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Impact of extreme drought and incentive programs on flooded agriculture and wetlands in California's Central Valley

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Between 2013 and 2015 a large part of the western United States, including the Central Valley of California, sustained an extreme drought. The Central Valley is recognized as a region of hemispheric importance for waterbirds which use flooded agriculture and wetlands as habitat. Thus, the impact of drought on the distribution of surface water needed to be assessed to understand the effects on waterbird habitat availability. We used satellites to quantify the impact the recent extreme drought on the timing and extent of available waterbird habitat during the non-breeding season (July – May) by examining flooding in agriculture (rice, corn, and other crops) and managed wetlands across the Central Valley. We assessed the influence of habitat incentive programs, particularly The Nature Conservancy's BirdReturns and the Natural Resources Conservation Service's Waterbird Habitat Enhancement Program (WHEP), at offsetting waterbird habitat loss related to drought. Overall, we found significant declines in open water in post-harvest agriculture (20 – 80% declines) and in managed wetlands (47 – 59% declines) during the 2013 – 2015 drought compared to non-drought years 2000 – 2011. Crops associated with the San Joaquin Valley, specifically corn, as well as wetlands in that part of the Central Valley exhibited larger reductions in open water than rice and wetlands in the Sacramento Valley. However, seasonal wetlands on protected lands had a marginally significant ($P<0.10$) higher amount of open water in the drought years than those on non-protected lands. A large fraction of the daily open water in rice during certain times of the year, particularly in the fall for BirdReturns (64%) and the winter for WHEP (100%), may have been provided through incentive programs underscoring the contribution of these programs. However, further assessment is needed to know how much the incentive programs directly offset the impact of drought in post-harvest rice or simply supplemented funding for activities that might have been done regardless. Our, first of its kind, landscape analysis documents the significant impacts of the drought on freshwater wetland habitats

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in the Central Valley and highlights the value of using satellite data to track surface water and waterbird habitats. More research is needed to understand subsequent impacts on the freshwater dependent species that rely on these systems and how incentive programs can most strategically support vulnerable species during future drought.

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Impact of extreme drought and incentive programs on flooded agriculture and wetlands in California's Central Valley

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ABSTRACT

Between 2013 and 2015 a large part of the western United States, including the Central Valley of California, sustained an extreme drought. The Central Valley is recognized as a region of hemispheric importance for waterbirds which use flooded agriculture and wetlands as habitat. Thus, the impact of drought on the distribution of surface water needed to be assessed to understand the effects on waterbird habitat availability. We used satellites to quantify the impact the recent extreme drought on the timing and extent of available waterbird habitat during the non-breeding season (July – May) by examining flooding in agriculture (rice, corn, and other crops) and managed wetlands across the Central Valley. We assessed the influence of habitat incentive programs, particularly The Nature Conservancy's BirdReturns and the Natural Resources Conservation Service's Waterbird Habitat Enhancement Program (WHEP), at offsetting waterbird habitat loss related to drought. Overall, we found significant declines in open water in post-harvest agriculture (20 – 80% declines) and in managed wetlands (47 – 59% declines) during the 2013 – 2015 drought compared to non-drought years 2000 – 2011. Crops associated with the San Joaquin Valley, specifically corn, as well as wetlands in that part of the Central Valley exhibited larger reductions in open water than rice and wetlands in the Sacramento Valley. However, seasonal wetlands on protected lands had a marginally significant ($P<0.10$) higher amount of open water in the drought years than those on non-protected lands. A large fraction of the daily open water in rice during certain times of the year, particularly in the fall for BirdReturns (64%) and the winter for WHEP (100%), may have been provided through incentive programs underscoring the contribution of these programs. However, further assessment is needed to know how much the incentive programs directly offset the impact of drought in post-harvest rice or simply supplemented funding for activities that might have been done regardless. Our, first of its kind, landscape analysis documents the significant impacts of the drought on freshwater wetland habitats in the Central Valley and highlights the value of using satellite data to track surface water and waterbird habitats. More research is needed to understand subsequent impacts on the freshwater dependent species that rely on these systems and how incentive programs can most strategically support vulnerable species during future drought.

KEYWORDS: agriculture, California, drought, habitat incentive program, water, waterbirds, wetlands

INTRODUCTION

The Central Valley of California is a region of hemispheric importance for waterbirds (Gilmer et al. 1996; Shuford, Page & Kjelmyr 1998; CVJV 2006). With 90% of the historically occurring natural wetlands in the Central Valley gone (Frayer, Peters & Pywell 1989), agricultural crops that are flooded post-harvest and hydrologically-managed wetlands are essential resources for migratory waterbirds (Elphick & Oring 1998; Dybala et al. 2017; Shuford & Dybala 2017). However, provisioning these crops and wetlands as waterbird habitat is dependent on a highly managed water system, and the availability of water is dynamic (Reiter et al. 2015; Reynolds et al. 2017). Climate change projections suggest that the inter-annual variability in the amount of waterbird habitat may increase with time, even if long-term declines in average precipitation are not projected to be substantial (Matchett & Fleskes 2017), making understanding how to manage through extremes critically important.

Between 2013 and 2015, the Central Valley of California and a large part of the western United States sustained a severe drought (Griffin & Anchukaitis 2014). Because California's water is so highly managed, anthropogenic factors play a large role in determining when and where drought impacts appear on the landscape (Hanak & Lund 2012). Further, drought status, as measured by changes in precipitation, within the Central Valley may be less important to the availability of water in the Valley than the amount of snow pack in the surrounding Sierra Nevada which is the source of much of the Valley's water (Carle 2015). Previous analyses highlighted that while drought conditions across California's Central Valley may be observed as a reduction in surface water in the southern Central Valley (San Joaquin Valley) in the year of the drought, often multiple years of drought are required to see changes in the northern portion of the Central Valley (Sacramento Valley; Reiter et al. 2015). The recent extreme and multi-year drought affecting California provides opportunity to gain additional insights into how more prolonged and extreme variations in the hydrology of the Sacramento and San-Joaquin watersheds may influence the distribution of waterbird habitat. This is especially important given that the incidence of such extremes is projected to increase in the future (Synder, Sloan & Bell 2004; Matchett & Fleskes 2017).

In response to the drought, water restrictions (e.g., Term 91: Stored Water Bypass Requirements) were put into place in the Central Valley in the fall of 2014. The impact of these restrictions, increasing water costs (Howitt et al. 2014), and lack of precipitation on the distribution of surface water needs to be assessed to understand the impacts on waterbird habitat availability. Concurrent with this recent drought has been the implementation of two incentive programs to help offset the cost of flooding agricultural fields to provide wetland habitat for migratory waterbirds (i.e., The Nature Conservancy's BirdReturns program [Reynolds et al. 2017; Golet et al. *In Press*]; Natural Resources Conservation Service's Waterbird Habitat Enhancement Program [WHEP; Strum et al. 2014]). The extent to which these incentive programs offset habitat losses due to drought is not known. BirdReturns focused specifically on shorebirds, providing habitat <10cm deep, in September and October and then again February to early April. WHEP incentivized flooding from November to February and then a staged draining of those fields in February to provide habitat into March.

Previous analysis of Central Valley water availability quantified the extent of open surface water in the Central Valley between July and December for 2000 – 2011 (Reiter et al. 2015). To better characterize the magnitude and impacts of the recent severe drought and to assess the relative contribution of flooded habitat as the result of incentive programs, analyses of more recent data compared to longer-term estimates (2000 – 2011; Reiter et al. 2015) of water extent were needed. Hence, our objectives with this study were to:

1. Quantify the impact of the recent extreme drought between 2013 and 2015 on the timing and extent of available waterbird habitat (flooded agricultural fields and managed wetlands) during the non-breeding season (July – May) across the Central Valley.
2. Assess the influence of two incentive programs, BirdReturns and WHEP, at offsetting waterbird habitat loss as the result of drought.

