Winter management of California’s rice fields to maximize waterbird habitat and minimize water use

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A B S T R A C T
Rice agriculture provides habitat for waterbirds in California’s Sacramento Valley, a region that has lost over 90% of natural wetlands. Developed as an agronomic practice, winter-flooding of rice fields also provides habitat for waterbirds but alternatives are needed with predicted declines in water availability. During the winters of 2009–2010 and 2010–2011, we compared waterbird density and water depths of Sacramento Valley rice fields in four post-harvest management treatments that varied in the amount of water used: maintenance flooding, one-time flooding, non-flooded with boards left in water control structures, and non-flooded with boards removed from water control structures. Densities of waterbirds were higher in the flooded treatments compared to non-flooded treatments. One-time flooding provided the most suitable water depths for shorebirds and long-legged waders while maintenance flooding provided the most suitable water depths for dabbling ducks. Our results confirm that the practice of winter-flooding rice fields provides waterbird habitat. However, increased habitat value and potentially less water use could be achieved using a combination of traditional and alternative flooding practices.

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1. Introduction

Habitat loss is one of the primary threats to wildlife throughout the world (Wilcove et al., 1998). For waterbirds, habitat has been lost as wetlands have been drained and converted to agriculture, flood plains have been disconnected from rivers and developed, and bays and lagoons have been dredged or filled (Frayer et al., 1989; Finlayson and Davidson, 1999). Furthermore, waterbird habitat is projected to be vulnerable to climate change, as warming temperatures and increasing demand by people decrease water availability (Joyce et al., 2011; Gardali et al., 2012). In the face of these stresses, waterbird conservation depends on finding creative solutions to maintain habitat availability.

Rice fields provide important alternative habitat for waterbirds in many of the world’s regions where natural wetlands have been degraded or altered (Renssen et al., 1991; Fasola and Ruiz, 1996; Lawler, 2001). Rice fields in the Central Valley of California are one reason the region is internationally important for waterbirds. Over 350,000 shorebirds and almost 3 million dabbling ducks use the region each year (Shuford et al., 1998; Collins et al., 2011), despite the loss of over 90% of the seasonally inundated wetlands that historically were present (Frayer et al., 1989; Heitmeyer et al., 1989).

In California, 96% of all rice cultivation occurs in the Sacramento Valley (Fig. 1). Annually, over 140,000 ha (67%) of harvested rice fields in the Sacramento Valley are flooded in winter providing 85% of all flooded habitat in this region (CVJV, 2006) and supporting over 50 species of waterbirds (Day and Colwell, 1998; Elphick and Oring, 1998). California rice provides habitat for 9 species of dabbling ducks, 8 species of long-legged waders and 13 species of shorebirds (Elphick and Oring, 1998; Eadie et al., 2008), including three species of special concern in the state of California and two species of federal conservation concern (Shuford and Gardali, 2008; USFWS, 2008).

State regulations enacted in the 1990s restricting the amount of post-harvest rice stubble burning (Rice Straw Burning Act, AB 1378, 1991) resulted in an increase in the amount of rice that is winter-flooded to promote decomposition of rice stubble (crop-related plant material remaining in the field after harvest). The shift from burning to flooding for stubble decomposition had the unintended consequence of creating high value habitat for waterbirds (Fleskes et al., 2005; Miller et al., 2010) while providing agronomic benefits to farmers (Bird et al., 2000) and increasing the recreational value of rice through waterfowl hunting opportunities. Changes in water availability threaten the environmental,
agronomic, and cultural benefits of winter-flooded rice fields and present an opportunity for stakeholders to work collaboratively and develop rice field management practices that provide multiple benefits. Most winter-flooding is implemented for agronomic reasons but developing a better understanding of the consequences that these flooding practices have on waterbird habitat would allow an evidence-based approach to waterbird conservation strategies in California rice (Sutherland et al., 2004).

Specific habitat requirements vary among waterbird guilds (i.e. dabbling ducks, long-legged waders, shorebirds) using winter-flooded rice fields of the Sacramento Valley and must be considered when designing new field management practices to enhance rice for waterbirds. The specialized feeding ecology of shorebirds requires water depths less than 15 cm (Elphick and Oring, 1998; Isola et al., 2000; Taft et al., 2002). Traditional water depths of winter-flooded rice fields are 20–25 cm (Elphick and Oring, 1998); these depths are appropriate for many waterfowl but do not provide habitat for shallow water obligates such as shorebirds (CVJV, 2006). In addition to specific water depths, shorebirds and dabbling ducks prefer open expanses of habitat for foraging and roosting (Helmers, 1992; Isola et al., 2000), the availability of which can be affected by post-harvest field management. Long-legged waders have less restrictive habitat requirements and use a variety of habitat types, including vegetated and open, flooded and non-flooded (Butler, 1992; McCrimmon et al., 2001). Given the varied needs of waterbirds and the importance of winter-flooded rice, it is necessary to develop field management practices that create diversity in rice field conditions seasonally that are compatible with agriculture and waterbirds.

