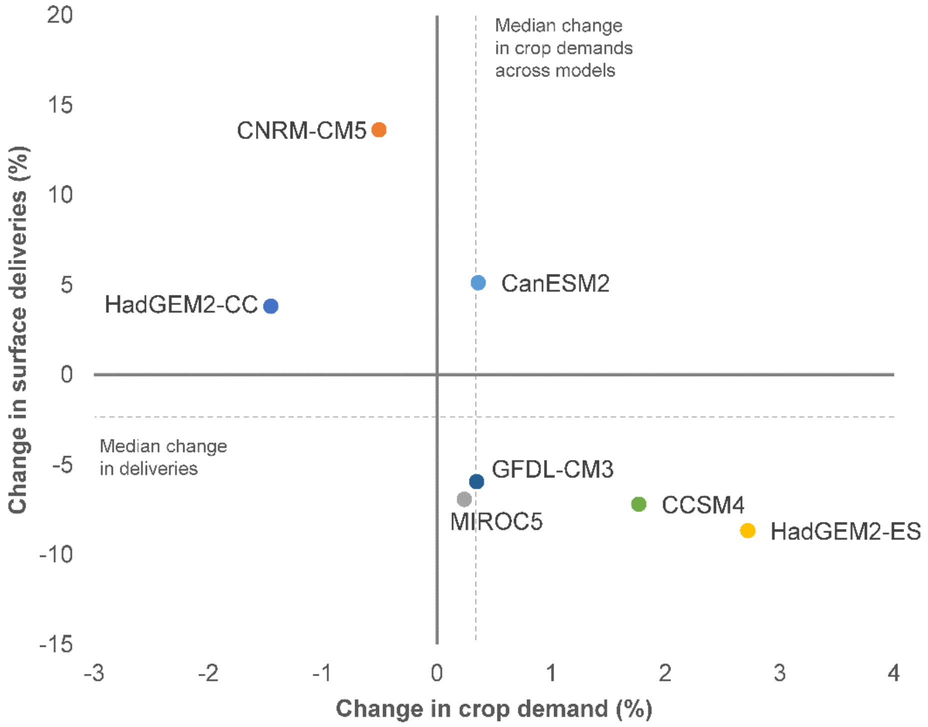
[18] These estimates take into account both the effects of higher evaporative demand (which increases crop water use) and the effects of higher CO_2 in the atmosphere (which has a counteracting effect by increasing crop water use efficiency).

[19] The increase in crop demand is an endogenous variable in our hydroeconomic model; each crop has a different increase in evapotranspiration, and the model obtains the optimal scenario considering these increases. These assumptions result in a slight variation in crop demand increases for different model results, ranging from 65 taf to 71 taf.

[20] Crop demands are driven by evapotranspiration, which is a function not only of temperature, but also of humidity, radiation, wind, and other factors. We used "warmest" vs "coldest" to simplify terminology.

FIGURE A5

Projected changes in surface water deliveries and crop water demand under different climate models



SOURCE: Authors' calculations using data from seven downscaled global models.

NOTE: Evapotranspiration data for the GFDL-CM3 model was not available, so in this figure we show the median of the other six models. To look at warm-dry and cold-wet outcomes, we used HadGEM2-ES and CNRM-CM5, respectively, as bookend scenarios.

Potential Effects of Increased Environmental Regulation on Farm Water Availability

The State Water Resources Control Board (SWRCB) is responsible for adopting and updating the Water Quality Control Plan for the San Francisco Bay/Sacramento–San Joaquin Delta Estuary (Bay-Delta Plan), which establishes water quality control measures and flow quantities needed to provide reasonable protection of beneficial uses in the watershed. This plan is proposing to increase flows into the Delta, a change that could constrain farm water supplies in the San Joaquin Valley in two ways. First, a proposed increase in environmental flows in some rivers within the San Joaquin River hydrologic region would decrease supplies available to divert for agriculture. Second, proposed increases in Delta outflows could cause a reduction in Delta exports through the State Water Project (SWP) and Central Valley Project (CVP)—some of which go to farms in the San Joaquin Valley. There is still considerable uncertainty about the magnitude of environmental flow increases that would be required. We used current proposals to estimate the reductions in farm water supplies caused by this potential reallocation of water to the environment.

Increase in environmental flows in the San Joaquin River tributaries. In 2018, the SWRCB voted to require an increase in instream flows for three San Joaquin River tributaries—the Stanislaus, Tuolumne, and Merced rivers. The proposal involves maintaining 30 to 50 percent of unimpaired flow in these rivers from February through June, which on average would reduce farm water supplies by 293 taf per year (SWRCB 2018). We allocated these cuts among basins and subunits by estimating the total quantity of surface water that each district takes from each river, and then calculating the proportional cuts. Only four basins—Eastern San Joaquin, Modesto, Turlock, and Merced—would be affected, but the reductions would be locally important.

Impacts to Delta exports from increased Delta environmental flows. It is also anticipated that increased environmental flows in the Sacramento River and the Delta could affect Delta exports to the San Joaquin Valley. The March 2022 proposal for Voluntary Agreements to Update and Implement the Bay–Delta Water Quality Control Plan envisages reducing exports by 125 taf during dry and below-normal years, and 175 taf during above-normal years, with no change during critically dry and wet years. Based on historical patterns of year types, this would entail an average reduction in total Delta exports of 73 taf per year. Assuming that San Joaquin Valley water users contribute to these cutbacks in proportion to their share of Delta exports (around 60%) (Escriva-Bou 2019b), this would represent a reduction of 44 taf in the region. We have allocated these reductions proportionally to the amount of water that districts receive from Delta exports. Note that the voluntary agreement proposal also envisages significant acquisitions of environmental water through purchases; such transfers—not considered here—could further reduce water available for farms through the water market.

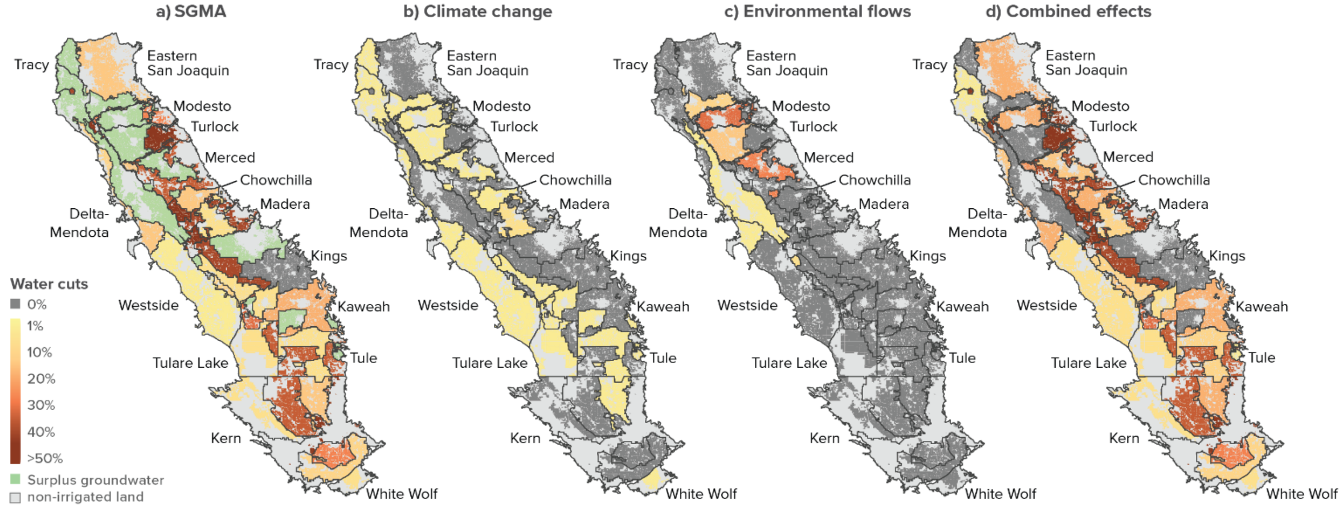
As with the reduction in deliveries brought by climate change, these reductions in deliveries would also reduce groundwater recharge, so we corrected the final reduction in availability using the irrigation efficiency ratio (see Box A2 for more details).

Combined Effects on Farm Water Supplies

Figure A6 shows the reductions in farm water supplies resulting from the three changes examined here for each subunit: attaining groundwater sustainability under the historical climate (panel a), impacts on supplies and demands from climate change (panel b), reductions in supplies from proposed new environmental flow requirements (panel c), and finally the combined effect of these changes (panel d). Even with the relatively limited projected median changes from climate change and Delta flows, an important share of the San Joaquin Valley will face significant water cuts to meet SGMA mandates, and increased flow requirements on the San Joaquin River tributaries will substantially impact several east-side basins.

FIGURE A6

Farm water reductions from SGMA, climate change, and proposed environmental flow requirements



a) SGMA

b) Climate change

c) Environmental flows

d) Combined effects

SOURCE: Author estimates using a variety of sources (see text).

NOTE: The maps show the estimated reductions in water availability for each of the 49 subunits used in our analysis from a) SGMA implementation, b) median climate change projections, c) environmental flow changes, and d) the cumulative effects of all three. Subunits shown in light green in panel a have groundwater in excess of irrigation water demands when taking into account surface water availability. As described in note 14, we assume that these subunits share some of this groundwater with others in the basin, and reserve some for their own use (e.g., as drought mitigation). This groundwater surplus reduces the net impact of surface water losses from climate change (panel b) and environmental flow changes (panel c), as shown in the cumulative effects map (panel d). In all maps we used a 1 percent cutoff to show effects, so water reductions below this threshold are not shown.

Potential Adaptations in the Agricultural Sector

Other developments could help the San Joaquin Valley adapt to increased water scarcity. Among these options, increasing flexibility through water trading and expanding water supplies—mostly by increasing groundwater recharge—could mitigate some of the economic and land fallowing losses. Similarly, increasing agricultural productivity—through management and technological innovations that raise prices or yields, or lower unit costs of production—could help increase the value of outputs with the same amount of inputs (land, labor, and other supplies), or maintain similar production value with fewer inputs. In this section, we explain how we considered water trading, water supply expansion, and increased agricultural productivity in our analysis.

It is also important to note that our analysis does not account for other potential sources of income that could further ease adaptation in the valley. Lands coming out of intensive crop production could find other beneficial uses: Ayres et al (2022a) show how deploying solar energy production on lands currently used for irrigated agriculture could generate revenues for farm owners, and Peterson et al (2022) describe the potential for water-limited agriculture in the valley. The state is also working on programs to reduce the vulnerability of drinking water wells by paying farmers to fallow land through the LandFlex program. Other similar initiatives—such paying farmers to make water available for environmental flows—are also being explored. Some of these strategies could have broader public benefits, in addition to boosting farm incomes.

