Supplementary Material

Water shortage risks from perennial crop expansion in California’s Central Valley

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Supplementary Material 1: Datasets

1.1 County and District Boundaries

This study focuses on the Tulare Lake Basin in the southern Central Valley of California. The region includes four counties (Kern, Tulare, Kings, and Fresno) and 30 major irrigation districts, shown in the figures below. These values are compared with the districts’ annual water supplies, drawn from their Agricultural Water Management Plans (AWMPs). These plans must be submitted every five years for all agricultural water districts supplying irrigation water to areas more than 25,000 acres under the Water Conservation Act of 2009. Most irrigation districts in Tulare Lake Basin have complied with the rule and submitted AWMPs to California’s Department of Water Resources (DWR), where the reports are now publicly available. The districts receive water supplies from a mix of state/federal project contracts, local surface water supplies, and groundwater. Irrigation districts with sparse published data or without any recent AWMPs are excluded from the analysis of water demand, but are still included in the spatially distributed crop dataset.
Figure S1. The four counties comprising Tulare Lake Basin

Studied Irrigation Districts in Tulare Lake Basin:

| District Key | Arvin - Edison Water Storage District | Alta Irrigation District | Berrenda Mesa Water District | Buena Vista Water Storage District | Consolidated Irrigation District | Cawelo Water District | Delano - Earlimart Irrigation District | Dudley Ridge Water District | Fresno Irrigation District | James Irrigation District | Kern Delta Water District | Kern - Tulare Water District | Lost Hills Water District | Lindmore Irrigation District | Lower Tule River Irrigation District | North Kern Water Storage District | Orange Cove Irrigation District | Pixley Irrigation District | Riverdale Irrigation District | Shafter - Wasco Irrigation District | Semitropic Water Service District | Tulare Irrigation District | Tulare Lake Basin Water Storage District | Westlands Water District | Wheeler Ridge - Maricopa Water Storage District |
|--------------|--------------------------------------|--------------------------|-------------------------------|-----------------------------------|---------------------------------|------------------------|------------------------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Percent perennial crops (2016) | Dry-year groundwater use (percent of total) |
| AEWSD | Arvin - Edison Water Storage District | 51% | 61% |
| AID | Alta Irrigation District | 73% | 86% |
| BMWD | Berrenda Mesa Water District | 96% | 94% |
| BVWSD | Buena Vista Water Storage District | 56% | 52% |
| CID | Consolidated Irrigation District | 96% | 91% |
| CWD | Cawelo Water District | 19% | 57% |
| DEID | Delano - Earlimart Irrigation District | 96% | 37% |
| DRWD | Dudley Ridge Water District | 100% | 30% |
| FID | Fresno Irrigation District | 89% | 11% |
| JID | James Irrigation District | 52% | 57% |
| KDWD | Kern Delta Water District | 27% | 30% |
| KTWD | Kern - Tulare Water District | 92% | 30% |
| LHW | Lost Hills Water District | 100% | 30% |
| LID | Lindmore Irrigation District | 89% | 68% |
| LTRID | Lower Tule River Irrigation District | 28% | 78% |
| NVSD | North Kern Water Storage District | 89% | 92% |
| OGD | Orange Cove Irrigation District | 99% | 84% |
| PID | Pixley Irrigation District | 34% | 84% |
| RID | Riverdale Irrigation District | 34% | 78% |
| SWWD | Shafter - Wasco Irrigation District | 85% | 77% |
| SWSD | Semitropic Water Service District | 70% | 87% |
| TID | Tulare Irrigation District | 28% | 35% |
| TLBLWSD | Tulare Lake Basin Water Storage District | 0% | 64% |
| WWD | Westlands Water District | 44% | 58% |
| WRMWS | Wheeler Ridge - Maricopa Water Storage District | 73% | 36% |

Figure S2. Irrigation districts chosen for study within Tulare Lake Basin. Crop data taken from Pesticide Use Report analysis, and groundwater data taken from Agricultural Water Management Plans as described in the manuscript.
1.2 County Commissioner crop dataset