In the winters of 2009–10 and 2010–11, we used an experimental approach to (1) evaluate the effectiveness of four post-harvest management practices developed and designed in collaboration with rice farmers and the rice growing community, including two intentionally flooded treatments (maintenance flooding and one-time flooding) and two passively flooded treatments (boards-in and boards-out), to provide habitat for three guilds of wintering waterbirds (dabbling ducks, long-legged waders, shorebirds), (2) determine if the effectiveness of each treatment changes through the winter, (3) evaluate the effect of four habitat variables (water depth, rice stubble, dirt clods and rainfall) on bird use of each treatment, and (4) determine if leaving boards-in water control structures could provide shallow water habitat specifically for shorebirds.

Fig. 1. Location of rice farms surveyed for waterbirds in the Sacramento Valley, CA, December–January 2009–2010 and 2010–2011. Farms are grouped according to region (see Section 2.4).
Table 1
Waterbirds species observed during surveys of four rice field management treatments (maintenance, one-time, boards-in and boards-out) in December–January 2009–2010 and 2010–2011 in the Sacramento Valley, CA.

<table>
<thead>
<tr>
<th>Shorebirds</th>
<th>Dabbling ducks</th>
<th>Long-legged waders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black-bellied plover (Pluvialis squatarola)</td>
<td>Gadwall (Anas strepera)</td>
<td>Great blue heron (Ardea herodias)</td>
</tr>
<tr>
<td>Semi-palmated plover (Charadrius semipalmatus)</td>
<td>American wigeon (Anas americana)</td>
<td>Great egret (Ardea alba)</td>
</tr>
<tr>
<td>Killdeer (Charadrius vociferus)</td>
<td>Mallard (Anas platyrhynchos)</td>
<td>Snowy egret (Egretta thula)</td>
</tr>
<tr>
<td>Black-necked stilt (Himantopus mexicanus)</td>
<td>Northern shoveler (Anas clypeata)</td>
<td>White-faced ibis (Plegadis chihi)</td>
</tr>
<tr>
<td>American avocet (Recurvirostra americana)</td>
<td>Northern pintail (Anas acuta)</td>
<td>Black-crowned night-heron (Nycticorax nycticorax)</td>
</tr>
<tr>
<td>Greater yellowlegs (Tringa melanoleuca)</td>
<td>Green-winged teal (Anas crecca)</td>
<td>Sandhill crane (Grus canadensis)</td>
</tr>
<tr>
<td>Long-billed curlew (Numenius americanus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western sandpiper (Calidris mauri)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Least sandpiper (Calidris minutilla)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dunlin (Calidris alpina)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-billed dowitcher (Limnodromus scolopaceus)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wilson’s snipe (Gallinago delicata)</td>
<td></td>
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</tbody>
</table>

2. Methods

2.1. Study area

The Sacramento Valley is located north of the Sacramento–San Joaquin River Delta in the Central Valley of California (Fig. 1). Average annual rainfall, generally falling between the months of November and February, is 51 cm and the region historically flooded in late winter creating over 600,000 ha of seasonal wetlands (Heitmeyer et al., 1989). Today, flooded habitat is provided by over 200,000 ha of rice and 24,000 ha of managed wetlands (CVJV, 2006) irrigated by a series of highly managed, interconnected canals and ditches (Garone, 2011).

2.2. Study species

We studied three waterbird guilds commonly found in rice fields, dabbling ducks (Anseriformes), long-legged waders (Pelecaniformes and Sandhill crane [Grus canadensis]), and shorebirds (Charadriiformes). Waterbird species observed in this study are listed in Table 1.