Water trading

Water trading is an important tool for managing scarce water supplies because it enables water to go to the most productive farmlands. In California, roughly 1.5 million acre-feet of water—mainly surface flows—is traded annually; on average, this is about 4 percent of all water used by cities and farms (Hanak et al. 2021).

In the 2019, crop revenues were cut by 43 and 63 (basin and valley trading). In Water and the Future of the San Joaquin Valley, we estimated that local trading of both groundwater and surface water within groundwater basins could reduce the costs of adjustment by about 40 percent, and expanding surface water trading across basins within the valley could reduce these costs by about 60 percent. But as noted, that study relied on older estimates of water balances across basins. Now we can explore trading using updated estimates of overdraft, and see how trading might affect management within basins that have pronounced differences in local water availability. We can also explore some new scenarios—like the consequences of trading within these local areas (subunits)—and what might happen when only groundwater trading is allowed within basins. To anticipate the results, we find, as before, that trading substantially lowers the economic costs of adjustment.

Here we estimate a variety of trading options, from least to most flexible:

- Inflexible management (no trading). Water cannot be reallocated, so any water reduction required within a subunit will affect everyone proportionally, with all crops taking the same percentage cut, regardless of how much income they generate.[21] Our base cases showing the effects of SGMA, climate change, and increased environmental flows all use this inflexible management scenario.
- Local trading. Both groundwater and surface water can be traded locally (within subunits).[22] For surface water, this might be a more realistic scenario than inflexible management, as there is often considerable local trading—especially within the same water district. This is also the scale at which groundwater trading is most likely to develop first.

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[21] This scenario might overstate the costs of water shortages, since farmers with a portfolio of crops within a local area would likely make some adjustments on their own farms, putting more of the water on higher-value crops and cutting back on acreage with lower-value crops, even if there was no trading across farms.

[22] One of the reasons for building a more detailed local dataset was to distinguish between areas with significant surface water resources and areas more reliant on groundwater. This allows us to assess local impacts more accurately.

- Basin-wide trading. Under SGMA, groundwater basins are the primary geographic units used to assess the sustainability of water management practices. Both groundwater and surface water trading within basins could help reduce the costs of bringing basins into balance, by getting water to the crops with the greatest income potential. In this appendix, we mainly consider flexible trading of both groundwater and surface water. But the new data also allow us to explore patterns when only groundwater is traded (see for instance Figure A13 below); this approach could allow the identification of hot spots where groundwater purchases (and increased pumping) might create risks of negative impacts on neighboring wells or land subsidence.[23]
- Valley-wide surface water trading. By allowing all surface water to move freely across the valley, we can show how water would move to the crops and areas where shortages would be causing the greatest losses in income. Such trading might further reduce the regional economic costs of adapting to water scarcity. This is an optimistic scenario; although surface water trading is already a common way to secure regular supplies in some areas, additional water movement might be constrained by regulations or lack of infrastructure.[24] We assume groundwater will not be allowed to move across basins, consistent with greater legal restrictions on this resource.

Some methodological caveats about trading are worth noting. The underlying hydro-economic model allows water to move from one use to another if it increases the profitability of water used in crop production. The different scenarios constrain the geography within which this trading can happen (or whether it can happen at all—as in the inflexible scenario). The model assumes that there are no other constraints to trading water—such as local, state, or federal rules restricting water movement, infrastructure limitations, or the unwillingness of some growers to buy or sell water, even if it appears that, at face value, this would be the most economically advantageous option. In practice, all of these factors can and do limit the extent of trading. Our results are instructive, however, for understanding how trading could lessen the adaptation costs of having less water available for valley agriculture—and they may help identify institutional and infrastructure measures that could be broadly beneficial, facilitating more flexibility while avoiding significant harm to non-trading parties, including other water users and the environment. For a more extensive discussion of such issues, including SGMA considerations, see Ayres et al. (2021).

Water supply expansion

In 2019, we conducted a detailed analysis of water supply options, obtaining the likely range of "new water" that they would provide, and the average costs for each supply option (Escriva-Bou 2019c). We found that combining various feasible options, the likely total increase is 250–570 taf/year, and the most likely range is 380–470 taf/year.[25] Among the available options, the least expensive involves capturing more local runoff, especially with groundwater recharge and reoperation of reservoirs to expand the joint storage potential of surface and groundwater storage. Other options also may be feasible, although many uncertainties remain.

This study does not update the 2019 analysis of new supplies. Instead, we assume two scenarios of potential supply expansion to assess the benefits that new supplies could provide:

- Expanding water supply by half a million acre-feet. This scenario adopts the approximate amount of feasible and affordable water we found in the 2019 report, which would largely come from increased groundwater recharge from high-flow events on local rivers.

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[23] See Ayres et al. (2021) for a detailed discussion of these "third party" concerns and ways to mitigate them.

[24] When surface water acquired through water trading is an important part of regular supplies, these volumes are included in local water budgets and our estimates of baseline water deliveries.

[25] This exercise used a Monte Carlo simulation approach to explore how much valley agriculture would be willing to pay for different combinations of supplies at different potential costs. The "likely" increased water availability range includes supplies with costs that farmers are willing to pay for in at least one combination. The "most likely" water availability range includes options that appear feasible in at least half of all combinations. For details see Escriva-Bou (2019c).

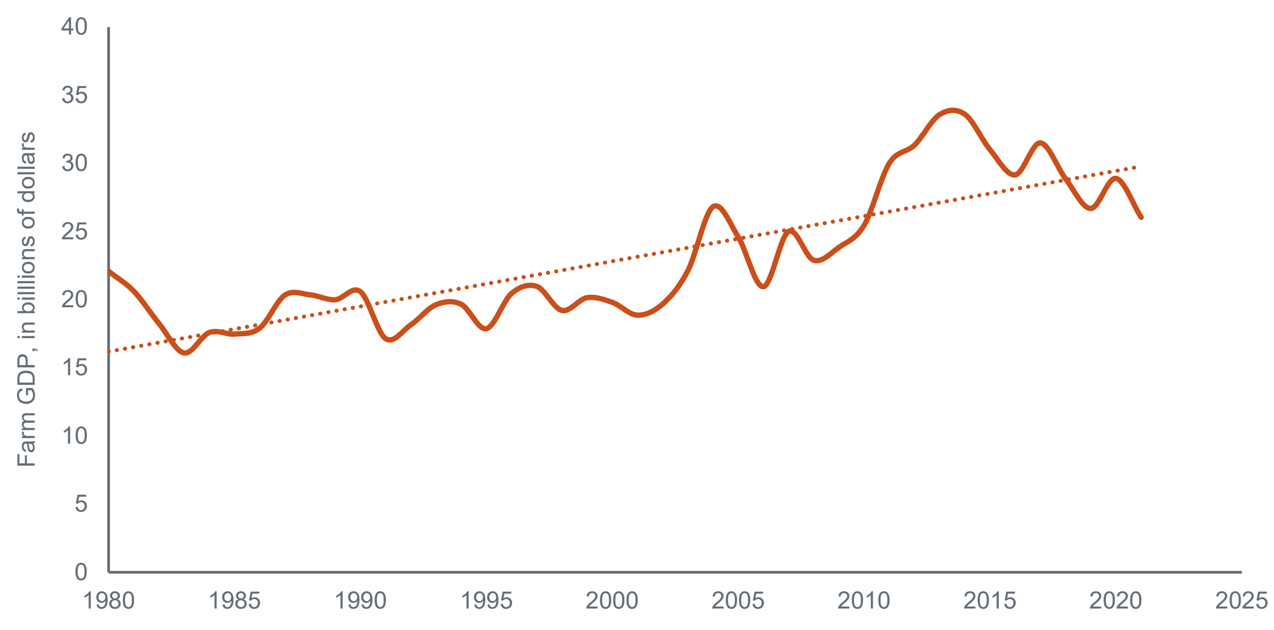
- Expanding water supply by one million acre-feet. This scenario—roughly double the amount of new water supplies we modeled in 2019—should be considered very optimistic. An increase of this magnitude might be achieved by actions to transfer more Sacramento River water to the region, either from increased water purchases from Sacramento Valley farmers or increased capture of high-flow events in Sacramento Valley rivers.[26] In addition, with the changing precipitation patterns brought on by climate change—such as less snow and more rain—it is possible that more floodwater could be recharged, and that operations could be optimized to maximize surface deliveries under changed climate conditions. Such actions would mitigate some of the supply losses anticipated from the changing climate.[27]

Increase in agricultural productivity

Productivity measures the quantity of output produced with a given quantity of inputs. Growth in agricultural productivity reflects improvements in farmers' production efficiency and technological progress. California's farmers have been increasing productivity over time. Examples include the adoption of new, higher-yielding, and more pest-resistant varieties; innovations in irrigation and harvest equipment; and agronomic practices that improve quality and yields. The valley's shift to crops like fruits, nuts, and vegetables, which generate more revenue and profit per unit of water—as well as more farm jobs—has also increased productivity. Adjusted for inflation, the value added from farm output and related food processing has more than doubled since the late 1960s despite little change in acreage or water used (Hanak et al. 2018), and the rate of annual increase in real farm GDP has averaged more than 1.5 percent since 1980 (Figure A7).

FIGURE A7

California's real farm GDP has been growing over the past 40 years



SOURCE: USDA Economic Research Service.

NOTE: The chart shows California's farm net value added in 2022 dollars from the primary production of crop and animal products.

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[26] In 2019, we only considered increased Delta exports from reservoir reoperations. Another possible scenario would be increased trading agreements with Sacramento Valley farmers, who have more options for increasing groundwater banking operations than in the San Joaquin. In addition, Gartrell et al. (2022) show that there is potential for some additional Delta imports in wet years without changing regulatory requirements.

[27] As noted earlier, in our climate change analysis we did not modify current reservoir rules and operations. These operations could be adapted to work better under changed conditions.

We use a simple measure of productivity increases, based on the historical evolution of crop yields in the San Joaquin Valley from 1980 to 2018. Most crops have shown significant increases in yields per acre, with vegetables and orchard crops in the top positions. If trends since 1980 continue, yields would increase by an average of 17 percent by 2040, and almost 30 percent for some important crops like almonds and pistachios. Projecting these trends, we obtain yields by 2040 for each crop, and conservatively assume that future yield increases might be limited to half of the historical trend.[28] We hold applied water and farm labor per acre constant; this is equivalent to assuming that applied water and farm labor productivity per unit of output increase at the same rate as yields per acre.

In the main results we show the productivity increases in a scenario that also includes substantial water trading and new supplies, but productivity increases would likely occur under any scenario. As a basis for comparison, we also describe the effects of productivity growth on the most constrained supply scenario, with inflexible management (no water trading or new supplies).

This exercise should be considered just one of the many possible ways that productivity could increase. In our example we made the simplifying assumption that real input and output prices remain constant, such that technological and management innovations affecting yields, water, and farm labor productivity are the only source of productivity changes. In reality, it is likely that the actual increase in productivity will be a combination of many factors—as it has been in the past.

