Assessing Water Use for Almond and Alfalfa Fields in the San Joaquin Valley Using Remote Sensing

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ABSTRACT

As droughts threaten the future of agriculture in California's San Joaquin Valley (SJV), studying the changing water use of the region's thirstiest crops is imperative. Remote sensing via satellites is a cost-effective and increasingly precise method for tracking land use and associated water use at large spatial and temporal scales. In this study, I investigated water use dynamics for almond orchards and alfalfa fields in the SJV using remotely sensed data. I first observed government statistics to determine how land use for almonds and alfalfa has been changing state-wide and within each county of the SJV. I analyzed five years of evapotranspiration (ET) data to compare the water use per unit area for both crops. Finally, I determined the effect of drought on relative almonds and alfalfa water consumption and water use efficiency (WUE) using an aridity metric. Results showed that almond acreage has steadily expanded while alfalfa acreage has steadily declined across nearly all counties and operation sizes. I found that almonds use more water than alfalfa; on average annual almond ET was greater than alfalfa ET by 108.95 mm. I found that during drought, almond ET increases and the crop becomes less efficient at using water. These results have implications for water management, since what little water is available during drought should be used intentionally and efficiently. Expanding almond acreage in place of more water-efficient annual crops threatens to exacerbate water shortages during a climatic era where steady water flows are no longer a guarantee.

KEYWORDS

OpenET, evapotranspiration, drought, climate, Google Earth Engine

INTRODUCTION

California has experienced nearly perpetual drought for the last two decades, and predicted climate trends indicate the severity of these droughts are very likely to increase over the 21st century (NIDIS 2022, Hicke et al. 2022). Notably, droughts pose a threat to the agriculture sector, which is highly climate-sensitive (Mishra and Singh 2010). Producing sufficient agricultural products is heavily dependent on water availability, as drought has been shown to reduce yields, damage soil ecosystems, and increase job loss (Geng et al. 2015, Kuwayama et al. 2019, Parker et al. 2020). The southern area of California's Central Valley, known as the San Joaquin Valley (SJV), is of particular importance as it is one of the world's most productive agricultural regions and the backbone of California's agricultural industry (Galloway et al. 1999). The SJV is also a highly resource-intensive area; irrigated agriculture accounts for up to 80% of California's managed water supply use. The response of the agricultural sector contributes significantly to how drought will impact the state (Shivers et al. 2018). Identifying how water use on farms is changing due to agricultural land cover changes and an increasingly extreme climate is key to predicting future water stress and developing effective policy to prevent shortages.

Decisions regarding which crop to grow in times of drought in California are driven by economic favorability, not water requirements. Many drought analyses suggest that farmers in California respond to water scarcity by fallowing lower value-per-unit-water field crops and switching to higher-value fruit and nut crops (Shivers et al. 2018, Gebremichael et al. 2021). This is a worrying trend, as farmers in times of drought may be choosing to plant crops that have higher water needs, such as almonds, which could exacerbate already severe water shortages. Almonds, which are notoriously thirsty crops, have an outsized impact on agricultural water use. One analysis found that the water footprint of California almonds was 3.56 liters—nearly one gallon—per single almond kernel (Schauer and Senay 2019). Importantly, of the main California crops, almonds are simultaneously the most profitable crop and the crop with the highest water footprint per unit weight (Fulton et al. 2019). Moreover, almonds are a top commodity throughout the Central Valley and production is rapidly increasing despite recent water shortages (CDFA 2020). Of the field crops that have significant agricultural acreage in the valley, it is reported that alfalfa is primarily being replaced by almonds and pistachios in periods of drought

(Schauer and Senay 2019). Alfalfa is also known to be a water-intensive crop, but unlike almonds it has the lowest farm-gate price of all California crops (Fulton et al. 2019). Alfalfa's high water demand combined with its low value makes it unlikely to be a good crop choice during drought, explaining the crop shifts observed in the literature (Gebremichael et al. 2021). The changing land use, and resulting water use, for almond and alfalfa fields across and within multiple counties can be assessed using remote sensing techniques. There exists limited data after 2018 on remote sensing-based water use trends for almonds and alfalfa at the scale of the entire SJV, which is crucial for understanding changing water needs in the region as California feels the effects of a warming climate.

Evapotranspiration (ET) is a useful metric capable of quantifying crop water use. Land surface elements are constantly losing water vapor to the atmosphere through evaporation, and vegetation also experiences water vapor loss via the opening of leaf stomatal pores through the process of transpiration (Zhang et al. 2016). For agricultural fields over unconfined aquifers, ET is often equivalent to consumptive water use, which is the removal of water from available supplies without a return to a water resource (Melton et al. 2021). ET has been widely used to approximate consumptive water use as well as real irrigation application on agricultural lands (eg. Jofre-Čekalović et al. 2022, López-López et al. 2018, Stevens et al. 2012, Droogers et al. 2010). Remote sensing provides relatively frequent and spatially contiguous measurements for estimating ET, and therefore water use, in a cost-effective way (Zhang et al. 2016). OpenET is a new, open-access web-based platform that combines data from six satellite-driven models to present ensemble field-scale agricultural ET values across the western United States (Melton et al. 2021). A very good agreement between the ET values from all the OpenET models and the ET values from an eddy-covariance flux tower was demonstrated for an irrigated almond orchard in the SJV (Melton et al. 2021). This data can be used to determine consumptive water use for both almonds and alfalfa, which is useful considering water deliveries for irrigated agriculture in the western U.S. are infrequently measured (Marston et al. 2022). As the platform was only released to the public in 2021, few studies have tapped OpenET's potential to perform large-scale water use analyses, particularly for almonds and alfalfa in the context of drought.

In this study, I will investigate water use dynamics for almond orchards and alfalfa fields in the SJV. I will do this by first observing government statistics from the U.S. Department of Agriculture to determine how land use for almonds and alfalfa has been changing in California as a whole and within each county of the SJV. I will then analyze five years of remotely-sensed ET data to compare the water use per unit area for both crops. Finally, I will determine the effect of drought on relative almonds and alfalfa water consumption and water use efficiency (WUE). To do this I will collect governmental almond and alfalfa acreage data, as well as almond and alfalfa ET, climate, and productivity data. I expect governmental statistics will show a clear upward trend in almond acreage across all SJV counties, in line with the California almond boom reported in the literature, but a moderate decrease in alfalfa acreage. I expect almonds will use slightly more water than alfalfa since prior research suggests almonds have the highest water footprint. Finally, I expect alfalfa will experience more stress than almonds during drought, since many farmers switch away from alfalfa when water is low.

METHODS

Study site

California is an agricultural powerhouse. Over half of the nation’s fruits and nuts are grown in California, accounting for over $20 billion in value (CDFA 2021). California’s Central Valley runs along the center of the state, bounded by the Sierra Nevada to the east and the Coast Ranges and San Francisco Bay to the west. The southern two-thirds of the Central Valley is known as the San Joaquin Valley (SQV), a region characterized by mild winters and hot, dry summers (USGS California Water Science Center). Average annual rainfall in the SJV ranges between 5 and 16 inches (Neely et al. 2021, Galloway et al. 1999). With extensive agricultural production and increasingly frequent droughts, the SJV has a sustained dependency on groundwater resources for irrigation (Neely et al. 2021, Helalia et al. 2021). This is particularly true for perennial nut crops such as almonds, which are the crop with the highest water footprint value per unit weight (Fulton et al. 2019). In 2016 almonds accounted for 28% of the Central Valley’s total cultivated cropland acreage, making it the most dominant crop in the region (Gebremichael et al. 2021). Though grown less in the SJV than almonds, alfalfa, an annual crop, is similarly water-intensive. In 2018, alfalfa accounted for 9% of the volumetric water use in the Central Valley, which made it the 5th largest water user (Schauer and Senay 2019). Aside from almonds and alfalfa, crops such as grapes, pistachios, tomatoes, lettuce, oranges, and walnuts are widely grown throughout the SJV (CDFA 2021). Agricultural land in the SJV spans eight counties, from north to south: San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare, and Kern (USDA NASS 2021). This study will analyze water use dynamics for almonds and alfalfa across these counties.

Land use data collection

To obtain land use statistics and determine how almond and alfalfa acreage has changed in California over time, I used the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Quick Stats Database (n.d.). The Quick Stats Database allows the user to customize queries of agricultural data by commodity, location, and time period. I performed two state-wide queries, one for each crop (Table 1). The USDA Census of Agriculture is taken once every five years, making census data for almonds and alfalfa limited. Survey data, however, is offered yearly for both crops (USDA NASS 2022). Note that area harvested for alfalfa was the data category most comparable to area bearing for almonds. USDA survey data is collected more frequently than census data but it is less precise and less exhaustive. For example, census data for almonds records acreage for both area bearing and area bearing and non-bearing (BNB), while survey data only records acres bearing. Using available data, I visualized trends in total almond and alfalfa acreage in California across time in bar graphs. Operation size data is provided within the domain selection output, so I also visualized acreage totals across time, categorizing by operation size.

Table 1. State-wide queries. Data collected from the USDA NASS Quick Stats Database.