2.3. Post-harvest management

We investigated four post-harvest management treatments that differed in the amount of and timing of water that was applied to fields. The design of rice fields allows farmers the ability to deliberately or passively (via rainfall collection) flood fields, and to manage water levels by either retaining (boards-in) or removing (boards-out) wooden boards in water control structures. Two treatments consisted of intentional flooding, maintenance and one-time, and two treatments consisted of passive flooding, boards-in and boards-out. The most common flooding practice in the study area is maintenance flooding, or actively flooding fields by leaving boards in water control structures and adding water to maintain a specific water depth from December through January; this practice uses the greatest amount of water. One-time flooding involves leaving boards in water control structures and applying water only once during the winter; this practice uses less water than maintenance flooding. In non-flooded fields, boards removed from water control structures before harvest are not replaced after harvest (boards-out) allowing any precipitation over the winter to drain from the fields. Replacing boards in water control structures (boards-in) may allow some rainwater to be captured passively. Water is not intentionally applied to non-flooded fields. Owing to the clay-based soil of much of the Sacramento Valley, we hypothesized that water applied via one-time flooding would drain slowly and provide shallow water habitat throughout winter. We also hypothesized that relative to fields where boards were left out of water control structures, fields with boards in would passively collect rainfall, retain it longer, and create shallow water habitat.

2.4. Study design

We categorized rice fields at each farm in our study to one of the four treatments based on how the farmer managed the fields in winter: (1) maintenance, (2) one-time, (3) boards-in, and (4) boards-out. The amount of flooded habitat in the surrounding landscape is known to affect waterbird densities (Elphick, 2008) and we grouped farms into three geographic areas: south, central, and north. The north region contained both flooded rice and managed wetlands, the central region contained flooded rice only and the south region contained one large, isolated rice farm adjacent to a managed wetland (Fig. 1). Rice fields are divided into sub-fields called paddies, separated by internal earthen levees and we considered the individual paddy to be the sampling unit. We selected survey points from our population of paddies using generalized random tessellation stratified (GRTS) sampling methodology which enabled the selection of spatially balanced random locations with respect to the management treatments used on the farm and in the region (Stevens and Olsen, 2003).

2.5. Data collection

We conducted bi-monthly waterbird surveys at the paddy level from pre-determined survey locations. We surveyed the area within a 200 m fixed-radius extending from the edge of the paddy into the field and bounded on either side by the internal levees that form the paddy. Surveys were conducted between 0700 h and 1700 h and we haphazardly varied the order that points were surveyed to avoid bias in waterbird counts due to time of day. We identified all waterbirds to species and counted all individuals using the survey area. All survey areas were scanned for at least two minutes; there was no maximum time limit for completing a count although we completed the count as rapidly as possible to avoid double counting birds. We did not count waterbirds that flew over the survey area during the survey.

Rice fields are leveled for precision water flow and have very little microtopography, thus we recorded water depth to the nearest inch during each survey using two color-coded wooden stakes placed along the center of each survey area at 50 m and 200 m from the survey point. We visually estimated the percent of the survey area with standing rice stubble as a measure of cover in each treatment. To account for roughness in the fields due to varying types of mechanical stubble management that might influence habitat value, we assigned survey areas a score of 1 for the presence of dirt clods and 0 for no clods in fields that were not flooded.

We determined the amount of precipitation (cm) that fell between survey periods from the California Irrigation Management
Table 2

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>Fields flooded and maintained at a specific depth with additional water applied as needed</td>
</tr>
<tr>
<td>One-time flooding</td>
<td>Fields flooded and thereafter received no additional water other than precipitation</td>
</tr>
<tr>
<td>Boards-in</td>
<td>Fields that are not intentionally flooded but had boards replaced in water control structures</td>
</tr>
<tr>
<td>Boards-out</td>
<td>Fields that are not intentionally flooded and did not have boards replaced into water control structures</td>
</tr>
<tr>
<td>Depth</td>
<td>Water depth in cm at each survey area on each visit</td>
</tr>
<tr>
<td>Stubble</td>
<td>Percent of survey area where rice stubble was present</td>
</tr>
<tr>
<td>Dirt clods</td>
<td>Presence (1) or absence (0) of dirt clods in the survey area</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Amount of rain in cm that fell between survey periods</td>
</tr>
<tr>
<td>Region</td>
<td>Location of the farm in the Sacramento Valley, north, central and south</td>
</tr>
<tr>
<td>Year</td>
<td>2009–10 and 2010–11</td>
</tr>
</tbody>
</table>

Information Systems (CIMIS; http://www.ipm.ucdavis.edu/WEATHER/index.html) weather stations in Yolo, Sutter and Colusa counties. Surveys were not conducted in wind speeds > 32 kph, heavy fog, or steady rain.