The Socioeconomic Consequences of Groundwater Sustainability, Climate Change, and New Environmental Regulations

So far we have shown the importance of crop production in the San Joaquin Valley's economy—as well as how it affects related sectors—and we have described some of the most important future water-related challenges and opportunities that valley agriculture will be facing by 2040. Here we assess how these developments may affect the socioeconomic activity in the valley, by comparing present conditions with modeling scenarios for 2040. It bears stressing that these estimates focus on the losses from taking land out of intensive crop production; they do not account for other potential economic activities on these lands, or the costs the region would incur from further depletion of groundwater reserves in the absence of SGMA.

Methods

We estimate the farm-related costs under the valley's potential agricultural futures by looking at a chain of effects. We first explore how farmers may change their cropping decisions when they face new water constraints or opportunities, estimating crop acreage, farm output, and several other measures of the economic value of production in 2040 (see Box A1, above). We then look at changes in related downstream industries: the effects of reduced feed crop output on the valley's dairy and beef industries, and the effects of reduced crop and animal products on local food and beverage processing.

For modeling crop production and water use, we employed the openAG model (Medellín-Azuara et al. 2022).[29] This model includes 49 local subunits within 15 groundwater basins in the valley (shown in Figure A1). We

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[28] Future yield increases might be limited, for instance, by the rate of carbon fixation through photosynthesis (Medellin-Azuara et al. 2011).

[29] The Open Agricultural Production Model employs data on land use, production costs, price, yield, and applied water to estimate profit-maximizing patterns of crops under varying conditions. Data for these inputs in California are available from various state and federal agencies and University of California studies such as the UC Davis Crop Cost and Return Studies, US Department of Agriculture National Agricultural Statistics Service, and the California Department of Water Resources. Open-AG treats each of its regions (in this case, the 49 subunits) as a single farm; it assumes that a representative farmer in each region uses all farm water—along with other inputs—efficiently at the local level. This approximates conditions in which all surface and groundwater used by farms could be freely traded within a subunit. For the inflexible management scenario, we do not allow these farms to adjust water use, and instead just implement proportional cuts to all crops commensurate with the level

present results for the 15 basins and some maps with detailed information at the subunit level. The analysis of cropping activity assumes a base case with 2018 land use and constant commodity prices at 2017–19 average levels.[30] Since many downstream activities take place in different locations than crop production, we conduct the analysis of downstream effects for the eight San Joaquin Valley counties as a group, using a 2019 model of the regional economy (IMPLAN).[31]

Scenarios

We model the agricultural economy's response to restricting water use under several different water supply and demand management scenarios. We consider nine scenarios for 2040, each building on top of the preceding one, and report average annual effects:

1. SGMA. A reduction in 2.7 maf/year in groundwater pumping to achieve sustainability. This scenario uses an inflexible management scheme (no trading), in which all crop acreages are reduced in the same proportion within each subunit.
2. SGMA + climate change. A reduction of 226 taf/year in water availability from declining surface deliveries and an increase of 0.4 percent in crop water demands (approximately 70 taf/year), on top of SGMA cuts. This scenario also assumes inflexible management (no trading).
3. SGMA + climate change + environmental flows. A reduction of 293 taf/year in surface deliveries for environmental flows (e-flows) in the northeastern part of the valley, plus a reduction of 44 taf/year in Delta imports, on top of SGMA and climate change (translating to a total reduction in water availability of 409 taf/year when considering recharge losses). This is the most constrained scenario for farm water availability—with combined cutbacks totaling 3.15 maf annually—and we use it as the future baseline. It assumes inflexible water use (no trading).
4. Local trading. This scenario begins our exploration of water trading as a loss mitigation strategy. It allows both surface water and groundwater to be shared flexibly within each of 49 subunits that have similar water availability. Current practice lies somewhere between the inflexible use approach and this one; many irrigation districts allow local surface water trading, but groundwater trading is still rare.
5. Basin trading. In this scenario, surface water, groundwater, or both can be shared flexibly within each of the 15 groundwater basins. Relative to the local trading scenario, this allows water to move across subunits, as long as it remains within the basin. The most additional trading will occur in basins that have subunits with very different water supply conditions. Whereas groundwater can be traded within the same basin by simply changing the locations of pumping (and keeping good accounts), infrastructure limitations could constrain the movement of surface water across subunits. For some basins with large internal differences in water availability—such as Turlock, Kings, Kaweah, and Kern (Figures 1b and 1c)—achieving the modeled level of trading would require substantial changes in practice.
6. Valley trading. Here we allow valley-wide trading of surface water to cope with increasing water scarcity. This is an optimistic scenario; although surface water trading is already a common way to secure regular supplies in some areas, additional water movement might be constrained by regulations or lack of

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of groundwater pumping cuts needed to attain sustainability. While the model in Medellín-Azuara, Escriva-Bou, and Jezdimirovic (2019) used a 2010 base case (land and water use) with 2012 prices, we use now a 2018 base case with 2017–19 prices. Another assumption that differs from the 2019 study is that we now allow any crop (except corn, as explained in note 43) to be fallowed completely, while in the 2019 study all crops were limited to fallow no more than 75 percent of their baseline acreage. The change in this assumption decreases the overall revenue losses for the current study, as all the less economically productive crops will be fallowed first.

[30] It is worth noting that California is a price-taker for most commodities—so changes in output are not likely to significantly impact global prices. There are some notable exceptions, such as almonds, where California's dominance can affect global markets. Significant declines in such crops could cause product prices to rise, further incentivizing growers to prioritize directing scarce water to them.

[31] IMPLAN is an input-output model that provides a snapshot of a region's economy and spillover effects from economic events from one sector to the rest of the economy, which includes other sectors, households, and government. In this data source, crop revenues were lower in 2019 ($17 billion) than our 2018 estimates from the openAG model ($24 billion), which rely on USDA County Agricultural Commissioners' reports for the economic measures. In the analysis of regional economic results, we adjust the IMPLAN crop values to match our openAG model results by increasing the IMPLAN base values.

infrastructure. We assume groundwater will not be allowed to move across basins, consistent with greater legal restrictions on this resource.

7. <u>Expanded supplies (0.5 maf/year)</u>. On top of valley-wide trading, this scenario assumes that a half million acre-feet per year in new water supplies is captured within the valley or imported and then shared flexibly with the subunits most in need. This scenario approximately replicates the amount of feasible and affordable water we modeled in the 2019 report. Because the 0.5 maf factors in losses from irrigation systems, the actual increase in water availability is ~604 taf/year.
8. <u>Expanded supplies (1 maf/year)</u>. This scenario explores the addition of 1 maf annually in water supplies that are shared flexibly in areas with strong demand. This is a very optimistic projection—more than double the volume we considered to be cost effective in our previous analysis. Sources might include local recharge, changes in operations to capture more flood flows under new climate conditions, and imports from other regions. As above, the actual increase in water availability is larger, given irrigation losses.
9. <u>Increased productivity</u>. We assume half the yield increase we have seen in the past on top of flexible water trading and 1 maf /year of expanded supplies. We assume comparable increases in the productivity of applied water and farm labor per unit of output. In the discussion, we also report some results for increased productivity under the most constrained supply scenario, with inflexible management, to show how productivity growth would soften economic losses even in the absence of water trading and new supplies.[32]

Modeling Results

This section provides estimates of the effects of the different 2040 scenarios on crops, dairy, beef, and food and beverage industries. First, we show the impacts created by the supply constraints, then the potential benefits of trading, and then the effects of new supplies and increased productivity. Finally, we summarize the results for all nine scenarios. Throughout, we present graphical results for the valley as a whole as well as more detailed geographical breakdowns. Table A3 summarizes the valley-wide numerical results for all nine scenarios.

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[32] The results of the latter scenario are only reported in the discussion of the results, not in Table A3 or the charts.

TABLE A3

Overview of regional water, land, and economic adjustments under different scenarios

	SGMA	Climate change	E-flows	Local trading	Basin trading	Valley trading	Expanded supplies (0.5 maf)	Expanded supplies (1 maf)	Increased productivity
Water reduction (maf)	2.68	2.85	3.15	3.15	3.15	3.15	2.55	1.94	1.94
Land fallowing (acres)	720,878	787,645	870,881	828,900	804,612	851,089	646,254	475,275	462,823
Crop production losses									
Revenues ($ million)	3,769	4,095	4,465	2,873	2,244	1,741	1,184	840	(3,216)
Value added ($ million)	2,962	3,215	3,501	2,216	1,688	1,258	848	602	(2,542)
Employment	33,845	36,679	39,968	27,389	23,080	19,543	14,632	10,462	(17,039)
Dairy and beef production losses									
Revenues ($ million)	570	613	698	649	964	1,114	1,044	854	974
Value added ($ million)	169	183	212	255	388	435	417	363	399
Employment	1,039	1,121	1,285	1,325	1,989	2,268	2,147	1,805	2,025
Processing industries' losses									
Revenues ($ million)	2,914	3,286	3,555	2,700	2,815	2,939	2,214	1,679	(1,248)
Value added ($ million)	680	760	825	587	561	556	395	291	(470)
Employment	5,844	6,543	7,127	5,287	5,222	5,194	3,820	2,917	(3,694)
Cost of new supplies ($ million)	-	-	-	-	-	-	250	500	500
Total economic losses									
Revenues ($ million)	7,253	7,994	8,717	6,222	6,022	5,794	4,692	3,872	(2,990)
Value added ($ million)	3,811	4,158	4,539	3,058	2,637	2,248	1,910	1,756	(2,113)
Employment	40,729	44,343	48,379	34,001	30,290	27,005	20,599	15,184	(18,708)

SOURCES: Authors' estimates.

NOTES: E-flows are environmental flows. All of these scenarios report average annual impacts for 2040 relative to current conditions. Each scenario builds on the water availability and management assumptions of the previous scenario. For the estimates of economic losses, positive numbers represent a reduction with respect to the baseline (current conditions), and numbers in parentheses represent an increase with respect to this baseline. For the scenarios with expanded water supplies, the increase in available water is larger than the net supplies brought to the basin, given the return flows that recharge the aquifer (see Box A2).

