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Key Points:
- The groundwater footprint of agricultural production increased with the California drought, predominantly in the Tulare Basin
- Food transfers declined over the course of the drought, but total virtual water transfers increased, driven by embodied groundwater
- Local and global consumers doubled their reliance on the already overexploited Central Valley Aquifer during the drought

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Drought impacts to water footprints and virtual water transfers of the Central Valley of California

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Abstract The Central Valley of California is one of the most productive agricultural locations in the world, which is made possible by a complex and vast irrigation system. Beginning in 2012, California endured one of the worst droughts in its history. Local impacts of the drought have been evaluated, but it is not yet well understood how the drought reverberated through the global food system. Here we quantify drought impacts to the water footprint (*WF*) of agricultural production and virtual water transfers (*VWT*) from the Central Valley of California. To do this, we utilize high-resolution spatial and temporal data sets and a crop model from predrought conditions (2011) through 3 years of exceptional drought (2012–2014). Despite a 12% reduction in harvested area, the *WF* of agricultural production in the Central Valley increased by 3%. This was due to greater crop water requirements from higher temperatures and a shift to more water-intensive orchard and vine crops. The groundwater *WF* increased from 7.00 km^3 in 2011 to 13.63 km^3 in 2014, predominantly in the Tulare Basin. Transfers of food commodities declined by 1% during the drought, yet total *VWT* increased by 3% (0.51 km^3). From 2011 to 2014, groundwater *VWT* increased by 3.42 km^3, offsetting the 0.94 km^3 reduction in green *VWT* and the 1.96 km^3 decrease in surface *VWT*. During the drought, local and global consumers nearly doubled their reliance on the Central Valley Aquifer. These results indicate that drought may strengthen the telecoupling between groundwater withdrawals and distant consumers of agricultural commodities.

1. Introduction

California is one of the most productive agricultural areas in the world and is commonly referred to as the "fruit and vegetable basket" of the United States, responsible for nearly half of U.S. grown fruits, vegetables, and nuts. California's agricultural industry is made possible by a complex and vast water system that relies on precipitation, surface water, and groundwater. From 2012 to 2014, California experienced its worst drought in over a millennium [*Griffin and Anchukaitis*, 2014]. Although local impacts have been examined [*Howitt et al.*, 2014; *Cooley et al.*, 2015; *Swain*, 2015], it is not yet well understood how the drought has impacted distant consumers of California agricultural commodities through the global food system. In this paper, we examine drought impacts to water footprints of agricultural production and food and virtual water transfers from the Central Valley of California, including tracing these flows to their final destination of consumption. Broadly, this study elucidates how local climate shocks reverberate through the global food system and highlights the critical role of groundwater aquifers.

Drought is not an uncommon occurrence in California, but the 2012–2014 drought was exceptional. For only the second time in its history, California proclaimed a State of Emergency due to drought on 17 January 2014. In 2015, Governor Brown introduced unprecedented mandatory water use restrictions on urban users, requiring them to reduce usage by 25%. In California, where irrigation is responsible for 74% of water withdrawals [*Maupin et al.*, 2014], drought is particularly impactful to agriculture, which is crucial to the identity, culture, and economy of California. In 2014 alone, drought led 173,200 additional hectares of irrigated cropland to be fallowed, $2.2 billion in economic cost, and the loss of 17,100 jobs [*Howitt et al.*, 2014].

The impacts of the drought to agriculture would have been much worse if not for California's conjunctive water use system, which permits farmers to rely more on groundwater during times of surface water deficits. However, farmers are currently extracting much more groundwater from the Central Valley Aquifer (boundaries shown in Figure 1) than is being recharged, leading to an annual average depletion of 1.85×10^9 m^3 since 1960 [*Faunt*, 2009] and nearly double that rate during the current drought [*Faunt and Sneed*,

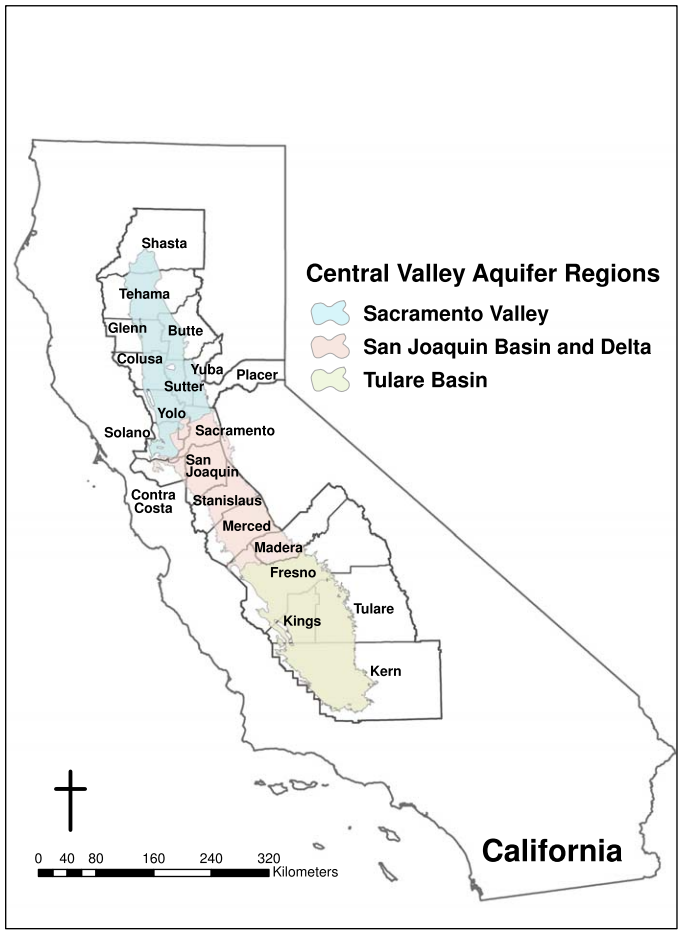

Figure 1. Map of the Central Valley Aquifer of California. The major basins of the Central Valley Aquifer are the Sacramento Valley (blue), San Joaquin Basin and Delta (red), and Tulare Basin (green). The 20 counties overlying the Central Valley Aquifer are provided.

2015]. During average climate conditions, 40% of irrigation in the Central Valley comes from groundwater, but during drought groundwater provides closer to 70% of irrigation supplies, with more reliance on groundwater in the arid Tulare and San Joaquin Basins, and less groundwater use in the more humid Sacramento Basin [*Faunt and Sneed*, 2015; *Jones*, 2015].

The Central Valley Aquifer system is likely to be under even greater pressure in the future. Anthropogenic warming is expected to increase the frequency of dry, warm years in California, thereby increasing the likelihood of severe droughts [*Diffenbaugh et al.*, 2015]. Additionally, demand for water is increasing among environmental, urban, and agricultural uses [*Faunt*, 2009], while continued groundwater depletion [*Famiglietti et al.*, 2011], salinization of the deeper aquifers [*Schoups et al.*, 2005], and new legislation restricting future groundwater withdrawals (e.g., the 2014 California Sustainable Groundwater Management Act) will reduce groundwater availability. This not only has implications for Californians who depend on the aquifer for agricultural and urban uses but also has the millions of people globally who consume groundwater dependent agricultural products grown in the Central Valley [*Marston et al.*, 2015].

Much is understood about local impacts of drought to agricultural production [*Howitt et al.*, 2014; *Cooley et al.*, 2015; *Faunt and Sneed*, 2015]. However, the food system is global in nature, such that agricultural commodities are part of a complex supply chain and typically consumed far from their location of production, in an example of a telecoupled system [*Liu et al.*, 2013, 2015]. The trade of water-intensive food commodities is referred to as "virtual water trade" [*Allan*, 1998; *Hoekstra and Hung*, 2005] and links distant consumption of water-intensive goods to local water use and impacts. Increasingly, it is critical to understand the nonlocal impacts of drought. Does the global food system amplify or dampen the impacts of local droughts shocks? On one hand, global food supply chains may propagate drought risk to distant consumers through the disruption of complex supply chains [*D'Odorico et al.*, 2010; *Suweis et al.*, 2015]. On the other hand, the impacts of local climate shocks, such as droughts, may be mitigated if a country imports the same agricultural commodity from multiple producers, all of which experience spatially and temporally uncorrelated climate shocks.