METHODS

Study Area

We considered the Central Valley Joint Venture planning region (Dybala et al. 2017) to be the focal area for this study. We further divided up the region for some analyses according to Shuford & Dybala (2017) and defined the Sacramento Valley, the Sacramento-San Joaquin River Delta, the San Joaquin Valley, and the Tulare Basin (Fig. 1). The Central Valley falls completely within the Great Valley ecoregion (Hickman 1993), and extends >400 km north to south and up to 100 km east to west; bounded by the Sierra Nevada and California Coastal Range mountains. The Central Valley climate is generally cooler and wetter in the north (Sacramento Valley) than in the south (San Joaquin Valley and Tulare Basin). Water allocation and use in the Central Valley is highly managed and the southern portion of the Valley often relies on the water transfers from the north (Hanak & Lund 2012). Consequently, there is less flooded agriculture in the south and higher year to year variability in flooding compared to in the north (Reiter et al. 2015). The majority of surface water in the Central Valley originates from snow pack in the surrounding Sierra Nevada mountains (Carle 2015).

Data and Models

We derived data on the distribution of open water across the Central Valley for 1 July – 15 May using satellites and the supervised classification remote sensing techniques of Reiter et al. (2015). We used Landsat 5's Thematic Mapper for the period of 2000 – 2011 and Landsat 8's Operational Land Imager and Thermal Infrared Sensor for the period of 2013 – 2015. Separate boosted regression tree models were developed for each of the satellite's sensor suites (Elith &

Leathwick 2009). We used data combined from ground and aerial surveys (*n* = 10,221 for our Landsat 5 model and *n* = 27,058 for our Landsat 8 model) to develop our models and to compare the relative bias associated with the predictions from each model. To prevent classification bias influencing our inference in this analysis, we bias-corrected the estimates of open water by the average difference between the true and estimated open water calculated using the ground-truth data for each sensor. We used separate correction factors for wetlands, rice, corn, and other crops.

We evaluated open water dynamics from July – May for the whole valley across several waterbird habitat specific cover types (seasonal and semi-permanent wetlands, rice [*Oryza* spp.], corn [*Zea mays*], and other suitable filed crops and row crops [e.g. *Triticum* spp.; *Gossypium* spp.; *Solanum lycopersicum*]; see Dybala et al. 2017). To derive the amount of water by specific cover types (and to ensure that changes in water were not the result of changes in base acreages of potential habitat), we used two layers for wetlands and for agriculture representing the early 2000s (Stralberg et al. 2011) and then more recent habitat maps (Petrik, Fehringer & Weverko 2014; The Nature Conservancy 2007 – 2014, unpublished data). We considered cover types that were the same in both time periods as the baseline for assessing the proportion of each cover type that was open water. We overlaid the open water layers on the habitat base layer to derive the proportion of each cover type that was open water.

Because the dynamics of water in the Central Valley are often non-linear, we followed Dybala et al. (2017) and used generalized additive mixed models (GAMMs; Wood 2006; Wood & Scheipl 2014) to assess the influence of time of year, drought, precipitation, region and protected status (wetlands only) on the proportion of open water in selected cover types between 1 July and 15 May of the following year. We evaluated GAMMs separately for each cover type. We fit a set of five models to agricultural crop data for 2000 – 2015 and 6 models to wetland cover type data (Table 2; also see covariate descriptions below). We filtered our data to only include satellite images with <50% cloud cover and then weighted observations in the model by the percent that was cloud free (50 – 100%). We included a random effect of water year and individual observation to account for correlation among years and overdispersion in the data, respectively.

We characterized the impact of annual water conditions and drought by considering our full 2000 – 2015 data set to include three sets of water years (year types): non-drought years 2000-2011 (2002 – 2006), drought years 2000 – 2011 (2000 – 2001, 2007 – 2011); and recent drought (2013 – 2015). For our analysis, we considered a drought year to include any water year designated as “drought” or “critical” by the State of California Department of Water Resources (CDWR). The State’s criteria for “drought” or “critical” are based on the projected runoff (million acres feet) on 1 May (see http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST for details on the level for each classification and data access). We also considered all year combined of the 2000 – 2011 set as the recent long-term average with which to compare with the 2013 – 2015 drought.

Because rainfall likely influences the extent of open water on the landscape, we evaluated models that included estimates of total precipitation within the last two and four weeks. Rainfall data were taken from daily historic rainfall amounts recorded at weather stations via the NOAA National Climatic Data Center (www.ncdc.noaa.gov/cdo-web). To characterize rainfall, we used data from weather stations in the northern and southern parts of the valley (Sacramento Metropolitan Airport and Fresno Yosemite International Airport) which had consistent temporal coverage across our study period. For each station, we calculated two- and four-week running totals then averaged these across stations. This precipitation data was then matched to the average date of the three main Landsat scenes covering the Central Valley for a given two-week period. These models allowed us to characterize the effect of rainfall and specifically if there were differences in the effect across cover types. We hypothesized that agriculture cover types would be more likely to show a precipitation signature as there are many hectares that are not flooded in any given July – May period whereas a larger fraction of managed wetlands is likely flooded already by mid-to-late winter (Dybala et al. 2017) when precipitation is likely to have its greatest impact.

We also suspected during this most recent drought that even though protected wetlands received cuts in water allocation, privately managed wetlands might show the greatest decline in open water due to increases in water costs. To assess the impact of drought on private versus protected area wetlands, we considered protection status as a single-factor in models and allowed an interaction with the year type (Table 2). We derived the protection status using the California Protected Area Database (CPAD 2016) overlaid on the habitat cover type layer to identify wetland cover types that fell within a protected area. The California Protected Area Database defines protected areas as those that are owned in fee and managed for open space purposes. Any cover types that fell outside of a protected area were assumed to be private or not protected. Since nearly all agriculture is on private land, we did not evaluate this factor for models of rice, corn, or other crops.

To be able to better understand how within year temporal availability of open water might differ in this dynamic system and given that interactions with smoothing terms (herein, day) are hard to include in GAMMs, we also fit separate GAMMs for each of the three year types (non-drought 2000 – 2011, drought 2000 – 2011, recent drought 2013 – 2015) in each cover type. We plotted the model fitted values and 95% CI for each of the three data sets for each crop type to evaluate variation in the magnitude of the differences through the year.

To characterize spatially variability in the impact of drought on wetlands, we compared the dynamics of open water in seasonal wetlands between the Sacramento Valley and San Joaquin Valley. These are the regions of the Central Valley with the most extensive managed wetlands and previous analyses have shown differences in the impact of drought between the two regions (Reiter et al. 2015). We fit separate GAMMs to seasonal wetland data from each region that compared all three year-type groups (non-drought 2000 – 2011, drought 2000 – 2011, recent drought 2013 – 2015).

Incentive Programs

To characterize the relative contribution of the BirdReturns and WHEP habitat incentive programs, we calculated the proportion of the total estimated flooded rice habitat in the Sacramento Valley that was provided by these programs. Specifically, we evaluated the contribution of fields that were flooded between July 2013 and May 2014 and again between July 2014 and May 2015. We compared the relative contribution of these programs to the habitat available in rice during the most recent drought (2013 – 2015) as a measure of the relative return on investment.