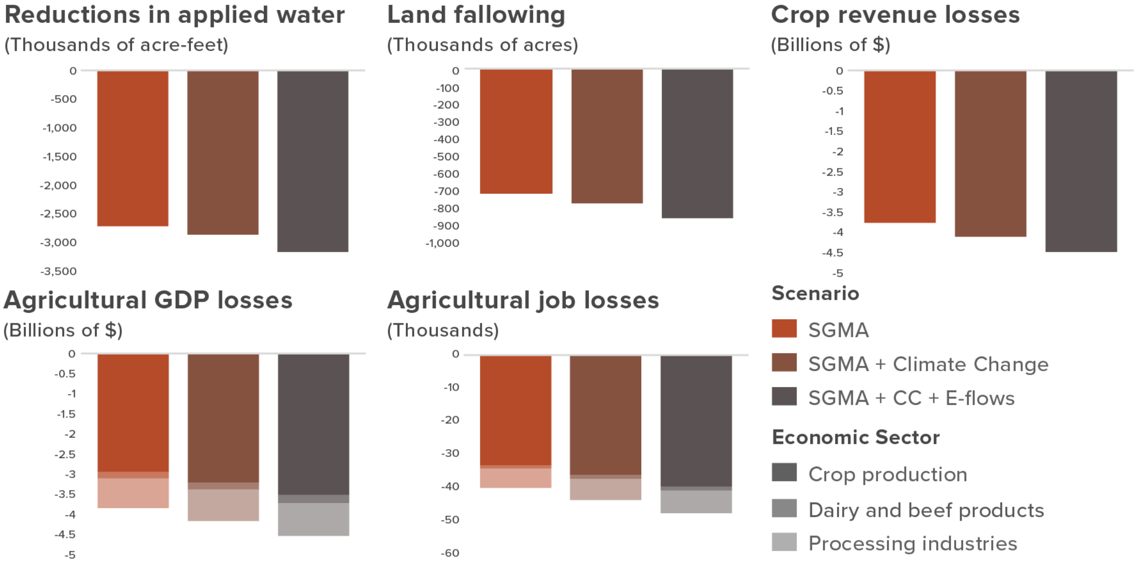
The implementation of SGMA, coupled with climate change and environmental regulations, will constrain water availability and result in fallowed croplands

Overall, we estimate that implementing SGMA could cause a reduction in 2.7 maf/year in applied water in the valley, or 17 percent of applied water supplies. Considering an inflexible management scenario, SGMA would require the fallowing of around 721,000 acres of cropland, reducing crop revenues by $3.8 billion per year and ag-related value-added or GDP by $3.8 billion, and resulting in the loss of more than 40,000 ag-related jobs. Climate change (considering the median scenario) would increase the total expected fallowing to 800,000 acres, with crop revenue losses of $4.1 billion, ag-related GDP losses of $4.2 billion, and ag-related employment losses of more than 44,000 jobs. With increased environmental regulations on top of these other water supply constraints, water supplies would decrease by almost 20 percent, fallowing would increase to 870,000 acres, crop revenues would decrease by $4.4 billion, and ag-related GDP and jobs would decline by $4.5 billion and 48,000 jobs, respectively (Figure A8).

We also evaluated two more extreme climate change scenarios to gauge the effect of the uncertainty in climate projections. Using modified deliveries and crop demands from a warm-dry model (HadGEM2-ES) on top of the most constrained scenario, land fallowing would increase to almost 1.1 million acres (+24% relative to SGMA + CC + e-flows scenario), and crop revenue losses would rise to $5.8 billion (+29%). With a wet-cold model (CNRM-CM5), land fallowing would decrease to 542,000 acres (–38% relative to SGMA + CC + e-flows scenario), and crop revenue losses would be $2.6 billion (–42%).[33]

FIGURE A8

SGMA implementation would cause the most significant water supply-related impacts, but climate change and increased environmental regulations would add additional costs to valley agriculture



SOURCE: Authors' estimates.

NOTE: All of these scenarios report average annual impacts for 2040 relative to current conditions. Each scenario builds on the water availability assumptions of the previous scenario. All three scenarios assume inflexible water management (no trading).

Figure A9 shows cropland changes with these new water supply constraints by groundwater basin. The Kern basin would be the most impacted, with around 180,000 acres fallowed (over a quarter of the total acreage). Climate change impacts are noticeable in most of the basins, but are especially important in those west-side basins supplied with water imported through the Delta, including the Westside and the Tulare Lake basins. In contrast, the impact of increased environmental regulations is most important in the northeastern basins, especially Merced and Modesto, but also Eastern San Joaquin and Turlock.[34] Under current proposals in the voluntary agreements, the basins receiving Delta imports would also be affected, but much less so.[35]

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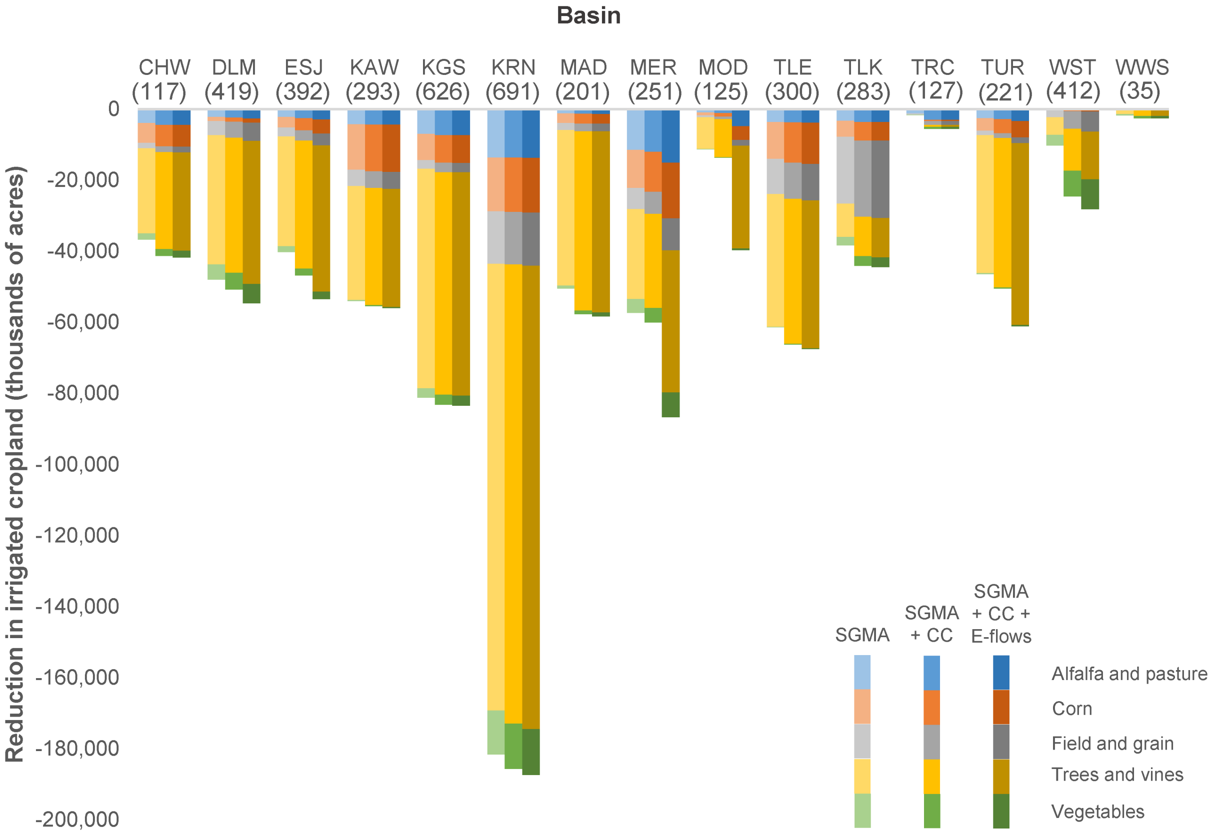
[33] To be comparable with the previous calculations, we used an inflexible water use model in which trading is not allowed. In the wet scenario, many basins will have more water availability than they actually need to meet baseline crop water demands; valley-wide trading would further lower costs.

[34] In the Turlock basin, the impacts are especially felt in the eastern subunit; the cuts in river water to water users in the western part of the basin would result in their needing to tap more of their surplus groundwater, with less available to share with the users in the eastern part of the basin.

[35] This includes basins on the west side of the valley and the CVP's cross-valley contractors on the east side, as well as SWP recipients in the Tulare Lake and Kern basins.

FIGURE A9

Adaptations to SGMA cause most of the land fallowing, but climate change and environmental regulations have significant impacts in some basins



SOURCE: Authors' estimates.

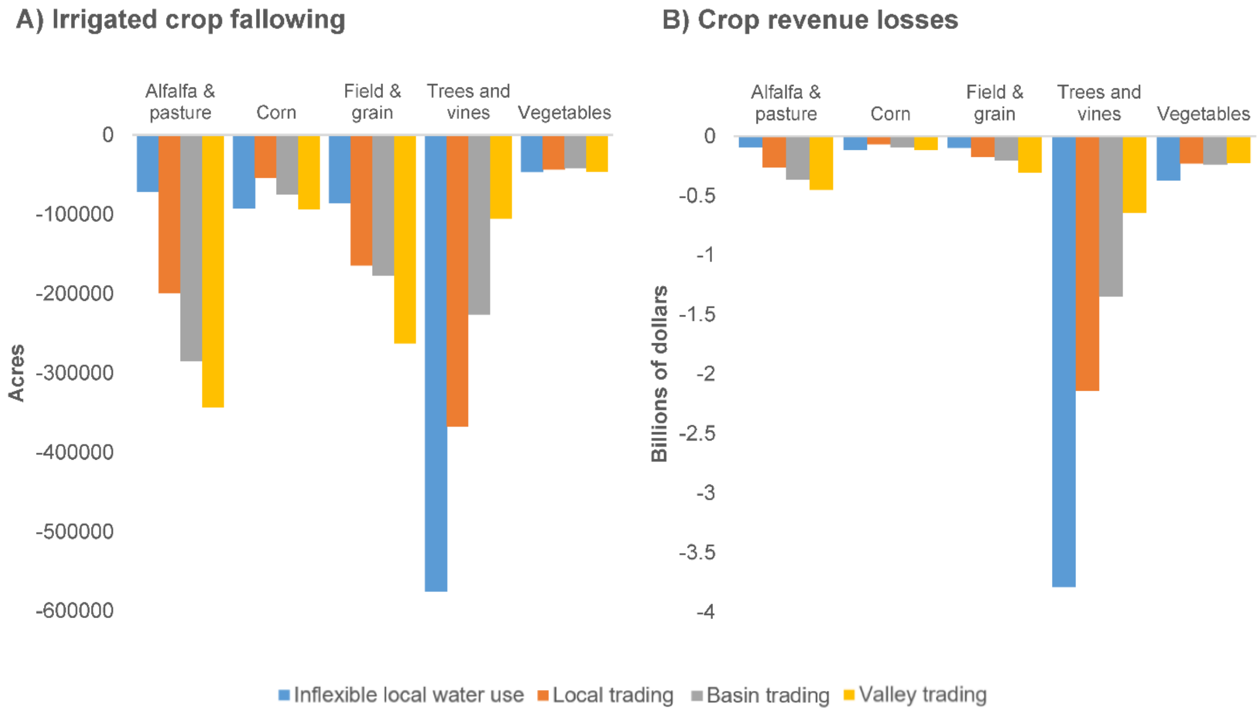
NOTE: The acronyms for the basins are spelled out in Figure A1. Numbers in parentheses show the baseline irrigated cropland in each basin, in thousands of acres. As above, all of these scenarios report average annual impacts for 2040 relative to current conditions. Each scenario builds on the water availability assumptions of the previous scenario, with each adding to the water supply constraints of the previous one. All three scenarios assume inflexible water management (no trading).