	Almond Query	**Alfalfa Query**
Program	Census and Survey	Census and Survey
Sector	Crops	Crops
Group	Fruit & Tree Nuts	Field Crops
Commodity	Almonds	Hay
Category	Area Bearing, Area Bearing & Non-Bearing	Area Harvested
Data Item	Almonds - Acres Bearing, Almonds - Acres Bearing and Non-Bearing	Hay, Alfalfa - Acres Harvested
Domain	Area Bearing & Non-Bearing, Total	Area Harvested, Total
Geographic Level	State	State
State	California	California
Year	1996, 1997, 2002, 2007-2021	1919 - 2022
Period Type	Annual	Annual
Period	Year	Year

For the second set of NASS queries, I determined how almond and alfalfa acreage have changed across individual counties. I again performed two separate queries (Table 2). For both almonds and alfalfa, only census data is available at the county level. I downloaded the resulting two datasets and from these I created bar graphs to visualize almond and alfalfa acreage trends over time for each county in the SJV. To more effectively compare crop acreage counts between counties, I scaled the values to county size using land area statistics from the United States Census Bureau (n.d.). I converted this data, which was provided in square meters, to acres for each county, and created bar graphs of the scaled crop acreage across time for each of the eight counties.

Table 2. County-wide queries. Data collected from the USDA NASS Quick Stats Database.

	Almond Query	**Alfalfa Query**
Program	Census	Census
Sector	Crops	Crops
Group	Fruit & Tree Nuts	Field Crops
Commodity	Almonds	Hay
Category	Area Bearing, Area Bearing & Non-Bearing	Area Harvested
Data Item	Almonds - Acres Bearing, Almonds - Acres Bearing and Non-Bearing	Hay, Alfalfa - Acres Harvested
Domain	Area Bearing & Non-Bearing, Total	Area Harvested, Total
Geographic Level	County	County
State	California	California
Ag District	San Joaquin Valley	San Joaquin Valley
County	Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, Tulare	Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, Tulare
Year	2017, 2012, 2007, 2002	2017, 2012, 2007, 2002, 1997
Period Type	Annual	Annual
Period	Year	Year

Evapotranspiration, climate, and productivity data collection

To obtain ET, climate, and productivity data, I first created shapefiles of almond and alfalfa fields in each county of the SJV. For this I used the USDA CropScape feature to access the Crop Data Layer (CDL) (2021). The CDL is a land cover classification raster product spanning the continental United States. CDLs are derived annually using a supervised land cover classification of satellite imagery in conjunction with ground truth data (Boryan et al. 2011). From the CDL I download TIFF maps of almond and alfalfa fields in each county. I downloaded one map for each year during the 2017-2021 period, as these are the five years that OpenET currently offers for ET data. In QGIS 3.22.13, I layered these five maps for each respective crop and county. Using the raster calculator feature, I summed the five layers and then converted the resulting layer into a vector. The USDA CDL gives each crop a value for identification purposes. Almond fields have a value of 75 and alfalfa fields have a value of 36. To isolate fields where the crop had been present across all five years, I deleted from the attribute table all fields with a value less than 375 for almonds and 180 for alfalfa. To clean the resulting vectorized crop maps, I calculated the area of each polygon using the field calculator in the attribute table, then deleted all polygons with an area less than 16,199 sq. meters, corresponding to approximately 4 acres. I then simplified the polygons with a tolerance of 75 meters using the geometry tools, and deleted holes in the polygons with areas less than 3,000 sq. meters using the processing toolbox. I repeated this process for both crops in each SJV county, resulting in 16 unique ESRI shapefiles (Figure 1). Each shapefile contained between 85 and 3,166 field-shaped polygons. The almond shapefiles contained a total of 13,808 polygons across the eight counties, while the alfalfa shapefiles contained 2,578 polygons.

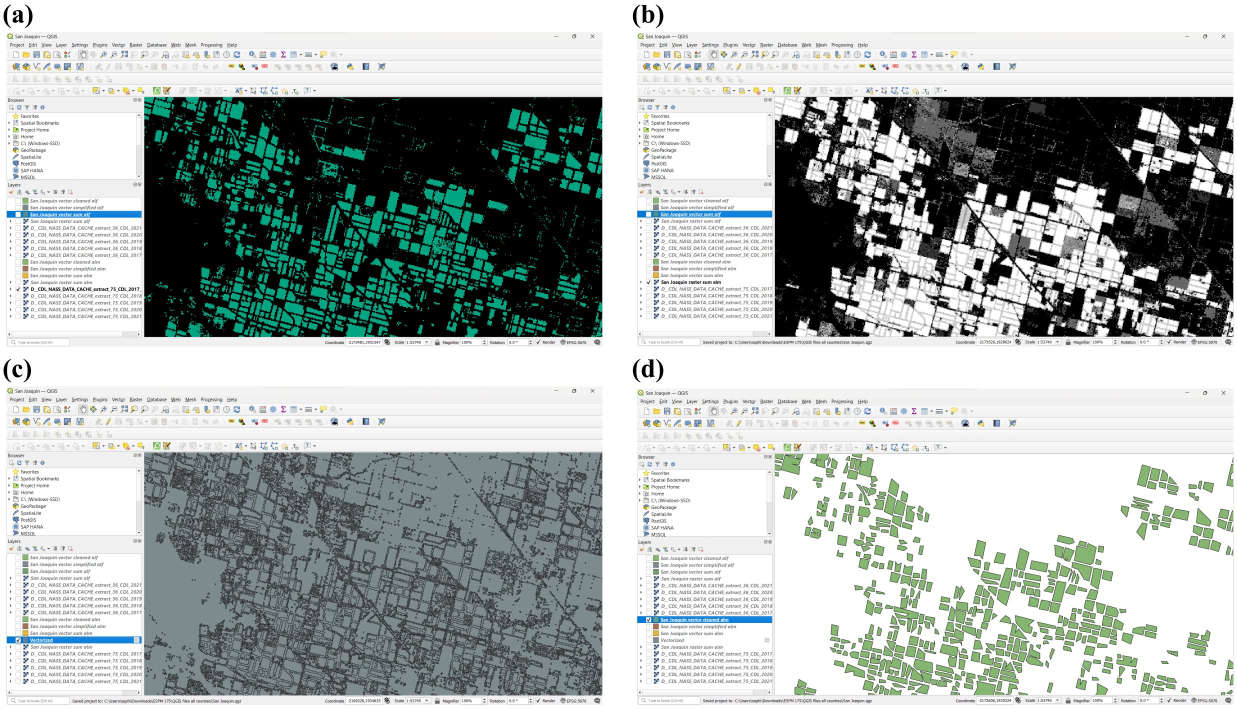
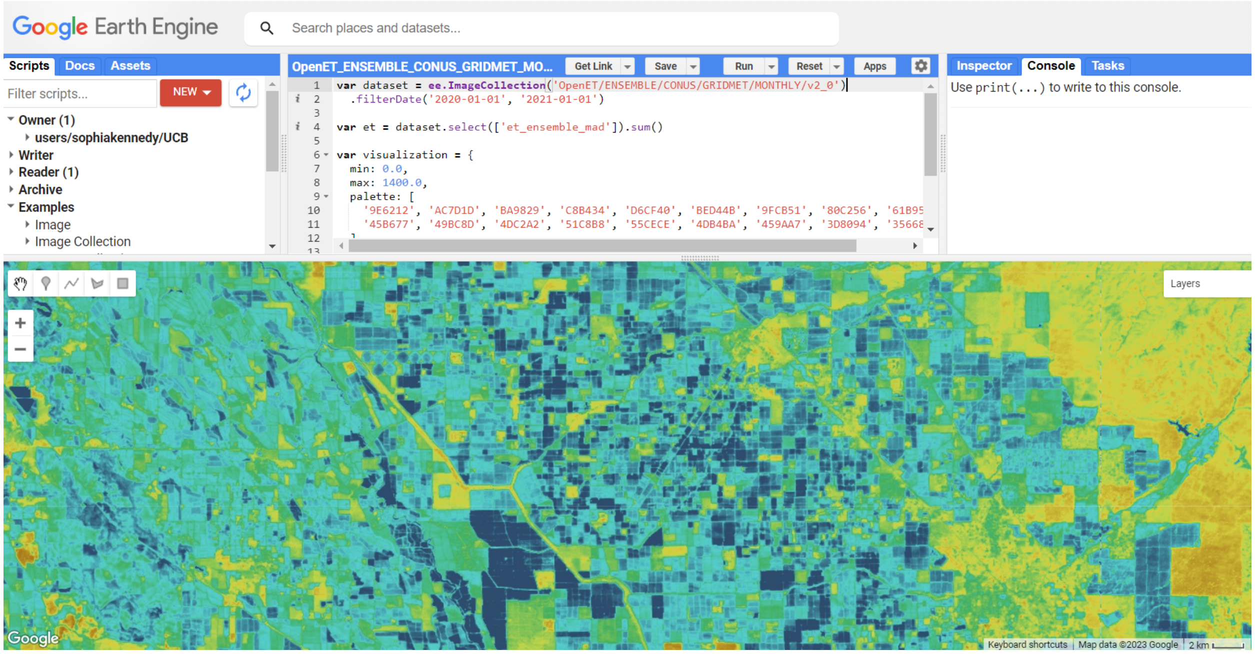


Figure 1. The QGIS interface when making the San Joaquin County almond shapefile. The graphic shows (a) one of five almond CDL TIFF rasters imported for San Joaquin County, (b) the sum of those five almond rasters, (c) the vectorized raster sum, and (d) the final vector shapefile after cleaning. This four-step process was repeated for both crops in each county, producing 16 shapefiles total.

With my shapefiles created, I obtained ET, climate, and productivity data by sending my 16 shapefiles into Google Earth Engine (GEE), a cloud-based geospatial analysis platform, and performed image mean reductions within the shapefiles on three raster datasets available within GEE's data catalog. The OpenET CONUS Ensemble Monthly Evapotranspiration v2.0. dataset provided ET values at 30-m resolution, which successfully captured the spatial variability of ET between fields across the SJV (Figure 2).



```
var dataset = ee.ImageCollection('OpenET/ENSEMBLE/CONUS/GRIDMET/MONTHLY/v2_0')
  .filterDate('2020-01-01', '2021-01-01')

var et = dataset.select(['et_ensemble_mad']).sum()

var visualization = {
  min: 0.0,
  max: 1400.0,
  palette: [
    '9E6212', 'AC7D1D', 'BA9829', 'C8B434', 'D6CF40', 'BED44B', '9FCB51', '80C256', '61B95
    '45B677', '49BC8D', '4DC2A2', '51C8B8', '55CECE', '4DB4BA', '459AA7', '3D8094', '35668
  ]
```

Figure 2. The Google Earth Engine interface. An example of the spatial variability of annual ET between fields captured by OpenET in the SJV.