As the incentive programs largely focused on the Sacramento Valley, we developed a GAMM of rice flooding using a subset of the data for that geography for the comparison (Fig. 1). We considered a combined model for the 2013 – 2015 data that included a smoother term of day of the year relative to 1 July and an observation level random effect to account for overdispersion. We then multiplied the model-fitted proportion flooded by the estimated amount (ha) of rice planted in each year (216,105 ha in 2013 and 169,606 ha in 2014; Dybala et al. 2017) to get the area that was open water in each day. We then back-calculated to get the proportion of habitat provided per day in the each of the two year sets. Because the duration of flooding can influence the value of the habitat, we considered a metric “habitat ha days” for additional comparisons. Habitat ha days is the sum of all flooded ha across all days in the year. Each flooded ha on a day contributes one habitat ha day to the calculation.

To account for habitat (rice with water with depth >0cm) remaining after the end of the incentivized flooding practice as the fields slowly drained, we estimated the average duration of in which there was water post-practice end date using data from another study in rice (Point Blue unpublished data). We fit a GAMM to estimate the probability that an individual field would have waterbird habitat (>0cm depth or >0%flooded or >%50 saturated) as a function of the days since the initiation of draining the field using observations from February – March in 2012 and 2013. Because data had repeated visits to individual fields, we considered field as a random effect in the model. We multiplied the fitted probabilities by day since draining was initiated by the amount of habitat when the draining started in the different incentive program datasets to estimate the amount of habitat remaining. We evaluated both a minimum estimate of habitat provided (assumes no habitat provided during drawdown following of end of practice) as well as the model corrected estimates.

Overall, we evaluated relative model fit for each cover type and analysis using the adjusted-R^2. We characterized the effect size of covariates in our logistic GAMMs using the odds for individual effects (Zuur et al. 2009). Specifically, we calculated the percent change by a drought year over non-drought or average years 2000 – 2011 in our models as $(e^{Bxi} – 1)*100$; where B_{xi} is the coefficient estimate for factor *x*, level *i*. All statistical analyses were completed using R v.3.3 (R Core Team 2017) and the ‘gamm4’ package (Wood & Scheipl 2014).

RESULTS

Assessment of water classification models suggested some subtle differences in bias between our Landsat 5 and Landsat 8 derived data (Table 1). Overall, across cover types the Landsat 8 model was more accurate. Among cover types, open water in freshwater emergent wetlands was predicted with the lowest accuracy by both satellites. Only in the case of corn did the directionality of the bias differ between the sensors. We used these cover type specific values to correct our observed estimates from each classification model.

Models for open water in rice, corn, seasonal and semi-permanent wetlands were a reasonable fit to the data and explained 30 – 79% of the variance (Table 2). Models for other crops consistently explained relatively less of the variation. There were significant declines in open surface water during the recent drought (2013 – 2015) in all cover types evaluated except for semi-permanent wetlands (Table 3, Table 4). In the agricultural landscape, the recent drought resulted in significantly less open water than the long-term average and non-drought years, with respective yearly declines in rice (25 and 46%), corn (77 and 81%), and other crops (64 and 71%) (Fig. 2). However, in rice this effect was no longer significant after accounting for precipitation (2-weeks or 4-weeks) which had a significant positive effect on open water and was prominent in non-drought years (Fig. 3, Table 3). For both corn and other crops, precipitation had a marginally significant ($P < 0.10$) to significant ($P < 0.05$) positive effect on open water, however the effect of recent drought remained significant even after precipitation was controlled for in the models (Table 3).

While seasonally flooded managed wetlands showed significant declines in open water in the recent drought (47 – 59% declines) compared to historic non-drought and average years (Fig. 4; Table 4), changes in semi-permanent wetlands were not significant, though all drought variable coefficients had point estimates that were negative. Precipitation did not have a significant effect on managed wetlands, however, between 2000 and 2015 seasonal and semi-permanent wetlands had different amounts of open water with respect to protected areas during drought years. Semi-permanent wetlands had significantly ($P<0.05$) higher open water on non-protected land (35 – 43%) compared to protected areas whereas seasonal wetlands had marginally significant ($P<0.10$) more open water in protected areas (56 – 62%) than on non-protected land (Table 4). The effects of protected land appear to be magnified during the recent drought with significant interactions detected between protection and recent drought years compared to non-drought years 2000 – 2011 and all years 2000 – 2011. The direction of the interaction was the same for seasonal and semi-permanent wetlands.

Patterns of seasonal wetland inundation differed between the Sacramento Valley and the San Joaquin Valley, as did the impact of drought (Fig. 5). Seasonal wetlands in the Sacramento Valley overall have a higher proportion of open water and experienced, on average, 63 – 69% declines in open water during the 2013 – 2015 drought while the San Joaquin Valley had declines of 85 – 86% (Table 5). Additionally, the San Joaquin Valley showed evidence of a lower but more prolonged peak in open water than the Sacramento Valley in both drought and non-drought years (Fig. 5).

Modeling year types separately emphasized the temporal differences in water dynamics among years. In particular, it highlighted the period with the largest reductions in open water occurring between October and March (Fig. 2, Fig. 4). In rice, the recent drought reduced open water particularly in February and March but also in April and May, while in corn and other crops there was substantially reduced water in nearly all months. The reductions in water in all crops were particularly pronounced October to March and then again in May. In seasonal and semi-permanent wetlands, the nearly 50% reduction in water was largely observed between October and March (Fig. 4).

The effect of incentive programs was noticeable when looking at flooding on the landscape in rice in the Sacramento Valley (Fig. 6). The total area incentivized as part of BirdReturns in the region was 4,980 ha in spring 2014, 2,759 ha for fall 2014, and 1,357 ha for spring 2015 (Golet et al. *In Press*). Given the composition and duration of practices, this resulted in a minimum estimated total of 168,022 habitat ha days between 1 February and 4 April 2014 and, 85,666 habitat ha days between 1 September 2014 and 31 March 2015. WHEP incentivized 32,473 ha and 32,471 ha of habitat creation respectively in 2013 – 2014 and 2014 – 2015, which resulted in a minimum of 3.3 million habitat ha days across the entire time period. Our model suggested that there is a > 0 probability of waterbird habitat for up to 30 days after the end of the incentivized practice and the initiation of draining. After accounting for a slow drawdown of water after the practices were complete and draining was initiated, BirdReturns provided an estimated total of 221,072 habitat ha days occurring between 1 February and 4 May 2014 (adds 30 days to latest end date of practice) and 128,046 habitat ha days between 1 September 2014 and 30 April 2015, while WHEP provided 3.7 million habitat ha days in both 2013 – 2014 and 2014 – 2015. On days when the program was active between 1 September and 31 October 2014, BirdsReturns provided 14 to 64% (mean = 39%) of the waterbird habitat in flooded rice fields (Fig. 6). In the spring (2014: 1 February – 4 May; 2015: 1 February – 28 April) BirdReturns provided proportionally less habitat than in fall with on average 6% per day (min = 1%, max = 14%). When active in the winter (1 November to 31 January) WHEP, on average, provided 68% (Min = 35%, Max = 100%) of the daily flooded rice and while between 1 February and 7 March, WHEP provided 31% (min = 15%, max = 48%)

DISCUSSION

The extreme drought recently experienced in California had impacts on human, agricultural, and natural systems. Our study highlights that the drought caused a significant reduction in open water habitats across the agricultural and wetland landscapes of the Central Valley and that the impact varied spatially and temporally. The observed decline ranged from 20 – 80% depending on cover type, time of year, and region. Overall, post-harvest flooded rice declined less during the drought than flooded corn, other waterbird compatible crops or seasonal wetlands. Further, seasonal wetlands in the San Joaquin Valley declined more than in the Sacramento Valley confirming previous observations of spatial differences in the impact of drought across the Central Valley (Reiter et al. 2015).