In this study, we evaluate the impact of drought to agricultural water footprints and virtual water transfers from the Central Valley of California. Our work builds on recent high-resolution studies of water footprints and food and virtual water flows in the United States. The water footprint of crops and derived crop products has been established for all states in the U.S. [*Mekonnen and Hoekstra*, 2011; *Mubako and Lant*, 2013],

with additional work on California [*Fulton et al*., 2012, 2014; *Mubako et al*., 2013]. These studies, however, do not distinguish between surface water and groundwater sources and do not account for interannual variability in water footprints. High-resolution intranational food transfer data have been used to evaluate food and virtual water flows within the United States [*Lin et al*., 2014; *Dang et al*., 2015]. *Marston et al*. [2015] determine virtual groundwater transfers from overexploited aquifers of the United States, as well as the major U.S. cities, U.S. states, and international export destinations that are most reliant upon agricultural production from these aquifers. These recent studies refined our understanding of the spatial variability in water footprints and virtual water transfers under average climatic conditions. However, climatic variability and extremes, such as drought, significantly impacts agricultural production, trade, and embedded water resources [*Dalin and Conway*, 2016; *Zhuo et al*., 2016], making it essential to better resolve food and virtual water flows in time, which is a major novelty of this study.

We integrate high-resolution databases and models to quantify the water footprints of agricultural production and virtual water transfers from California's Central Valley from 2011 (baseline, no drought) through 3 years of consecutive, exceptional drought (2012–2014). A major novelty of our methodology is that we distinguish precipitation, surface water, and groundwater contributions to the total water footprint of agricultural production. Our study describes (i) how local water footprints have evolved over the course of the drought, (ii) how local drought shocks propagate to distant consumers of water-intensive goods, and (iii) how distant consumption of virtual water resources is linked with local water impacts. In this way, we aim to address the following questions. (i) How do agricultural production water footprints in California evolve with drought? (ii) How does drought impact food and virtual water transfers from California? (iii) How is global demand for California agriculture contributing to local water resources impacts? The paper is organized as follows. We describe our methods in section 2. Our results are detailed and discussed in section 3. We conclude and highlight implications of our work and future research needs in section 4.

2. Methods

In this section, we describe how we quantify the water footprints and virtual water transfers from the 20 counties overlying the Central Valley of California (map provided in Figure 1). We calculate the total water footprint of agricultural production, which is composed of contributions from precipitation (i.e., "green water") and irrigation supplies (i.e., "blue water"). A major novelty of our approach is that we further distinguish the irrigation component into surface and groundwater sources. We also explain how we calculate virtual water transfers from the Central Valley. Note that we use the term "transfers" because we examine subnational and international flows of agricultural commodities and embodied water. We reserve the standard trade terms (i.e., "trade," "import," and "export") solely for international exchanges of goods.

Drought impacts to agricultural production and transfers are highly local and time dependent, which necessitates the use of high-resolution spatial and temporal data. To determine the impact of the California drought, we pair empirical databases with modeled estimates of crop evapotranspiration. Refer to Table 1 for key data sources and models used in this study. We quantify the water footprints of crop production at the annual temporal scale, county spatial scale, and for each source of water (i.e., rainfall, irrigation from surface water sources, and irrigation from groundwater sources). We also quantify virtual water transfers at the annual and county scale for each source of water. The counties of the Central Valley are shown in Figure 1 and listed in supporting information Table S6.

First, we detail how we calculate the virtual water content of agricultural products. Second, we describe the agricultural production and transfer data sets. Then, we explain how we quantify water footprints of agricultural production. Lastly, we describe how virtual water contents and food transfer data are brought together to quantify virtual water transfers.

2.1. Virtual Water Content Estimates

The virtual water content (*VWC*) of a crop is defined as $VWC = ET/Y$, where *ET* is the total crop evapotranspiration (m^3_{water} $area^{-1}$) and *Y* is the crop yield (t_{crop} $area^{-1}$). *VWC* is equivalent to the water footprint of crops [*Hoekstra and Chapagain*, 2011] and indicates the amount of water embodied in crop production over the entire growing season. *VWC* values were calculated for each crop, county, and year (2011–2014) combination.

Table 1. Primary Data Sources and Models Used in This Analysis[a]

Model or Data Source	Description	Spatial Resolution	Temporal Resolution
CADFA [2017]	Crop production and yield data	County and state	Annual
CDWR [2015]	Climate data	Point	Daily
CUP+ model [*Orang et al.*, 2011]	Crop evapotranspiration model	County	Daily
CDWR [2013]	Irrigation water source	County	Annual
U.S. Drought Monitor [2016]	Drought index	County	Weekly
FAF4 [2015]	Commodity transfers	FAF Zone	Annual

[a]A brief description of each item is provided along with its spatial and temporal resolution.

The 67 crops included in this study (see supporting information; SI) represent 98.5% of the harvested crop tonnage of California reported in the 2012 USDA Census of Agriculture. Importantly, we quantify the fractional contribution of each major water source to total crop *ET*. In other words, we segment the contribution of green (i.e., effective precipitation) and blue water (i.e., irrigation) to total crop *ET*. Additionally, we further segment blue water into irrigation from surface and groundwater sources. In this way, we estimate *VWC* from green, surface, and groundwater sources (i.e., VWC_{green}, $VWC_{surface}$, and VWC_{ground}, respectively).

2.1.1. Crop Evapotranspiration

The *ET* of each crop was calculated using the *Consumptive Use Program Plus* (CUP+) model. The CUP+ model is a dynamic soil water balance model developed by the California Department of Water Resources (CDWR) and the University of California, Davis to help water agencies and growers determine crop water requirements in California. The CUP+ model computes reference evapotranspiration (ET_O) using the daily Penman-Monteith equation. Daily weather data, including solar radiation, maximum and minimum temperature, dew point temperature, wind speed, and precipitation, were inputs to the model and came from *CDWR* [2015]. Planting and harvest dates, maximum soil depth, and available water holding capacity were provided within the model databases. The maximum rooting depth for each crop was taken from *USDA SCS* [1983].

Using the CUP+ model, we determine crop-specific daily evapotranspiration (ET_c). To do this, we follow a similar methodology as *Doorenbos and Pruitt* [1977], in which different crop coefficients (K_c) are applied during the growing season to represent how plant water requirements vary during different growth periods. Each day, K_c is determined and multiplied by ET_O to arrive at daily ET_c. Total crop *ET* is determined by the sum of all daily ET_c values during the cropping season. Total crop *ET* estimates crop evapotranspiration from all water sources (i.e., rainfall, surface, and groundwater sources).

Importantly, the CUP+ model distinguishes between *ET* from rainfall and *ET* from irrigation supplies (ET_i). In CUP+, irrigation occurs when the soil water content in the effective root zone is less than half of capacity. This assumption is in accordance with the management allowable depletion historically used by most irrigators [*USDA SCS*, 1993; *Ozdogan et al.*, 2010]. Irrigation water is applied until the soil water content returns to field capacity. The cumulative *ET* for the entire crop season attributed to irrigation is given by

$$ET_i = CD_{sw} - \Delta WC = (CET_c - CE_{spg} - CE_r) - \Delta WC = \sum_{i=1}^{n} NA_i \tag{1}$$

where ET_i is *ET* of applied water (i.e., irrigation), CD_{sw} is the cumulative daily change in soil water content, ΔWC is the difference between initial and final soil water content, and NA_i is the net water application. CET_c, CE_{spg}, and CE_r are the seasonal cumulative crop evapotranspiration, cumulative effective seepage, and cumulative effective rainfall contribution, respectively [*Orang et al.*, 2013]. CUP+ does not distinguish between *E* and *T* and does not incorporate capillary rise, unlike other *ET* models used to determine high-resolution water footprints [*Chukalla et al.*, 2015; *Zhuo et al.*, 2016]. However, depths to the water table are considerable in the Central Valley, so capillary rise is negligible for crop growth in this region. An important feature of our approach is that we use daily climate data to force CUP+, whereas other studies use monthly climate variables [*Chukalla et al.*, 2015; *Zhuo et al.*, 2016]. Importantly, CUP+ simulations encompassed several months before the growing season to appropriately capture antecedent soil moisture conditions.

Note that although the CUP+ model distinguishes between rainwater and irrigation supplies, it does not break irrigation water down between surface and groundwater sources. Thus, the CUP+ model is used to

calculate county-level and crop-specific ET_{green} and ET_{blue} for each year of the drought. We explain how we separate the surface and groundwater contribution to irrigation in the next section.

2.1.2. Surface and Groundwater Contributions

As described in the previous section, we use the CUP+ model to distinguish precipitation and irrigation contributions to total *ET* for each crop and county. Here we explain how we additionally segment irrigation into surface and groundwater contributions for each county overlying the Central Valley Aquifer for the years 2011–2014. First, we obtained data from the California Department of Water Resources on surface and groundwater irrigation volumes for all available water years, which were 2002–2010 [*CDWR*, 2013]. Note that irrigation data from CDWR are provided annually (for the years 2002–2010) at the county spatial resolution but are not crop specific. Data on irrigation by crop and for the years of this study (i.e., 2011–2014) would improve our estimates, but these data do not exist, unfortunately.

