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Ecosystem Services Mapping for Sustainable Agricultural Water Management in California's Central Valley

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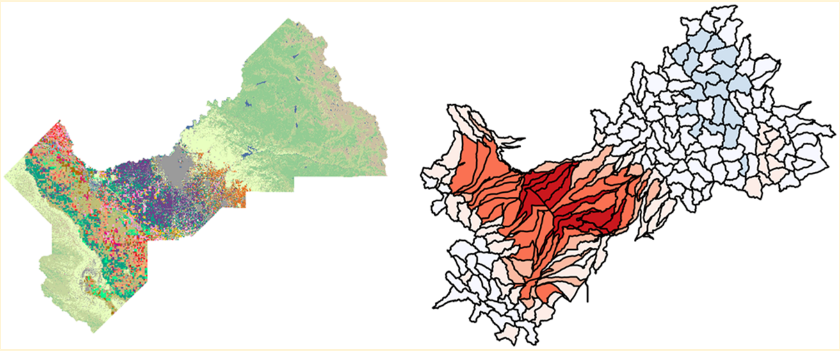
Supporting Information



ABSTRACT: Accurate information on agricultural water needs and withdrawals at appropriate spatial and temporal scales remains a key limitation to joint water and land management decision-making. We use InVEST ecosystem service mapping to estimate water yield and water consumption as functions of land use in Fresno County, a key farming region in California's Central Valley. Our calculations show that in recent years (2010−2015), the total annual water yield for the county has varied dramatically from ~0.97 to 5.37 km^3 (all ±17%; 1 MAF ≈ 1.233 km^3), while total annual water consumption has changed over a smaller range, from ~3.37 to ~3.98 km^3 (±20%). Almost all of the county's water consumption (~96% of total use) takes place in Fresno's croplands, with discrepancy between local annual surface water yields and crop needs met by surface water allocations from outside the county and, to a much greater extent, private groundwater irrigation. Our estimates thus bound the amount of groundwater needed to supplement consumption each year (~1.76 km^3 on average). These results, combined with trends away from field crops and toward orchards and vineyards, suggest that Fresno's land and water management have become increasingly disconnected in recent years, with the harvested area being less available as an adaptive margin to hydrological stress.

INTRODUCTION

With ~40% of terrestrial land devoted to food production, the management of agricultural lands has tremendous consequences for ecosystem services.[1−4] By 2050, total global food demand is estimated to double with population growth and increased demand for animal protein;[5] meanwhile, global food production growth has plateaued and even declined in some regions[6] and anticipated climate changes further threaten production.[7] Agricultural intensification has been promoted as a solution to an increasingly strained land base, in that high yields could theoretically enable a smaller land footprint, and spared land could be protected, used for other ecosystem services, or both.[8] Although intensification of agricultural production might reduce pressure to convert additional native habitat to cropland or pasture land, intensification has additional ecosystem consequences beyond land use.[1]

In particular, land and water use are closely intertwined. Roughly 70% of freshwater use worldwide is for agricultural production, and agricultural management plays a key role in local hydrology through these direct surface and groundwater withdrawals, as well as through changes in local soil properties and runoff. However, across most agricultural regions, there is little direct information, unless individual farmers report it, on how much groundwater is being used to supplement local water supply and surface water transfers. Such data (how much water is being used, whether or not that use is sustainable over the long run, and what crops or products are driving it) are clearly critical for ensuring long-term food and water security. Ideally policymakers and stakeholders would share detailed mappings of water supply and water demand, by crop, at relevant spatial and temporal scales, so that the potential for (and costs and trade-offs of) more-efficient land and water use could be directly investigated.

As a case-study in these interconnections, it is notable that the State of California has recently endured five years of drought. Annually, California consumes around 42 million acre-ft water, of which 80% is for food production.[9] However, water

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conservation in the state is not a simple task because agricultural production is an important component of California's economy and also of regional and national food security. California's predominant agricultural region, the Central Valley, is known as the fruit basket of the United States and produces 96% of the nation's canned tomatoes, 96% of its broccoli, and 99% of its almonds.[10] In the Central Valley the challenges of food security and water sustainability are thus closely linked and cannot be addressed in isolation.[11,12] These issues are only expected to worsen: rising temperatures and more-frequent droughts are expected in California over the next century due to climate change.[13]

Our study site, Fresno County, sits at the heart of California's Central Valley and is emblematic of the ecosystem tensions associated with intensive agriculture worldwide. In 2015, the county's total gross production value of agricultural commodities was among the highest in the United States at \$6.6 billion, 18% of the county's overall GDP and over 12% of California's total agricultural value output.[14,15] Agricultural production in the county relies heavily on both surface and groundwater irrigation.[16] Total groundwater withdrawals vary from year to year, and no comprehensive data on withdrawals exist because farmers are not required to report privately pumped groundwater. However, over the past 20 years, the Fresno Irrigation District itself has pumped between 0.51−0.79 km^3 of groundwater each year to support production of its signature crops.[17−19] Moreover, the water table level has been dropping at an average rate of over 0.25 m per year for the past 80 years.[17,20]

We use ecosystem services mapping via the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to quantify water yield and demand in Fresno County's 213 watersheds from 2010 to 2015; the differences between estimated consumption and production provide estimates of the magnitude of unsustainable water withdrawals in the county. We disaggregate water demand and inferred groundwater use to individual crops[21] and then link those estimates to reported county agricultural data to and to derive returns to land and water for the county's top crops over time. We thus demonstrate how ecosystem services mapping, by facilitating coupled analysis of production of ecological services (supply) and consumption of those services (demand) in spatially explicit manner, can be used to quantify the hydrological and economic impacts of different land-management and climate scenarios.