I also obtained climate and productivity data from two datasets within the GEE data catalog. From each of the three GEE datasets, whose names I will abbreviate as OpenET, TerraClimate, and Landsat GPP, I extracted data between 2017 and 2021 for each crop and county (Table 3). I loaded my 16 OpenET datasets, 16 TerraClimate datasets, and 16 Landsat GPP datasets into Jupyter Notebook 6.4.12 to organize and visualize the data. I multiplied all PDSI data by 0.01, all reference ET data by 0.1, and all GPP data by 0.0001 to achieve the correct scale, and consolidated the datasets for easier manipulation.

Table 3. Google Earth Engine data extraction specifications. Each of the three datasets are freely available within GEE's data catalog.

Dataset	Dataset Type	Band(s)	Data Type
OpenET CONUS Ensemble Monthly Evapotranspiration v2.0.	Image Collection	et_ensemble_mad	Evapotranspiration
TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces, University of Idaho	Image Collection	pdsi, pet, pr	Palmer Drought Severity Index (PDSI), Reference evapotranspiration, Precipitation
Landsat Gross Primary Production CONUS	Image Collection	GPP	Gross Primary Production

Statistical analysis

I analyzed differences in annual ET between almonds and alfalfa fields in the SJV using a paired T-test within R-studio Version 4.1.2 (2021). In Jupyter Notebook 6.4.12 I analyzed four main relationships using regression analysis: aridity and water use, aridity and WUE, aridity and crop stress, and drought severity and water use. I compared the strength of each relationship by crop. I calculated aridity, crop stress, and WUE values using water use, productivity, and precipitation data (Table 4).

Table 4. Descriptions of variables used in analysis.

Variable	Description
Land use	Acres harvested and acres bearing
Water use	Evapotranspiration (ET) [mm]
Water availability (excl. irrigation)	Precipitation (P) [mm]
Aridity	Reference ET / P [mm/mm]
Crop stress index	1 - ET / Reference ET
Water use efficiency	GPP / ET [kg*C / mm]

RESULTS

State-wide USDA statistics review

I found from USDA data that total almond acreage in California steadily increased across all recorded years, while total harvested alfalfa acreage has steadily decreased in recent years. On average, BNB almond acreage increased by 189,797 acres between census years and bearing acreage increased by 144,181.33 acres between census years during the period 2002-2017. Conversely, I found using census data that total harvested alfalfa acreage has steadily declined since 2002, losing an average of 134,808.33 acres every five years since 2002. Harvested acreage did, however, increase by 222,145 acres between 1997 and 2002. Interestingly, in 1997 and 2002, California harvested alfalfa acreage was nearly double BNB almond acreage. By 2017, however, BNB almond acreage had grown to nearly double harvested alfalfa acreage (Figure 3).

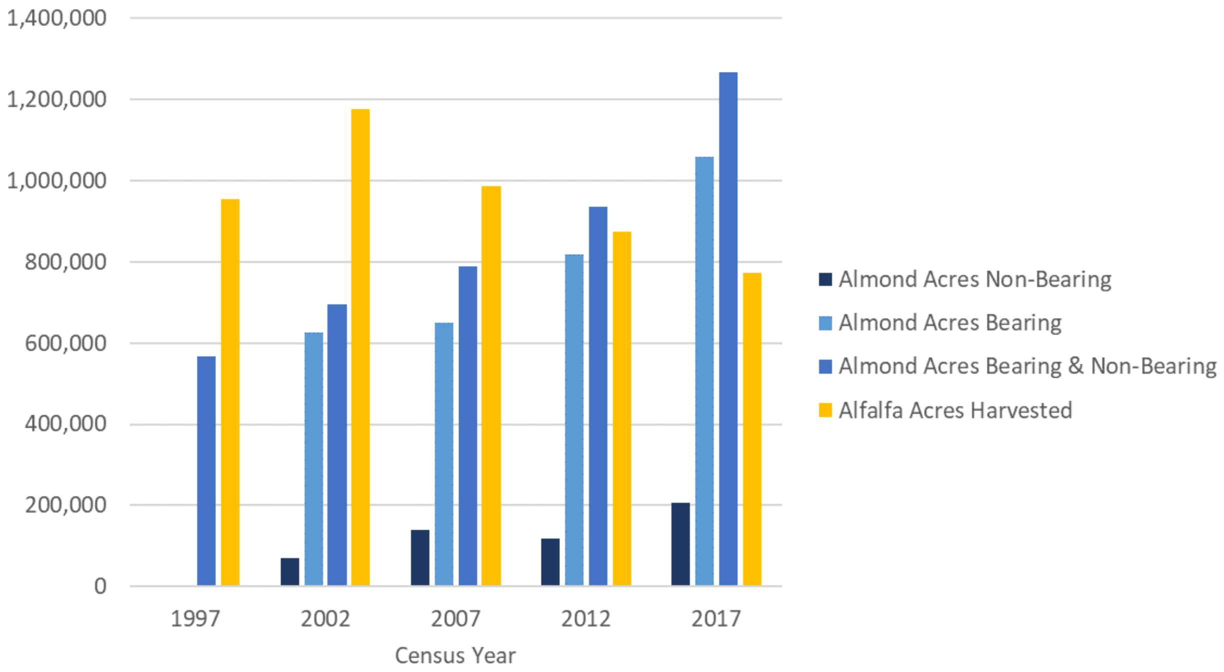


Figure 3. Total almond acreage and total harvested alfalfa acreage in California using USDA agricultural census data. Almond acreage is categorized into acres bearing, non-bearing, and bearing and non-bearing (BNB). Data from the 1997 census is limited.

Survey data similarity indicates that almond land use is steadily increasing. The largest yearly increase in almond land use occurred between 2018 and 2019 at 90,000 bearing almond acres. Two out of the three second-largest increases occurred in the following years, at 70,000 bearing almond acres each. On average, bearing almond acreage increased by 48,571.43 acres each year between 2007 and 2021. By contrast, survey data shows a steady decline of alfalfa harvested acreage. The largest yearly decrease indicated by survey data occurred between 2006 and 2007 at 110,000 harvested alfalfa acres. On average, harvested alfalfa acreage decreased by 40,000 acres each year between 2007 and 2021 (Figure 4).

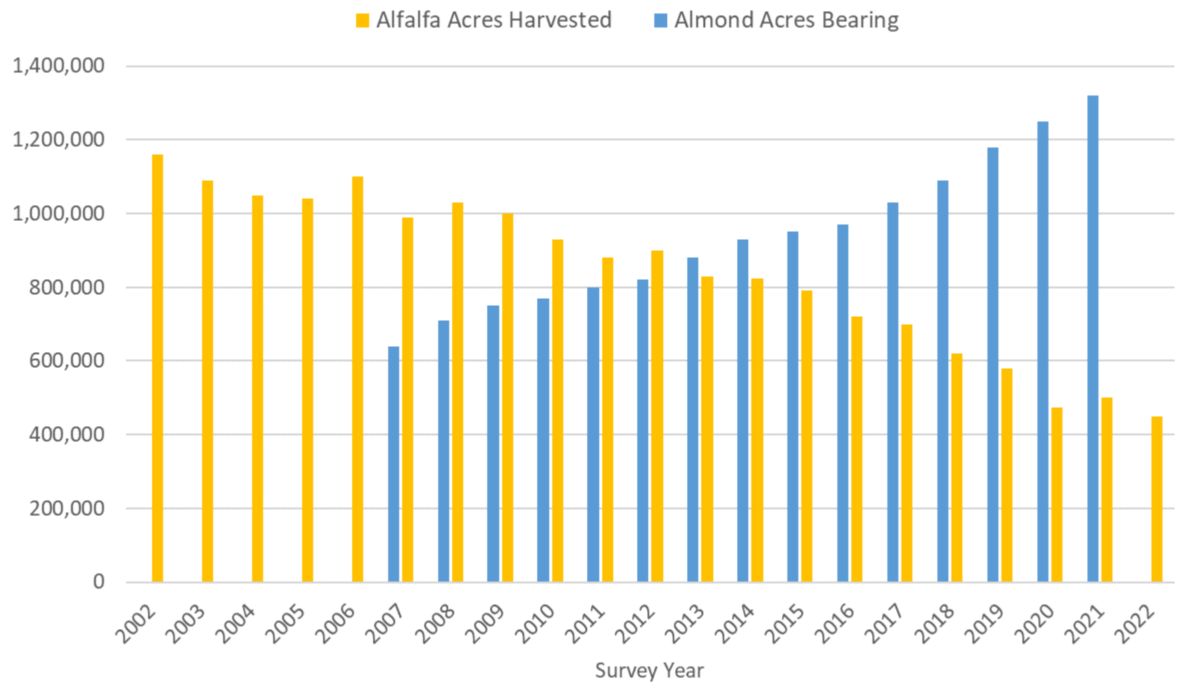


Figure 4. Total almond acres bearing and alfalfa acres harvested in California using USDA agricultural survey data. Limited data available for almond acres bearing prior to 2007 or after 2021.