Next, we used these data to quantify the fraction of total irrigation coming from groundwater (i.e., the groundwater fraction, *GF*) for 2002–2010. Then, we determined the relationship between *GF* and a county-level drought index (*DI*; refer to SI) for 2002–2010. *DI* data were obtained from the U.S. Drought Monitor [2016]. The relationship between *GF* and *DI* varies across counties in the Central Valley, likely due to differing surface water rights and availability, as well as differences in agricultural production practices. Counties located in the wetter northern region had a relatively consistent reliance on groundwater, irrespective of drought conditions. In other words, *GF* does not vary with *DI* in these counties, so an average *GF* value was calculated based on their historic groundwater use and used to approximate *GF* from 2011 to 2014. Supporting information Table S5 shows the *GF* between 2011 and 2014 for counties overlying the Central Valley Aquifer system that do not exhibit a relationship between drought and groundwater irrigation.

We constructed county-specific relationships between the groundwater fraction and drought intensity for counties located in the central and southern portions of the Central Valley (see Figure 2). Regressions in Figure 2 show the location-specific relationship between *GF* and *DI*. The relationships plateau as we might expect, since individual locations eventually reach a limit to groundwater pumping. This limit varies by location and is constrained by location-specific groundwater availability (well yields). The most senior water right holders will continue to have priority to any surface water supplies that are available during drought. Note that the blue points in Figure 2 present data from 2002 to 2010.

We fit a logarithmic trend line to the observed data, because this functional form best fits the data and enables us to employ a conservative approach when projecting *GF*. The logarithmic functional relationship means that *GF* levels off with increasing *DI*, thereby capturing location-specific surface water rights and groundwater pumping limits. The other extreme would be if the groundwater wells had all been pumped dry during the drought, such that we are overestimating the groundwater fractions available during the drought. However, it is important to note that we restrict our analysis with production data (see next section), meaning that water resources must have been available and used to meet crop demands.

To estimate *GF* for 2011–2014, we use *DI* data for 2011–2014 in conjunction with the regression relationships. The red points in Figure 2 illustrate estimated values of *GF* from 2011 to 2014. Since the 2012–2014 drought is the worst on record, we had to extrapolate beyond the *x* axis bounds of the regression equation in some instances (typically just for the year 2014). However, extrapolation was often minimal (e.g., Colusa, Glenn, and Sacramento counties) since California experienced the seventh driest 3 year period between 2007 and 2009 in terms of state-wide precipitation and it was the only other time a state-wide proclamation of emergency was declared due to drought. Importantly, note that most projected values of *GF* (i.e., red points) fall within the *GF* bounds of the observed past, despite the fact that *DI* for the year 2014 falls outside the bounds of historic *DI* observations. This means that estimated values of *GF* have been observed before, making them feasible and conservative. Only one estimate of *GF* during the drought exceeds observed values: Fresno's 2014 *GF* was 1.69% greater than the historical maximum. In 2014, river runoff in the Tulare Basin was 27% of average, while state and federal water project deliveries reached record lows; final allocations from the California State Water Project were 5% of assigned allocations [*McEwan et al*., 2016]. This unprecedented reduction in surface water availability likely dramatically increased the amount of groundwater used to meet irrigation demands beyond historical observations, giving us confidence that our *GF* estimate is likely conservative in this region.

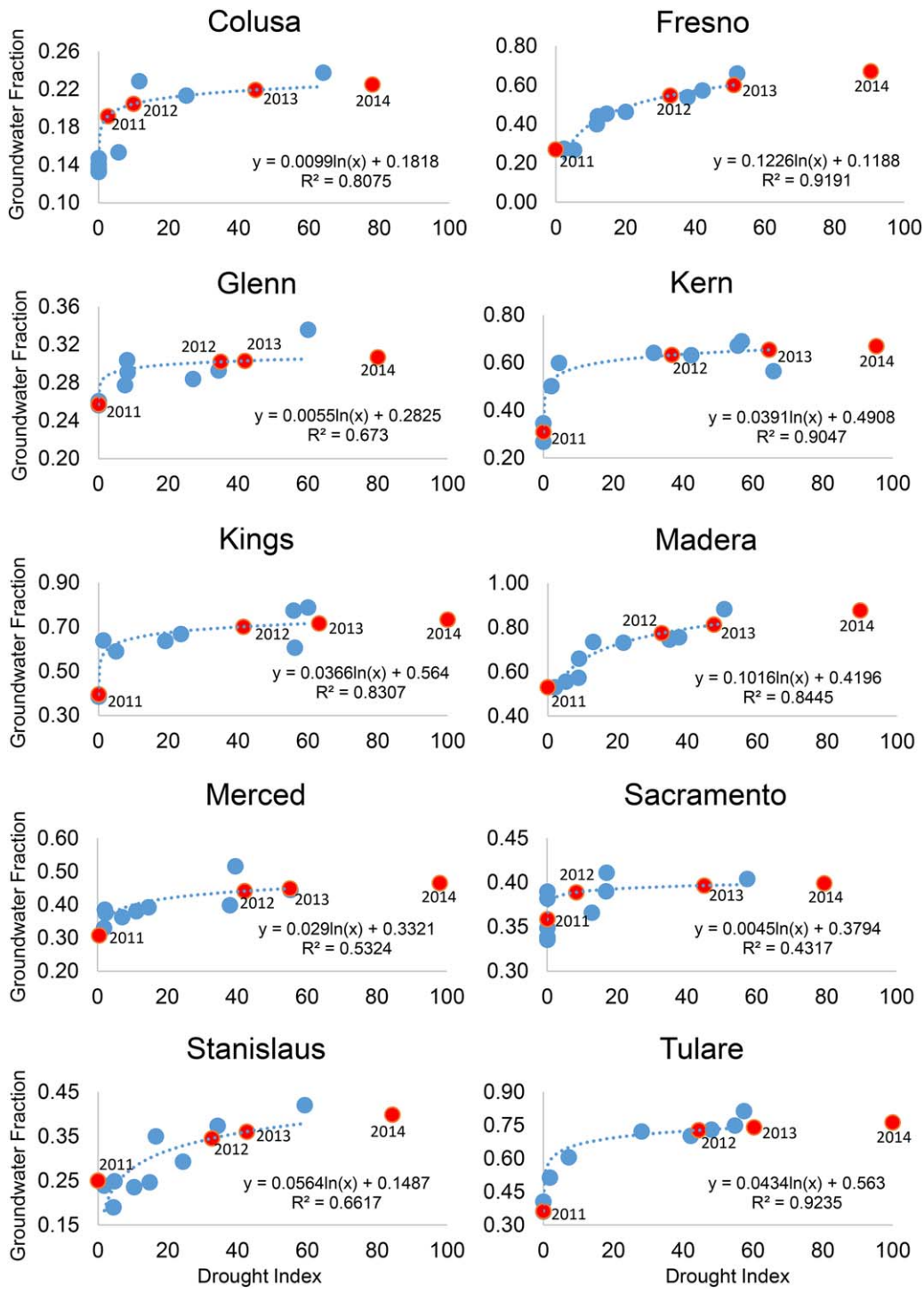

Figure 2. Regression equations relating the fraction of irrigation from groundwater (*GF*) to the drought index (*DI*). *DI* ranges from 0 to 100, with 100 being the most severe drought. The trend line is shown, along with its equation and its coefficient of determination. Empirical values of *GF* and *DI* from 2002 to 2010 are represented by blue markers. Estimated values of *GF* for 2011–2014 are shown with red markers and are labeled by year.

Irrigation supplies from surface water sources are estimated by the difference between the total irrigation requirement and the groundwater contribution. Then, we obtained crop yield values for each county, crop, and year from the California Department of Food and Agriculture (CADFA) [*CADFA*, 2017] (see next section).

We used the water source specific *ET* values in conjunction with *Y* values to determine *VWC* by water source. Note that our approach to segmenting irrigation into surface and groundwater sources is more refined in space than it is by crop. For this reason, crop-specific groundwater and surface water footprints should be used with caution and are not reported in the SI.

2.2. Agricultural Production and Transfers

Here we explain the data sources used to evaluate agricultural production and commodity transfers in California. We also explain how transfer data were interpolated across spatial and temporal scales.

2.2.1. Agricultural Production

We use annual, county-level data on agricultural production, harvested area, and yields from the California Department of Food and Agriculture (CADFA) [*CADFA*, 2017]. Below, we explain how we combine this information with crop *VWC* to obtain the water footprints of agricultural production. We also use crop production data from *USDA NASS* [2016]. Data from *USDA NASS* [2016] are primarily used to estimate rainfed production in the Central Valley, which is a relatively minor component of total production, since the vast majority of agriculture in the Central Valley is irrigated. Refer to the SI for the list of crops included in this study.