■ MATERIALS AND METHODS

We use the InVEST water yield model to quantify natural water yield and predicted water consumption in Fresno County. InVEST is a platform for ecosystem services valuation, the science of assigning value to services provided by a given ecosystem and integrating a more-quantitative understanding of those services into land-use decision-making.[22−24]

At a basic level, the InVEST water yield model takes local environmental conditions and land use and land cover data as inputs and calculates net water balance at the watershed scale. The model calculates the amount of water yield per 900 m^2 pixel scale as the difference in precipitation and actual evapotranspiration. The actual evapotranspiration is a function of reference evapotranspiration, root-restricting layer depth, plant available water content, and land use (Figure 1. InVEST can also be used to estimate water demand (consumption), which is a function of land-use type. Detailed methodology and equations for the water yield and consumption model can be found in the InVEST user guide.[21]

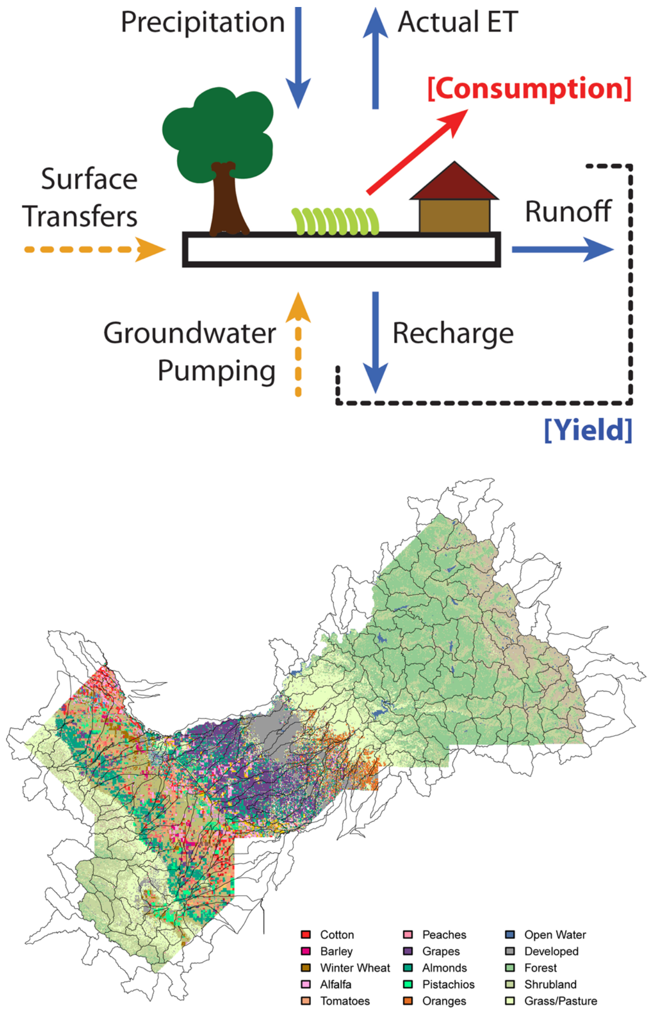

Figure 1. (Upper panel) Simplified schematic of the InVEST water yield and consumption models (based on the InVEST model).[21] (Lower panel) Map of land use and land cover, as well as watershed boundaries, for Fresno County, CA, in 2015. (Map produced by authors using R statistical software with publicly available Cropland Data Layer[28] and watersheds map.)[25] In the InVEST model, land use and landcover data at a 30 m × 30 m resolution are integrated with soil and weather parameters to estimate water yield, or the difference between precipitation and actual evapotranspiration, at the watershed level. Consumption is estimated as a function of land use and landcover type. Water needs for agricultural areas, which are met by either surface water transfers from upstream or groundwater withdrawals, can be inferred as the difference between consumption and yield when consumption exceeds yield.