Trading would reduce economic losses significantly

Since we assume inflexible water management in the runs described above, water supply cuts would translate into uniform rates of fallowing across all crops. Perennial orchards and vineyards—crops which generate relatively high economic value—are more present in areas with higher overdraft levels, so they experience relatively higher cutbacks under this management approach (61% of current acreage, but 66% of acreage cutbacks when no trading is allowed). Flexible demand management, with water trading, is key to minimizing negative impacts on the economy. This is because water trading enables water to go to the farmlands generating the highest economic returns from water use. Figure A10 presents how several trading scenarios would change the resulting crop mix and reduce crop revenue losses. Trading would displace less profitable crops like alfalfa, pasture, and other field and grain crops to keep trees and vines in production. (See Figure A16 below for a comparison of acreages by crop category across all scenarios.)

FIGURE A10

How water trading affects crop choice and revenues



SOURCE: Authors' estimates.

NOTE: These scenarios report average annual impacts for 2040 relative to current conditions; they all assume a base case for irrigation water cutbacks of SGMA + climate change + environmental flow increases. Each scenario builds on the water management assumptions of the previous scenario (for instance, basin trading also includes local trading).

Using the metric of crop revenues, local trading of both groundwater and surface water within subunits can reduce the costs of adjustment by 36 percent, and allowing for surface and groundwater trading within basins can reduce these costs by 50 percent. When valley-wide surface trading is allowed, crop revenue losses would be 61 percent lower than with inflexible water management. In contrast, water trading has only a small impact on land fallowing; with constant water supplies, the only changes to cropped acreage come from crop shifting, and these effects are relatively small. From 871,000 acres of crop fallowing in the most water-constrained scenario, fallowing would fall to 829,000 acres with local trading and 805,000 acres with basin trading; it would rise back up slightly—to 851,000 acres—in the valley-wide trading scenario.[36]

For the regional economy, it is even more important to understand the effect of trading on GDP and jobs. Figure A11 shows these estimates for the agricultural sector as a whole, including crops and downstream activities (dairy/beef and food and beverage processing). Trading reduces crop revenue losses by shifting crop acreage away from feed crops to reduce the fallowing of perennial crops. This reduction in feed crops impacts the dairy and beef sectors, as well as related processing industries. In particular, trading over a broader geographic scale—within basins or valley-wide—has more substantial impacts on animal sectors and related processing by increasing the reduction in feed crop acreage. But these impacts are overshadowed by the larger benefits of trading on the crop economy, and we nevertheless see a significant, progressive reduction in GDP and job losses in the regional economy when water flexibility increases.

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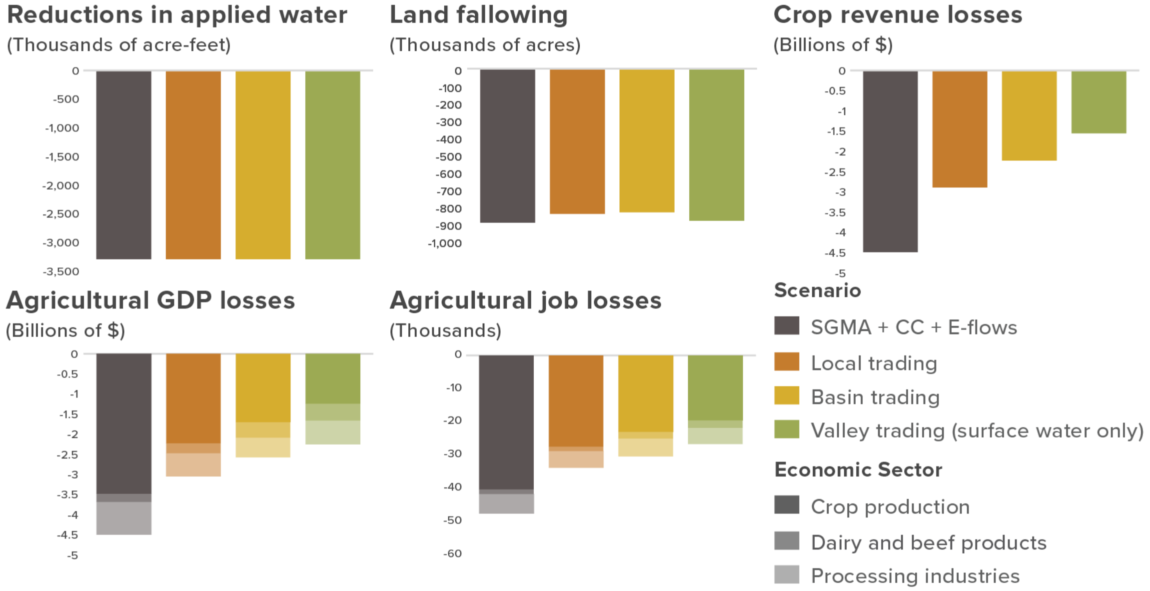
[36] The increase in fallowing for the valley trading scenario, relative to local or basin trading, occurs because grain and field crops in some of the west-side basins would be replaced by more water-consuming crops in other basins.

FIGURE A11

How water trading affects crop revenues and broader economic indicators



SOURCE: Authors' estimates.

NOTE: These scenarios report average annual impacts for 2040 relative to current conditions; they all assume a base case for irrigation water cutbacks of SGMA + climate change + environmental flow increases. Each scenario builds on the water management assumptions of the previous scenario (for instance, basin trading also includes local trading).

Looking at the basin level, it is possible to see how the crop mix changes across scenarios, and what types of trading would be most advantageous for the basin's crop economy (Figure A12).

- **Local trading** would be particularly beneficial in basins like Kaweah, Kings, Kern, Merced, or Tule, because the diversity of the preexisting crop mix would allow for a more substantial transfer of water to more lucrative crops facing shortages. In basins like Madera, with less crop diversity, local trading would generate fewer benefits because there are fewer opportunities for lucrative transfers.
- **Basin trading** would allow subunits within a basin to share water to reduce the economic burden of water scarcity. Basins like Delta Mendota or Kings, which have large differences in water availability across subunits, would see large economic gains from basin trading, while others basins like Madera or Chowchilla would see almost no benefit. The large Westside basin, which lies within a single irrigation district, has only one subunit, and does not see any additional effects from basin trading.[37]
- **Valley trading** would allow surface water to move freely across the valley. Basins with significant field and grain crop acreage (such as Westside, Tulare Lake, and Delta Mendota) would become exporters of water, sending it to basins facing the prospect of significant cutbacks in perennial crops, including Madera, Kern, and most other east-side basins.

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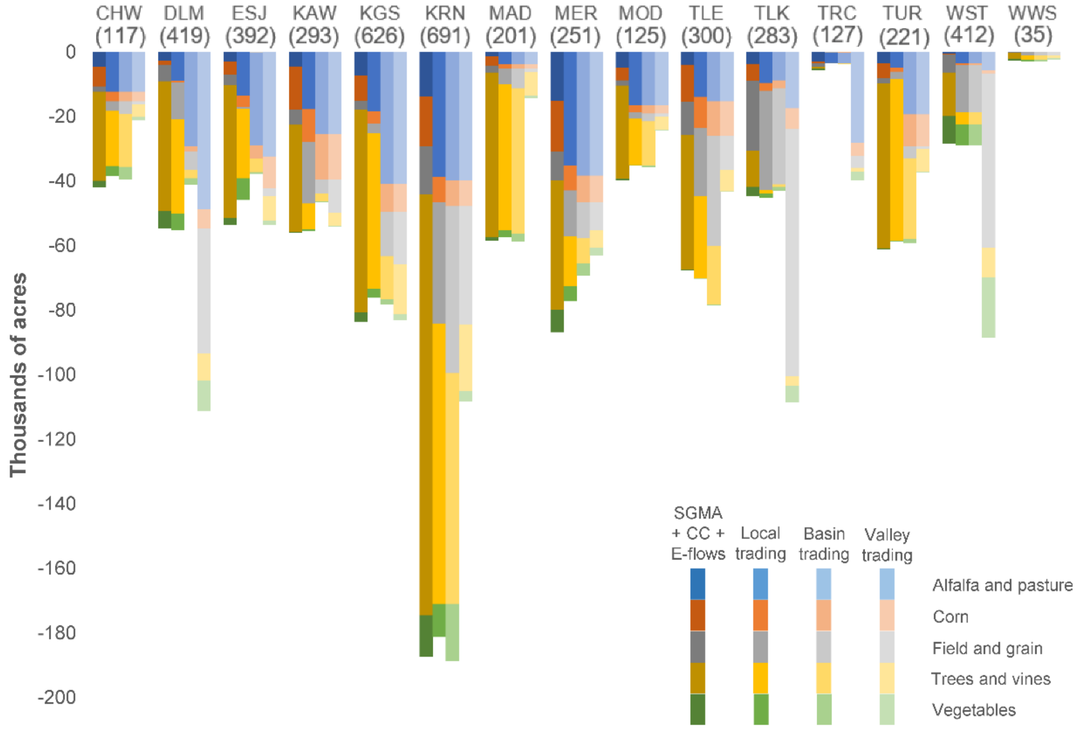
[37] The only other basin with a single subunit is White Wolf, south of the Kern Basin, which is relatively small.