2.2.2. Agricultural Transfers

We estimate annual and county-level agricultural transfers from the Central Valley of California. To do this, we use version four of the Freight Analysis Framework (FAF4) [*FAF4*, 2015]. The FAF4 data set relies on several sources to reconstruct domestic and international commodity transfers but its foundation is the Commodity Flow Survey (CFS) and international trade data are from the U.S. Census Bureau. The CFS is a quarterly survey administered every 5 years (years ending in "2" and "7") that samples more than 100,000 establishments on their shipment activity, including a description of the transported good and its commodity code, the good's origin and final destination, weight, value, and mode of transportation. The survey data sample is used to estimate the total value and weight of goods shipped in each industry [*CFS*, 2014].

The movement of goods is traced from the point of production to the place of final consumption (this includes using the product as an input to value-added agriculture). Domestic origin and destination locations are represented by 132 FAF Zones, which are composed of 84 U.S. metropolitan areas and 48 state or substate areas (refer to supporting information Table S2 for the full list). International shipment destinations are represented by eight countries or regions: Africa, Canada, Eastern Asia, Europe, Mexico, Rest of Americas, Southeast Asia and Oceania, and Southwest and Central Asia. Supporting information Table S3 lists all countries within each international region.

Transfers of individual goods are not reported. Instead, commodities are aggregated according to the Standard Classification of Transported Goods (SCTG) coding system. The FAF4 data set, along with the CFS data set that it is based upon, tracks transfers from every sector of the economy. However, in this study, we only use transfers of agricultural products. Our analysis uses SCTG 02 (Cereal Grains), SCTG 03 (Agricultural Products Except for Animal Feed), and SCTG 04 (Animal Feed and Products of Animal Origin). The individual crops that comprise each of these categories can be found in supporting information Table S4.

The FAF4 data set reports commodity transfers for the years 2012, 2013, and 2014. To determine transfer volumes for 2011, we scale 2012 food transfers by agricultural production data [*CADFA*, 2017]. For instance, if a FAF Zone harvested 5% more cereal grains in 2011 than in 2012, then 2011 transfers would be 5% greater than 2012. This assumption captures potential changes in trade volume but presumes that relative trade patterns do not significantly change between 2011 and 2012. We spatially disaggregated the transfer data from the FAF scale to the county scale. This was achieved by multiplying a county's crop production by the fraction of the total production that is transferred out of the corresponding FAF Zone. So if a county produced 50% of a FAF Zone's animal feed, for example, it is assumed that 50% of the FAF Zone's transfers can be attributed to that county. Disaggregating the origin of commodity flows based upon production data is a similar approach employed by *Hoekstra and Mekonnen* [2016]. However, our empirical information on commodity transfers is provided at the subnational scale, compared with the international trade data disaggregated in *Hoekstra and Mekonnen* [2016].

The final step was to disaggregate the transfer volumes of SCTG categories to transfers of individual crops. Together, all these processes can be simplified into one equation:

$$T_{c,a,n} = P_{c,a,n} \cdot \frac{T_{SCTG,FAF,a}}{P_{SCTG,FAF,a}} \tag{2}$$

Here the transferred tonnage (T) of an individual crop (c) was calculated for each year (a) and county (n) by multiplying a crop's harvested tonnage (P) by the fraction of production that was transferred out of the associated FAF Zone. It was assumed that the difference between a FAF Zone's total crop production and the tonnage transferred out of the FAF Zone is what remained in the origin FAF Zone. In this way, mass balance was achieved. The agricultural tonnage remaining in the FAF Zone of production can be attributed to postharvest loss, food storage, internal consumption, or further processing into other products (e.g., corn into high fructose corn syrup).

2.3. Water Footprints of Agricultural Production

The water footprint of agricultural production (WF) for each crop-county-year was calculated as

$$WF_{c,a,n,w} = P_{c,a,n} \cdot VWC_{c,a,n,w} \tag{3}$$

where P indicates agricultural production, VWC is virtual water content, and the subscripts c, a, n, and w denote crop, year, county, and water source, respectively. Thus, water footprints are sensitive to changes in farmer decisions (e.g., crop production patterns and irrigation source), climate (e.g., effective precipitation and temperature), and crop response (e.g., ET and yield).

2.4. Virtual Water Transfers

Virtual water transfers (VWT) for each crop-county-year were calculated as

$$VWT_{c,a,n\rightarrow FAF,w} = T_{c,a,n\rightarrow FAF} \cdot VWC_{c,a,n,w} \tag{4}$$

where T indicates commodity transfers, VWC is virtual water content, and the subscripts c, a, n, and w denote crop, year, county, and water source, respectively. The subscript $n \rightarrow FAF$ indicates the transfers from the county of origin (n) to a specific FAF Zone. VWT are traced from each county overlying the Central Valley Aquifer to 132 domestic destinations and 8 world regions. There are more than two million virtual water transfers quantified in this study. When reporting our findings, we aggregate our results along particular spatial scales, water sources, or commodity resolutions of interest in order to make the results more clear.

Due to a lack of supply chain data, we did not trace virtual water flows associated with processed agricultural goods, livestock, or meat products. Available data do not indicate how the drought impacted where these products sourced their primary agricultural inputs from and what water source was used. Estimates of the total virtual water transfers leaving a FAF Zone are conservative since a portion of the agricultural products remaining in the FAF Zone of origin (and the water embedded within them) will be processed or consumed by livestock and these secondary products will eventually be transferred and consumed outside the region.

3. Results and Discussion

Here we quantify the impact of drought in California to agricultural production and yields, virtual water contents, the water footprint of agricultural production, and food and virtual water transfers from the Central Valley. Our results present one example of how local climate shocks propagate through the global food system.

3.1. Drought Impacts to Agricultural Area, Yields, and Production

Figure 3 presents the relative change (%) in harvested area, yields, and production over the course of the drought. From Figure 3, it is clear that harvested area decreased over the course of the drought, while yields actually increased and production remained relatively constant. Table 2 shows the values of harvested area, yields, and production by commodity category for each year of the study. Harvested area changed from 3,441,708 ha in 2011 to 3,029,297 ha in 2014, a 12% decline. This fallowing of less productive agricultural area helps to explain the yield gains (refer to yellow line in Figure 3). Nearly half of all crops saw 2014 yields maintain or exceed predrought yields in 2011. Crop production in the Central Valley, which represents approximately 75% of crop production in California by mass, only saw a 2% decline from 2011 to 2014. The vast majority of the decline in production occurred among cereal crops and animal feed crops, which saw a

28% and 10% decline, respectively (refer to Table 2). Other agriculture crop categories (namely fruits, nuts, and vegetables), actually saw a 7% increase in production during the drought, despite a 9% decline in harvested area (refer to Table 2).

3.2. Drought Impacts to Virtual Water Content

The drought had two distinct impacts on the *VWC* of crops. First, *VWC* values were generally larger during the drought (2012–2014) than in 2011 (predrought) (refer to Figure 4). This is because high temperatures during the drought increased plant water requirements (numerator of *VWC*) while, in some instances, also reduced crop yields (denominator of *VWC*). Second, different water sources were used for crop irrigation during the drought. Since there was less rainfall available to meet crop water requirements during the drought, farmers increasingly relied on irrigation. Additionally, as the drought progressed, the water used for irrigation was increasingly obtained from groundwater sources. This is reflected in steady increases in the groundwater components of *VWC* shown in Figure 4, particularly in the Tulare Basin.

The average *VWC* was between 27% and 59% higher in the Sacramento Basin than in the San Joaquin and Tulare Basins. Although *ET* requirements for the same crop are lower in the cooler Sacramento Basin, average yields are also much lower. Nearly 40% of the Sacramento Basin's crop production is attributed to cereal grains (SCTG 2), which has average yields between 30 and 50% that of crops classified as SCTG 3 and SCTG 4 that are more widely grown in the San Joaquin and Tulare Basins (see Table 2). In comparison, only 1–5% of crop production in the San Joaquin and Tulare Basins is classified as cereal grains. Thus, the Sacramento Basin's overall crop yield is roughly two thirds of the other two basins due to differences in cropping patterns. The lower yields lead to higher *VWC* in the Sacramento Basin, despite lower *ET* values.

Seventeen of twenty Central Valley counties saw average VWC_{ground} increase during the drought, some by more than twofold. VWC_{ground} within the Tulare Basin increased by 149% from 2011 to 2014 on average, reflecting increased dependency on groundwater in this basin. The San Joaquin and Sacramento Basins experienced average VWC_{ground} increases of 71% and 14%, respectively. In 2014, average VWC_{ground} of the Tulare Basin was 370.91 $m^3\ t^{-1}$. The average VWC_{ground} was 199.22 $m^3\ t^{-1}$ in the San Joaquin Basin and Delta and 208.77 $m^3\ t^{-1}$ in the Sacramento Valley. Permanent crops have VWC_{ground} values 4.5 times greater than average VWC_{ground} during the worst year of drought, with crops like almonds consuming 11.5 times more groundwater than average. We provide green and blue *VWC* values by county for 2011–2014 in the SI.