Environmental Data Inputs. The InVEST model outputs spatially resolved mapping of water yield, water consumption, and water resupply (the difference of water yield and water consumption) at the watershed scale, with attributed output values for each watershed (map of county watersheds obtained from Geospatial Gateway[25]). The model does not account for any potential surface water and groundwater transfer between watersheds; hence, water yield per watershed is contributed only by the water generated within each watershed. For county-level statistics, we then aggregate results from the county's watersheds. County administrative lines do not perfectly correspond to watershed boundaries, so our analysis is based

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Table 1. Average (2010−2015) Land and Water Use for Top 10 Crops, Based on Data from the Fresno County Annual Crop & Livestock Report and InVEST Model output[a]

crop	model crop annual water use ($m^3/900m^2$)	model land use area (km^2)	model water use (km^3)	actual harvest area (km^2)	actual harvest water use (km^3)	total production value (millions of $)
alfalfa	1100	411	0.502	238	0.291	87.6
almonds	900	840	0.840	648	0.648	950.1
barley	250	57	0.016	45	0.013	4.4
cotton	500	362	0.201	314	0.174	205.9
grapes	600	785	0.523	848	0.565	954.5
oranges	700	157	0.122	108	0.084	165.8
peaches	700	36	0.028	63	0.049	162.9
pistachios	900	200	0.200	166	0.166	224.3
tomatoes	450	410	0.205	433	0.216	512.3
winter wheat	400	394	0.175	201	0.089	33.9
total (or average*)	650*	3652	2.812	3064	2.295	3301.7

crop	total production (metric tonne)	returns to water ($/$m^3$)	returns to land ($/$m^2$)	unit price ($/ton)	production per unit water (kg/m^3)	yield on harvested area (kg/m^2)
alfalfa	389636	0.30	0.37	225	1.33	1.63
almonds	176447	1.45	1.45	5385	0.27	0.27
barley	15823	0.43	0.12	280	1.33	0.37
cotton	145748	1.16	0.65	1413	0.83	0.46
grapes	1171823	1.70	1.13	815	2.10	1.40
oranges	343341	1.98	1.54	483	4.16	3.23
peaches	153828	3.35	2.61	1059	3.15	2.45
pistachios	39054	1.49	1.49	5744	0.27	0.27
tomatoes	4865989	2.37	1.19	105	22.52	11.26
winter wheat	165214	0.41	0.18	205	2.48	1.10
total (or average*)	7466903	1.46*	1.07*	1571*	3.84*	2.24*

[a]Returns to land and water are calculated using the harvested area, and harvest water use is calculated by scaling the modeled water use by the ratio of harvested to modeled crop area. Production values provided by the county are not dry-weight values. (A version of the table in U.S. Customary Units is included in the Supporting Information.).

on all watersheds that sit either entirely or partially within the county (see Figure 1).

As inputs to the InVEST model, we use high-resolution annual temperature and precipitation data for Fresno County provided by the PRISM modeling group[26] as well as annual reference evapotranspiration, root-restricting layer depth, and plant available water content maps. Reference evapotranspiration is the amount of supplied solar energy (expressed as a depth of water, e.g., mm) to vaporize water.[21] Root-restricting layer depth is defined as the soil depth at which root penetration is inhibited due to physical constraints.[21] Fresno County's root-restricting layer depth was acquired from Soil Survey Geographic (SSURGO) database's soil property map.[27]

Plant available water content is defined as the fraction of water that can be stored in the soil profile that is available for plants' use, and it is often represented as a thickness on a per-square-meter basis (e.g., mm of water per mm of soil).[21] Fresno County's plant available water content was obtained through the SSURGO database.[27] Available water storage within the root-zone depth (mm) and root zone depth (mm) measurements were extracted from the soil property map. The ratio of available water storage to root zone depth yielded the plant available water content profile.

Land-Use Data. We use Fresno County's cropland data layers for 2010−2015.[28] The cropland data layer is a georeferenced and crop-specific land-cover data layer in raster format at a 30 m × 30 m resolution. The map is composed of 80 types of land use and land cover (LULC), including 54 crop types. Each 30 m × 30 m pixel is assigned the value of its predominant land use or land cover type (i.e., if the majority of the area is a pistachio orchard, the entire pixel is classified as pistachio cropland). Imagery used in the production of the land-use map (cropland data layer) is orthorectified to a radial root-mean-square error of around 10 m.[28] This potentially leads to discrepancies between model-calculated area for a given crop type (i.e., the sum of all pixels classified as a given type) and the actual harvested area. For crop-area-based measures (e.g., returns to land, total water use for a given crop), we use harvested areas as reported by the county and scale our modeled water use and inferred deficit accordingly. (Although annual cropland data layers are available starting in 2007, they are at 56 m × 56 m resolution prior to 2010, resulting in greater uncertainty in pixel classification. We therefore use only the consistent set starting in 2010 for any analysis that includes water-yield estimates.)