2.6. Data analyses

2.6.1. Effects of treatment on waterbird density
We calculated the area (ha) of each survey area using ArcMap Version 9.3.1 (© 1999–2009 ESRI Inc.). We summarized the total number of individuals of each species observed and due to the large number of zeros and non-normal distribution of bird counts, we summed counts for each sampling area in each year. We employed zero-inflated negative binomial regression (ZINB; Zuur et al., 2009) to quantify the effect of treatment on abundance of each of the three guilds (Table 1), during the experiment (December–January 2009–2010 and 2010–11). We estimated mean waterbird density (birds/ha) in each of the four treatments and compared among treatments using 95% confidence intervals (95% CI) for each guild. We also evaluated whether the effect of treatments varied by region, year, or rainfall within a year. We quantified regional variation in the treatment effect on densities of each waterbird guild using a region by treatment interaction. Because all treatments did not occur in all regions, we combined maintenance and one-time flooding into a “flooded” category when evaluating regional differences in the treatment effect. We also evaluated annual variation in the treatment effect using a year by treatment interaction.

2.6.2. Habitat correlates of waterbird density
We evaluated additional ZINB regression models that included covariates hypothesized to explain differences in waterbird density among treatments. These included three habitat variables: water depth (cm), average percent rice stubble in the survey area, and the presence of dirt clods in the survey area (Table 2). We also evaluated whether the effect of rainfall (cm) since prior survey was different among treatments using an interaction model. We averaged the observed water depth, stubble, and rainfall from each visit at each survey area across each year. Finally, we evaluated the effect of dirt clods and rice stubble on shallow-water obligate (shorebird) use of boards-in and boards-out treatments (Table 2). In all models we included the natural logarithm of the area surveyed (ha) as an offset term.

We evaluated the relative support for each model considered using Akaike’s Information Criterion corrected for small sample size (AICc; Burnham and Anderson, 2002). We calculated the difference between the AICc of each model and the model with the lowest AICc in the model set (ΔAICc) to identify the best supported model for each guild. We considered models with ΔAICc < 2 to be in the top model set. We further quantified relative support for each model given the data and the set of models evaluated using Akaike weights (w; Burnham and Anderson, 2002). We considered coefficient estimates with 95% CI that did not overlap zero to be significant.

2.6.3. Within year variation in potential habitat
Due to high overdispersion in the count data, we were unable to evaluate within year variation in the effectiveness of each treatment on waterbird abundance using ZINB models. Instead, using our water depth data, we evaluated the probability that the water depth of each treatment was within the preferred range for each guild on each visit. First, we modeled the probability of occurrence of each waterbird guild as a function of water depth using a mixed effect logistic regression (Pinheiro and Bates, 2000) where the quadratic form of water depth was a fixed effect and sampling location was a random effect. We then defined optimal depth ranges for each guild using 50% of the maximum probability of occurrence based on the fitted models. This captured >80% of the distribution of occurrence for all guilds.

We employed mixed-effects logistic regression to quantify the effect of treatment on the probability of achieving optimal depths for each guild as defined in our study. We also evaluated models with an interaction between flooding treatment and date (standardized 1 = December 1 in each year) and an interaction between flooding treatment and visit interval (1 = 1–15 December, 2 = 16–31 December, 3 = 1–15 January, 4 = 16 January–31 January) to assess within year trend and variation in habitat availability among treatments.

We considered coefficient estimates with 95% CI that did not overlap zero to be significant. Fixed effects used in these models included flooding treatment, date, visit and the interaction between date or visit with flooding treatment; the random effect was sampling location.

All statistical analyses were conducted using R v2.8 (© The R Foundation for Statistical Computing) and specifically the pscl package for ZINB analysis (Zeileis et al., 2008) and the lme4 package for mixed-effects logistic regression analyses (Bates et al., 2011). We evaluated the fit of all models using residual plots, and by including an intercept and variance only model in all analyses as a null model for comparison.

3. Results
We conducted waterbird surveys from 1 December to 29 January in 2009–2010 at five rice-growing farms and from 7 December to 4 February at eight farms in 2010–2011 (Fig. 1). In 2009–2010, we surveyed a total of 187 points (59 maintenance, 29 one-time, 42 boards-in and 77 boards-out). In 2010–2011, we surveyed a total of 244 points (78 maintenance, 14 one-time, 72 boards-in and 77 boards-out). We observed a total of 27 species representing six waterbird guilds for a total of 13,330 birds in 2009–2010 and 21,869 in 2010–2011. We had sufficient data for analysis of 24 species from 3 guilds (Table 1).