3.3. Drought Impacts to Agricultural Production Water Footprints

The total *WF* of crop production in the Central Valley peaked at $27.38 \times 10^9\ m^3$ in 2012. In 2011, before the onset of the drought, the total *WF* was $26.21 \times 10^9\ m^3$. On average, for every 1 m^3 reduction in the green *WF* during the drought there was a 1.42 m^3 increase in the blue *WF*. This is due to increased crop *ET* during drought years, which is related to higher temperatures (between one and three degrees Celsius across the Central Valley) and a shift to more water-intensive orchard and vine crops.

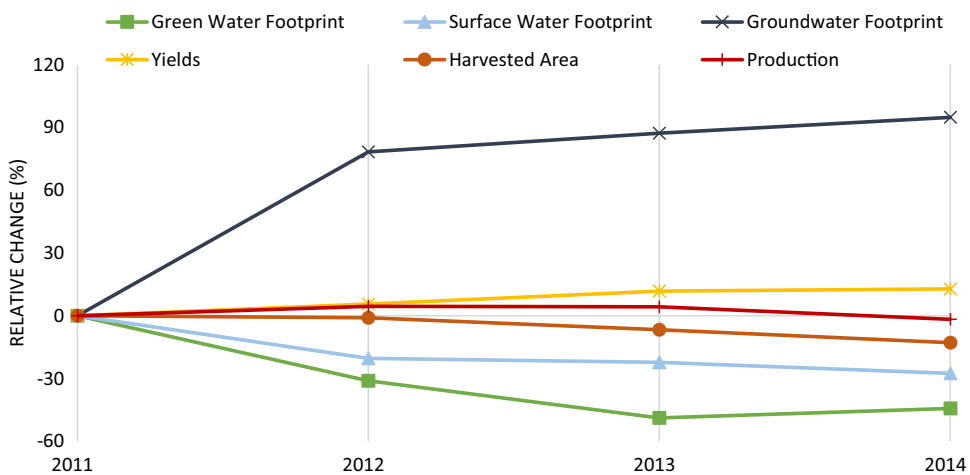

Figure 3. Relative change (%) in study variables over the course of the drought.

Table 2. California Central Valley Harvested Area (ha), Yields (t ha^{-1}), and Production (t) Predrought (2011) and During the Drought (2012–2014)[a]

Harvested Area	2011	2012	2013	2014
Cereal grains	566,728	549,601	500,391	373,390
Other agricultural	2,165,484	2,150,788	2,036,481	1,995,848
Animal feed	709,496	740,716	709,636	660,059
Yield	2011	2012	2013	2014
Cereal grains	8.57	8.80	9.27	9.26
Other agricultural	15.90	16.85	18.10	18.68
Animal feed	28.19	28.94	29.52	26.47
Production	2011	2012	2013	2014
Cereal grains	4,339,420	4,234,356	4,209,809	3,121,597
Other agricultural	27,019,786	28,339,488	28,494,048	29,013,069
Animal feed	13,044,531	13,823,431	13,605,543	11,509,284

[a]Cereal grains (SCTG 2), other agricultural products (SCTG 3), and animal feed (SCTG 4) are provided. Yield gains in cereal grains and other agricultural crops over the course of the drought can be explained by the fallowing of less productive agricultural lands and changes in crop mix.

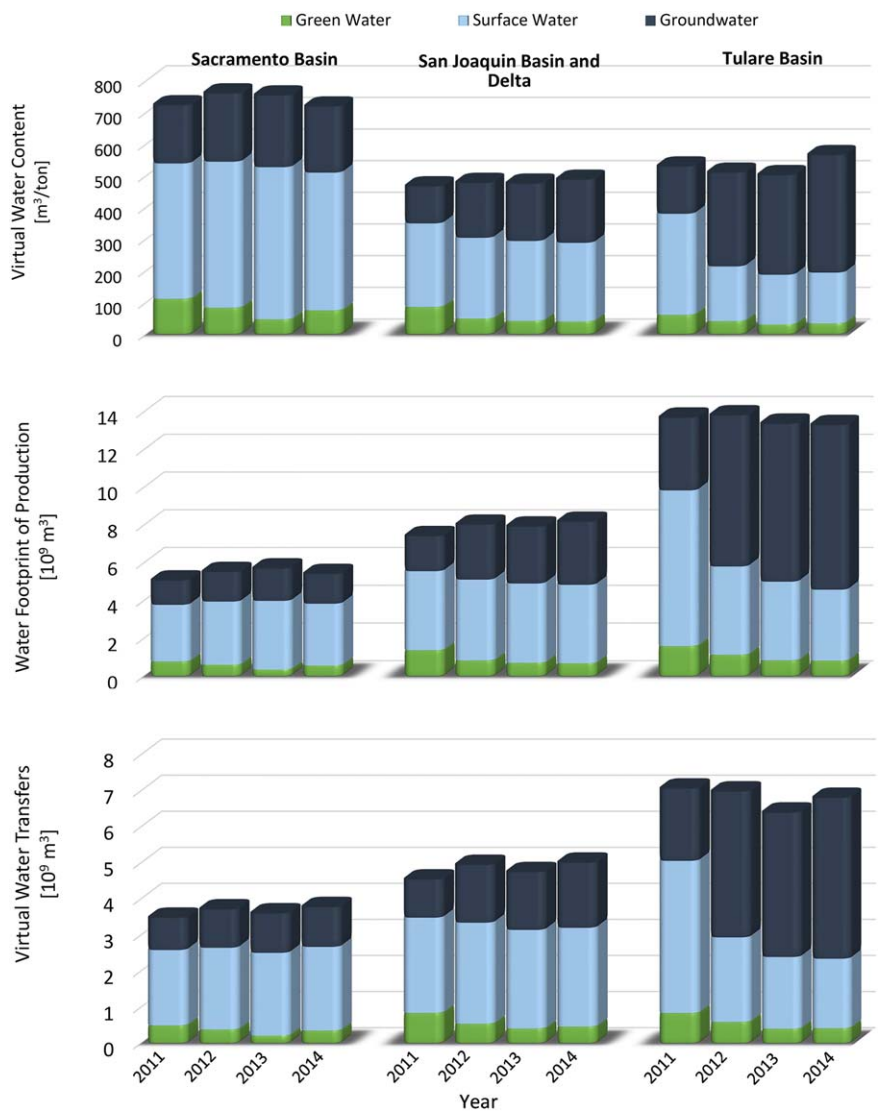

Figure 4. Virtual water content (m^3 t^{-1}), water footprint of agricultural production (m^3), and virtual water transfers (m^3) predrought (2011) and during the drought (2012–2014) by water source are shown for the three basins of the Central Valley Aquifer: Sacramento Valley, San Joaquin Basin and Delta, and Tulare Basin. Note the increased contribution of groundwater over time, particularly in the Tulare Basin.

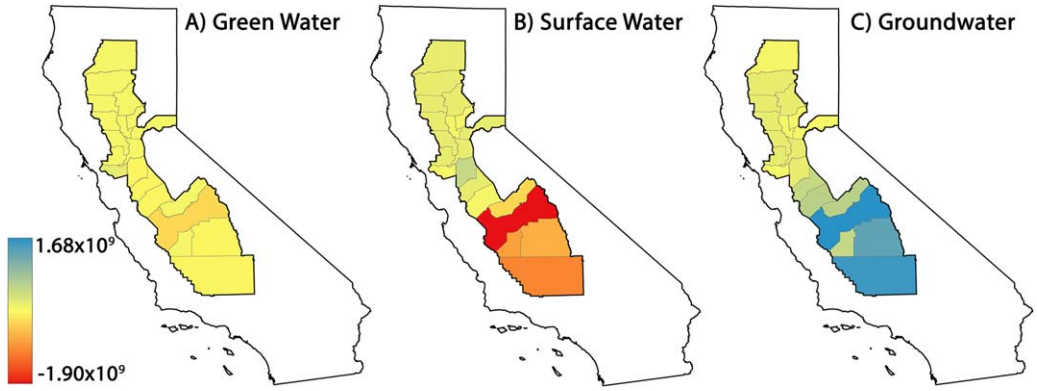

Figure 5. Drought impacts to the water footprint of agricultural production in the California Central Valley. Figures indicate volumetric changes (m^3) from predrought (2011) to drought conditions (2014) for (a) green water footprints, (b) surface water footprints, and (c) groundwater footprints. Note that green and surface water footprints predominantly decrease, while groundwater footprints increase, particularly in the Tulare Basin.