The U.S. Department of Agriculture (USDA) publishes an annual compilation of crop reports produced by the California County Agricultural Commissioners, with data available from 1980-2016. County commissioners are responsible to collect and curate agricultural production data, including planted acreage, yield, and market prices. When unable to interview farm corporations, the reports often use pesticide permitting reports to fill in the gaps in acreage estimates. The thoroughness of these crop reports suggests high accuracy, and the dataset is presumed to have the most trustworthy acreage estimates for the region. However, the dataset is aggregated at the county scale, and does not include spatially distributed information at a finer resolution, such as the irrigation district scale, which would enable a comparison of agricultural water supply and demand. The county commissioner reports are therefore used for validation of more disaggregated data at the irrigation district level.

Figure S3. Crop acreage and prices averaged for the most common perennials (almonds, pistachios, oranges, table grapes, wine grapes) and annuals (alfalfa, silage, cotton, wheat, tomatoes) grown in the four counties.
1.3 California Pesticide Use Reports dataset

Pesticide Use Reports (PUR) from the California Department of Pesticide Regulation (DPR) provide a thorough dataset for estimating crop acreages at finer geographic resolution. The reports include the county, meridian, township, range, and section of almost all pesticide permits submitted since 1974. The dataset resolution is shown below, where each grid cell is approximately 640 acres, or 1 square mile.

Figure S4. The examined irrigation districts divided into the 1-square-mile sections included in each Pesticide Use Report.

Although the pesticide use reporting system is extremely thorough, several assumptions must be made to consider it a complete representation of yearly crop decisions within the region. Each individual crop must receive a pesticide application at least once per season, a reasonable assumption for most of the most commonly grown fruits and vegetables in the Tulare Lake Basin. This is most problematic in regions growing mostly grasslands and forage crops, since they usually use fewer pesticide applications. Growers must also consistently submit logs of pesticide use that accurately describe the acres of each crop type planted. If pesticide use reporting is not enforced or observed to a reasonable extent, the acreages derived from the dataset will not be a useful estimate of crop choices within the region. While laws requiring pesticide reporting have been in effect since 1970, the DPR established clearer legal authority to require full use reporting beginning in 1990.
Supplementary Material 2: Acreage Calculation

2.1 Acreage Calculation

Acreage estimates for each crop type listed in the dataset were calculated by filtering the reports in each square-mile section for unique parcel codes, batch numbers, and crop codes, each of which are described in detail by the DPR documentation (DPR, 2016). For years 1974-1989, the analysis takes the maximum acreage treated for each group of permits with a matching batch number and crop type in the database. From 1990 through 2016, the acreage is calculated from the maximum acres planted value for each subset of permits with a common crop type and site location identification code.

To reduce erroneous double-counting of agricultural land in some years, the aggregated acreage within each 1-mile section is normalized to match the known maximum of 640 acres within each section. This step limits the extent to which multiple pesticide applications under different crop or batch labels could overestimate total acreage in a region. Assuming farms in a section followed similar methods of compiling and submitting pesticide use reports (i.e., multiple reports for each land parcel, or multiple parcels combined into one report), the normalization maintains the relative prevalence of different crop types in each section.

Each crop category is manually labeled as a perennial crop or annual crop based on the common planting style of the fruit or vegetable. For most crop types, the correct classification was easily verifiable. Table S4 illustrates the categorical breakdown of individual field and orchard crops listed in the PUR dataset. Crop acreages within the two categories are then summed to analyze the shift in planting decisions over time.

2.2 Data Validation

To validate the acreage calculations, crop acreages from the PUR dataset are upscaled to the county level and compared to the County Commissioner data for the four counties in the Tulare Lake Basin. This comparison is shown in Figure S5, with all crops included in the comparison except pasture range. Silage corn appears to be double-counted in the County Commissioner data and is excluded from the County Commissioner comparison in order to maintain consistency between the two datasets. Pasture rangeland does not receive sufficient pesticide applications to be accurately captured by the PUR dataset. These assumptions should not affect overall calculations, since rangeland is rarely irrigated.