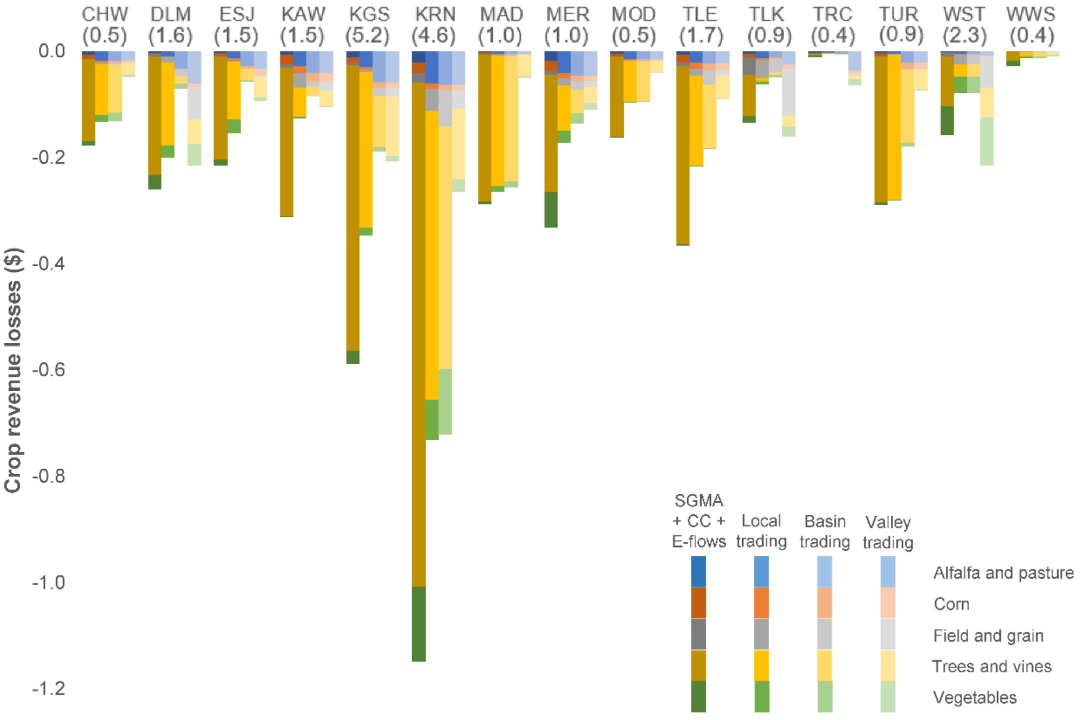
FIGURE A12

Trading would reduce economic losses significantly by allowing a shift in the mix of crops that will be fallowed

a) Irrigated crop acres by basin



b) Crop revenues by basin



SOURCE: Author estimates.

NOTE: The acronyms for the basins are spelled out in Figure A1. These scenarios report average annual impacts for 2040 relative to current conditions; they all assume a base case for irrigation water cutbacks of SGMA + climate change + environmental flow increases. Each scenario builds on the water management assumptions of the previous scenario (for instance, basin trading also includes local trading).The darker bar is the baseline with inflexible water use (no trading); subsequent scenarios progressively add flexibility in the type of trading that can be done.

We also mapped the local consequences of the trading scenarios in terms of net import and export of water. Figure A13 shows regions that would sell or buy water under different scenarios. The panel on the left shows water movement when only groundwater trading is allowed within basins, and where the most water-constrained subunits would try to buy water from their neighboring areas. With groundwater trading, buying water means pumping additional water at the buyer's location, which could raise concerns about additional physical impacts on other parties—such as interference with local wells and land subsidence. Therefore, areas in red in the left panel of Figure A13 could experience localized pumping impacts if basin-wide groundwater trading is allowed, while areas in green would experience less pressure on their aquifers. In future work, we plan to explore these potential vulnerabilities in greater detail, incorporating the likelihood of trading depending on crop type and the local prevalence of well impacts and subsidence risk. Groundwater market design could ensure that significant impacts of this type are either avoided or mitigated (Ayres et al. 2021). It is also important to keep in mind that SGMA implementation should reduce such impacts by progressively reducing groundwater overdraft; groundwater trading is a way to reduce the costs of these cutbacks while moving toward sustainability.

The right-hand panel shows water movement when valley-wide surface trading is allowed. Most of the west-side basins would likely sell some water to other basins, while Kern and many east-side basins would be looking for opportunities to buy water.[38] Note that the third-party issues with surface water trading are different than for groundwater. Purchasing surface water brings water into the area, and can actually improve groundwater basin conditions because of higher irrigation return flows. So the areas selling water would be more likely to raise concerns about third-party impacts of such trades—primarily because of reduced economic activity as irrigated acreage declines, but potentially also because of reduced return flows.[39] There will generally be opportunities to address third-party impacts of trading, while still generating benefits from trade. In the case of surface water trading, this type of assessment of the economic incentives for trading could help identify infrastructure needs.

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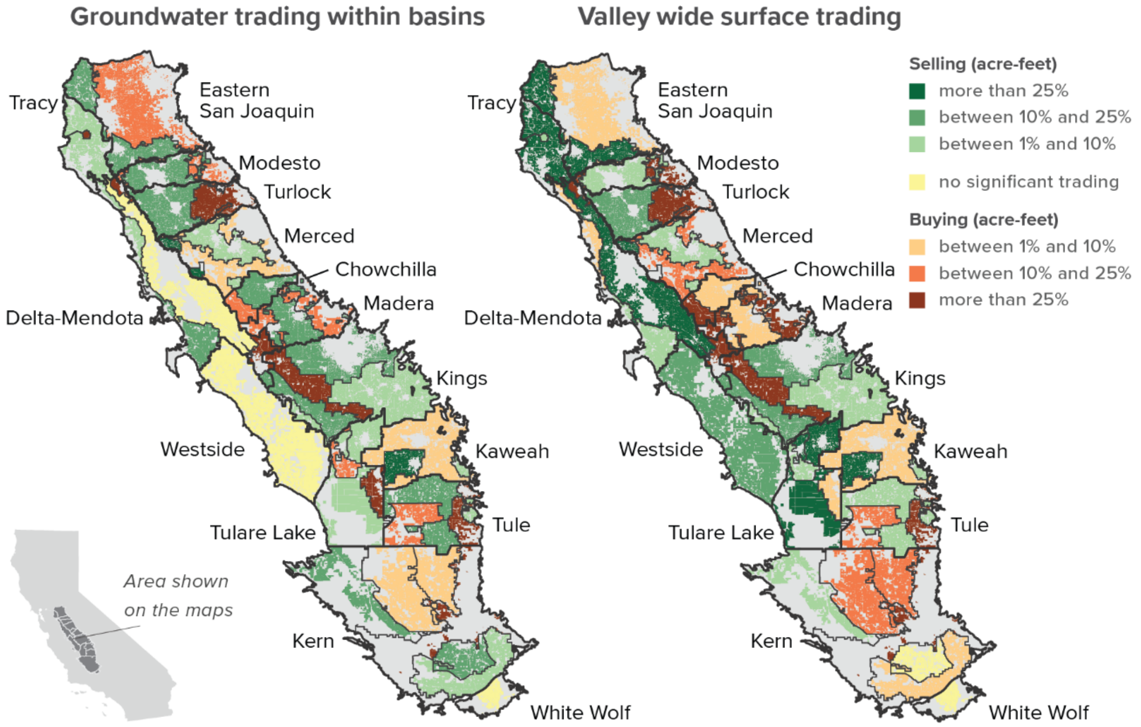
[38] The relatively high share of annual crops in a basin like Westside could reflect a risk management response to the high interannual variability of surface water supplies, where growers maintain some acreage in annual crops to have the flexibility to withstand years with very low water deliveries. As groundwater banking opportunities expand, such growers may prefer to store this water for their own use in dry years, rather than selling it to other parties.

[39] The issue of return flows was raised as an objection to surface water trades out of the Modesto basin during the last drought (Ayres and Bigelow, 2022b). For discussions of third-party issues and potential ways to resolve them, see Ayres et al. (2021) and Ayres and Bigelow (2022b).

FIGURE A13

Different types of trading may have local consequences that need to be considered


Groundwater trading within basins

Valley wide surface trading

SOURCE: Authors' estimates.

NOTE: The percentages show the ratio between the amount of water traded with respect to the initial water use—serving as an indicator of the impact of trading in the subunit's water supply. The amount of water traded is obtained as the difference in water use (groundwater in the left panel and surface water in the right panel) with respect to the inflexible scenario (where trading is not allowed). We do not depict trading that may occur within subunits. As an example, there is no significant within-basin (cross-subunit) groundwater trading shown in the Westside basin (left panel) because this basin is composed of a single subunit (Westlands Water District), and the overall groundwater use doesn't change. But within subunits, there still might be spatial concentration of pumping pressures because lands with different crop types would be more likely to buy or sell water.

New supplies and increased productivity would soften impacts

Finally, we show the potential benefits of expanding water supplies and increasing productivity, on top of flexible water management with local, basin, and valley-wide trading (Figure A14).

When half a million acre-feet of extra supplies are brought to the valley, fallowing would decline to 646,000 acres, GDP losses would decline to $1.9 billion, and jobs to less than 21,000s—58 and 57 percent reductions relative to the most restrictive scenario (SGMA + climate change + environmental flow increases with inflexible management). If a million acre-feet of extra water were available, fallowing would fall to 475,000 acres; GDP losses would decrease to $1.8 billion, and job losses would decrease to just over 15,000—61 and 69 percent less than in the most restrictive scenario. These GDP estimates assume a price tag for new water of $500 per acre-foot. Even at the hefty price of $1,000 per acre-foot, acquiring an additional 0.5 maf in new supplies would result in a slightly higher regional GDP than a future with flexible trading and no new supplies; and while there would be no GDP gains from adding 1 maf in new supplies at this price, job losses would still be lower.[40] Beyond the potential physical availability of new supplies, the cost of this water will likely determine how much supply expansion actually occurs.

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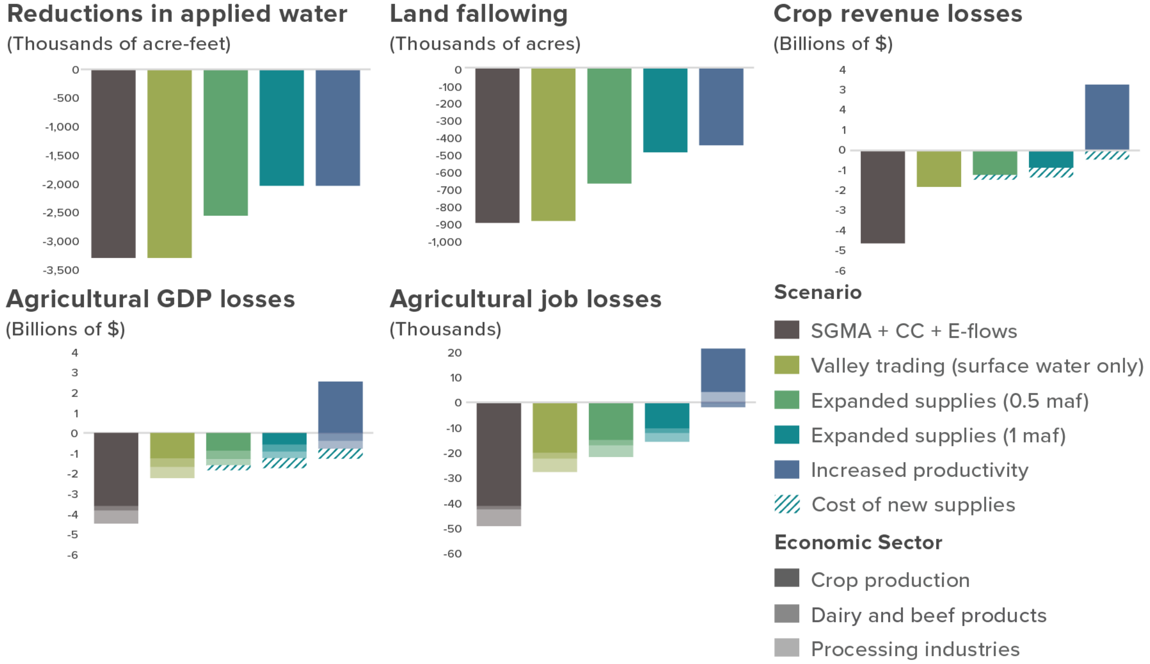
[40] To see this, double the costs for water in Table A3; water at $1,000/af would reduce final economic results for revenues and GDP by an additional $250 or $500 million, depending on the scenario. This exercise also shows that when valley trading is allowed, water tends to go to the most productive (higher value) uses first; it would go to less productive uses when more water is brought in (compare the gains in the 0.5 and 1 maf scenarios).