All almond operation sizes exhibited at least a small increase in BNB almond acreage across the five census years (Figure 5). While it should be noted that the bins created by the USDA to categorize operation size are unequal, important characteristics of the distribution are still visible. Since 2002, more almond acreage has been part of the largest category of USDA operation size than any other category. Moreover, the most almond acreage growth in CA is within large operations of 1,000 or more acres. Relatively few almond acres are part of operations that are smaller than 50 acres (Figure 5).

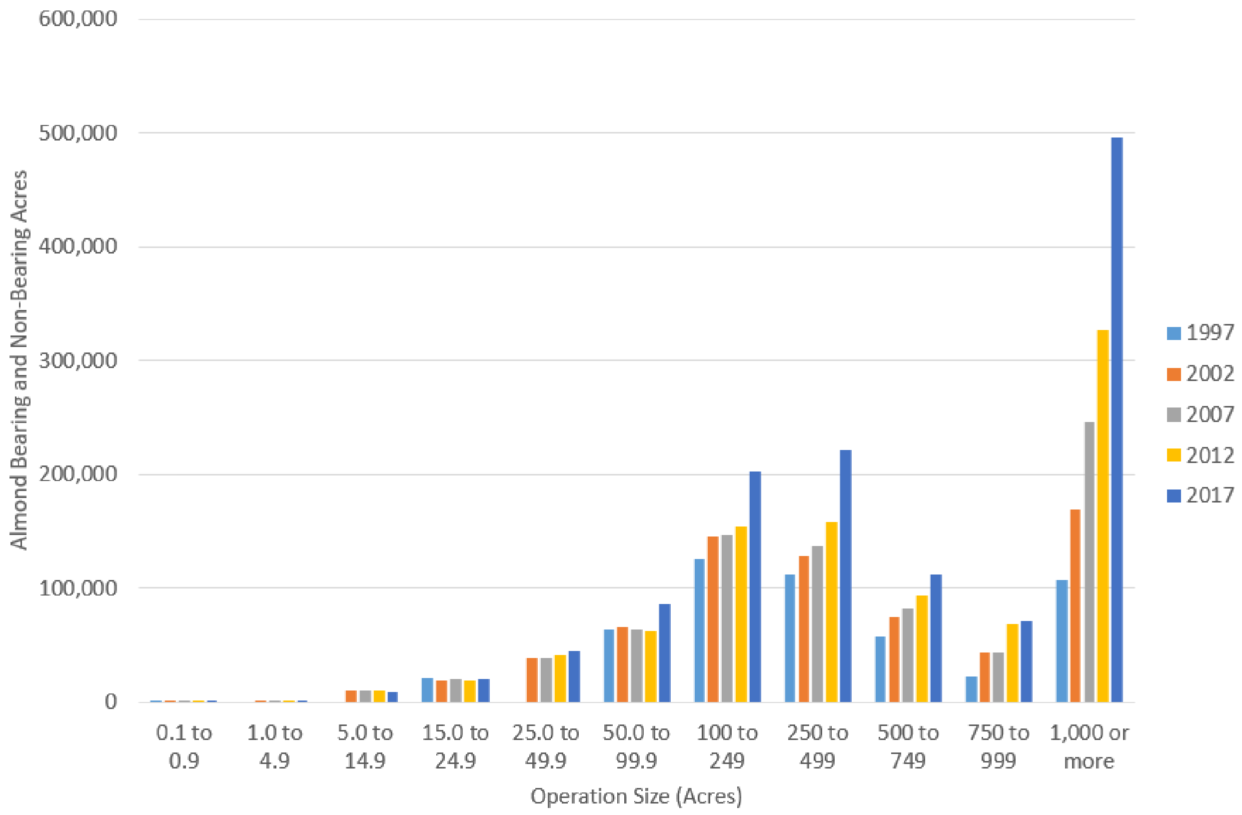


Figure 5. State-wide BNB almond acreage by operation size. 1997 data was unavailable for some of the bins.

Decreases in harvested alfalfa occur across most operation sizes (Figure 6). While it should again be noted that the bins created by the USDA are unequal, important characteristics of the distribution are still visible. The majority of alfalfa acreage in CA falls within 100-2,000 acre operations. As with almonds, relatively few alfalfa acres are part of operations that are smaller than 50 acres (Figure 6).

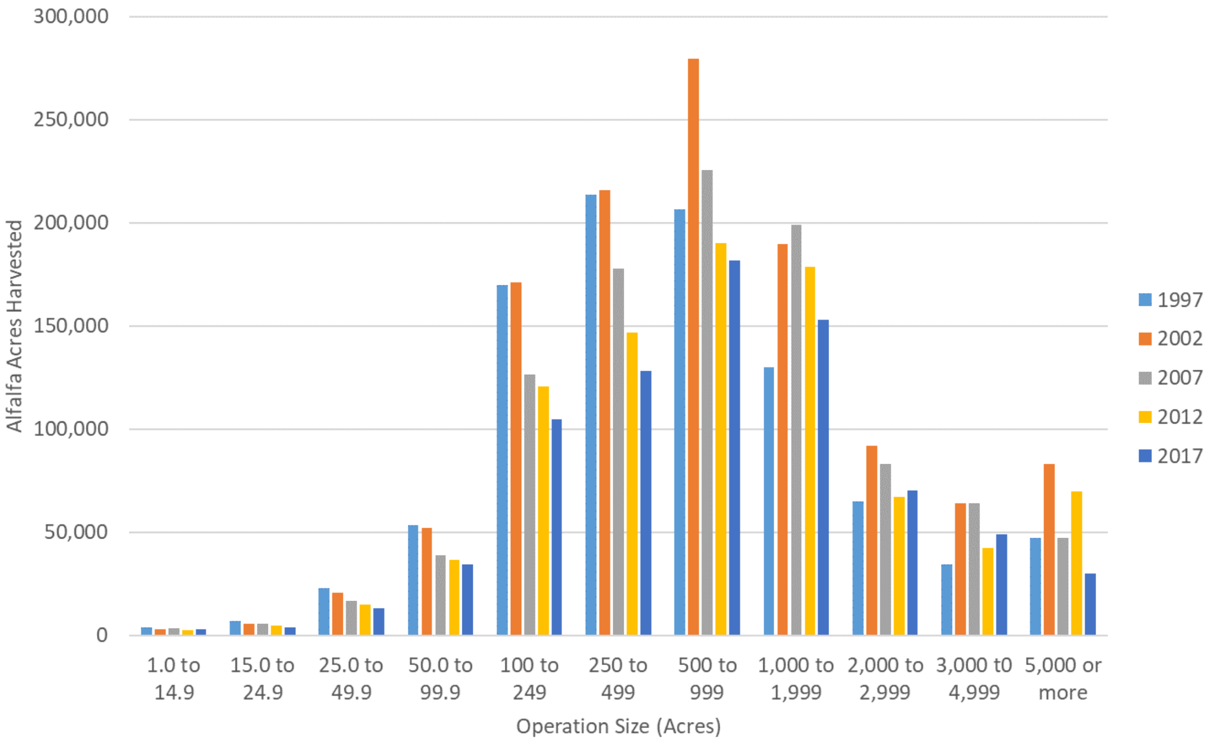


Figure 6. State-wide harvested alfalfa acreage by operation size. Data available for agricultural census years 1997, 2002, 2007, 2012, and 2017.

USDA statistics review by SVJ county

Almonds

Between nearly every census year across all eight SJV counties, BNB almond acreage increased. The only exception was a small decrease between 2002 and 2007 in San Joaquin County. On average, 21,253.17 BNB almond acres were gained every five years between 2002 and 2017 in each county. The largest increase across this 15-year period occurred in Fresno, at 127,283 BNB acres (Figure 7). While Fresno had the greatest total almond acreage as of 2017, when scaled to county size, Stanislaus County led across all years. Scaled values are calculated as the percentage of total county acreage that is occupied by the crop (Figure 7 and 8).

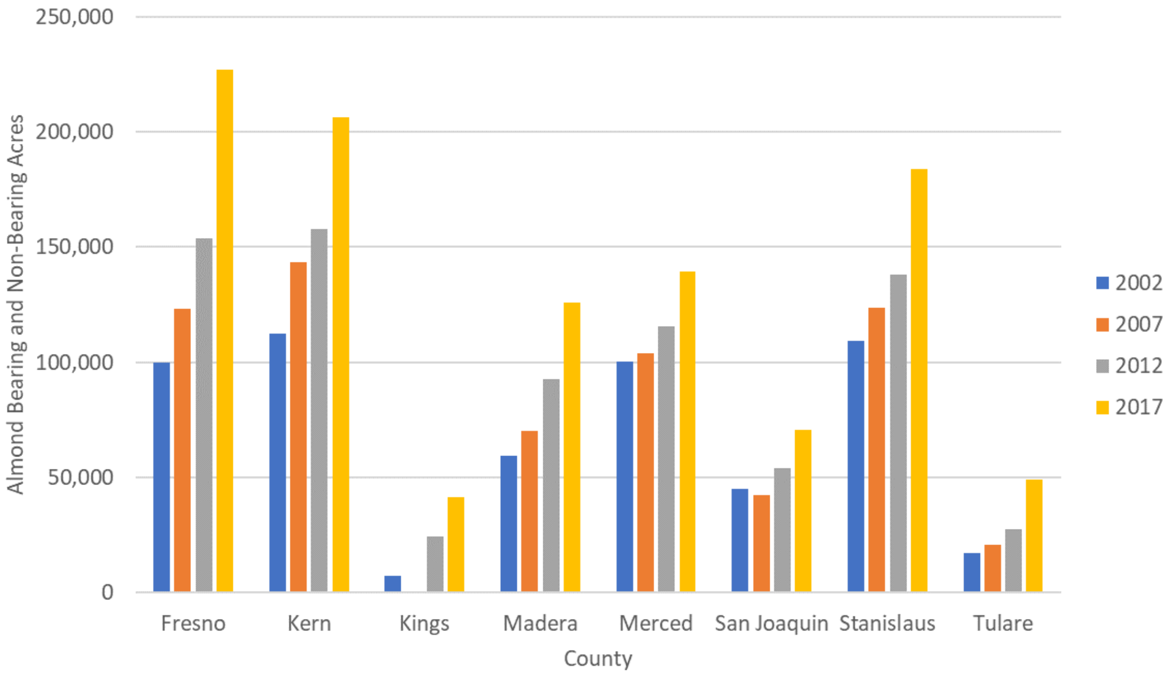


Figure 7. County-level almond acreage trends. BNB almond acreage for eight SJV counties across four agricultural census years: 2002, 2007, 2012, and 2017. Kings County data for 2007 not listed in USDA records.