In Figure S5, Fresno, Kings, and Kern County follow the County Commissioner trends fairly consistently throughout the time period, with annual crops diverging slightly from the larger area estimates given by the county commissioners. Structural changes to how the California Department of Pesticide Regulation organized and labeled the reports led to a decrease in estimates between years 1989 and 1990, not seen in the County Commissioner values. Most apparent is the dramatic dip in both perennial and annual crops in Tulare County during this time. Although these drought years are classified as “critical” (CDEC, DWR, 2017), the values clearly to not represent the actual planting decisions in the region seen in the county data.
The general trends of the compiled PUR archives remain intact over the long term and reflect crop levels reported by the County Commissioners. While this comparison does not guarantee the accuracy of crop data derived from PUR at finer spatial scales, it is one of the few available options for validation. Another argument for its validity is that the more gradual yearly changes of perennial crops compared to those of annual crops accurately portrays what one might expect of a landowner’s planting decisions, since tree crops require larger initial investment and are grown with the intent of producing for decades. Almonds, walnuts, and pistachios have respective productive lifespans of 25, 35, and 60 years; three of the most commonly grown crops in this region (Marvinney et al., 2014).
3.1 Water demand estimates

*Table S1. Applied Water 2010 Estimates for Tulare Lake Hydrologic Region (DWR, 2018)*

| Crop group | 2010 Applied Water Estimate [acre-foot / acre] | Crop group | 2010 Applied Water Estimate [acre-foot / acre] |
|------------|-----------------------------------------------|------------|-----------------------------------------------|
| Wheat, barley, oats, miscellaneous grain and hay, and mixed grain and hay | 1.52 | Tomatoes for processing | 2.32 |
| Cotton | 3.00 | Tomatoes for market | 1.76 |
| Sugar beets | 2.82 | Melons, squash and cucumbers | 1.74 |
| Corn (field and sweet) | 3.13 | Onions and garlic | 2.73 |
| Beans (dry) | 2.75 | Potatoes | 1.72 |
| Safflower | 2.38 | Artichokes, asparagus, beans (green), carrots, celery, lettuce, peas, spinach, flowers nursery and tree farms, bush berries, strawberries, peppers, broccoli, cabbage, cauliflower and brussel sprouts | 1.26 |
| Flax, hops, grain sorghum, sudan, castor beans, miscellaneous fields, sunflowers, hybrid sorghum / sudan, millet and sugar cane | 2.67 | Almonds and pistachios | 4.04 |
| Alfalfa and alfalfa mixtures | 4.96 | Apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs, walnuts and miscellaneous deciduous | 3.78 |
| Clover, mixed pasture, native pastures, induced high water table native pasture, miscellaneous grasses, turf farms, bermuda grass, rye grass and klein grass | 4.65 | Grapefruit, lemons, oranges, dates, avocados, olives, kiwis, jojoba, eucalyptus and miscellaneous subtropical fruit | 3.15 |
| | | Table grapes, wine grapes and raisin grapes | 2.61 |
Water demand for each district was calculated using the equation below, where \( D \) is the regional water demand (acre-feet), \( N \) is the number of crops grown in the region, \( AW \) is applied water depth (acre-foot per acre), and \( A \) is the planted area (acres).

\[
D = \sum_{i}^{N} AW_i * A_i
\]

Figure S6. Yearly acreage of perennial and annual crops for four selected irrigation districts in Tulare Lake Basin with consistently majority annual crops.
3.2 Agricultural Water Management Plans

Finally, estimates of water demand at the irrigation district scale are compared to the available supplies of surface and groundwater during wet and dry years. The yearly surface and groundwater supplies, reported by the district agricultural water management plans, are sorted as either a wet supply or a dry year supply based on the official water year type classification from the DWR. Data from wet years were then compared with the amount of water demanded based on the 2016 acreage estimates for each irrigation district. This comparison was used to evaluate the differences between the total volume of water sources available to a region and the minimum water volumes needed for sustaining perennial crops in the region. We can then evaluate how surface and groundwater limitations (due to drought and/or regulation) could influence districts differently depending on their portfolio of water supply sources and their fraction of perennial crops.