The 2013 – 2015 drought appears to have been more severe in reducing waterbird habitat than previous droughts between 2000 and 2011. Estimates of open water for the 2013 – 2015 drought were lower than drought years between 2000 and 2011 across nearly all models and cover types. The length and severity of the drought likely contributed to the observed decline as water restrictions were enacted and the cost of water began to increase (Howitt et al. 2014). More intensive modeling, however, is needed to tease out these policy and socio-economic drivers of changes in water applied to the landscape.

Our analysis highlights that precipitation can help supplement the open water habitat that is largely created through intentional water diversions to wetlands and flooded agriculture from snow melt in the Sierra Nevada (CVJV 2006; Hanak & Lund 2012; Golet et al. *In Press*). The strong positive effect of precipitation was most noticeable in agricultural cover types and particularly in rice. Based on our models, much of the reduced flooding in rice in the recent drought compared to non-drought years may be the result of less rain and potentially less saturated soils that can become open water with additional rainfall. While much of this precipitation-driven water detected using satellites may be shallow, it certainly has value for shorebirds, wading birds and other freshwater dependent taxa, even if it is too shallow for most waterfowl (specifically ducks; Strum et al. 2013).

Mid-winter or peak flooding (November to February) appeared most affected across cover types. Fall, which is generally the driest time of the year (Reiter et al. 2015) and is already a period of habitat limitation for migratory shorebirds (Dybala et al. 2017), remained dry across cover types evaluated, but did not show particularly significant reductions in open water during the drought. The flooding pattern was similar in spring, however our results suggest that open water in post-harvest rice declined very quickly and was particularly low March through May during the 2013 – 2015 drought. Open water in rice during April and May, which is associated with the planting of the rice crop, was also delayed during the drought, supporting previous findings of drought impacts on open water and exacerbating the mismatch in the timing of habitat for migratory birds (Shaffer-Smith et al. 2017).

Open water in post-harvest rice experienced some of the smallest declines compared with other crop types and seasonal wetlands. While this is consistent with previous work that highlights the resilience of the Sacramento Valley compared to other regions (Reiter et al. 2015), in part driven by many rice growers having senior water rights, our results also suggest that a large fraction of the open water in rice (up to 100% of observed) during certain times of the year, particularly fall and winter, may have been provided through incentive programs. The value of incentive programs to generate habitat and ecosystem services in the Central Valley has been documented (Duffy & Kahara 2011, DiGaudio et al. 2015, Golet et al. *In Press*), yet this is the first regional-scale assessment of the effectiveness and additionality of incentive programs in providing wetland habitat during drought and further underscores the contribution of these programs. BirdReturns was particularly effective at providing habitat in fall; a period that is already thought to be food limiting for migratory shorebirds (Dybala et al. 2017). Fields enrolled in BirdReturns during in fall 2014 had some of the highest shorebird densities ever reported for agriculture in this region, confirming this to be a time of habitat deficit (Golet et al. *In Press*). The Waterbird Habitat Enhancement Program was effective during the period of peak flooding when nearly 70% of available habitat on was provided by the program. However, it is not known what proportion of those individuals enrolled in either BirdReturns or WHEP would have adopted the enhancement practices even if the incentive payments were not available (Baumgart-Getz, Prokopy & Floress 2012; Reimer et al. 2014). Further assessment is needed to know how much the incentive programs directly offset the impact of drought in post-harvest rice or simply supplemented funding for activities that might have been done regardless.

Wetland habitat availability in the Central Valley is highly dynamic both within and among years. While habitat availability appeared to decline substantially during some points of the year in certain cover types, our analysis does not directly assess the potential impacts to the wildlife that rely on these systems. Recent work by Petrie et al. (2016) indicated that the drought in the Central Valley could have had significant impacts on waterfowl populations. They used expert opinion to develop drought scenarios and a bioenergetics model to determine impact to waterfowl from a food energy perspective. The scenario they developed assumed a 25% decline in flooded wetlands in 2014 – 2015. Our satellite and model derived estimates for the same period suggest a much more severe impact of the drought on wetlands than was assumed by Petrie et al. (2016).

Parameterizing their bioenergetics model with data from this study could help to further illuminate the species and population level impacts of the drought. Similarly, a recently developed bioenergetics model for shorebirds could further assess the impacts of drought on these species which rely on open water cover types in wetlands and flooded agriculture (Dybala et al. 2017). However, integrating our data with bioenergetics models for waterfowl or shorebirds will require the development of two additional parameters for drought not evaluated here; changes in wetland moist soil seed productivity (Naylor 2002) and changes water depth profiles (Dybala et al. 2017).

Open water in seasonal wetlands declined significantly during the recent drought in both the Sacramento Valley and the San Joaquin Valley; regions that were also found to differ in their inundation patterns. While generally the peak proportion of open water is higher in seasonal wetlands in the Sacramento Valley compared with the San Joaquin Valley, the peak proportion of open water appears to occur earlier and remains on the landscape longer in the San Joaquin Valley (November through March) compared to further north (end of November through early March). While we do not know the exact cause of these different patterns, recent studies of overwintering shorebirds in the Central Valley suggest that shorebirds in the more hydrologically dynamic Sacramento Valley move longer distances and migrate out of the area significantly more than birds in the San Joaquin Valley (Point Blue unpublished data). Differential patterns of wetland inundation may be driving some of these observed differences. Incorporating different flooding patterns among regions of the Central Valley into bioenergetics models (Petrie et al. 2016; Dybala et al. 2017) could inform strategies of how to maximize the value of the habitat created across the whole landscape for waterfowl and shorebirds.

CONCLUSIONS

Climate change models and habitat projection scenarios for California indicate the strong likelihood of increasing temperatures and more, potentially extreme, variation in precipitation patterns (Snyder, Sloan & Bell 2002; Matchett & Fleskes 2017). With more limited water resources, incentive programs and wetland managers will need to be ever more strategic in how they allocate water. While many sophisticated models of water scenarios can be evaluated (e.g. Draper et al. 2003, Yates et al. 2009), understanding how water and wetland habitats are ultimately distributed on the landscape in space and time is needed for water managers to make decisions that maximize the value of the limited water resources for wildlife (DWR 2009). While more work is needed to understand the specific driving mechanisms and spatial patterns of water in the Central Valley to help guide decisions on precisely where and when to put water in this highly managed landscape, our assessment provides a perspective of the impacts of extreme drought and where water management needs to focus in the face of additional, and potentially more extreme, drought events.

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Figure 1

Map of the Central Valley study area in California, USA.

The Central Valley Joint Venture boundaries and specific regions of the Central Valley are identified.