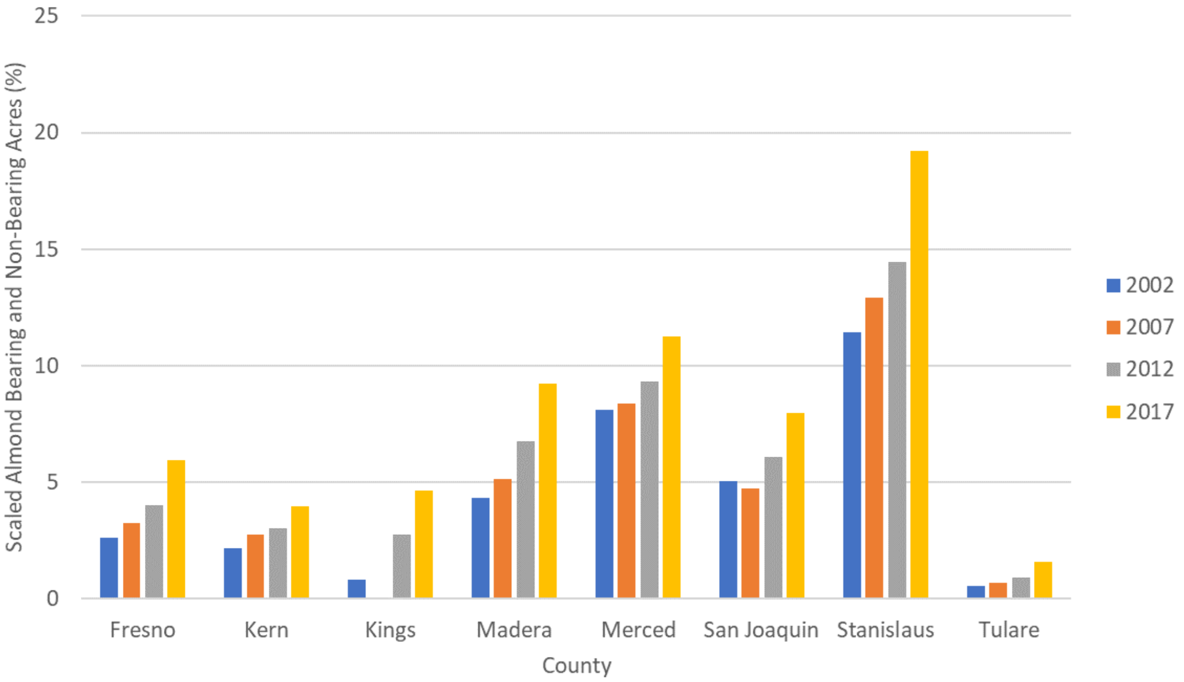


Figure 8. Scaled county-level almond acreage trends. BNB almond acreage as a percent of total county acreage for eight SJV counties across four agricultural census years: 2002, 2007, 2012, and 2017. Kings County data for 2007 not listed in USDA records.

Alfalfa

Between 2002 and 2017 across all eight SJV counties, harvested alfalfa acreage decreased according to census data. On average, 10,820.75 acres were lost every five years during that time period in each county. The largest decrease between 2002 and 2017 occurred in Kern County, with a loss of 49,253 acres of harvested alfalfa (Figure 9). When scaled to county size, however, Kings County experienced the largest drop during that 15-year period with a loss of 5.08 percentage points. Scaled values are represented as the percentage of county acreage occupied by harvested alfalfa (Figure 10). Comparing alfalfa to almonds, I found that in general, almonds now take up a larger percentage of county area than alfalfa. In 2002, alfalfa acreage accounted for on average 4.58% of total county acreage, while BNB almond acreage accounted for only 4.38% on average. In 2017, average scaled BNB almond acreage rose to 7.98%, while alfalfa dropped to 2.52% (Figure 8 and 10). Average acreage changes between census years for alfalfa and almonds during the period 2002 - 2017 are summarized below (Table 5).

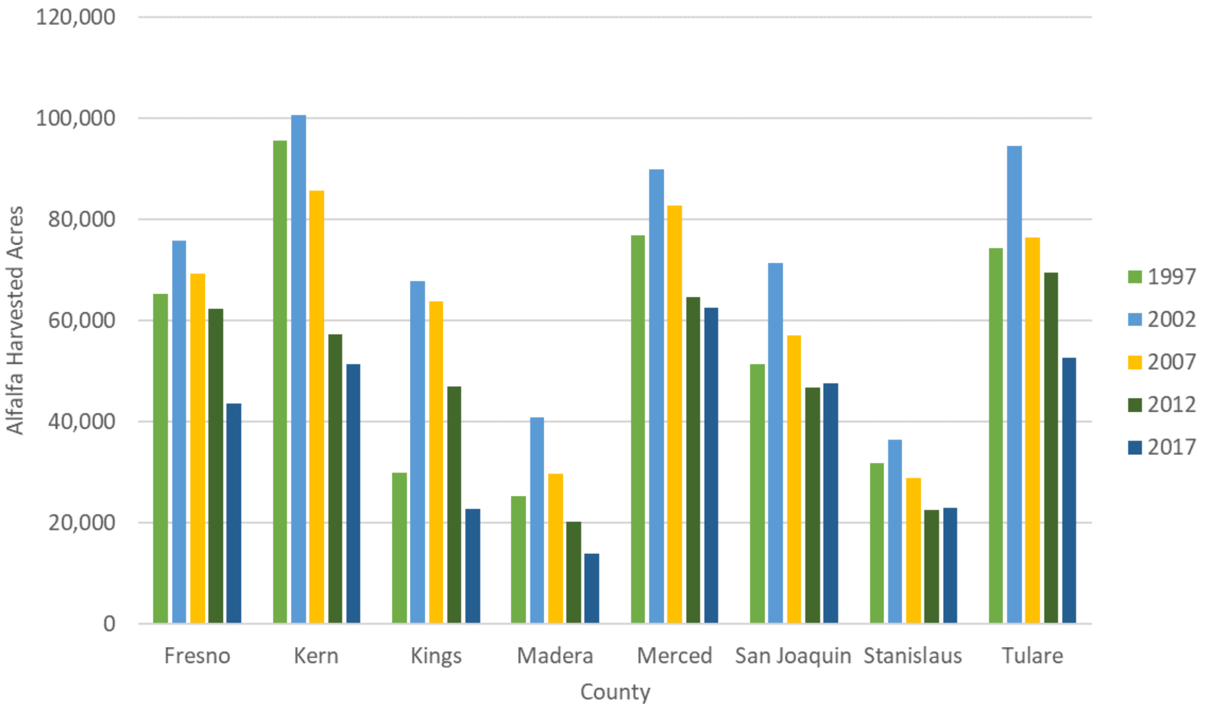


Figure 9. County-level alfalfa acreage trends. Alfalfa harvested acreage for eight SJV counties across five agricultural census years: 1997, 2002, 2007, 2012, and 2017.

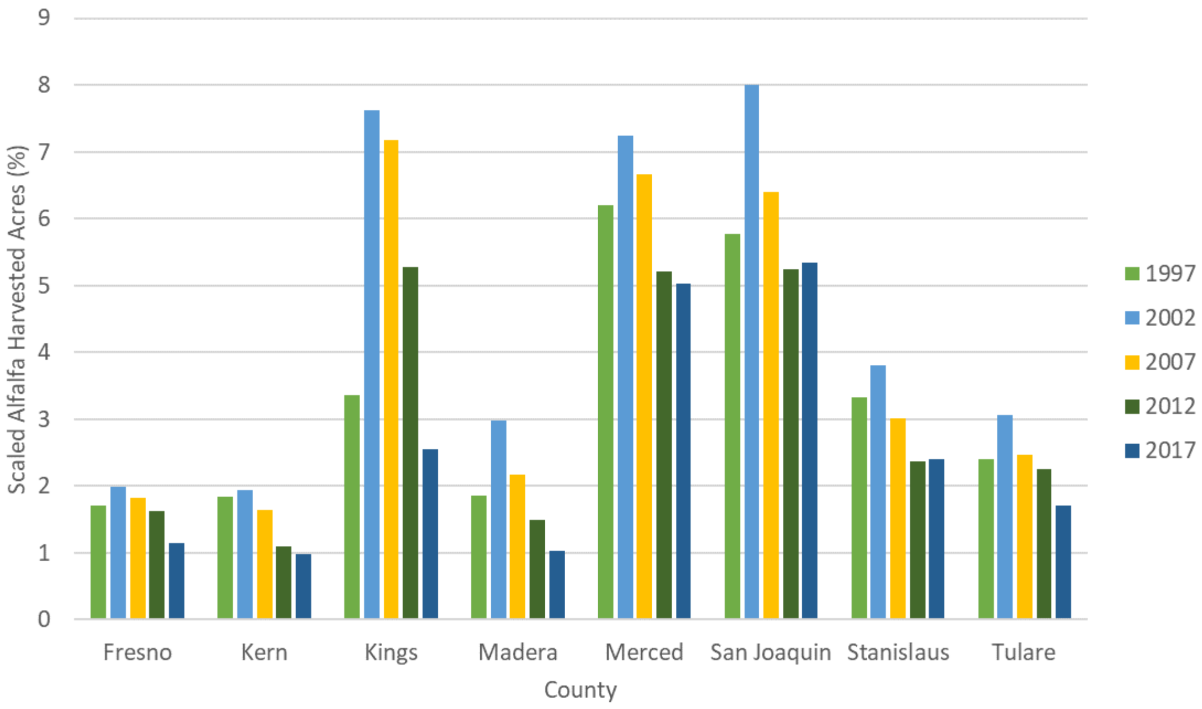


Figure 10. Scaled county-level alfalfa acreage trends. Harvested alfalfa acreage as a percent of total county acreage for eight SJV counties across five agricultural census years: 1997, 2002, 2007, 2012, and 2017.