Overall, waterbirds were more abundant in flooded treatments (maintenance, one-time) than in non-flooded treatments (boards-in, boards-out; Fig. 2). None of the guilds had significantly different densities in the one-time treatment relative to the maintenance treatment (Fig. 2). All guilds had significantly lower densities in the boards-in and boards-out treatments relative to maintenance flooding. The 95% CI of boards-in density estimates for dabbling ducks slightly overlapped with the one-time flooding treatment. Also, 95% CI of boards-out density estimates for shorebirds and long-legged waders overlapped with the one-time flooding treatment. There was no significant difference between boards-in and boards-out treatments for any waterbird guild (Fig. 2).

Models including covariates hypothesized to influence waterbird density often provided a better fit to the data than the treatment only model and were always an improvement over the intercept only model (Table 3). For dabbling ducks, the
Table 3
Results of zero-inflated negative binomial regression of factors influencing waterbird abundance in winter rice fields in the Sacramento Valley, CA from December–January 2009–2010 and 2010–2011 with the top performing model for each guild bolded. All models include intercepts for the count and zero-inflation component and an overdispersion variance parameter for the count. Models containing an interaction effect also contain the main effects of the covariates in the interaction. The intercept model includes only the intercepts (count and zero-inflation) and overdispersion variance.

<table>
<thead>
<tr>
<th>Model</th>
<th>$K^a$</th>
<th>Dabbling ducks</th>
<th>Shorebirds</th>
<th>Long-legged waders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td></td>
<td>$\Delta AIC^b$</td>
<td>$w_c$</td>
<td>$\Delta AIC_c$</td>
</tr>
<tr>
<td>Treatment</td>
<td>6</td>
<td>51.14</td>
<td>0.00</td>
<td>25.28</td>
</tr>
<tr>
<td>Treatment × rainfall</td>
<td>10</td>
<td>50.33</td>
<td>0.00</td>
<td>25.72</td>
</tr>
<tr>
<td>Treatment × region</td>
<td>11</td>
<td>0.00</td>
<td>1.00</td>
<td>18.06</td>
</tr>
<tr>
<td>Treatment × year</td>
<td>10</td>
<td>27.95</td>
<td>0.00</td>
<td>19.42</td>
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<tr>
<td>Rainfall</td>
<td>4</td>
<td>72.11</td>
<td>0.00</td>
<td>46.28</td>
</tr>
<tr>
<td>Region</td>
<td>5</td>
<td>74.65</td>
<td>0.00</td>
<td>45.92</td>
</tr>
<tr>
<td>Year</td>
<td>4</td>
<td>76.06</td>
<td>0.00</td>
<td>45.11</td>
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<td>Habitats</td>
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<td>Water Depth</td>
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<td>quadratic Water Depth</td>
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<tr>
<td>quadratic Stubble</td>
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<td>0.00</td>
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<tr>
<td>Intercept</td>
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<td>74.07</td>
<td>0.00</td>
<td>44.41</td>
</tr>
</tbody>
</table>

$^a$ Number of parameters.  
$^b$ AIC$_c$-min(AIC).  
$^c$ Akaike weight.

top model received 100% of the Akaike weight and indicated that densities among treatments varied across regions; however the data were not sufficient to evaluate dabbling duck density in the boards-out treatment. A quadratic effect of water depth was the best supported habitat model for dabbling ducks and was a substantial improvement over the treatment only model. The top model for long-legged waders, a treatment by year interaction, also received 100% of the Akaike weight. A quadratic effect of water depth was the second ranked model. For shorebirds the top model included a quadratic effect of water depth and was nine AIC units better than the next best model and received 98% of the Akaike weight. Analyses of non-flooded treatments (boards-in and boards-out) showed that shorebird use did not differ significantly with the presence of dirt clods ($\beta_{dirt-clods} = 0.14; 95\% CI: -0.15, 0.87$) but decreased significantly with increasing amount of stubble ($\beta_{stubble} = -5.72; 95\% CI: -7.84, -3.60$).

Based on occurrence, each guild was associated with a specific range of water depths (Fig. 3). Dabbling ducks used water depths greater than shorebirds (>16 cm) and densities peaked at 26 cm. Long-legged waders used a wide range of water depths (0–23 cm) peaking at 12 cm. Probability of shorebird occurrence peaked between 8 cm and 11 cm, declining at greater depths. Based on these results we defined the following optimal depth ranges for our within year analysis: >16 cm for dabbling ducks, >0–23 cm for long-legged waders and >0–15 cm for shorebirds.