Figure S7. Estimated water demands for selected irrigation districts with primarily annual crops.
Figure S8. Estimated water demands for selected irrigation districts with primarily perennial crops
Figure S9. Estimated water demand for irrigation districts with historical shifts from perennial to annual crops
Supplementary Material 4: Economic Analysis

Estimated water demands for each irrigation district are compared with the dry-year water supplies available according to the Agricultural Water Management Plans (AWMPs). Scenarios are generated by reducing available groundwater by 10 percent increments of the estimated dry-year pumping levels, assuming both 1996 and 2016 crop distributions. The chosen groundwater reduction levels are subjective and meant to estimate revenue loss should groundwater reductions occur. They illustrate general groundwater cutbacks due to legal or environmental factors, but do not reflect any actual prediction of how SGMA regulations will be carried out, which remains uncertain.

The analysis assumes surface water availability equivalent to the amount received in past dry years, as reported in the Agricultural Water Management Plans. Water shortages are then calculated as the difference between agricultural water demanded and the estimated total water supply from both surface and groundwater (reduced by 10% increments) during a dry year.

The analysis assumes landowners can use groundwater wherever it is most needed within the irrigation district. Field crops are fallowed first, followed by orchard crops, as required to meet pumping reductions. Within each of the two land types (annual/field crops, perennial/orchard crops), crops are fallowed as needed to maximize total revenue from the available agricultural water and minimize cost from pulling high-value orchard crops. In practice, landowners may not always be able to trade pumped water to the highest-value crops in the region. This analysis therefore likely underestimates the severity of economic loss from curtailments.

The acreage of each fallowed crop is then converted to revenue loss based on the would-be agricultural revenue from the crop yield given full availability of irrigation water. Crop revenue is calculated from yield-per-acre and price-per-unit estimates from the County Commissioner dataset, while perennial pulling and replanting costs are calculated from the UC Davis Agricultural Resource Economics tool Tree Loss Calculators and Vine Loss Calculators (UC Agricultural Issues Center, 2017). The analysis uses the cost associated with pulling and replacing trees after 5 years after planting. These assumptions reflect that many farmers may not own orchards in the beginning or end of their lifecycles, and therefore would not have the option to fallow less-productive acres. The cost per acre could be reduced if farmers are able to pull older trees towards the end of their productive lifespan, or before investing multiple years in tree maturation.

All code supporting the analysis is available on GitHub as indicated in the acknowledgements section of the manuscript.

The regulated irrigation deficit (RDI) scenarios are generated by assuming farmers can irrigate their perennial orchards at 50% of the applied water demanded (results from RDI values of 40% and 60% are shown in Figure S9). The effect of such watering on crop yield varies by crop type and regional climate (Kirda, 2000). For this analysis, we assume RDI will eliminate the crop yield for the current year while yields for subsequent years will return to average. In reality, lingering effects of RDI have been known to reduce yields in the following years, but these losses have been ignored since they are highly variable and the cost estimates are only evaluated for a single drought year (Galindo et al., 2018).
Table S2. Estimated percent loss of agricultural revenue with district-wide groundwater pumping reductions, based on results from the economic analysis assuming an RDI value of 0.5. The baseline total agricultural revenue is calculated by multiplying crop acreages with their respective yield-per-acre averages and price-per-unit crop (drawn from the County Commissioner dataset [USDA NASS, 2019]). These values result from the same analysis as Figure 4 of the manuscript, only in dollar values instead of percent revenue.