Table 5. Average acreage changes between each census in thousands of acres during the period 2002 - 2017. The USDA agricultural census is taken every five years. Average acreage change for each SJV county is displayed, as well as total average change in the SJV and total average change in California. The final column calculates average yearly acreage change state-wide between 2002 - 2017. These calculated values may differ from those calculated from survey data, which is less precise.

Crop	Data Item	Fresno	Kern	Kings	Madera	Merced	San Joaquin	Stanislaus	Tulare	SJV	California	California yearly
Almond	Acres bearing	32	22	16	17	10	7	22	7	133	144	29
Almond	Acres bearing and non-bearing	42	31	17	22	13	9	25	11	170	190	38
Alfalfa	Acres harvested	-11	-16	-15	-9	-9	-8	-4	-14	-87	-135	-27

Almond and alfalfa evapotranspiration

On all observed time scales, almond ET per unit area proved to be higher than alfalfa ET per unit area. Averaged across all years and counties, monthly almond and alfalfa ET followed the expected bell curve, with a peak in the summer months. Almond ET was consistently higher than alfalfa across all months, but especially in May, June, and July (Figure 11a). Almond average annual ET was also greater than alfalfa average annual ET in each of the five years when averaging across all counties (Figure 11b).

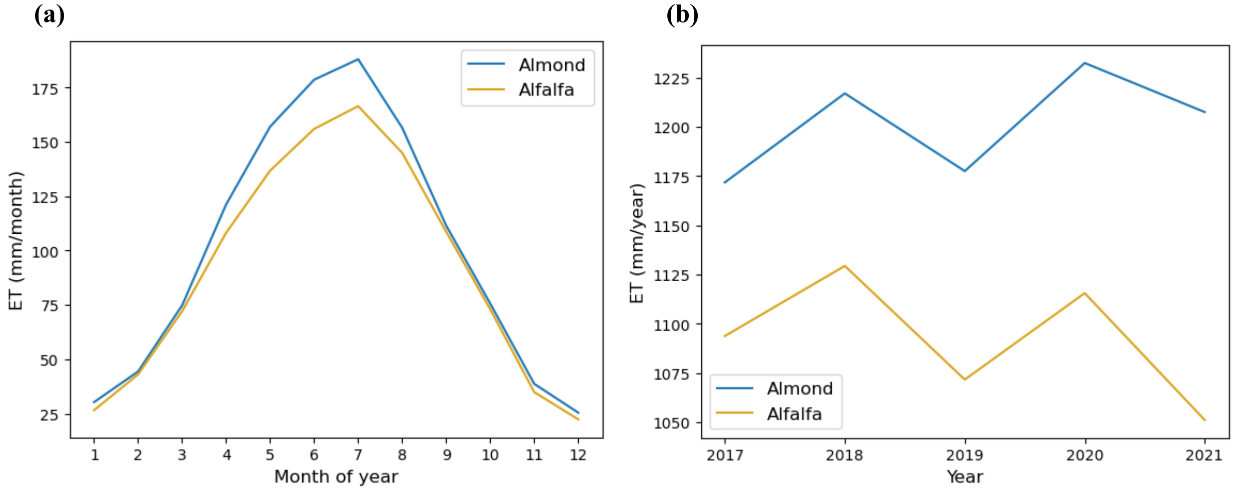


Figure 11. Almond and alfalfa ET comparison across time. (a) Average monthly almond and alfalfa ET (mm) in all SJV counties between 2017-2021. (b) Average annual almond and alfalfa ET (mm) for all SJV counties across the 2017-2021 period.

In each of the eight SJV counties, average annual almond ET was higher than average annual alfalfa ET. This was especially true in Kings County, where the difference was 276.80 mm. Excluding Kings County, on average the difference between annual almond and alfalfa ET was 84.97 mm (Figure 12).

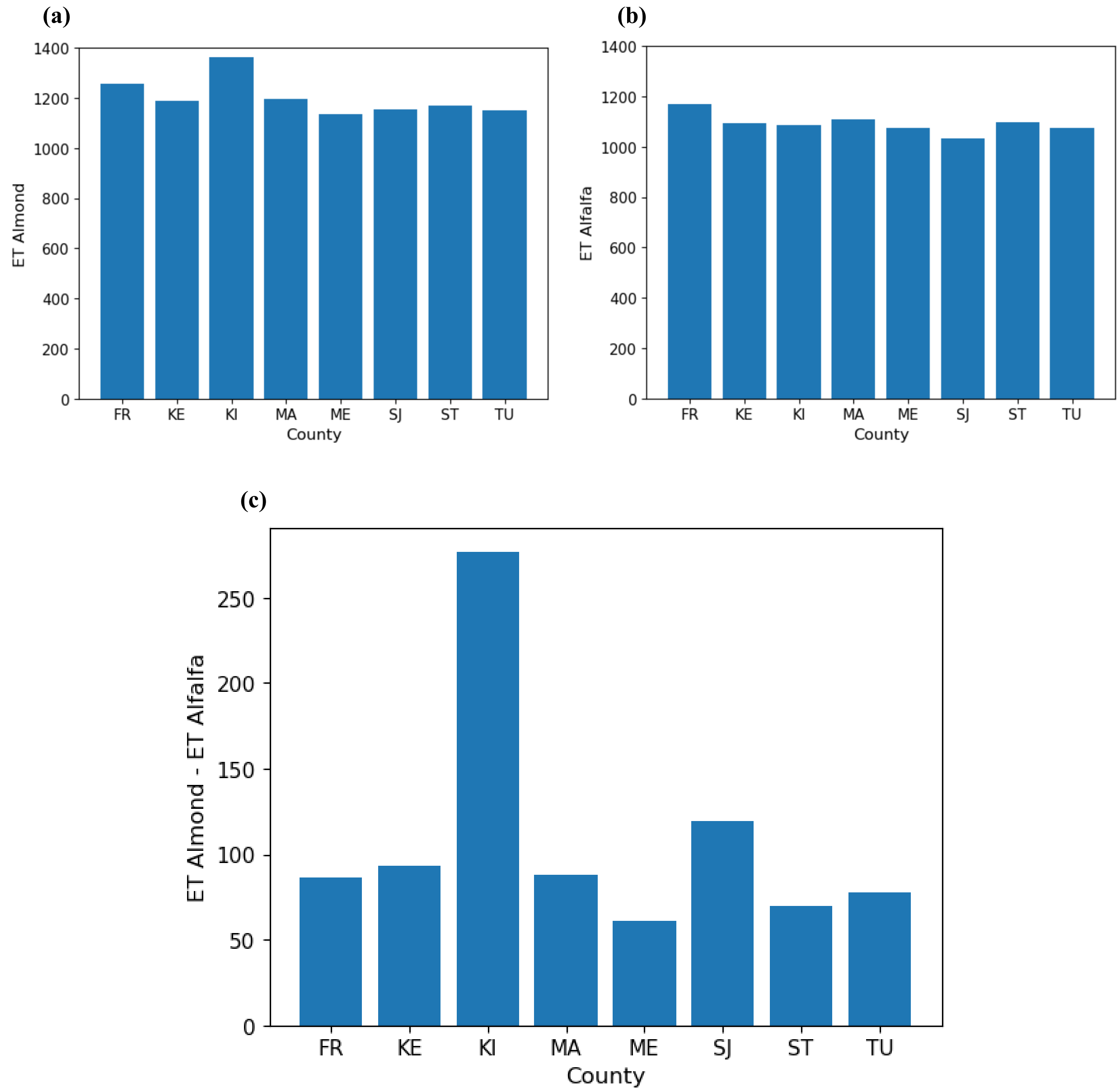


Figure 12. County annual ET comparison. Average annual ET (mm) of (a) almond and (b) alfalfa for each county, and (c) the difference in annual ET between almonds and alfalfa by county.

The difference between almond and alfalfa average annual ET was statistically significant (paired T-test: t = -8.78, df = 39, p-value = 8.89e-11). Each point in each box plot corresponds to an average annual ET value from one county in one of the five years. Almonds had a wider spread than alfalfa, but the mean was higher by 108.95 mm. In every county and year except Tulare County in 2017, almond ET was higher than alfalfa ET (Figure 13).