The flooding treatment that provided the highest probability of habitat within the preferred depth range varied for each guild (Fig. 4). The maintenance treatment had the highest probability of providing water depths for dabbling ducks (0.40–0.75) and the one-time treatment significantly less (0.08–0.31). Boards-in and boards-out provided little to no dabbling duck habitat (<0.10). There was a significant interaction between treatment and date for dabbling duck depths. The maintenance treatment declined significantly in the probability of providing preferred water depths for dabbling ducks through the winter ($\beta_{maintenance-date} = -0.03; 95\% CI: -0.02, -0.04$). One-time ($\beta_{one-time-date} = 0.04; 95\% CI: 0.02, 0.06$), boards-in ($\beta_{boards-in-date} = 0.07; 95\% CI: 0.03, 0.11$), and boards-out ($\beta_{boards-out-date} = 0.07; 95\% CI: 0.03, 0.11$) treatments all had significant increasing probability of providing preferred dabbling duck water depths over the winter. The probability of shorebird-suitable water depths was highest in the one-time treatment (0.42–0.73), followed by the maintenance treatment (0.27–0.51) which had minimal overlap with boards-in (0.12–0.27) and boards-out (0.12–0.26). Potential long-legged wader habitat was similar between the maintenance (0.73–0.85) and one-time treatments (0.75–0.91) and reduced in the boards-in (0.13–0.30) and boards-out treatments (0.13–0.28).

Shorebird-suitable water depths ($\beta_{maintenance-date} = 0.02; 95\% CI: 0.01, 0.03$) and long-legged wader suitable water depths ($\beta_{maintenance-date} = 0.01; 95\% CI: 0.00, 0.02$) in the maintenance treatment increased significantly over the season with the greatest amount of potential habitat for both guilds available at the end of the season. There was no significant interaction between date and any other treatment for these guilds.

4. Discussion

Our study demonstrates that, in California, the intentional addition of water to rice fields post-harvest creates high-value waterbird habitat. Diversifying post-harvest field management...
using a combination of flooding practices (maintenance and one-time) can increase habitat availability of winter flooded rice for a variety of waterbird species while continuing to provide stubble decomposition benefits. Non-flooded treatments had lower waterbird densities than flooded treatments and likely provide less reliable stubble decomposition. Moreover, we did not identify significant benefits of the boards-in treatment over the boards-out treatment to provide shallow water habitat suggesting that passive rainwater capture may be of limited value for waterbirds. Yet, reducing rice stubble in fields after harvest provides the greatest potential for increasing shorebird use of non-flooded treatments. The effectiveness of each treatment indicates that a combination of flooding strategies, that benefit waterbirds and farmers, are available and have the potential to conserve water resources across the rice landscape of California. Given the worldwide production of rice and increasing need to provide alternative habitat for waterbirds it is important to note that providing multiple water depths and habitat types have also emerged as suggestions for regional-level rice field management in Europe (Lourenço and Piersma, 2009).

4.1. Non-flooded treatments: Boards-in and boards-out

Neither the boards-in nor boards-out treatments required intentional addition of water to a rice field; flooded habitat could only be created via rainfall. These practices required the least financial investment to farmers as winter water was not purchased for flooding (maintenance, one-time). The average rainfall observed in this study had a limited effect on waterbird use of each treatment and average water depth was a more important factor explaining waterbird use of rice fields.