Water Demand and Seasonality Factor. To translate environmental inputs into water yields, InVEST requires information on water-use requirements for different LULC classifications as well as information on hydrological seasonality. This is input as a water-demand table with specified water use requirements for agricultural and residential activities. The estimated average water use for various LULC is given in cubic meters per pixel (900 m^2) per year. Annual water requirement for the top 10 crops by area, together around 90% of the county's total agricultural area, are displayed in Table 1. The remaining 44 crops, or the remaining 10% of agricultural area, was assigned an annual water requirement approximated by the median water use of the top 10 crops, or 550 mm. Residential

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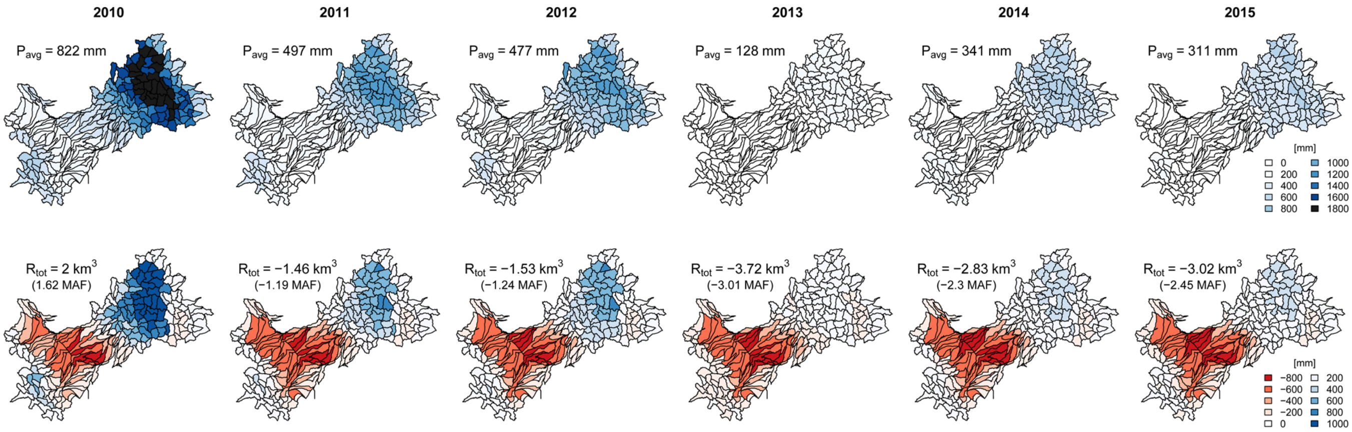

Figure 2. (upper) Average precipitation and (lower) water resupply (yield − consumption) by watershed for Fresno County in 2010−2015. (Maps produced by authors using R statistical software, showing publicly available precipitation data[26] and InVEST model output overlaid on a watersheds map.)[25]

water use in Fresno County was calculated to be approximately 200 m^3/900 m^2 from the Fresno County Annual Water Report.[29] We use effective rainfall, defined as the percentage of rainfall that becomes available to plants and crops, instead of total precipitation, for crop water use. Fresno County's average monthly precipitation is 50 mm from November through March, and effective rainfall is 20 mm from November through March.[30] Annual effective rainfall is thus around 100 mm (as almost no rain falls between March and November). The water demand table is displayed in the Supporting Information.

The seasonality factor, Z, is an empirical number that captures the regional precipitation pattern and hydrogeological characteristics, typically ranging from 1 to 20. Estimation of Z can be achieved by $0.2N$, where N is the annual number of rain events lasting longer than 6 h per year.[31] Based on the InVEST modeling study in region with similar seasonal precipitation pattern and the county's climate data, Z is estimated to be 5.[32]

Returns Calculations. We model crops' total annual water use as the product of water use per unit area and land use area. Dollar value, harvested area, and production per acre for the top 10 crops were obtained from Fresno County's crop and livestock reports;[14] average values for 2010−2015 are listed in Table 1. As described above, we scale values for crop water use based on the Cropland Data Layer by the ratio of reported harvested area to CDL area to estimate harvest water use. Next, dollar value per harvest water use (returns to water), dollar value per harvest area (returns to land), and production per harvest water use are calculated accordingly. Because our estimates ignore areas that are planted but not harvested, we thus provide a lower-bound estimate on crop water use, and our returns estimates provide upper bounds. We thus present the most-conservative analysis framework (low resource use and high returns).

Scenario and Uncertainty Analysis. The year-by-year analysis described above inherently contains farmer response to changing conditions (including hydrological), which are captured in changes in the harvested crop areas. In addition to this analysis, we also modeled responses using a fixed cropland map (2013) and different climate scenarios to isolate the uncertainty due to hydrological inputs versus land use inputs. We ran the model with precipitation input adjusted average values for strong El Niño, weak El Niño, moderate drought, and severe drought scenarios for comparison.

We investigated water yield uncertainty by conducting a sensitivity analysis with a range of ±10% errors in all inputs. Precipitation and evapotranspiration are the largest sources of uncertainty; the other environmental inputs such as root-restricting layer depth and plant available water content are less susceptible to temporal variability for potential modeling errors. Indeed, as the water yield model is more sensitive to precipitation than evapotranspiration, we use the error bounds contributed by precipitation deviation as it has larger influence on the water-yield output. On the consumption side, we likewise used both ±10% errors for both the estimates of crop water use and crop area.