| Irrigation District                                      | Estimated total annual agricultural revenue ($Millions) | Lost revenue at 25% reduction of GW supply ($Millions) | Lost revenue at 50% reduction of GW supply ($Millions) |
|---------------------------------------------------------|-------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Buena Vista Water Storage District                      | 178.4                                                 | 10.6                                                 | 28.6                                                 |
| Cawelo Water District                                   | 362.6                                                 | 22.5                                                 | 78.7                                                 |
| Consolidated Irrigation District                        | 1,281.3                                               | 127.8                                                | 408.8                                                |
| Delano - Earlimart Irrigation District                  | 539.0                                                 | 62.4                                                 | 150.8                                                |
| James Irrigation District                               | 103.1                                                 | 11.8                                                 | 77.2                                                 |
| Kern - Tulare Water District                            | 256.4                                                 | 22.3                                                 | 44.7                                                 |
| Kern Delta Water District                               | 279.2                                                 | 6.5                                                  | 16.4                                                 |
| Lindmore Irrigation District                            | 181.1                                                 | 0.0                                                  | 14.1                                                 |
| Orange Cove Irrigation District                         | 267.7                                                 | 68.1                                                 | 137.0                                                |
| Pixley Irrigation District                              | 180.4                                                 | 0.0                                                  | 7.7                                                  |
| Riverdale Irrigation District                           | 40.7                                                  | 2.3                                                  | 5.3                                                  |
| Semitropic Water Service District                       | 472.9                                                 | 33.5                                                 | 611.9                                                |
| Shafter - Wasco Irrigation District                     | 151.6                                                 | 53.6                                                 | 200.9                                                |
| Tulare Lake Basin Water Storage District                | 196.8                                                 | 3.8                                                  | 37.6                                                 |
| Westlands Water District                                | 1,889.9                                               | 420.5                                                | 1,095.6                                              |
| Wheeler Ridge - Maricopa Water Storage District         | 933.1                                                 | 156.7                                                | 260.4                                                |
| **Total in studied regions**                            | **7,314.2**                                            | **1,002.3**                                          | **3,175.8**                                          |
Table S3. Cost of pulling orchard crops in Tulare Lake Basin, estimated from Tree & Vine Loss Calculator created by the UC Davis Agricultural Issues Center (https://coststudies.ucdavis.edu/en/tree-vine-loss/)

| Orchard crop            | Estimated cost of pulling and replanting 5-year-old trees/vines (per acre) |
|-------------------------|--------------------------------------------------------------------------------|
| Almond                  | $29,748                                                                        |
| Apples                  | $29,188                                                                        |
| Blueberries             | $45,057                                                                        |
| Cherries                | $35,315                                                                        |
| Cling Peaches           | $13,422                                                                        |
| Grapes - Raisin         | $13,667                                                                        |
| Grapes - Table          | $7,389                                                                         |
| Grapes - Wine           | $17,173                                                                        |
| Lemon                   | $34,009                                                                        |
| Mandarins               | $41,631                                                                        |
| Nectarine               | $17,397                                                                        |
| Olive                   | $40,047                                                                        |
| Oranges                 | $16,955                                                                        |
| Peaches                 | $17,397                                                                        |
| Pear                    | $11,781                                                                        |
| Pistachio               | $33,138                                                                        |
| Plum                    | $18,197                                                                        |
| Pomegranate             | $16,937                                                                        |
| Prune                   | $15,783                                                                        |
| Walnut                  | $30,262                                                                        |

1. Almond price also used for cashew, chestnut, pecan, and nuts categories. 2. Apple price also used for pome fruit category. 3. Blueberries also used for blackberry, boysenberry, dewberry, loganberry, raspberry, blueberry, cranberry, gooseberry categories. 4. Orange price also used for tropical/subtropical fruit, banana, kiwi, cactus pear, cherimoya, mango, papaya, persimmon, cactus leaf, coconut, jojoba bean, avocado, fruits, and fruit trees. 5. Peach prices also used for apricot category. 6. Prune prices also used for date and fig categories.
Table S4. Grouping of crop types from PUR dataset