We validate our results against two sources. First, we compare our estimates with the California Water Plan Update 2013 [*CDWR*, 2013]. According to the California Department of Water Resources (CDWR), irrigation withdrawals for the 20 counties in this study were 28.07×10^9 m^3 in 2010. We use CDWR irrigation efficiency parameters to convert our consumptive water use estimates into withdrawal values. We estimate irrigation withdrawals in 2011 as 31.20×10^9 m^3. Our 2011 value is roughly 11% higher than the 2010 CDWR value. This is reasonable given there was a 6% increase in harvested crop area between 2010 and 2011.

Second, we validate our numbers against *Howitt et al*. [2014]. *Howitt et al*. [2014] estimate California's 2010 irrigation groundwater usage as 9.87×10^9 m^3, based on CDWR water use records. In 2010, CDWR records show that irrigators in Central Valley counties were responsible for 81% of groundwater use within California. Thus, based on these numbers, groundwater use in the Central Valley was roughly 8.01×10^9 m^3 in

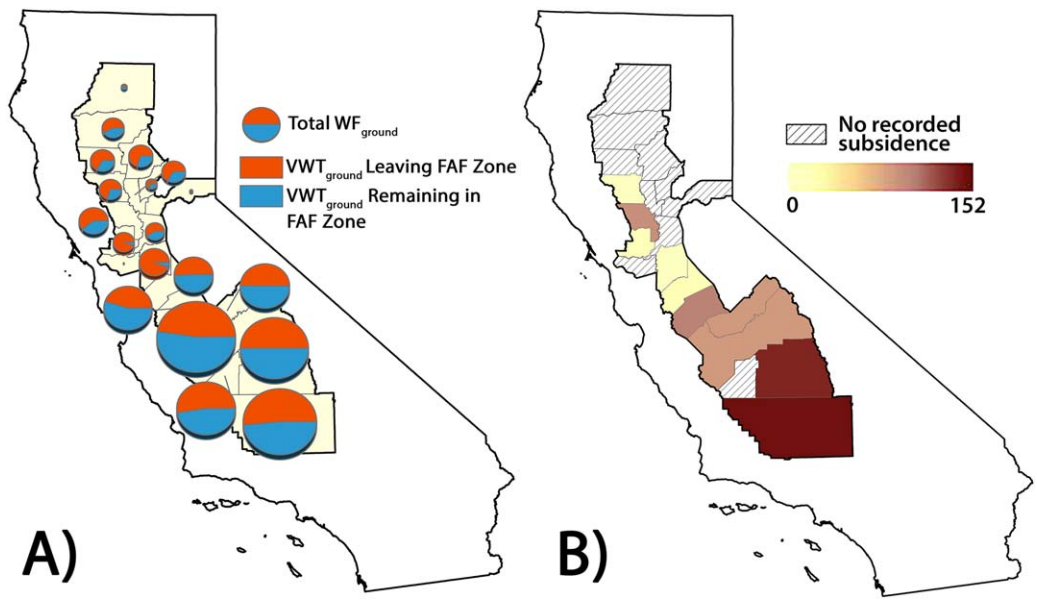

Figure 6. (a) Map of groundwater footprints and (b) map of subsidence for counties in the Central Valley of California. (a) Each circle is scaled according to the total groundwater footprint of crop production of each county aggregated from 2011 to 2014. The fraction of virtual groundwater transfers that leave the FAF Zone of production is shown in orange, while the fraction of virtual groundwater transfers that remain within the FAF Zone is blue. (b) Land subsidence recorded by USGS extensometers and continuous GPS measurements between 2011 and 2014 is mapped. Dark red indicates greater subsidence. Counties with no subsidence measurements are hatched. Note that the Tulare Basin counties have the largest groundwater footprint of agricultural production and the most subsidence.

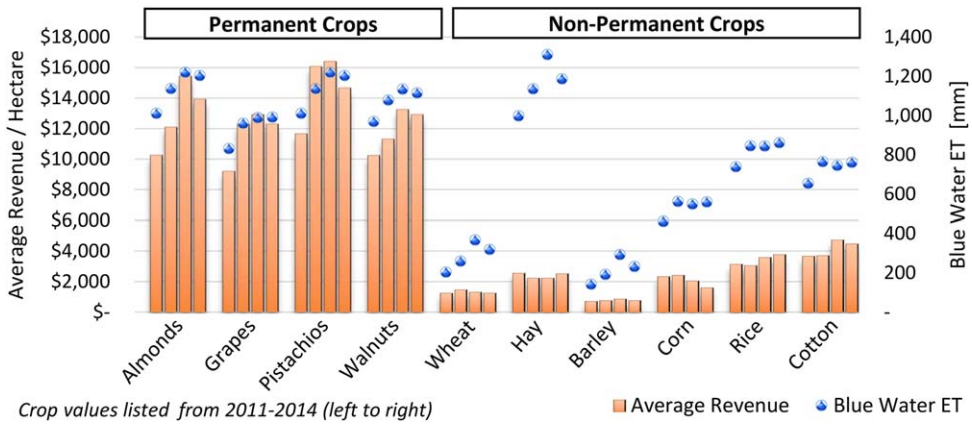

Figure 7. California Central Valley crop revenue and irrigation requirement from 2011 to 2014. Bars indicate the average revenue per hectare of crop production. Blue circles show the average crop evapotranspiration from irrigation. Permanent (tree and vine) crops with the greatest increase in harvested area during the drought are compared with nonpermanent (field and vegetables) crops with the greatest decrease in harvested area. With the exception of hay, which is often harvested (and irrigated) multiple times per year, permanent crops have significantly higher *ET* requirements per hectare than the most fallowed nonpermanent crops.

2010. *Howitt et al*. [2014] projected an increase of 6.17×10^9 m^3 in groundwater irrigation across the Central Valley from 2010 to 2014. So groundwater use in the Central Valley would be 14.18×10^9 m^3 in 2014, according to *Howitt et al*. [2014] estimates. We estimate 2014 groundwater use to be 13.63×10^9 m^3. So our estimate compares favorably with *Howitt et al*. [2014] and is only 3.9% less.

Nearly all of the increase in the blue *WF* of production is due to increased groundwater consumption. In fact, 7 of the 20 Central Valley counties had a double-digit percentage decrease in $WF_{surface}$ (refer to Figure 5). The WF_{ground} of agricultural production in the Central Valley increased from 7.00×10^9 m^3 in 2011 to 13.63×10^9 m^3 in 2014. The increase in groundwater footprints coincided with a reduction in surface water and green water footprints, shown in Figure 4. The Tulare Basin experienced the greatest increase in both absolute and relative terms in groundwater footprints during the drought. In the Tulare Basin, total crop groundwater consumption increased from 3.85×10^9 m^3 in 2011 to 8.72×10^9 m^3 in 2014 (see Figure 4).

Depletion of the Central Valley Aquifer is not spatially uniform since groundwater withdrawals and recharge vary across the aquifer. Our study estimates volumes of groundwater consumption; however, not all consumptive groundwater use is unsustainable. Previous studies [*Faunt*, 2009; *Famiglietti et al*., 2011] show that unsustainable groundwater use primarily occurs in the Tulare Basin, manifested by declining groundwater tables, subsidence, and reduced base flow. We find that the Tulare Basin consumed 3.81×10^9 m^3 more groundwater in 2014 than the Sacramento and San Joaquin Basins combined. Furthermore, we find that locations with the largest groundwater footprint of agricultural production experienced the highest levels of land subsidence during the drought, as illustrated by Figure 6. Figure 6b shows the maximum recorded subsidence from 2011 to 2014 derived from USGS extensometers and continuous GPS measurements. Remote sensing studies have shown land subsidence up to 330 mm in just eight months in 2014 [*Farr et al*., 2015], meaning that USGS in situ measurements likely do not capture some of the more extreme instances of subsidence in the region. Subsidence alters land-surface slopes and has caused costly operational, maintenance, and construction-design issues related to water-delivery and flood-control canals and other infrastructure [*Faunt and Sneed*, 2015].

From 2011 to 2014, the total irrigation water consumed in the production of cereal grains decreased by 16%, or 0.42×10^9 m^3. However, the blue water footprint of other agriculture products, such as fruits, vegetables, and nuts, increased by 6% (2.80×10^9 m^3) over this time period (see supporting information Figure S1). This reflects a reallocation of limited water supplies from low-value to higher-value crops during the drought.