RESULTS AND DISCUSSION

County-Level Water Yield and Consumption. The main results from InVEST's water yield and consumption models are shown in Figure 2. There is a total of 213 watersheds in the county, ranging in size from 36 km^2 (Escarpado Canyon−Panoche Creek) to 349 km^2 (Moreno Gulch). Within the county, the mean elevation increases gradually from around 100 m in the Central Valley to above 2500 m in the Sierra Nevada. Figure 2 highlights the spatial discrepancy between where water is produced and where it is consumed. Surface water resources are located predominantly in the Sierra Nevada (the eastern part of the county), but almost all consumption takes place on the valley floor (Figure 2).

There are about 50 highly productive forestland watersheds in the Sierra Nevada, together generating about 2.5 km^3 of water, 90% of the county's water yield. Conversely, 77 cropland-dominated watersheds are in net deficit. Upper Poso Slough and Moreno Gulch, the watersheds that have the highest water consumption per unit area, around 8000 m^3 per hectare, are located at the heart of the agricultural area. Water yield is strongly tied to vegetation type and coverage. Higher water yield in forestland is due to both the location of precipitation and deeper root and higher water storage capacity to capture and store more runoff. Sustainable forest management practices, such as clearing forest vegetation and selective timber harvesting, can contribute to greater forestland water yield.[33] Conversely, most crops are shallow root plants and are further susceptible to high evapotranspiration due to the lack of shadow and direct solar heating. More than half of the irrigated water on cropland can be lost in a sunny day due to direct evaporation, resulting in relatively smaller water yield service

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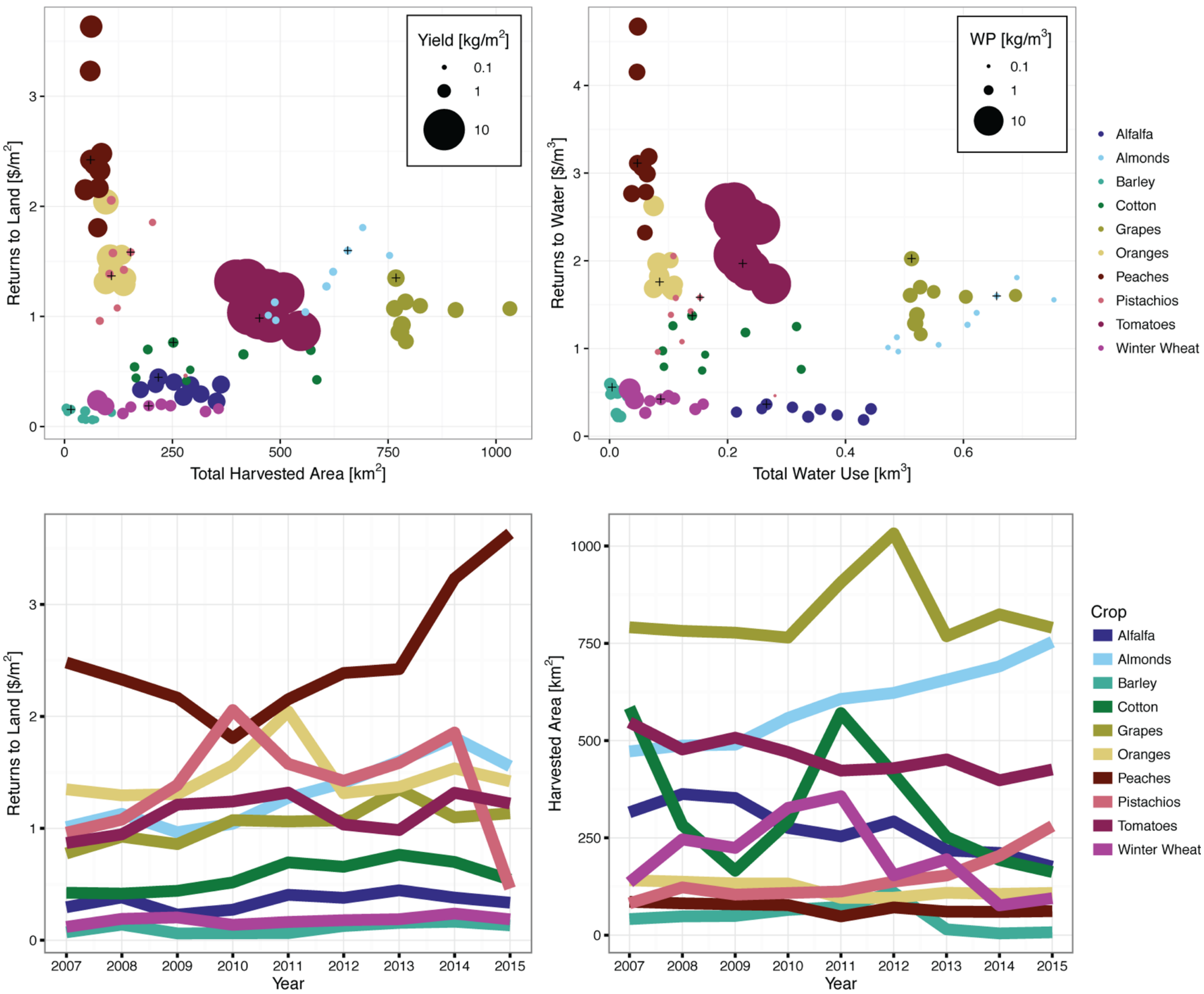