| Field Crops                      | Tree / Perennial Crops |
|----------------------------------|------------------------|
| Alfalfa                          | Almond                 |
| Alfalfa Sprout                   | Apple                  |
| Anise                            | Apricot                |
| Arrugula                         | Avocado                |
| Artichoke, Globe                 | Banana                 |
| Asparagus                        | Blackberry             |
| Bamboo Shoots                    | Blueberry              |
| Barley                           | Boysenberry            |
| Barley (Forage - Fodder)         | Bushberry              |
| Basil, Sweet                     | Cactus Leaf            |
| Bean Sprout                      | Cactus Pear            |
| Bean, Dried                      | Cashew                 |
| Bean, Succulent                  | Cherimoya              |
| Bean, Unspecified                | Cherry                 |
| Beet                             | Chestnut               |
| Beet (Forage - Fodder)           | Christmas Tree         |
| Bermudagrass                     | Citrus                 |
| Bok Choy                         | Cucumber               |
| Broccoli                         | Cranberry              |
| Brussel Sprout                   | Date                   |
| Cabbage                          | Dewberry               |
| Cabbage, Savoy                   | Fig                    |
| Canola (Rape)                    | Fruit Trees            |
| Cantaloupe                       | Fruits                 |
| Cardoon                          | Gooseberry             |
| Carrot                           | Grape                  |
| Carrot (Forage - Fodder)         | Grape, Wine            |
| Castorbean                       | Grapefruit             |
| Cauliflower                      | Jojoba Bean            |
| Celeriac                         | Kiwi                   |
| Celery                           | Kumquat                |
| Chayote                          | Lemon                  |
| Chervil                          | Lime                   |
| Chicory                          | Loganberry             |
| Chinese Cabbage (Nappa)          | Mango                  |
| Chinese Greens                   | Nectarine              |
| Chinese Okra                     | Nuts                   |
| Chive                            | Olive                  |
| Cilantro                         | Orange                 |
| Clover                           | Papaya                 |
| Cole Crop                        | Peach                  |
| Collard                          | Peric                  |
| Corn (Forage - Fodder)           | Persimmon              |
| Cotton                            | Pistachio              |
| Cotton (Forage - Fodder)         | Plum                   |
| Cottonseed Oil                   | Pomegranate            |
| Cucumber                         | Prune                  |
| Cucurbitis                       | Quince                 |
| Dайкон                           | Ramie                  |
| Dandelion Green                  | Raspberry              |
| Dill                             | Stone Fruit            |
| Eggplant                         | Tangerine              |
| Endive (Esarole)                 | Tangelo                |
| Fennel                           | Sunflower              |
| Fiber Crop                       | Tangerine/ Subtropical Fruit |
| Flax                             | Walnut                 |
| Gai Choy                         | Tomato, Processing     |
| Gai Lon                          | Tomato, Processing     |
| Garbanzos                        | Vegetable              |
| Garlic                           | Vegetable, Fruiting    |
| Ginger                           | Vegetables, Leafy      |
| Grain                            | Vegetables, Stem       |
| Grain Crops                      | Vetch                  |
| Grass, Seed                      | Watercress             |
| Hemp                             | Watermelon             |
| Herb, Spice                      | Wheat                  |
| Hops                             | Wheat (Forage - Fodder) |
| Horseradish                      | Vegetable              |
| Jicama                           | Vegetables, Fruiting   |
| Kale                             | Vegetables, Leafy      |
| Kohlrabi                         | Vegetables, Stem       |
| Leek                             | Vetch                  |
| Legume (Forage - Fodder)         | Watercress             |
| Lettuce, Head                    | Watermelon             |
| Lettuce, Leaf                    | Wheat                  |
| Lotus Root                       | Wheat (Forage - Fodder) |
| Melon                            | Yam                    |

Note: While alfalfa is a perennial crop, in this study it is placed in the group of field crops due to its relatively low cost of fallowing and replacement. The economic implications of alfalfa acreage are more closely aligned with those of other field crops rather than orchards and vines.