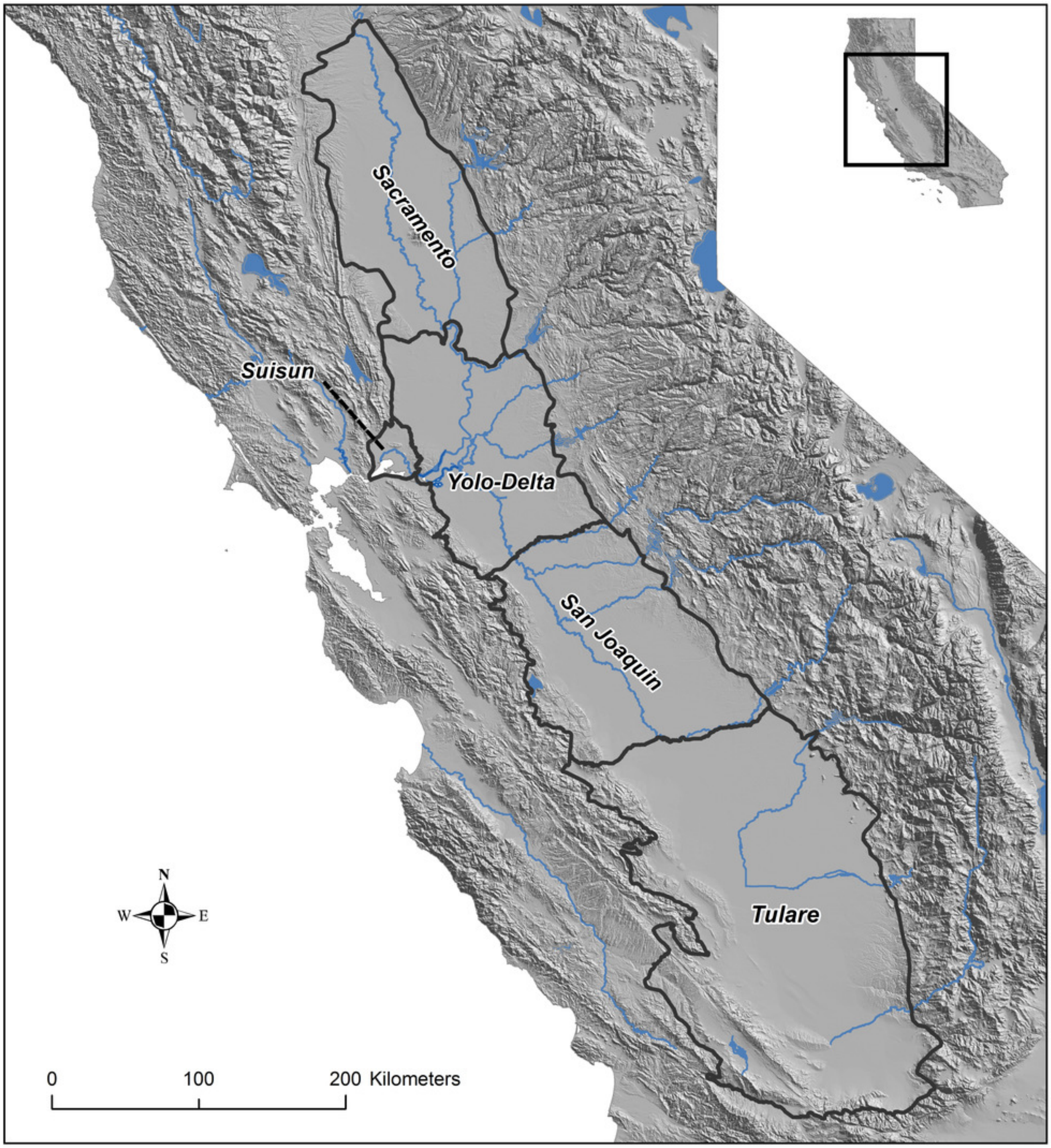

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Figure 2

Estimated proportion of rice, corn, and other crops that was open water in the Central Valley of California between 1 July and 15 May based on data from 2000 – 2011 and 2013 – 2015.

Estimates were derived from separate models for each year group of Non-Drought 2000 – 2011 (blue), Drought 2000 – 2011 (green), and Extreme Drought 2013 – 2015 (gray). Fitted means are plotted with 95% confidence bands.

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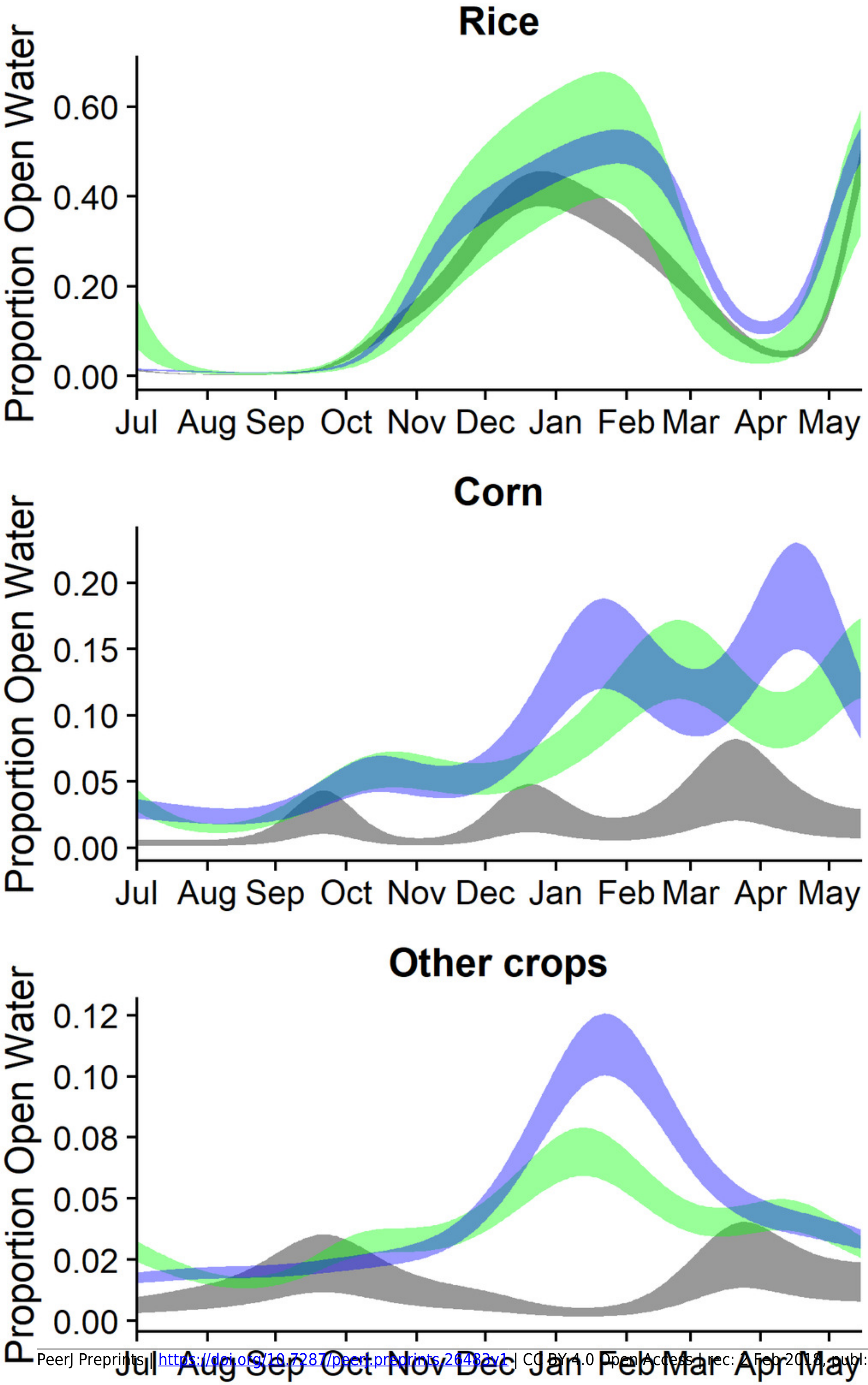
Rice
Proportion Open Water
0.60
0.40
0.20
0.00
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Corn
Proportion Open Water
0.20
0.15
0.10
0.05
0.00
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Other crops
Proportion Open Water
0.12
0.10
0.08
0.05
0.02
0.00
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May

Figure 3

Estimated proportion open water in rice 1 July – 15 May in the Central Valley of California in a non-drought year when accounting for precipitation.