Finally, continued advances in productivity would soften the impacts of water supply cuts facing the valley. If yields increase by just half the yield growth of the past 40 years—with corresponding increases in applied water and farm labor productivity—the decline in real crop revenues under the most restrictive (and costly) scenario would fall by half.[41] When we combine productivity growth, flexible trading, and 1 maf of new supplies—the scenario shown here—regional GDP and jobs would increase substantially relative to current levels despite 1.25 maf less irrigation water.[42] Trading increases the potential economic benefits of new supplies and productivity growth because growers will have incentives to allocate more water to the most productive crops.

FIGURE A14

New supplies and increased productivity could have important benefits for the valley



SOURCE: Authors' estimates.

NOTE: These scenarios report average annual impacts for 2040 relative to current conditions; they all assume a base case for irrigation water cutbacks of SGMA + climate change + environmental flow increases, with inflexible water management. Each scenario builds on the water availability and management assumptions of the previous scenario. The cost of new supplies (at $500/af) is included in estimates of revenue and GDP impacts in the two scenarios with expanded supplies, as well as the scenario with increased productivity (which assumes 1 maf of new supplies). Because the net economic impacts are positive for the latter scenario, it is only shown explicitly in the two supply expansion scenarios. See Table A3 for the numerical results.

Water from expanding supplies could help reduce the economic adjustment costs of implementing SGMA and other factors that are increasing water scarcity for valley agriculture. But it is important to keep in mind that not all valley farmland can support the costs of these new supplies. While the first half million acre-feet would reduce crop revenue losses by $600 million ($1,200 per acre-foot), the second half million acre-feet would reduce crop revenue losses by much less—$360 million ($720 per acre-feet). This is because the water would go first to the most profitable crops, and there is a decrease in the benefits of any additional water brought to the valley. As

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[41] This refers to a comparison of scenarios with the most water cutbacks and inflexible water management, with and without productivity growth. Without productivity growth crop revenues fall by 19 percent (Table A3); with productivity growth they fall by 9 percent.

[42] In our assumption, yields/acre increase, while water use/acre remains constant—i.e., output increases for the same units of land and applied water. We also assume that farm labor productivity increases by the same rate. Water-saving productivity increases are consistent with agronomic and genetic progress in increasing the harvestable output relative to net crop water needs (i.e., increases in harvestable biomass). Labor-saving technology innovations have also been occurring, and are likely to continue.

noted above, depending on the costs of additional water, growers may not have adequate incentives to pay for it relative to the net revenues they can earn in crop production.

Impacts on Downstream Sectors

Dairy and beef production

Table A3 provides estimates of revenues, GDP, and job changes for the dairy and beef sectors. Reduced production for dairies and beef cattle were based on the estimated reduction in feed crops.[43] For dairies and beef, the projected declines in silage and corn acreage result in substantial declines in output under the different scenarios.[44] For the most constrained scenario (SGMA + climate change + e-flows with inflexible water management), dairy and beef product revenues would drop by nearly $700 million, or 8 percent of sectoral revenues. The basin and valley trading scenarios would reduce feed crop acreage even more, increasing the potential impacts to the dairy and beef sectors. When trading is allowed at the basin level, a 12 percent reduction in dairy and beef products would cause a reduction of almost $1 billion dollars in revenues per year, and with valley-wide trading, the reduction would increase to $1.1 billion. Augmenting water supplies and increasing productivity will not change these estimates substantially, as most of the new water would go to perennial crops. Note that relative to crop production, dairy and beef sectors produce less value added (GDP) and fewer jobs per million dollars of revenues.[45]

Food and beverage processing

Food and beverage processing would also be impacted by crop fallowing and reductions in the dairy and beef sectors. We estimate that reductions in crop production would cause GDP losses of $825 million/year for the most restrictive scenario. Local trading would reduce these losses by nearly 30 percent, and basin and valley trading would cause small further reductions. These improvements in overall economic outcomes from trading occur despite losses from trading in the dairy and beef sectors, and related processing, because crop-related processing generates more value added.

Overview of Regional Economic Impacts

Finally, Figure A15 shows the overall results for all scenarios, and Table A3 (above) details the effects for each related sector.

In the most constrained scenario—when SGMA, climate change, and increased environmental regulations are considered all together and no trading is allowed—the reduction in agricultural revenues would be more than $10 billion, reducing GDP by almost $5 billion, and reducing employment by more than 50,000 jobs. These GDP and employment losses would represent a 2.5 percent drop in the size of the San Joaquin Valley's overall economy.

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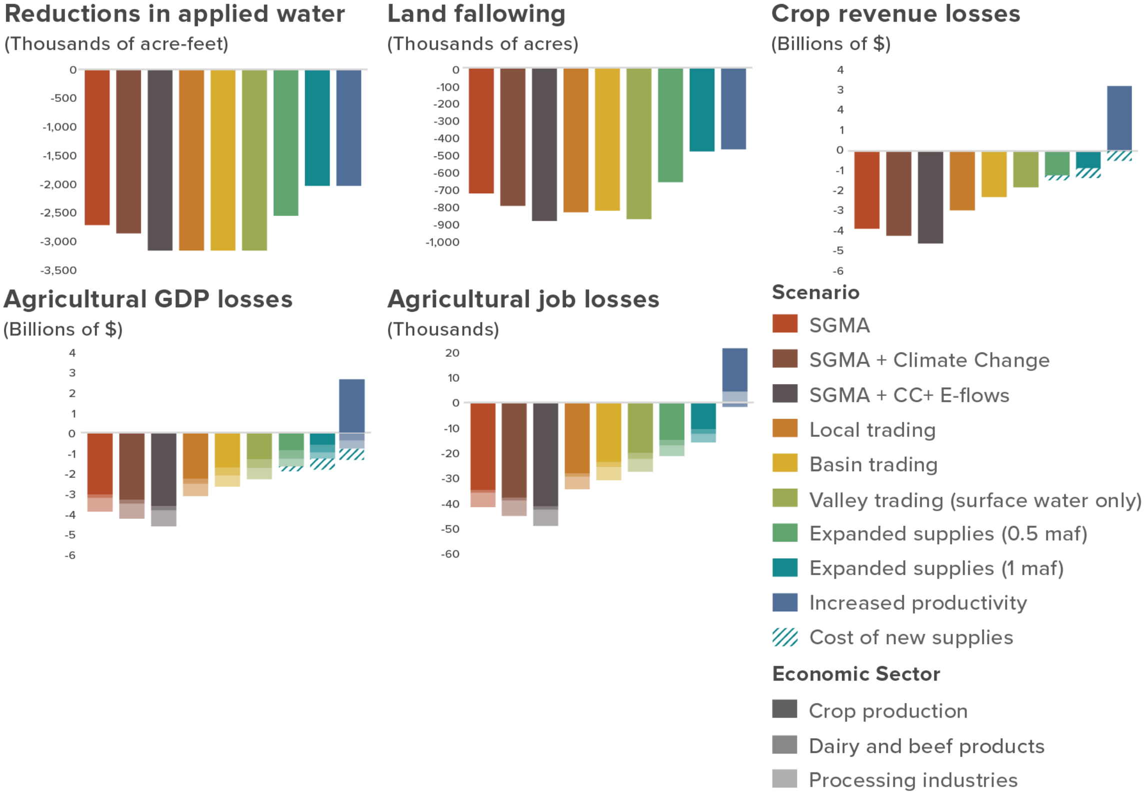
[43] Feed crops in the valley considered in the openAG model are alfalfa, silage corn, and irrigated pasture. Most corn in the San Joaquin Valley is for silage; unlike alfalfa, silage corn is often produced near dairy farms as it is costly to haul over long distances. Current dietary requirements for silage corn and other wet roughage create some system-wide inflexibility in water and land allocation beyond what is reflected in the market price for corn used in the openAG model. To account for this, we limit acreage reductions for corn in response to water shortages to 20 percent. We do not put restrictions on declines in acreage of alfalfa or irrigated pasture. We assume that the dairy industry would replace alfalfa hay with hay purchased from outside the region, but that it will experience proportional losses when corn silage output goes down. This may overstate dairy losses if improvements in feed technology make it possible for the sector to reduce its reliance on corn.
Beef cattle are often divided into three segments: cow-calf, feeder, and feedlot, each with somewhat different feed crop requirements. Our discussions with producers and other industry experts suggest that the sector adapts by changing diet composition and selling cattle out of the valley. We assume that the beef industry will experience some losses when irrigated pasture acreage goes down, with a 4 percent reduction in irrigated pasture leading to a 1 percent reduction in the herd. We assume that the industry would substitute local alfalfa hay with hay purchased from outside the region, at a comparable cost.

[44] Following decades of sustained growth, the valley's dairy herd has been relatively stable since the mid-2000s, with about 1.5 million cows.

[45] To see this, compare the ratios of value added and jobs to revenues in Table A1.