Basin-wide, all crop categories increased their dependency on groundwater during the drought. However, cereals continued to meet the majority (~70%) of their irrigation requirement from surface water sources. Fruits, nuts, vegetables, and animal feed crops went from groundwater supplying 32% of their

Table 3. Percent Change (%) in Agricultural Transfers From the California Central Valley to Major Destinations From 2011 to 2014

Destination	Cereal Grains (SCTG 2) (%)	Other Agriculture (SCTG 3) (%)	Animal Feed (SCTG 4) (%)	Total (%)
Africa	−52	−4	462	−38
Canada	−34	21	71	19
Eastern Asia	−52	−16	79	−1
Europe	−61	29	26	24
Mexico	39	13	62	32
Rest of Americas	−13	22	38	20
SE Asia and Oceania	−63	−37	−32	−40
SW and Central Asia	−41	8	−44	−25
United States	−25	−2	12	−2
World total	−28	−2	15	−1

irrigation requirement pre-drought to relying on groundwater to meet 57% of their irrigation needs in 2014. We estimate a smaller fraction of irrigation comes from groundwater sources than other studies, e.g., *Faunt and Sneed* [2015] and *Jones* [2015]. This is likely due to the conservative nature of our approach to estimating the contribution of groundwater to irrigation, as well as because our study encompasses all counties overlying the Central Valley Aquifer system. This includes the area of counties that is not directly over the aquifer, while other studies just evaluate the land directly over the aquifer.

Changes in the water footprint of crop production during the drought occur for four reasons: (1) a change in crop yield and harvested area; (2) an increase in crop evapotranspiration during drought years; (3) an increase in irrigation to compensate for rainfall deficits; and (4) an increase in groundwater irrigation due to reductions in surface water availability. There was an increase in the harvested area of permanent crops (vineyards and orchards) during the drought and a corresponding decrease in the harvested area of nonpermanent crops (field crops and vegetables), shown in supporting information Figure S2. Between 2011 and 2014, 490,254 less hectares of nonpermanent crops were harvested (29% reduction) in the counties overlying the Central Valley Aquifer. At the same time, 146,592 more hectares of permanent crops were harvested (15% expansion).

On average, the water requirement per hectare of permanent crops was approximately 91% higher than nonpermanent crops (see supporting information Figure S3). Thus, each additional hectare of permanent crops harvested during the drought would require nearly 2 ha of nonpermanent crops to be fallowed to maintain the same level of water consumption. A key exception is hay (including alfalfa), which, on a per hectare basis, consumes a considerable volume of water since the irrigated plot is harvested multiple times throughout the year. Permanent crops are also more likely to be insured than forage and field crops grown in California. Insured irrigated cropland requires farmers to maintain a certain level of water application to maintain insurance coverage, further reinforcing the water use implications associated with the transition from nonpermanent to permanent crops [*Deryugina and Konar*, 2017].

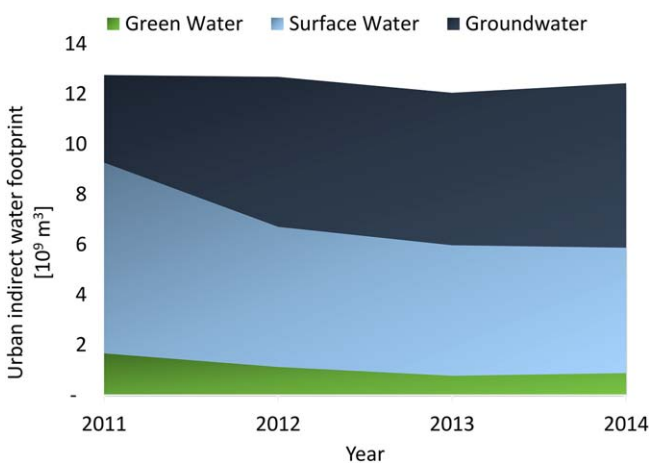

Figure 8. Indirect water footprint from the Central Valley of California cities: Fresno, Los Angeles, Sacramento, San Francisco, and San Diego by water source and year.

Figure 7 shows the blue *ET* requirement and the average revenue per hectare generated for permanent crops that saw the largest increase in harvested area and the nonpermanent crops that experienced the largest decline in harvested area from 2011 to 2014. In the first year of the drought, these permanent tree and vine crops saw a sharp price increase, while the most widely grown nonpermanent field crop prices remained relatively stable. Growing global demand for tree nuts is primarily responsible for the rise in prices and is likely to have caused the shift to more water-intensive tree nut crops. From an economic perspective, the reallocation of water to higher-value uses is

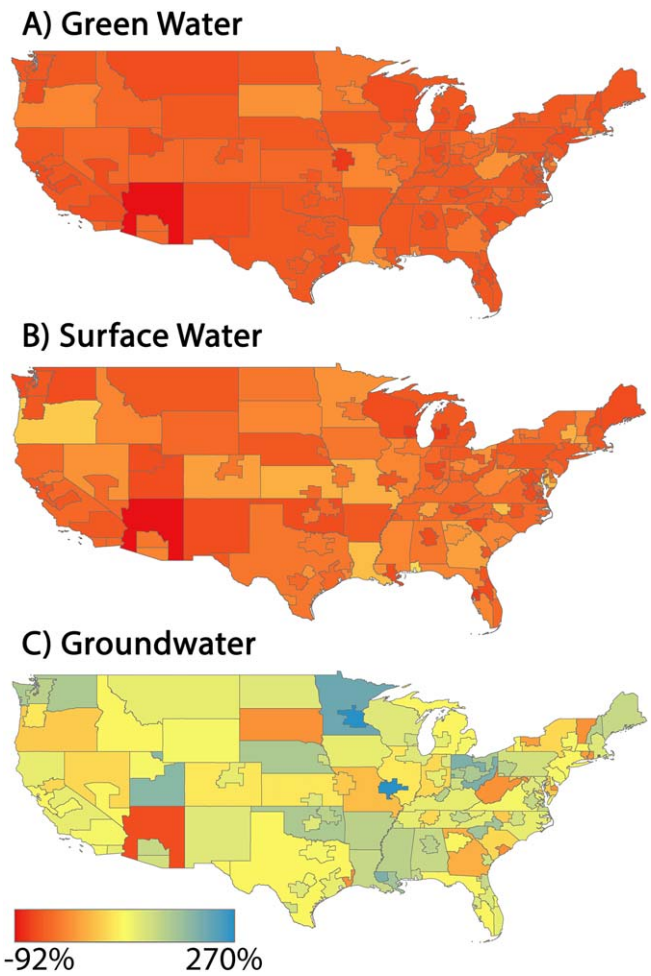

Figure 9. Percent change (%) in virtual water transfers from the California Central Valley to other areas of the United States between 2011 and 2014. Figures indicate (a) green, (b) surface, and (c) groundwater virtual water transfers within the United States. Note that green and surface virtual water transfers predominantly decrease, while groundwater transfers mostly increase.

encouraged [*Zilberman et al.*, 2002; *Marston and Cai*, 2016]—this is foundational to California's water market. However, from a drought management perspective, changing cropping patterns from easily fallowed field crops to tree and vine crops reduces flexibility in the water system.

3.4. Drought Impacts to Food and Virtual Water Transfers

Overall, food transfers from the Central Valley decreased by 1% from 2011 to 2014 (refer to Table 3). A decrease in food transfers was seen across 40% of all trade links, including 8 of the 10 largest trade links by tonnage. Transfers of cereal grains (SCTG 2) declined by 28%, with 95% of trade linkages facing a decline. Transfers of other agricultural products (SCTG 3) experienced a more modest decline of 2%, with tonnage falling across 27% of trade paths. Although production of animal feed (SCTG 4) decreased by 14% from 2011 to 2014, transfers increased by 15%. Nonetheless, 56% of animal feed was consumed, stored, or further processed in the FAF Zone of production. Note that there was large variation in food transfers during the drought depending on the transfer destination and food category.

From 2011 to 2014, total *VWT* from the Central Valley increased by 3% (0.51×10^9 m^3) (see Figure 4). During the same period, there was a 3% increase (0.71×10^9 m^3) in total *WF*. This can be explained by higher drought temperatures increasing crop evaporative demands and farmers switching to more water-intensive crops. These changes led to larger total water footprints and virtual water transfers, despite declines in total agricultural production and transfers. The driest year of the drought was 2013 [*Jones*, 2015], which is when VWT_{green} and WF_{green} reached their lowest values of 1.04×10^9 and 1.93×10^9 m^3, respectively. However, it was not until 2014 that reservoirs reached their lowest levels, leading to record-low distributions from federal and state water projects [*Jones*, 2015]. In 2014, $VWT_{surface}$ and $WF_{surface}$ reached its lowest value of 6.98×10^9 and 11.19×10^9 m^3, respectively.