Our results demonstrate that water depths do not reach the levels preferred by dabbling ducks from rainfall alone. The largest rain event in our study, 16.0 cm, occurred during the last visit interval (January 15–31) of the 2009–2010 season and was 164% of the average monthly rainfall in January. This rain event was not enough to increase the proportion of dabbling duck habitat in boards-in and boards-out treatments. Shorebird habitat also did not increase in boards-in and boards-out treatments after the same rain event which might be attributed to water depths exceeding those preferred by this guild. However, this seems unlikely since the flooded treatments increased in shorebird habitat during this time. Shorebird water depths increased in boards-in and boards-out treatments during visit two (December 15–31) perhaps due to heavier than normal rains during the last two weeks of 2009 (10.6 cm; 167% of average monthly rainfall). Based on the amount of habitat available between >0 cm and <16 cm during this period, we expected more shorebirds to use these treatments. Another factor that may affect shorebird use of non-flooded treatments is the...
presence of aquatic invertebrates, an important food resource. Densities of most aquatic invertebrates increase over time in winter-flooded rice fields (Manley et al., 2004; Loughman and Bazter, 1992). The short inundation time of boards-in and boards-out fields may not allow invertebrate populations the time needed to establish. Additional research is needed to assess invertebrate populations in winter rice fields and the effects of winter rain events on waterbird food availability. Our data also suggest that reduction or removal of stubble should be considered when managing for shorebird habitat in non-flooded rice fields to increase use. Rettig (1994) observed shorebirds most commonly in rice fields with vegetation cover <50% and studies in Europe show higher shorebird densities in fields with little standing vegetation or stubble (Lourenço and Piersma, 2009). However, it is important to note that densities of shorebirds in the non-flooded treatments were significantly lower than densities in flooded treatments. To support current populations of shorebirds in the Sacramento Valley, 100 ha of non-flooded fields would be needed to replace every 1 ha of rice fields where flooding is discontinued. The additional investment for stubble management (e.g., baling, incorporation) of non-flooded fields may exceed the capacity of growers; however, more detailed analysis, including financial investment and effects on shorebirds, is needed.

We did not find substantial benefits to waterbirds from boards-in and boards-out treatments in our study, however, in rice growing regions where rainfall is more plentiful, this practice may have greater habitat enhancement value (e.g. Lourenço and Piersma, 2009; Sánchez-Guzmán et al., 2007). Additionally, non-flooded treatments (boards-in and boards-out) can have conservation value to non-waterbirds. Elphick (2004) found more raptors and higher numbers of six species of passerines in non-flooded fields.

4.2. Flooded treatments: Maintenance and one-time

Both the maintenance and one-time treatments required the addition of water. Continuous addition of water to maintain a constant water depth throughout the winter in the maintenance treatment results in greater water use and increased financial investment by the farmer compared to the one-time treatment. In one irrigation district, water delivery for maintenance flooding was $49.79 per ha in 2013 while delivery for one-time flooding was $25.70 per ha (Glenn-Colusa Irrigation District, 2013); maintenance flooding costs farmers almost twice as much as one-time flooding for the same amount of land.

Dabbling duck densities were highest in the maintenance treatment but comparable to the one-time treatment, indicating that one-time flooding has conservation value to dabbling ducks while also providing substantial habitat value to other guilds. The proportion of dabbling duck water depths in the maintenance treatment was consistently high until the last survey period; the decrease in late winter was likely related to cessation of water delivery and subsequent decrease in water depths as growers prepared to drain fields at the beginning of February.

Densities of long-legged waders were similar to values reported by Elphick and Oring (2003) and were generally lower than shorebirds and ducks. The varied habitats used by long-legged waders in this study are reflected in the large water depth range predicted for the guild (>0 cm–23 cm) and the more consistent availability of preferred habitat over the study in all treatments. Long-legged waders exploit flooded and non-flooded fields alike as was documented by Day and Colwell (1998).

Shorebird densities in the maintenance and one-time treatments were also similar to previous shorebird density estimates from flooded rice fields in the region (Elphick and Oring, 2003). The greatest amount of shorebird habitat was provided by the one-time treatment while some shorebird habitat was available in the maintenance treatment. The reduced amount of shorebird habitat provided by the one-time treatment on the second visit (Fig. 4) had a corresponding increase in potential dabbling duck habitat provided by the one-time treatment on the same visit interval.

4.3. Other management considerations

Habitat preferences of waterbirds are well documented and our data support water depth as a primary consideration when managing habitat for waterbirds. Most shorebirds require shallow water (Colwell and Dodd, 1997; Taft et al., 2002) as confirmed by our preferred water depth range for this guild. Our estimates of optimal water depth for dabbling ducks were slightly higher than other published estimates (Elphick and Oring, 1998; Isola et al., 2000). The majority of dabbling ducks detected on our surveys were Northern Pintail (Anas acuta) and Northern Shoveler (Anas clypeata), two species that are commonly associated with water depths greater than 20 cm (Isola et al., 2000). A wider range of depths should be considered to provide habitat for dabbling ducks that prefer lower water (e.g. Green-winged Teal [Anas crecca]).