FIGURE A15

Increased trading, new supplies, and growing technological productivity could substantially reduce the effect of water supply constraints in the valley



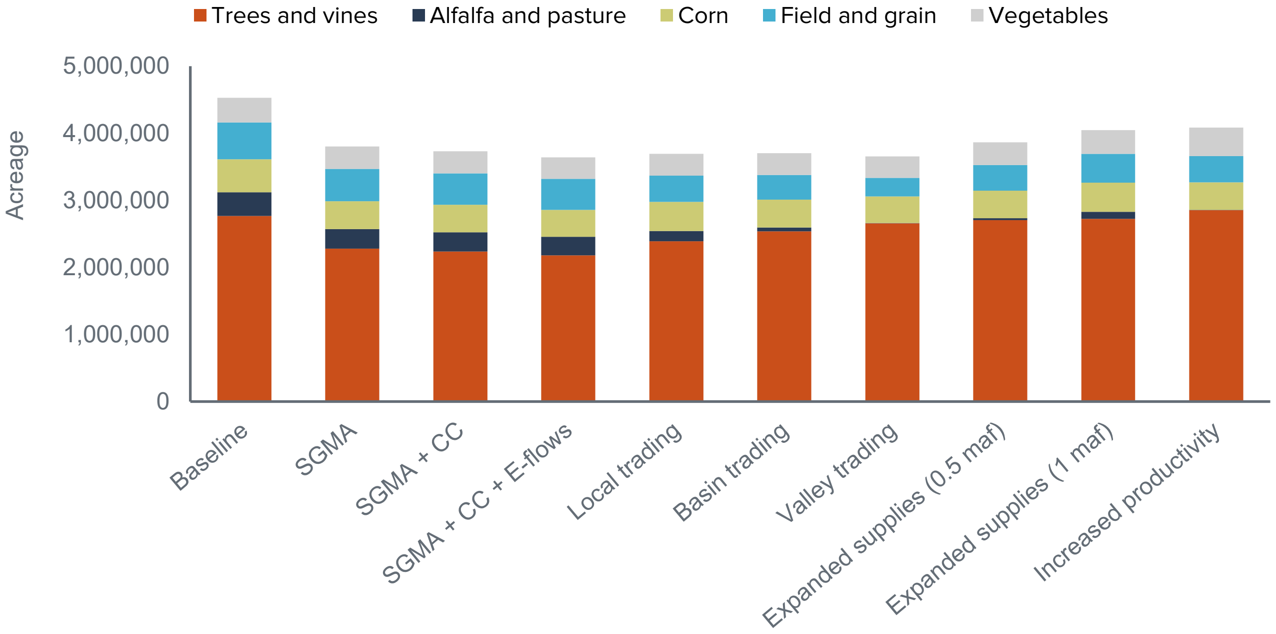
SOURCE: Authors' estimates.

NOTE: These scenarios report average annual impacts for 2040 relative to current conditions. Each scenario builds on the water availability and management assumptions of the previous scenario.

While water trading would reduce total agricultural sector revenue losses by 29–34 percent, it would have a much bigger mitigating impact on regional GDP (for which losses would fall by 33–50 percent). Similarly, trading would be beneficial for regional employment, with job losses decreasing in the inflexible scenario by 30–44 percent (from 48,000 to 34,000, 30,000, and 27,000 in the local, basin, and valley trading scenarios, respectively). As noted above, trading has different impacts on perennial crops versus feed crops, animal production, and processing: while it uniformly benefits perennials, it reduces feed crops that are important for the dairy and beef sectors, and in turn the food and beverage processing industries that depend on these products. Figure A16 summarizes these cropping shifts across the different scenarios; with full trading flexibility (the valley trading scenario), alfalfa and pasture acreage almost disappears from the region.

FIGURE A16

Crop acreages will change significantly across scenarios, and alfalfa and pasture would almost disappear with increased flexibility to reallocate water



SOURCE: Authors' estimates.

NOTE: These scenarios report average annual impacts for 2040 relative to current conditions. Each scenario builds on the water availability and management assumptions of the previous scenario.

New supplies could provide important benefits, reducing revenue and GDP losses, while also saving jobs. Relative to the most restrictive scenario, GDP losses would decline by 58–61 percent, and job losses by 57–69 percent, with 0.5 and 1 maf of additional supplies. But perhaps the most noteworthy effect of new supplies is the reduction in fallowing: with respect to the most restrictive scenario, expanding supplies by 0.5 maf or 1 maf would reduce fallowing by 225,000 acres and 396,000 acres, respectively.

Increased productivity (on top of valley trading and 1 maf of extra supplies) would help to offset losses. Revenues would increase by almost $3 billion, GDP by 2.1 billion, and nearly 19,000 jobs would be created relative to current baseline conditions. Here we are showing productivity increases on top of water trading and new supplies, but productivity growth is likely to continue under many scenarios, and it could help to soften the impacts of water supply cuts facing the region.

Comparison of the Results with Our 2019 Analysis

Although there are many differences between the assessment conducted here and the one we published in Hanak et al. (2019), the results presented in Table A3 above and in Table C6 in Medellin-Azuara et al. (2019) are broadly consistent. In this section we provide details about how the results compare.

Adjustments in baseline data

First, as noted above, the studies used a different baseline. Four elements are important:

- **Land use**. In the 2019 study, we used 2010 land use reported from NASS/CDFA; here we are using 2018 land use from LandIQ made available by DWR. The former dataset includes acreage at the county scale and includes double cropping—fields that might be planted with wheat or other crops in the winter, and tomatoes or other vegetables in the summer of the same year. The latter dataset presents results at the field scale (which we were able to clip to cover only the valley floor); it does not take into account double-cropping. The significant differences in the reported acreage (5.2 million acres for the 2019 study, and 4.5 million acres for this study) come from the inclusion of double cropping and cropped acreage at higher elevation than the valley floor in the NASS/CDFA data, as well as some potential reduction in crop acreage from 2010 to 2018 triggered by the 2012–16 drought. The crop mix has also changed significantly, as growers have continued to plant more acreage with perennial crops.

- **Applied water use**. In the 2019 study we used 2010 applied water use from DWR, while in this study we used more recent 2011–13 estimates, adjusted using a combination of data from OpenET and PRISM for crops that aren't explicitly reported in the DWR categories. While in the 2019 study we obtained a total applied water use of 16.2 maf, in this study we obtain 16.1 maf. Note that while the acreage has decreased substantially (~15%), the final applied water use only decreased slightly (<1%), resulting in much higher applied water use per acre of irrigated land. One key implication of this change is that more water use per acre means less fallowing for the same reduction in water availability.
- **Irrigation efficiency**. We have also updated the estimates of irrigation efficiency using DWR's Statewide Irrigation Systems Methods Survey for 2010, obtaining estimates at the subunit level. On average, these estimates are higher than those we used in 2019: 73 percent irrigation efficiency in the 2019 study, versus 79 percent in the current study. These estimates have a significant effect: the higher the irrigation efficiency, the lower the reductions in applied water use needed to end a given level of overdraft. Higher irrigation efficiency also results in less excess water that recharges the basin (less return flow). Finally, higher applied water use per acre and higher irrigation efficiency results in higher consumptive use (or higher evapotranspiration).
- **Economic data**. In the 2019 study we used 2010 data in 2010 dollars; here we use 2017–19 average prices and revenues, adjusted to 2019 dollars. In 2019, the crop revenue baseline was $20.8 billion, while in current study we estimate a baseline of $24.0 billion—a difference almost entirely accounted for by the general increase in prices during that period (17.2% cumulative rate of inflation).

Comparison of scenarios

Second, we have made some changes in the water availability and management scenarios, although there are points of comparison. Our water trading scenarios are richer in the current analysis, enabling us to explore trading within and among local areas within basins, as well as across the entire valley. In our 2019 study, our local trading scenarios were more similar to trading at the basin scale in this analysis (though with less geographic precision, and less accurate data on local groundwater deficits). Valley trading has a similar structure in the two studies, where surface water is able to move freely, but groundwater needs to stay in the basin.

The SGMA scenario in this study is conceptually similar to the SGMA scenario in the 2019 report. While both studies have similar overdraft (1.85 maf in the 2019 study versus 1.84 maf in the current study), we reported a 2.52 maf reduction in water use in 2019, versus a 2.68 maf reduction here. This reflects two counteracting differences: on the one hand, irrigation efficiency is higher in the current study, reducing the needed cutbacks in applied water; on the other hand, here we also accounted for excess groundwater in some subunits—making the final cutbacks higher. Applied water per acre is also higher here, so cutbacks result in less fallowing. On balance, we find SGMA implementation reduces irrigated acreage by ~720,000 in the current study, versus ~780,000 in the 2019 study.[46] But because our irrigated acreage baseline is now lower, our fallowing estimates are higher in percentage terms (15% in the 2019 study versus 16% here).

The most constrained scenario in the present study also has a counterpart in the 2019 study. Both include SGMA, climate change, and new environmental regulations, although the current study's estimates are more precise, with

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[46] The results in the text assume inflexible water management. For 2019, these results appear in Medellín-Azuara et al. (2019) (p. 17) and Escriva-Bou et al. (2019a).

more spatial details. The cumulative reduction in applied water is slightly greater in the current study (3.15 maf, versus 3.2 maf in the 2019 study), but the factors described above result in a lower land fallowing estimate (~830,000 acres) than in the 2019 study (~950,000 acres).[47]

Finally, it is also possible to compare scenarios with expanded supplies; we will compare the 0.5 maf scenario included in this study with our SGMA + climate change + new environmental regulations scenario from 2019, where we considered ~460 taf in new supplies. With expanded supplies and valley trading, we estimated a reduction of 2.56 maf in the 2019 study, versus 2.55 maf in the current study. This resulted in an estimated ~736,000 acres of land fallowing in 2019, and ~646,000 acres here (again, given the same counteracting effects explained above). Here we also included an additional scenario with 1 maf of new supplies, which would decrease the need to fallow lands to just under 500,000 acres. Note that the applied water reduction in that scenario (~2 maf) is similar to the level in the most widely reported scenario from our 2019 study (with SGMA cutbacks and +460 taf of new supplies); we estimated fallowing of 535,000 acres was likely.

Overall comparison of results

In summary, the land fallowing estimates have decreased slightly compared to the 2019 report, for similar levels of water reductions. This results principally from higher applied water use and higher irrigation efficiency in our current analysis. The scenarios with the most water restrictions (SGMA + climate change + environmental regulations), which are similar in both studies, would require between 650,000 and 870,000 acres fallowed in the current study; in the 2019 report that range was between 740,000 and 950,000 acres.

If more water supplies could be brought to the valley, these numbers would fall. In our 2019 report, we concluded that at least 500,000 acres of fallowing was likely, considering the impacts of SGMA plus close to 500 taf of new supplies—an amount we considered feasible at a cost agriculture could afford. Here, considering the additional impacts of climate change and proposed new environmental regulations, the expected level of fallowing with that volume of new supplies would be higher—650,000 acres. Almost 1 maf of new supplies would be needed to bring fallowing down to our earlier 500,000 acre estimate level. Potential water availability and costs will be the main constraints to reducing fallowing.

While the valley-wide results are broadly consistent between this study and the earlier one, the findings here rely on more recent, spatially explicit estimates of the crop portfolio and more refined local estimates of surface water availability and groundwater overdraft. This local detail provides a better basis for considering the implications of management approaches such as water trading, as well as scenarios for alternative uses of fallowed lands. In forthcoming work, we will further explore such issues to provide insights on promising approaches for adapting to growing water scarcity in the valley in ways that benefit the region's communities, economy, and environment. The accompanying dataset, *PPIC Water Supply Constraints at the Local Scale in the San Joaquin Valley*, may be helpful to others who wish to use this information in their own analyses.

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[47] In this case, we compared the basin trading scenario included in the present study with the local trading included in the 2019 study, which are roughly compatible.

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