‘No Precip’ assumes no rain falls whereas ‘Precip’ assumes average rainfall. Open water estimates were derived from generalized additive mixed models fit to water distribution data from 2000 – 2015.

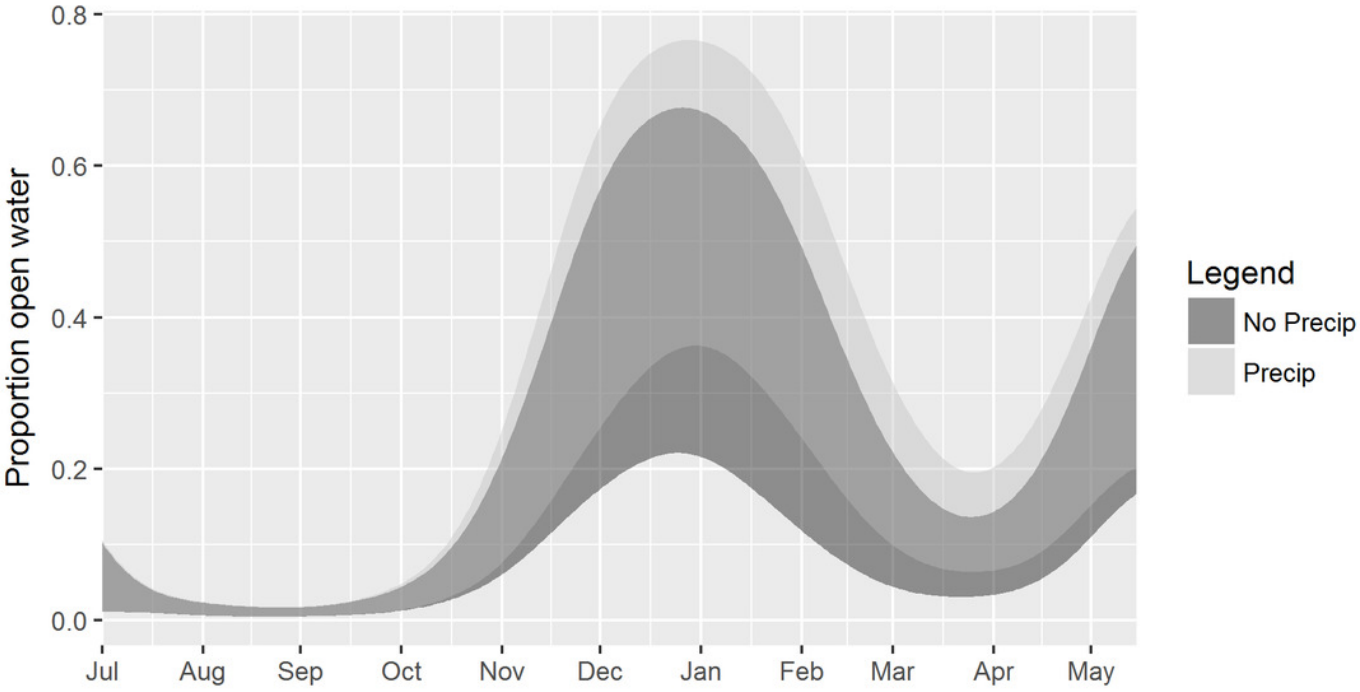

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Figure 4

Estimated proportion of seasonal wetlands and semi-permanent wetlands that was open water in the Central Valley of California between 1 July and 15 May based on data from 2000 – 2011 and 2013 – 2015.

Estimates were derived for each year group of Non-Drought 2000 – 2011 (blue), Drought 2000 – 2011 (green), and Extreme Drought 2013 – 2015 (gray) from separate models. Fitted means are plotted with 95% confidence bands.

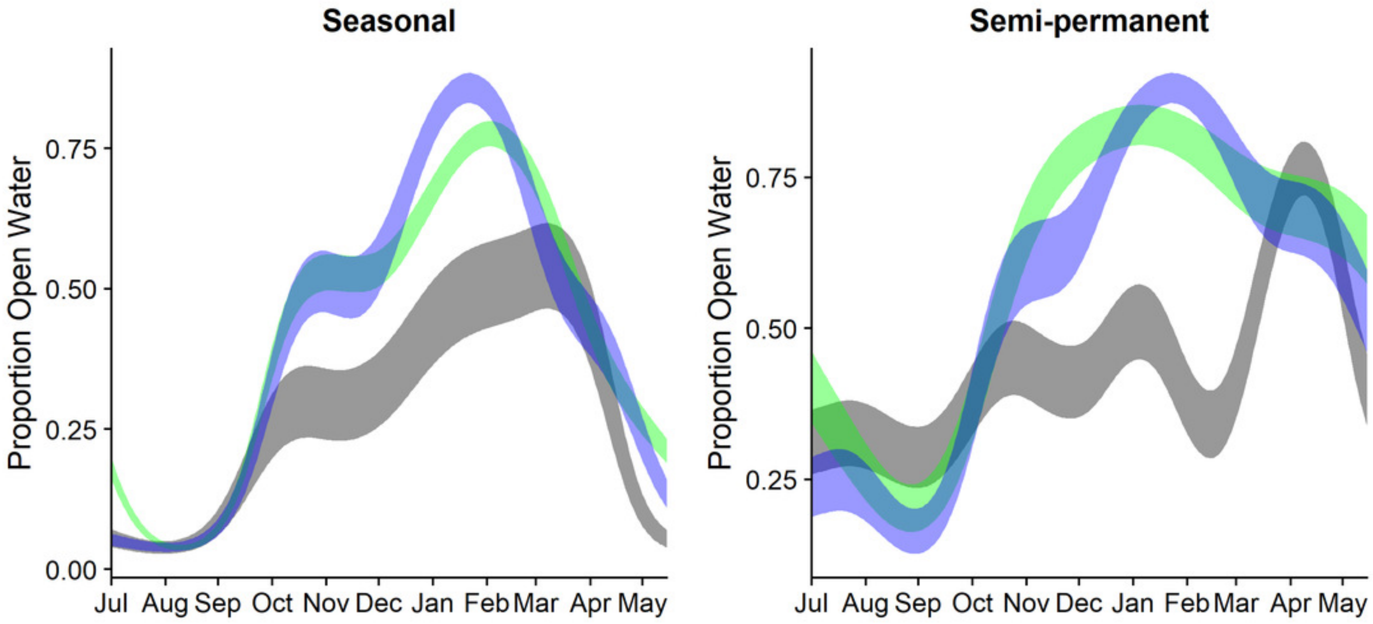

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Figure 5

Proportion of seasonal wetlands that was open water in the Sacramento Valley and San Joaquin Valley of California.

Estimates were derived using a single model and a factor for each year group of Non-Drought 2000 – 2011 (blue), Drought 2000 – 2011 (green), and Extreme Drought 2013 – 2015 (gray). Fitted means are plotted with 95% confidence bands.