Figure 3. (Upper left panel) Total water use vs returns to water, by crop, in 2007−2015. Size reflects yield (crop production per unit area). Annual and nontree crops can vary more flexibly in land and water use but tend to have lower returns to water than specialty perennials. (Upper right panel) Total harvested area vs returns to land, by crop, in 2007−2015. Size reflects water productivity (crop production per volume of water). In both upper panels, crosses indicate 2013 or the middle of the drought. (Lower left panel) Returns to land of top crops by year in 2007−2015. (Right panel) Harvested areas of top crops by year in 2007−2015.

compared to forestland.[34] The InVEST model does not distinguish between groundwater and surface water, but it can be safely assumed that water yield on forestland watersheds contributes to surface water through runoff into the Kings and San Joaquin Rivers, as well as other Sierra Nevada streams and creeks or to local aquifer recharge.[19]

We calculate that agricultural water use is 95.8% of total water use in the county, making sustainable water management an even higher priority. The average total annual water resupply across all watersheds is a deficit of ∼1.76 km^3 (−3.02 km^3 (deficit) to +2.00 km^3 (surplus)). Based on average 2010−2015 annual weather data, and cropland use maps, Fresno County's water yield output is estimated to be ∼2.05 km^3 (0.15 to 5.37 km^3, all ±17%), and total annual water consumption is ∼3.82 km^3 (3.37 to 3.98 km^3, all ±20%).

Our water consumption estimates are about 12% higher than the figures reported by the United States Geological Survey for 2010, which estimated total withdrawals at 3.44 km^3 of water, with 2.47 km^3 from surface water supplies and 0.97 km^3 from groundwater.[35] It is not surprising that our numbers are larger than USGS estimates, given that groundwater withdrawn from private wells is not tallied into water-management district, county, and state totals. California has seen a proliferation of hundreds of new private wells in the Central Valley, including Fresno County, and both local and satellite-based monitoring efforts have documented the decline in the depth of the water table and overall groundwater storage.[17,36,37]

In theory, a deficit at the county level could simply be an issue of scale, met by surpluses elsewhere that are then transferred into the county. The majority of Fresno's surface water allocations, however, are from the Kings river, draining watersheds and recharging the aquifer within the county borders.[38] Fresno Irrigation District receives a smaller amount of water in some years from the Friant Authority but none, for example, in 2014 and 2015.[39]

Breakdown by Crop. Table 1 shows the breakdown of productivity, land use, and estimated water use by the ten main crops by area produced in Fresno County, averaged over the

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2010−2015 time period. Since 2010, these crops covered on average more than 3035 km^2 (750 000 acres) and used an estimated 2.34 km^3 of water to produce 7.4 million metric tonnes (8.2 million tons) of harvest valued at \$3.3 billion. Alfalfa and nut crops (almond and pistachio) have the highest water consumption per unit area. Percent errors between model land use area (i.e., the sum of all pixels classified as a certain crop type) and reported harvest area range from as little as 18% on average (cotton) to as much as several hundred percent for peaches and oranges (see the Supporting Information). As discussed above, we scale our estimates to reported harvested area for a conservative analysis. Almonds and grapes have the largest harvest areas and total production value and together account for 50% harvest area and 62% of production value for the top 10 crops. Almond, grape, and alfalfa crops are the top 3 water consumers, although grape crops are much more efficient in terms of water use per production than either almonds or alfalfa. Alfalfa represents only 2% of the top 10 crops' total value but uses 10% of the top 10 crops' total harvest water. Also noteworthy is the fact that tomatoes represent 65% of total production by weight, but the tomatoes produced in this region are sold at lower prices because most are used for canning.

Peach ranks highest in both dollar return per unit water and dollar return per unit land use due to its relatively high productivity and unit price. Grape, tomato, orange, almond, and pistachio crops are relatively high in both returns to water and land. Almond and pistachio are the lowest in both production return per unit water and production return per unit land use, while tomato is the highest in both production return per unit water and production return per unit land use. Converting water use to more familiar units, we find that on average over the past 6 years, 1 almond (1.2 g) has required about 1.16 gallons of water to produce, and 1 pistachio (2 g) requires 2.24 gallons. However, despite this high water usage, almond and pistachio still have relatively high return on water due to their high unit prices. Although tomato has the least-expensive unit price, it has relatively high dollar value per harvest water due to its very high productivity. Alfalfa has the lowest dollar return per unit water due to their inexpensive unit price and low productivity. Winter wheat and barley have the lowest dollar return per unit land use due to relatively low productivity and unit prices.