The increase of total *VWT* over the course of the drought can almost entirely be attributed to the 3.42×10^9 m^3 of additional VWT_{ground} during that same period. The increase in virtual groundwater transfers offsets the 0.94×10^9 m^3 reduction in VWT_{green} and the 1.96×10^9 m^3 decrease in $VWT_{surface}$. The Tulare Basin in particular was responsible for 59% of all VWT_{ground} from the Central Valley. Figure 6 shows that areas reporting greater levels of subsidence transferred 3.7 times more virtual groundwater than areas with no recorded subsidence by USGS.

Urban areas of California are major indirect consumers of Central Valley water resources. From 2011 to 2014, five major urban areas (i.e., Fresno, Los Angeles, Sacramento, San Francisco, and San

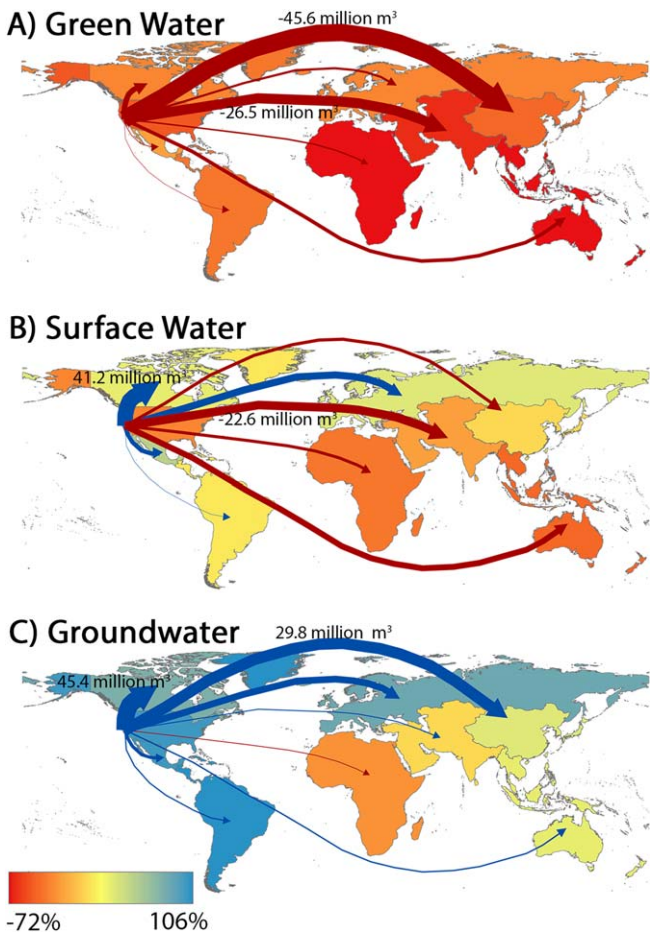

Figure 10. Percent change (%) in virtual water transfers from the California Central Valley to international destinations between 2011 and 2014. Figures indicate the percent change in (a) green, (b) surface, and (c) groundwater virtual water transfers. Arrows show the change in the volume of virtual water transfers (m^3) and are scaled relative to size. Volumes are provided for the largest links. Red arrows indicate a reduction in virtual water transfers; blue arrows signify an increase.

Diego) utilized 12.41 ($\pm$0.35) $\times$ 10^9 m^3 yr^{-1} of virtual water from the Central Valley. In comparison, Los Angeles physical water demand and aqueduct deliveries have averaged around 0.75 $\times$ 10^9 m^3 and 0.25 $\times$ 10^9 m^3 yr^{-1}, respectively, since 1990 [*LADWP*, 2013]. However, the portion attributed to each water source varied significantly between years (see Figure 8). In 2014, approximately 45% of surface water consumed by Central Valley crops was eaten or further processed (supporting jobs and local economies) by these five cities. Together, these urban areas experienced a 34% reduction in $VWT_{surface}$ between 2011 and 2014, reflecting a decrease in agriculture production and a switch in dependency from renewable surface water to the Central Valley Aquifer during the drought (there was an 89% increase in VWT_{ground}).

Overall, the State of California utilized 20.73 ($\pm$1.06) $\times$ 10^9 m^3 of virtual blue water from the Central Valley region each year between 2011 and 2014. In 2011, roughly 69% of the state's virtual blue water use could be attributed to surface water sources but the fraction of surface water shrank to 43% by 2014. To put the virtual water volumes in context, in 2013, 14.60 $\times$ 10^9 m^3 of potable water was supplied for residential and nonresidential users by the more than 400 urban water suppliers across the state [*California EPA*, 2016]. During the drought, urban water users in California were mandated to reduce their water use by 25%. California residential water users paid approximately \$1630 per 1000 m^3 of water in 2013 [*Gaur et al.*, 2013], while irrigators spent \$22.19 in pumping cost per 1000 m^3 of on-farm water (surface water and groundwater) and paid \$36.96 per 1000 m^3 for off-farm water supplies [*USDA*, 2014]. This highlights the high opportunity cost of water in agriculture in California, due to its heavy reliance on irrigation and proximity to urban areas.

Dependencies of U.S. cities and states on the Central Valley's water resources changed significantly during the drought. Reliance on the Central Valley Aquifer more than doubled for 69 FAF Zones from 2011 to 2014 (refer to Figure 9). At the same time, 31 FAF Zones increased their utilization of both the Central Valley's surface water and groundwater during the drought. No areas saw an increase in VWT_{green} during the drought. Rural Arizona saw a significant reduction (85%) in cereal grain receipts from the Central Valley, making it the only US FAF Zone to experience decreased dependency on the Central Valley Aquifer as the drought intensified.

VWT to international destinations increased by 4% during the drought. Figure 10 maps changes in virtual water exports from the Central Valley to international destinations from 2011 to 2014. All regions experience a decrease in VWT_{green} (see Figure 10), while five of eight world regions receive more $VWT_{surface}$ from the Central Valley over the course of the drought (note the predominantly blue shading in Figure 10b).

Conversely, all areas experience an increase in VWT_{ground} during the drought, except for Africa (see Figure 10c). Africa's decrease in VWT_{ground} is due to a significant reduction in cereal grain exports from the Central Valley during the drought (Africa disproportionately imports more of these goods than other regions). Thus, during the California drought, global consumers relied more heavily on the overexploited Central Valley Aquifer. This demonstrates how local changes in production, such as greater reliance on groundwater during drought, can propagate through the global food system and create complex patterns of dependencies on scarce resources by distant consumers.

4. Concluding Remarks

In an increasingly globalized economy, it is critical that we understand how local production shocks propagate through and interact with the global food trade system. In this paper, we quantified how severe drought impacted agricultural production, water footprints, and virtual water transfers of the Central Valley of California. We paired high-resolution data of food commodity transfers and production with modeled estimates of water footprints by county, year, and water source to better understand the ramifications of drought for the coupled water-food-trade system.

We showed that there was a 3% increase (0.71×10^9 m^3) in the total *WF* of agricultural production over the course of the drought, due to increased crop water requirements and shifts in production patterns. In particular, the groundwater *WF* increased from 7.00×10^9 m^3 in 2011 to 13.63×10^9 m^3 in 2014, predominantly in the Tulare Basin. Similarly, we found that food transfers decreased by 1% (0.32×10^6 t) during the drought, yet *VWT* increased by 3% (0.51×10^9 m^3). From 2011 to 2014, nonlocal groundwater *VWT* increased by 3.42×10^9 m^3, offsetting reductions in green and surface *VWT* (0.94×10^9 and 1.96×10^9 m^3, respectively). These findings demonstrate nonobvious patterns that emerge between drought, farmers' decisions on crop mixes and water use, and global commodity markets.

This study highlights the critical importance of existing national databases in the United States, which this study relied upon. Through this analysis, we were able to identify opportunities to improve national data collection efforts as well. In particular, the scientific and policy communities would dramatically benefit from high temporal resolution and metered water use data by source. It is important to note that we presented expected values only and do not quantify the uncertainty surrounding our results due to shortcomings in the input data. Quantifying the sensitivity and uncertainty of water footprint estimates is an area of active research [*Zhuo et al*., 2014; *Tuninetti et al*., 2015] and future research is needed to evaluate the additional uncertainties that are involved when commodity transfers are also considered.

Over the course of the drought, local and global consumers doubled their reliance on the Central Valley Aquifer (95% or 6.63×10^9 m^3). It is critical that groundwater resources are recharged following drought, so that they are there to draw upon during the next drought. Water pricing, water markets, property rights, managed aquifer recharge, and groundwater policy are critical to conserving our groundwater resources for use during future drought events [*Zilberman et al*., 2002]. Local solutions will continue to be essential to ensuring sustainability of the Central Valley Aquifer. In addition, our work enables consumers around the country and world to realize that they benefit from agricultural production that relies upon the Central Valley Aquifer. This information is critically important to help nonlocal Americans realize that they are connected to their distant, national resources and benefit from nonlocal infrastructure.

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