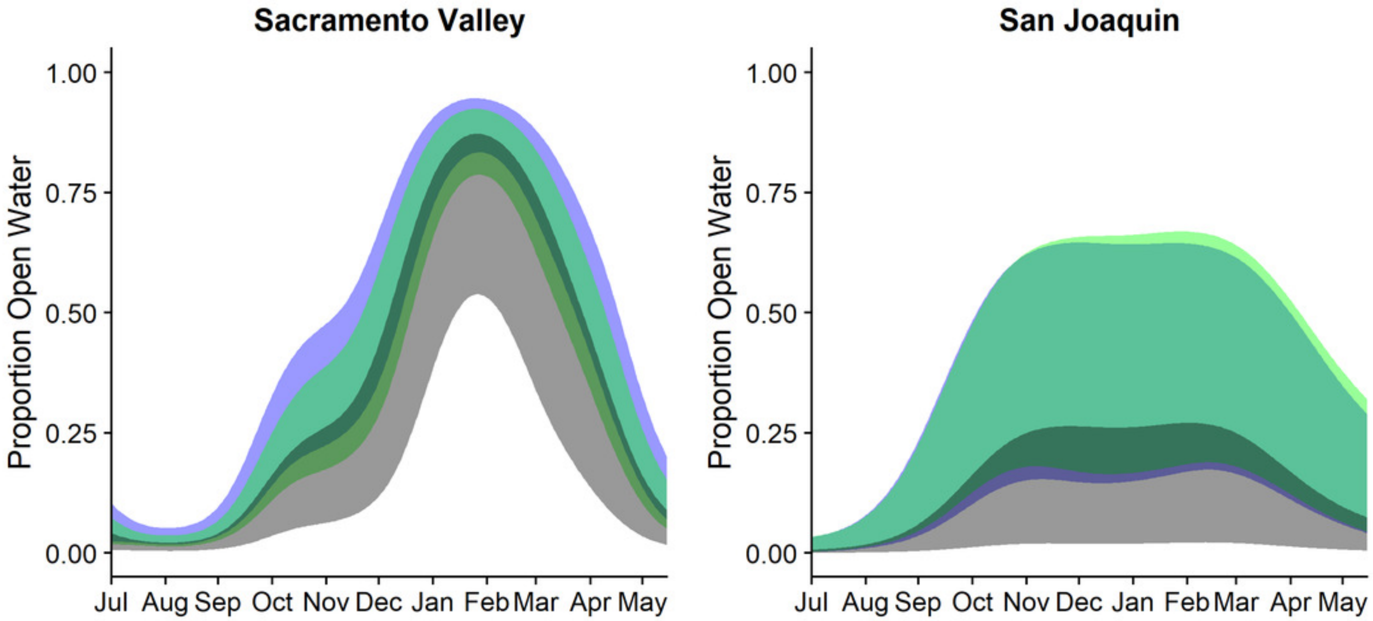

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Figure 6(on next page)

Estimated average daily percentage of open water in post-harvest rice provided by habitat incentive programs when active.

Incentive programs were The Nature Conservancy's BirdReturns Program (BR) and the Natural Resources Conservation Service's Waterbird Habitat Enhancement Program (WHEP). Three time periods evaluated were 1 September to 31 October (Fall), 1 November – 31 January (Winter) and 1 February to 4 April (Spring). Note: WHEP was only active 1 February – 1 March in spring as fields were drained.

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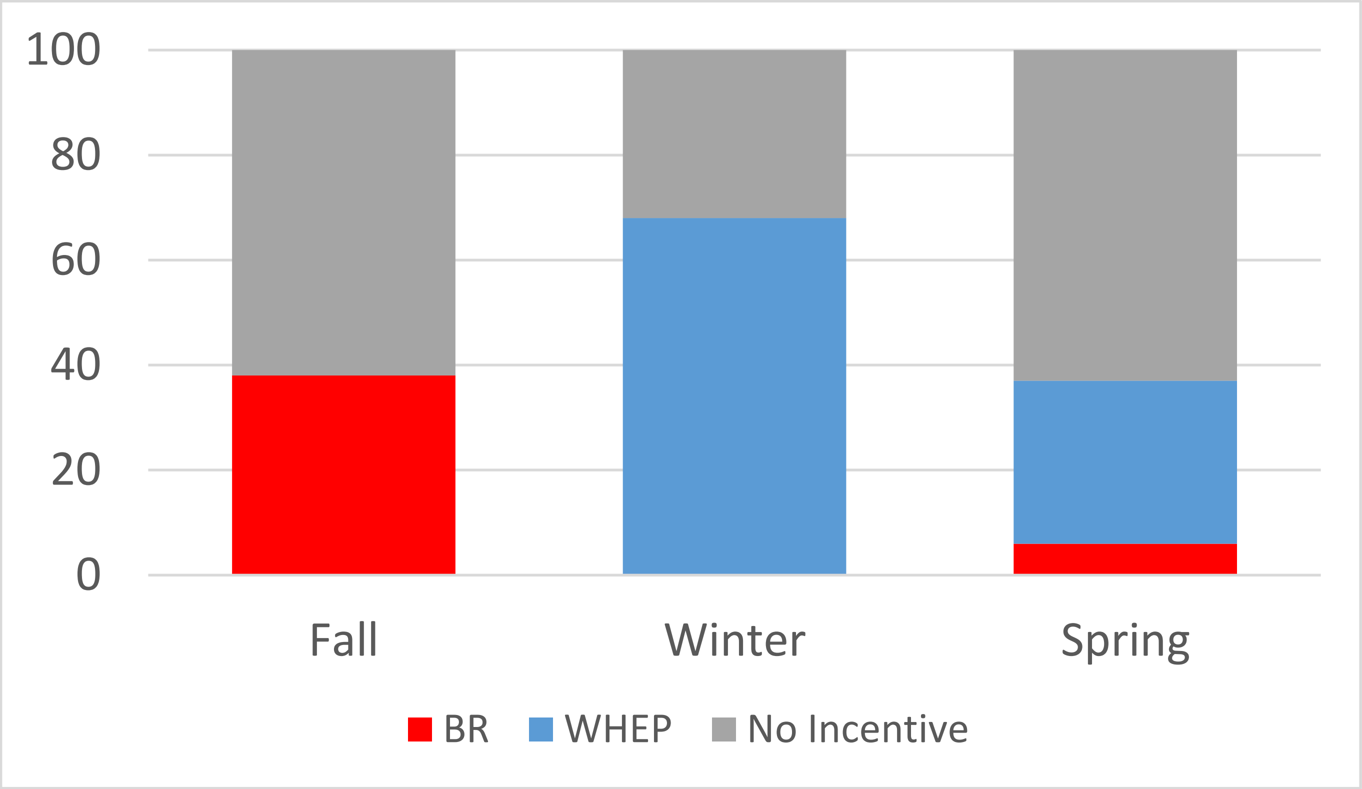
100
80
60
40
20
0
Fall
Winter
Spring
BR
WHEP
No Incentive

Table 1(on next page)

Summary of accuracy and bias of estimates of open water by different satellites (Landsat 5 ETM and Landsat 8 OLI) in different cover types for the Central Valley of California.

Satellite	Cover Type	N	Accuracy	Bias
Landsat 8	Corn	2237	0.95	0.05
Landsat 5	Corn	46	0.89	-0.07
Landsat 8	Rice	2756	0.94	0.04
Landsat 5	Rice	640	0.89	0.03
Landsat 8	Other	1005	0.99	0.001
Landsat 5	Other	475	0.96	0.003
Landsat 8	Freshwater emergent wetland	1765	0.88	-0.11
Landsat 5	Freshwater emergent wetland	5564	0.79	-0.01

1

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Table 2(on next page)

Adjusted-R^2 values for generalized additive mixed models fit to assess the proportion of open water in three crop types and two managed wetland types in the Central Valley of California 2000 – 2015.

Crop types included rice, corn, other crops (field crops, row crops, grain crops) and managed wetland types were seasonal and semi-permanent. Adjusted-R2 values indicates what proportion of the variance in the data the model explains. The protection variable was not included in crop type models.