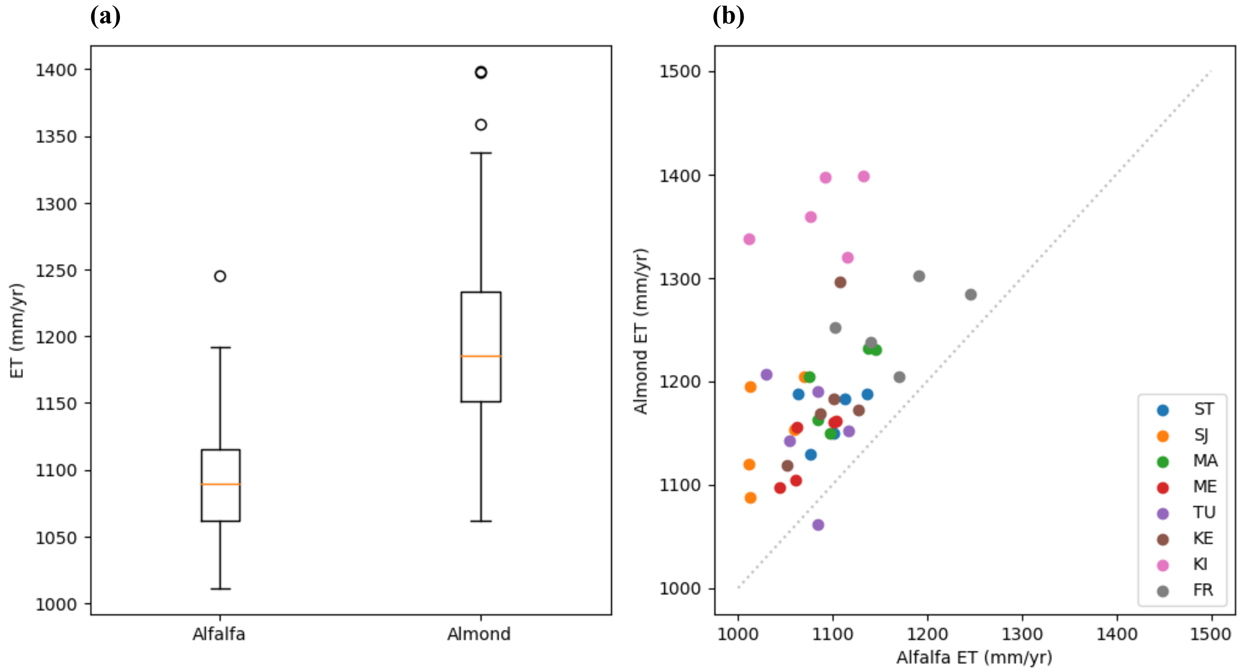


Figure 13. Almond and alfalfa annual ET comparison. (a) Each box plot summarizes 40 points, corresponding to five years of annual ET values across eight counties. (b) ET almond plotted by ET alfalfa. All points above the 1:1 line indicate almond ET is greater than alfalfa ET in that specific county and year.

Climate and water use dynamics

Looking at annual water use by county and year, I found that as aridity increases, almond annual water use increases (slope: 10.146, r: 0.473, p: 0.002) while alfalfa water use does not significantly change (slope: 3.185, r: 0.255, p: 0.112) (Figure 14a). Relatedly, I found that almond WUE decreases when aridity increases (slope: -3.301, r: -0.632, p: 1.204e-05). I didn't find any significant relationship for alfalfa (slope: -7.482, r: -0.173, p: 0.286) (Figure 14c). I then looked at crop stress as aridity increases. Almonds showed no significant relationship (slope: -0.0003, r: -0.022, p: 0.895), while alfalfa experienced increased crop stress (slope: 0.004, r: 0.304, p: 0.05) (Figure 14b). When using PDSI instead of aridity and looking strictly at dry years (that is, when PDSI<0), alfalfa water use decreases as drought severity increases (slope: 26.712, r: 0.504, p: 0.012) while almonds show no significant change in water use (slope: 12.827, r: 0.175, p: 0.415) (Figure 14d).

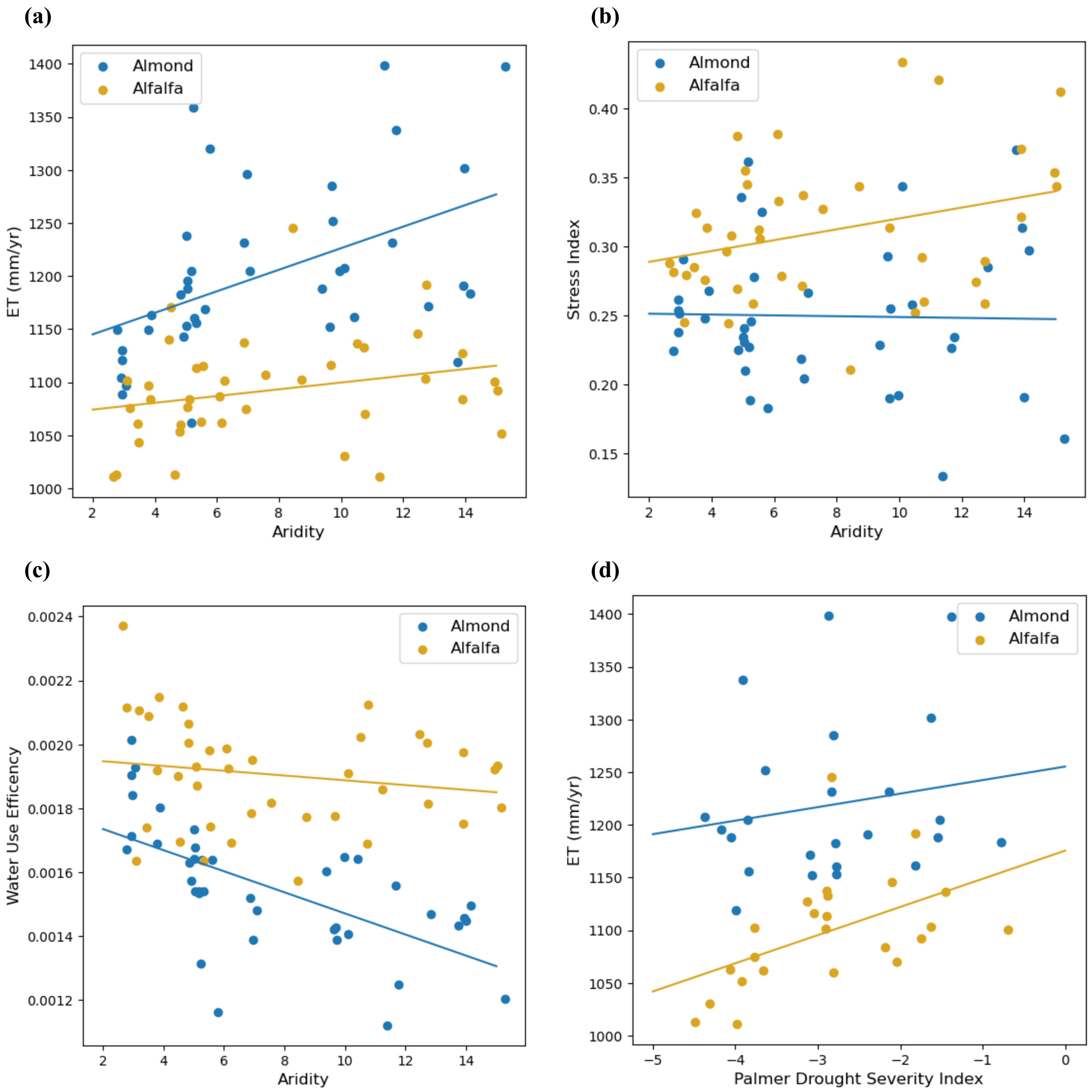


Figure 14. Climate and water use dynamics for 2017-2021. (a) Aridity and water use. (b) Aridity and crop stress index. (c) Aridity and WUE. (d) PDSI and water use. Here, a higher value for aridity indicates increased aridity. A lower value for PDSI indicates greater drought severity.

Finally, I observed that annual water consumption was consistently very high relative to what was available from precipitation each year for both crops, particularly in 2020 (Figure 15).

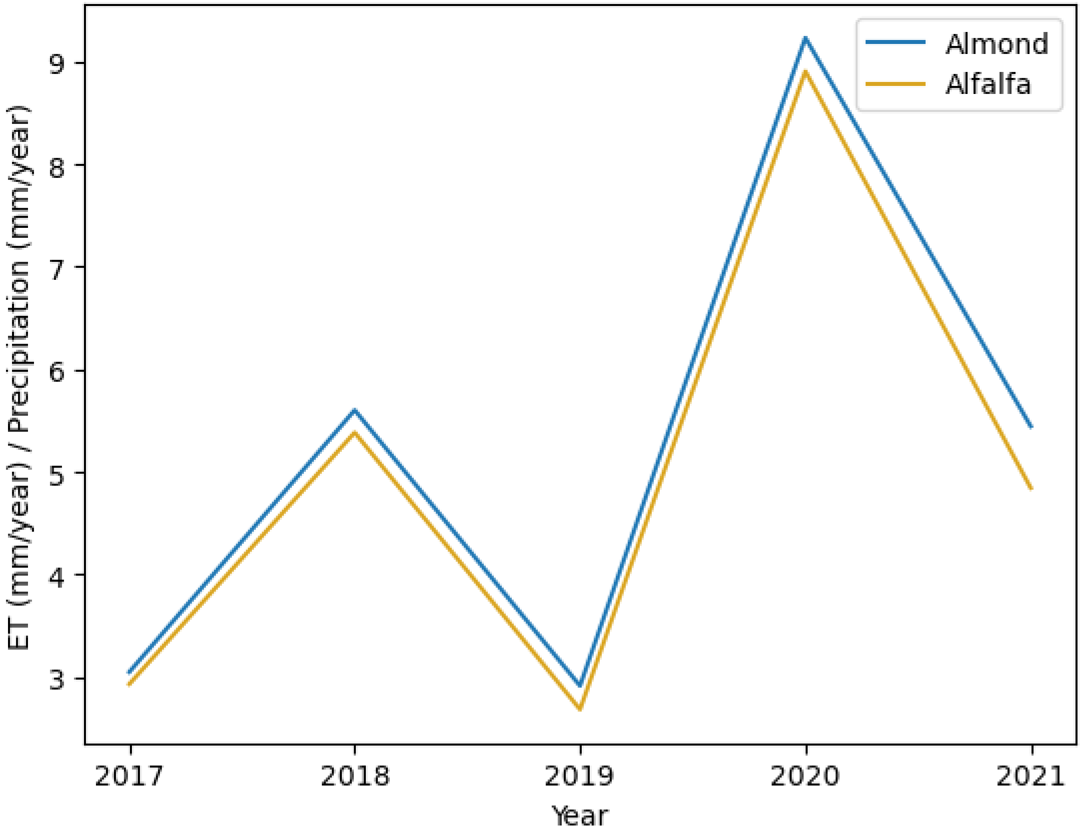


Figure 15. Annual water consumption relative to what was available from precipitation each year. Both ET and precipitation are measured in millimeters per year.