It is important to incorporate other agronomic and cultural factors that may influence feasibility or suitability of each management practice into the planning process. While not measured directly in this study, winter-flooding of rice fields increases stubble decomposition (Hill et al., 1999; Manley et al., 2005) including flooding at depths that are preferred by shorebirds (Bird et al., 2000) and that are more common in the one-time flooding treatment. Waterfowl use of winter-flooded rice further reduces rice stubble from 20% to 80% and can also reduce grassy weed biomass at harvest (Bird et al., 2000; van Groenigen et al., 2003). These studies show agronomic benefits to winter-flooding rice fields and recreational activities may offer further incentive for winter-flooding of rice. Wildlife-watching and hunting are both of cultural and economic importance in the Sacramento Valley. Approximately 75% of rice fields in California are hunted seasonally (Garr, 2002) with hunting club memberships generating supplemental income to rice farmers.

To sustain the multiple benefits of winter-flooding rice, consideration must be given to the amount of and regional variation of available water resources. Climate change models for California suggest decreased precipitation in the Central Valley and Sierra Nevada, potentially reducing spring flows and agricultural water availability (Joyce et al., 2011) and increasing risks to already sensitive species (Gardali et al., 2012). Thus, practices less reliant on vulnerable water resources that still provide waterbird habitat and agronomic benefits are needed. We demonstrated that one type of winter flooding that uses less water (one-time) can likely provide benefits consistent with current agronomic traditions and ecological benefits. One-time flooding was not widespread in our study and it was difficult to obtain an adequate sample size; one-time flooding comprised 16% of sample points in 2005–2010 and just 6% in 2010–2011. Further monitoring is needed to assess waterbird use with larger sample sizes of this practice across the rice growing region. However, the benefits of this practice are substantial enough to merit increasing awareness of the practice in the rice-growing community especially as an option for rice farmers seeking to reduce costs while also receiving the benefits of decomposition.

Engaging stakeholders in the development of new practices, as was done in this study, is a critical step toward adoption and implementation of new strategies. Working together, the rice growing community and conservation stakeholders can create a powerful partnership to advance the ecological benefits of rice without reducing agronomic efficiency. Communicating the importance of rice for wildlife conservation could go a long way toward sustaining rice lands in California and other regions where the majority of rice fields are privately owned and currently have low levels of
4.4. Recommendations for practice

Our results suggest that one-time in conjunction with maintenance flooding can provide habitat for a diversity of waterbirds. Our management recommendation for maximizing the conservation value of rice for the greatest diversity of bird species, specifically dabbling ducks, long-legged waders, and shorebirds in the Sacramento Valley rice landscape is to use a combination of one-time flooding and maintenance flooding while continuing to leave a subset of fields unflooded.

According to the Central Valley Joint Venture (CVJV, 2006), there are 195,000 ha of rice in the Sacramento Valley; 67% (140,000 ha) are flooded in winter. Shorebirds need 5125 ha of shallowly flooded habitat (<10 cm) in December and January to sustain population objectives. Half of this habitat objective must be met by winter-flooded rice and represents 2% of all rice that is currently winter-flooded. Ducks need 69,000 ha of flooded rice and are assumed to have negligible resource competition with long-legged waders which are assumed to use the same habitat. Based on these numbers, shallow flooding (via one-time or other means) could be employed on a subset of rice farms to meet shorebird needs without affecting waterfowl and long-legged wader needs. According to Elphick (2008), rice fields closer to refuges or managed wetlands should be prioritized for one-time flooding or other shallow water management.

Existing partnerships between the rice industry, rice growers, the U.S. Department of Agriculture’s Natural Resources Conservation Service (NRCS) and other stakeholders will help evaluate and guide the implementation of these management recommendations through public or private incentive programs such as the NRCS Wildlife Habitat Incentive Program. An integrated and balanced approach to winter rice field management will continue to provide agronomic benefits to farmers, recreational opportunities to the public, and habitat for waterbirds with the potential to reduce water use; a win-win for birds and farmers in the face of climate change.

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References

Bates, D., Maechler, M., Bolker, B., 2011. Linear Mixed-effects Models Using 54 Classes, R Package Version 0.999375-42.
Glenn-Colusa Irrigation District, 2013. 2013 Water Rates with Cover and Additional Water Rate Information.
Stevens, Shuford, Shuford, Sánchez-Guzmán, Rettig, Remsen, Pinheiro, Miller, 124


Shuford, W.D., Gardall, T. (Eds.), 2008. California Bird Species of Special Concern: A Ranked Assessment of Species, Subspecies, and Distinct Populations of Birds of Immediate Conservation Concern in California. California Department of Fish and Game and Western Field Ornithologists, Sacramento, CA and Camarillo, CA.