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Model	Rice	Corn	Other	Seasonal	Semi-Permanent
Day[1] + Year Type[2]	0.61	0.28	0.14	0.79	0.56
Day + Year Type*Protection[3]+ Precip2wk[4]	0.63	0.28	0.15	0.79	0.59
Day + Year Type*Protection + Precip4wk[5]	0.61	0.30	0.36	0.79	0.59
Day + Recent Drought[6]	0.63	0.29	0.14	0.79	0.56
Day + Recent Drought*Protection + Precip2wk	0.63	0.28	0.15	0.79	0.59
Day + Recent Drought*Protection + Precip4wk	0.62	0.30	0.36	0.79	0.59

[1] Day = indicator for day of the year between 1 and 319 starting as July 1 = 1

[2] Year Type = non-drought 2000-2011; drought 2000-2011; recent drought 2013-2015

[3] Protection = factor indicating whether the land is under protected status; ** this variable was not included in crop models

[4] Precip2wk = total precipitation measured for 2-weeks before the open water estimate from Landsat

[5] Precip4wk = total precipitation measured for 4-weeks before the open water estimate from Landsat

[6] Recent Drought = factor indicating data from years 2013-2015

1

Table 3(on next page)

Coefficient estimates (β) and percent change in water from models fit to assess the proportion of open water in rice, corn, and other crops in the Central Valley of California 2000 – 2015.

Coefficient estimates for Drought 2000 **–** 2011 and Recent Drought 2013 **–** 2015 should be interpreted relative to the intercept term of Non-Drought 2000 **–** 2011 (Models 1-3) and Average 2000-2011 (Models 4-6). Estimates in bold are statistically significant with P<0.05 and those in italics P<0.10.

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		Rice			Corn			Other		
Model	**Covariate**	**β**	**SE**	**%**	**β**	**SE**	**%**	**β**	**SE**	**%**
1	Non-Drought	-2.34	0.16		-3.01	0.13		-3.61	0.10	
	Drought	-0.26	0.21	-23	-0.10	0.17	-10	-0.06	0.13	-6
	Recent Drought	**-0.62**	**0.28**	**-46**	**-1.59**	**0.22**	**-80**	**-1.23**	**0.17**	**-71**
2	Non-Drought	-2.54	0.16		-2.93	0.14		-3.64	0.10	
	Drought	-0.24	0.22	-21	-0.10	0.17		-0.06	0.13	-6
	Recent Drought	-0.44	0.29	-36	**-1.67**	**0.23**	**-81**	**-1.20**	**0.18**	**-70**
	Precip 2-weeks	**2.02**	**0.34**		-1.07	0.64		*0.51*	*0.31*	
3	Non-Drought	-2.61	0.18		-3.08	0.14		-3.81	0.10	
	Drought	-0.25	0.22	-22	-0.10	0.17	-10	-0.05	0.14	-5
	Recent Drought	-0.43	0.29	-35	**-1.53**	**0.23**	**-78**	**-1.05**	**0.18**	**-65**
	Precip 4-weeks	**1.10**	**0.32**		0.37	0.37		**1.13**	**0.17**	
4	Average	-2.48	0.12		-3.06	0.09		-3.64	0.07	
	Recent Drought	*-0.48*	*0.26*	*-38*	**-1.54**	**0.20**	**-79**	**-1.20**	**0.16**	**-70**
5	Average	-2.68	0.12		-2.99	0.10		-3.68	0.07	
	Recent Drought	-0.30	0.26	-26	**-1.62**	**0.21**	**-80**	**-1.17**	**0.17**	**-69**
	Precip 2-weeks	**2.03**	**0.37**		*-1.07*	*0.64*		*0.51*	*0.31*	
6	Average	-2.74	0.14		-3.13	0.11		-3.84	0.07	
	Recent Drought	-0.29	0.31	-25	**-1.48**	**0.21**	**-77**	**-1.02**	**0.17**	**-64**
	Precip 4-weeks	**1.11**	**0.35**		0.36	0.37		**1.13**	**0.17**	

Table 4(on next page)

Coefficient estimates (β) and percent change in water from generalized additive mixed models fit to assess the proportion of open water in wetlands in the Central Valley of California 2000 – 2015.

Coefficient estimates for Drought 2000 – 2011 and Recent Drought 2013 – 2015 should be interpreted relative to the intercept term of Non-Drought 2000 – 2011 (Models 1-3) and Average 2000 – 2011 (Models 4-6). Estimates in bold are statistically significant with $P<0.05$ and those in italics $P<0.10$.

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Model	Covariate	Seasonal			Semi-permanent		
		β	**SE**	**%**	**β**	**SE**	**%**
1	Non-drought	-1.06	0.11		-0.08	0.17	
	Drought	0.07	0.16	7	0.07	0.24	7
	Recent Drought	**-0.64**	**0.21**	**-47**	-0.33	0.32	-28
2	Non-drought	-0.98	0.14		0.20	0.19	
	Drought	0.04	0.18	4	0.20	0.26	22
	Recent Drought	**-0.87**	**0.24**	**-58**	-0.38	0.34	-31
	Protected	-0.10	0.15	-10	**-0.44**	**0.19**	**-35**
	Protected*Drought	0.06	0.20	6	-0.21	0.26	-19
	Protected*Recent Drought	*0.48*	*0.27*	*62*	-0.03	0.36	-3
	Precip 2-weeks	-2.86	1.96		-8.84	4.18	
3	Non-drought	-1.03	0.14		0.12	0.20	
	Drought	0.04	0.19	4	0.19	0.27	20
	Recent Drought	**-0.85**	**0.24**	**-57**	-0.35	0.35	-29
	Protected	-0.10	0.15	-10	**-0.45**	**0.19**	**-36**
	Protected*Drought	0.06	0.20	7	-0.21	0.26	-19
	Protected*Recent Drought	*0.48*	*0.27*	*62*	-0.02	0.36	-2
	Precip 4-weeks	0.80	1.46		0.21	2.28	
4	Average	-1.02	0.08		-0.04	0.12	
	Recent Drought	**-0.68**	**0.19**	**-49**	-0.36	0.30	-31
5	Average	-0.96	0.09		0.30	0.13	
	Recent Drought	**-0.89**	**0.22**	**-59**	-0.48	0.31	-38
	Protected	*0.45*	*0.24*	*57*	0.08	0.33	9
	Protected*Recent Drought	-0.07	0.10	-7	**-0.55**	**0.13**	**-43**
	Precip 2-weeks	-2.81	1.67		-8.73	4.14	
6	Average	-1.01	0.10		0.22	0.14	
	Recent Drought	-0.87	0.22	**-58**	-0.44	0.32	-36
	Protected	0.45	0.25	*56*	0.09	0.33	10
	Protected*Recent Drought	-0.07	0.10	-7	**-0.56**	**0.13**	**-43**
	Precip 4-weeks	0.81	1.55		0.27	2.31	

Table 5(on next page)

Adjusted-R^2, coefficient estimates (β), and estimated percent change in water for models of open water in seasonal wetlands in the Sacramento Valley and the San Joaquin Valley 2000 – 2015.

Coefficient estimates for Drought 2000 – 2011 and Recent Drought 2013 – 2015 should be interpreted relative to the intercept term of Non-Drought 2000 – 2011. Estimates in bold are statistically significant with $P<0.05$ and those in italics $P<0.10$.

Region	R^2	Covariate	Estimate	SE	P	%
Sacramento	0.64	Non-Drought	-1.23	0.22		
		Drought	-0.34	0.29	0.25	-29
		Recent Drought	**-1.20**	**0.43**	**0.01**	**-69**
San Joaquin						
	0.46	Non-Drought	-1.74	0.42		
		Drought	0.11	0.58	0.85	11
		Recent Drought	**-1.91**	**0.74**	**0.01**	**-85**

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