DISCUSSION

As leading crops in the SJV, almonds and alfalfa both have the potential to significantly impact water use dynamics in the region. Almonds, which are steadily expanding across the valley, consistently use more water than alfalfa, which is steadily shrinking in acreage. These trends suggest the SJV will increasingly need more water to support agricultural production. Moreover, drought amplifies the differences between almond and alfalfa water use, WUE, and crop stress, in all cases suggesting that almonds are the less drought-friendly crop. As climate change worsens, the increased frequency and intensity of droughts mean that agricultural activity in the valley must move to become more efficient and aware of varying crop water needs.

Land use trends

Almond acreage is increasing and alfalfa acreage is decreasing across nearly all counties, years, and operation sizes, suggesting that these trends are not localized in time or space, but rather part of a large-scale shift in cropping pattern across the entire SJV. The almond and alfalfa acreage trends I observed align with studies that tracked almond and alfalfa acreage prior to 2018 in the Central Valley (Gebremichael et al. 2021, Schauer and Senay 2019) and in the Tulare Lake Basin (Mall et al. 2019). All studies similarly showed an increase in almonds and a decrease in alfalfa and suggest that alfalfa is being replaced by almonds. This study demonstrates that these trends have continued after 2018 within each county of the SJV. My study also suggests that almond acreage will not be decreasing anytime soon, as some of the greatest growth has been in recent years (Figure 4). My findings on county acreage trends, for example that Stanislaus County scaled almond acreage exceeded that of all other counties and is exhibiting the most recent growth (Figure 7), together with my findings on water use may be useful for water budget managers when predicting how much water different counties will require in the future.

The prevalence of large operations that hold most of the almond and alfalfa acreage in California (Figures 5 and 6) supports my methodology of sampling only CDL fields greater than or equal to 16,199 sq meters, corresponding to about 4 acres, since virtually no almond or alfalfa fields are that small. Given the data categories acres bearing and acres bearing and non-bearing, I calculated the acres non-bearing for almonds, which are primarily composed of young almond trees. Until they reach age four, young almonds have lower ET values than mature almonds (Drechsler et al. 2022). Some of the shapefiles I created to extract ET data may have been of young almonds, which would underestimate almond water use per unit area. Considering that non-bearing almond acreage was on average only 14.2% of all almond acreage (Figure 3), this would be a minor underestimation, likely not enough to substantially alter my results.

Water use differences

Across nearly all counties and years, almond orchards consistently used more water than alfalfa fields according to remotely sensed ET values, which suggests that the previously displayed increase in almond acreage and decrease in alfalfa acreage has likely resulted in more water use in the SJV. This is especially likely considering the documented shift in cropping patterns in the Central Valley from alfalfa, cereals, and cotton to fruit and nut tree crops (Gebremichael et al. 2021). A 2019 study found that between 2008 and 2018, over 100,000 hectares of alfalfa transitioned to different crop types, primarily almonds and pistachios (Schauer and Senay 2019). This same study tracked water use for multiple crops in the Central Valley and within Kern County prior to 2018, and at both scales found that almond water use in ET was higher than alfalfa water use as measured by ET (mm). This aligns well with my observed difference in almond and alfalfa annual water use. My study proves that this difference holds after 2018 and across all counties in the SJV, not just Kern. Keeping in mind that almond acreage in the SJV has grown to surpass alfalfa acreage by a wide margin (Figure 3), if the calculated per unit area value for annual ET of each crop were multiplied by the total area of the crops, the difference in net annual water use between the two crops would be especially stark. The contribution of almonds to water use across the valley cannot be ignored. My county-level water use findings, for example that almond fields in Kings County and Fresno County use more water per unit area than in other counties (Figure 12a), again may be useful for water budget managers predicting future county-level water demand. Looking at monthly water use, almonds unsurprisingly used more water than alfalfa on average in every month. The gap between the two crops was particularly large in the drier summer months, suggesting that aridity impacts almonds and alfalfa differently. This difference was explored further to draw conclusions about the impact of drought on these two crops.

Climate and water use dynamics

I found that as aridity increases, almond water use increases while alfalfa water use does not significantly change, which suggests that during drought, almonds could exacerbate water shortages. More broadly, drought could result in more water use across the valley if an increasing amount of land is converted to almonds. I also found that as aridity increases, almond WUE decreases while alfalfa WUE shows no significant change. This means that more water is being used to grow almonds without any resulting increase in almond productivity. With the observed shift toward planting almonds, agricultural efficiency may experience a large-scale decrease. This has implications for water management, since the state should be giving water to the crops that will use it most efficiently. Interestingly, my findings contradict recent field studies that have observed almond ET and WUE during periods of water stress. In small-scale controlled experiments, researchers found that reducing water supply to almonds increased WUE due to decreased transpiration (Karimi et al. 2015, Ranjbar et al. 2021). Conversely, I found that WUE decreased due to increased evapotranspiration. Perhaps the different metrics resulted in different results, for example Ranjbar et al. calculated WUE as photosynthetic rate divided by transpiration rate instead of GPP divided by evapotranspiration. An earlier study found that almond WUE increases under reduced-water supply because the soil water supply decreases (Barzegar et al. 2012). This leads me to believe that even in arid conditions, soil water supply on the almond fields I studied did not decrease, which allowed ET levels to remain high and WUE to stay low, as I observed in my study. I theorize that continued irrigation kept soil water levels high.

I showed that alfalfa experiences more stress and must regulate its water use as aridity increases, while almonds experience no significant change in water regulation. This again suggests that almonds continue to receive water, possibly because of their physical characteristics or due to continued irrigation. Even though irrigating during drought is expensive, the return for almonds is much higher than for alfalfa. Perhaps almond farmers are more likely, then, to accept higher water bills in order to keep their crops performing at the highest level. This is supported by a study on farmer behavior during water stress which found that during the 2012–2016 drought, some farmers bought million-dollar drilling rigs to be able to access deep aquifers and protect their investments in almonds (Gebremichael et al. 2021). These actions would not be necessary for crops like alfalfa, which are annuals and as such can be fallowed or rotated as needed on a yearly basis if water is scarce (Gebremichael et al. 2021).

When using PDSI instead of aridity and only in dry years, I found that only alfalfa experiences a drop in water use as drought severity increases, indicating once more that even during dry years, almonds continue to receive enough water to keep their ET levels high. A particularly interesting result was the ET/Precipitation ratio across the study period. ET values uniformly exceeded those of precipitation, indicating that much more water is being used on almond and alfalfa fields than is available from precipitation. In 2020, ET values for both crops were nearly 10 times as high as precipitation (Figure 15). This aligns with the low precipitation rates in the valley, but raises the question, is farming in a region where water is so scarce ecologically ideal?

Future directions

The scale and accessibility of remotely sensed data provides many avenues for the expansion of this study. While I averaged across counties when extracting ET, climate, and productivity data, using the same technology I could instead look at data at the scale of individual fields. Considering the abundance of insignificant p-values in the climate data analysis, decreasing the scale in order to increase the number of data points might more clearly portray the associations between climate and water use variables. Furthermore, from the same GEE database I could extract additional data, such as soil field capacity, for consideration during my water consumption and climate analyses. From the USDA databases I could download statistics about other major crops to more completely understand land and water use dynamics in the valley. Finally, I could expand my years of study as more OpenET data is released to the public to track water use on a larger temporal scale.

Broader implications

My findings suggest that planting more almonds in the SJV, particularly in the place of former alfalfa fields, will result in more water use. Drought, which is becoming more frequent and severe with climate change (Hicke et al. 2022), had a notable effect on water use dynamics. High water use and low WUE for almonds when water is scarce has implications for water management, since the state should aim to give water to the crops that will use it most efficiently. More generally, California should be planting crops that both use less water, and use the water they have efficiently, and I found that almonds do neither of these. Despite its higher efficiency, lower water use, and ease of rotation, planting alfalfa instead of almonds may not be ideal. Compared to many other annual field crops, alfalfa still uses a lot of water (Schauer and Senay 2019). Additionally, alfalfa is closely tied to the beef and dairy industries, which are widely considered resource-intensive and unsustainable (Butler 2005, Cusack et al. 2021). To suggest alternatives, strawberries, spinach and raspberries were all found to be both profitable and less water-intensive (Fulton et al. 2019). While my observed trends suggest almond acreage will most likely continue to increase, simply quantifying the crop's consumption of water over large areas is important for water resources planning, especially as drought becomes more prevalent. As a primary consumer of California's water, agriculture has tremendous potential to contribute to, but also ease, the water crisis in the state.

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