Comparing some of the metrics in Table 1 provides some perspective on which crops are the most productive, in terms of either total production or value of production, per unit land and water. Generally speaking, of course, water use, land use, production, and value of production are all positively correlated, but deviations from that trend are instructive in terms of efficient use of natural resources. Figure 3 shows that, within the top 10 crops, the field crops of barley, alfalfa, wheat (and, to a lesser extent, cotton) have lower returns per unit water but have also shown greater variation in area over time. Conversely, peaches, pistachios, and oranges have higher returns to water and land than average. The time series of returns to land and harvested area over time are shown in the lower panels of Figure 3. Most notably, the share of field crops in total acreage of the top crops has dropped dramatically, from 33% of harvested area in 2007 to 15% in 2015.

Time Trends and Climate Variability. Water yield and water consumption are driven mainly by weather and land use. The calculations in Figures 2 and 3 are based on year-by-year weather and crop use data, as described above. As such, this analysis contains endogenous land use adaptations by farmers. To place recent historical data into context, we also calculated water yield and resupply using average 1980−2010 data[26] with the 2013 Cropland Data Layer. These data are shown together in Figure 4. In an average year, even when accounting for 10%

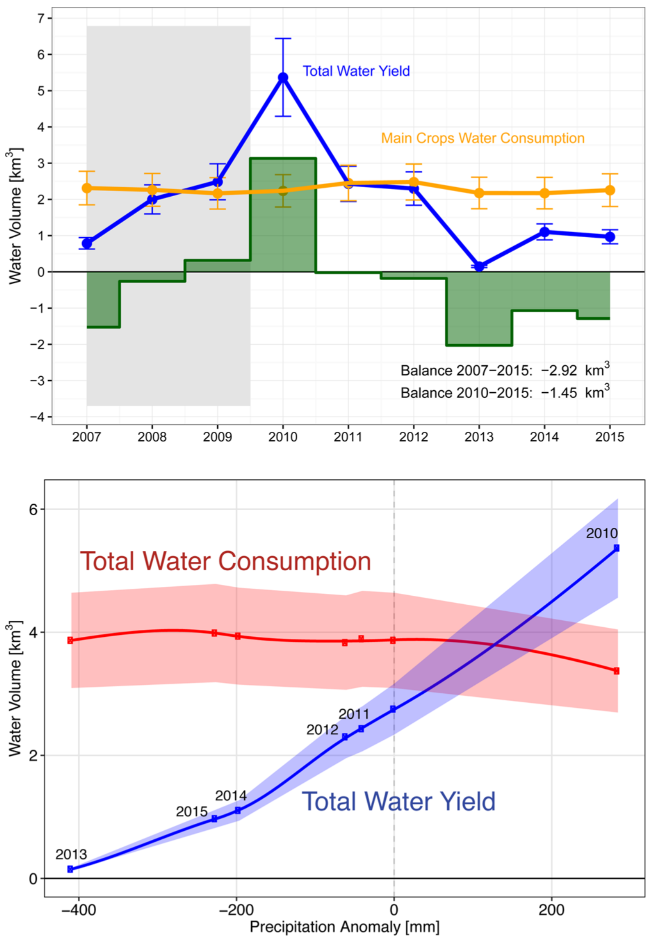

Figure 4. (Upper panel) Total water yield and water consumption by the 10 top crops in Fresno in 2007−2015. The gray shaded area indicates years in which the cropland data layer is at a 56 m × 56 m resolution, which adds uncertainty to both yield and consumption estimates. (lower) Yield and total consumption for Fresno, 2010−2015, as well as for average climatic conditions 1980−2010, plotted as a function of precipitation anomaly. For reference, weak and strong La Niña conditions correspond to moderate and severe drought conditions, respectively, with severe drought, moderate drought, weak El Niño, and strong El Niño conditions corresponding to −160, −80, +100, and +200 mm precipitation relative to the 1980−2010 average.

errors in either direction for precipitation, land coverage, and plant water-application rates, water use exceeds water yield. This becomes even more pronounced in drought years, both because yield declines (due to reduced precipitation) and because evapotranspiration rates rise, and less-effective rainfall exists for plants to use. In extreme drought years, like the ones California has experienced over the past 4 years, we estimate that water use is almost twice as large as water yield, as water use increases by 15%, mainly due to decreasing effective rainfall, and yield drops by 29% in the county. Conversely, we find that estimated water yield and use are well-matched in moist conditions such as weak El Niño years, and that yield exceeds needs in strong El Niño conditions. (El Niño events are

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associated with higher-than-average winter precipitation, including snowpack in the Sierra Nevada, in California.) The scenario modeling suggests that a strong El Niño event contributes to 21% less annual water consumption and 54% more water yield in the county. (However, the modeling of increased effective rainfall during an El Niño year may be an overestimation, as higher water runoff would result from concentrated rain events.) In strong El Niño years, the county could in theory provide near 1 million acre-ft of water for direct recharge of aquifers, which far exceeds the direct recharge investments of previous years (for example, in 2014, this amount was roughly 0.07 km^3).

We also include analysis using the 2013 Cropland Data Layer, but varying input precipitation only, in the Supporting Information. This similar results from this analysis are testament to both the very large fraction of the county planted in orchards and other similar crops (which do not likely change as much in area from year to year and thus have more-constant water demand) and the fact that water yield variability is driven predominantly by precipitation. California is known for its high precipitation variability (compared to the rest of the country), due in part to the fact that most of the precipitation comes in a small number of large events (atmospheric rivers).[40] Nevertheless, an examination of both recent years (Figure 4) and the constant-land-use-varying precipitation analysis indicate that consumption surpasses yield even in average years, which has important implications for long-run sustainability.

Implications for Adaptation. The increasing investment in high-capital cost orchards, vineyards, and specialty crops makes sense from a water and land productivity perspective, but it also effectively removes one margin of adaptation to hydrological variation, the changing of harvested area, from the arsenal of adaptive strategies. With high sunk costs in these kinds of nonfield crops, farmers will be more likely to pump groundwater, even in dry years. Indeed, as shown in the supplementary figures, harvested area and precipitation (and lagged precipitation) only have a statistically significant positive relationships for field crops. This decoupling of land and water management decisions from annual (or even multiyear) hydrology is troubling from a long-term sustainability perspective, even if California's aquifers are more abundant than once thought.[41] Water yield and consumption by the top 10 crops are plotted in time series in Figure 4, showing the very large variation in water yield compared to the relatively small variation in consumption.

Finally, we note that two crops, almonds and alfalfa, account for 40% of the county's annual average modeled water consumption, and elimination of their water demands together, as shown in Figure 4, would erase the annual modeled water deficit for the county in all but the driest years. However, dictating crop choice is obviously neither a feasible nor desirable policy recommendation. Rather, we suggest that ecosystem services modeling can be used to examine the trade-offs between water productivity, land productivity, total production, and value (e.g, Figure 3). This has two benefits: (a) in the short term, farmers near the end of the alfalfa life cycle may decide to switch to a somewhat substitutable crop; and (b) in the longer run, research efforts can be allocated to key economic crops that underperform relative to the mean on water productivity (e.g., alfalfa, almonds, and pistachios). In particular, research is needed on the ability of these key economic tree and fruit crops to perform using deficit irrigation.

Model Limitations. There are several limitations of InVEST modeling. First, the water yield model does not distinguish between surface water and deep groundwater or account for their interaction. The model assumes that all water yield from a pixel arrives the point of interest either as surface water flow or groundwater flow. Subsequently, the model sums and averages water yield to the watershed level. This has important ramifications when considering municipal (drinking) water supply. Currently, Fresno county uses groundwater for municipal water, as surface water flows do not meet drinking water quality standards in many cases. As a result, the county has existing and proposed infrastructure to directly recharge the aquifer using surface flows to maintain an adequate municipal supply. Second, the model produces only annual values of yield and consumption with no seasonal variation; hence, the model neglects nonlinearities that might be associated with extremes and does not account for the temporal dimensions of water supply and demand. It also does not account for additional effects of multiyear trends, such as the recent California drought. Third, the consumption model is not a set of process-based crop models but rather a simple estimate of annual water needs. Nevertheless, use of InVEST allows for the investigation of linked water and land-use decisions and facilitates estimates of otherwise unknown groundwater withdrawals.

Finally, while this analysis takes place at the county and watershed level, these are not closed borders. Most of the water generated in the eastern watersheds drains via the San Joaquin River, the Kings River, and to the eastern side of the Sierra Nevada. Because the county is not a closed hydrological system, some of the water generated within the county exits the county. (Likewise, some surface flows originate in other counties, and groundwater may be recharged by water originating in other counties.) The net impact of water consumption may thus be greater than the county-level deficit if more surplus surface water leaves the county than enters it. This question is beyond the scope of this analysis; however, because water management in California happens at numerous levels that do not exactly overlap with county or watershed boundaries, these dynamics thus remain critically important. In particular, this study highlights the potential for ecosystem services modeling to inform water allocations between water management districts and to provide sensible bounds to data that will be collected on groundwater withdrawals in the near future as part of California's recent Sustainable Groundwater Management Act.

Land management often focuses on one objective (for example, food production), at the expense of other services provided by the ecosystem. Similarly, water management might focus on hydrological objectives at the expense of the provisioning services provided by cropland. Unintended negative ecosystem or social consequences of a particular management scenario can then feedback and, in the longer run, negatively impact food production or sustainable water management potential.[42−44] Here, we have shown how ecosystem services mapping via InVEST can be used to better integrate land and water resource management through linked analysis of water yield and consumption as functions of land use. Quantifying returns to water and land by crop enables policymakers and consumers to evaluate the trade-offs inherent in agricultural land and water management. Similarly, understanding interannual variation may enable more-substantive direct groundwater recharge efforts during wet years without sacrificing crop productivity. Finally, by identifying economically important but relatively underperforming crops in terms

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of returns to water, we highlight where future research and development efforts might be focused for maximum impact.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b05426.

Details of InVEST model inputs; figures showing harvested and planted areas, adaptation of the area planted, constant land use and varying weather; and tables showing water demand and average land and water use. (PDF)

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