



Waterbird response to management practices in rice fields intended to reduce greenhouse gas emissions



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ABSTRACT

There are many benefits of agricultural landscapes for wildlife. In California's Central Valley, post-harvest flooding of rice fields increases the decomposition of rice stubble and provides habitat for over 50 species of waterbirds. These fields are also flooded during planting, providing habitat for spring migrants and locally breeding birds. Because California has lost over 90% of its historic wetlands, flooded rice is critical wildlife habitat, providing 80% of the total flooded habitat in the Sacramento Valley. Flooding rice fields, however, contributes to greenhouse gas (GHG) emissions. Several rice field management practices may reduce methane emissions including reduced flooding in winter, removal of rice straw after harvest (baling), and drill seeding during planting. During the winters of 2011–2012 and 2012–2013, we compared waterbird use in four combinations of post-harvest practices: baled/flooded, baled/non-flooded, non-baled/flooded, and nonbaled/non-flooded. We found significantly higher dabbling duck and shorebird densities in the non-baled/flooded practice compared to the other three practices. During the spring of 2012 and 2013, we compared waterbird use of drill-seeded fields (reduced GHG) with flooded fly-on seeded fields (status quo GHG). We found no significant differences in mean density between the two seeding practices for waterbirds. Our study found evidence that some post-harvest practices (reduced winter flooding, baling) that reduce GHG emissions from rice also reduce use by waterbirds. While reducing GHG is globally necessary to minimizing the impacts of climate change, doing so in an area of hemispheric importance for waterbirds should be done with caution.

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1. Introduction

The predicted impacts of climate change on wildlife and biodiversity are many (Bellard et al., 2012). Reducing greenhouse gas (GHG) emissions is necessary to minimize those impacts (IPCC, 2014). Agriculture contributes 10–12% of global anthropogenic GHG emissions and accounts for 52% of global anthropogenic methane (CH₄) emissions (Smith et al., 2007). Methane is a powerful GHG, 25 times more potent than carbon dioxide (CO₂). Rice agriculture contributes 5% of global methane emissions (Smith et al., 2007), and <1% of United States methane emissions (US-EPA, 2015). Rice agriculture is also recognized globally and nationally as important habitat for waterbirds (Stafford et al., 2010; Eadie et al., 2008). So, while reducing GHG emissions is globally necessary, practices that reduce GHG emissions from rice fields should

be evaluated for the unintended consequence of reducing the quantity or quality of wildlife habitat.

In some regions of the world where wetland habitat loss is extensive, rice fields provide important alternative wetland habitat for waterbirds (Fasola and Ruiz, 1996; Elphick, 2000). This is especially true in California's Central Valley, where 90% of the original natural wetlands have been lost, primarily to agriculture and urbanization (Frayer et al., 1989). Despite this loss of wetlands, nearly three million ducks, two million geese, and 350,000 shorebirds continue to overwinter in this region (Shuford et al., 1998; Olson, 2014), making the Central Valley an internationally important area for migratory waterbirds in the Pacific Flyway (Gilmer et al., 1982; WHSRN, 2003). A large proportion of these birds rely on flooded rice fields, which provide habitat for over 50 species of waterbirds during the non-breeding (Day and Colwell, 1998; Elphick and Oring, 1998) and breeding seasons (Eadie et al., 2008; Shuford et al., 2007).

Flooded rice fields generate GHGs because methane is produced by microbial decomposition of organic material in oxygen-deprived, flooded conditions (Mosier et al., 1998), which occur both during the growing and post-harvest seasons. During the growing season, methane emissions can be reduced in several ways, most of which involve drying the soils periodically. Recent work in California identified two practices with potential to decrease methane emissions during this time: drill seeding (planting

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seeds into a dry field) and periodic draining of fields during the summer growing season. Drill seeding, which we address here, has the potential to reduce methane emissions by 16% (EDF, 2011) over the traditional flooded fly-on seeding. During the non-growing season, methane emissions can be reduced by keeping the soils as dry as possible (Kang et al., 2002; Xu et al., 2003) and by adjusting the timing or amount of organic residue additions (Xu et al., 2000). Practices identified in California include reduced winter flooding and removal of rice straw after harvest via baling (Bossio et al., 1999; Suddick et al., 2010; EDF, 2011). These practices have the potential to reduce methane emissions by 13–32% on any given field over incorporating most rice residue into the soil and/or flooding post-harvest (EDF, 2011). Currently 3% of the 227,000 ha of rice grown annually in California are baled post-harvest, and approximately 47% of rice fields are flooded (Garr, 2014).

In California, agriculture contributes 8.9% of the state's anthropogenic GHG emissions and of that, rice agriculture contributes 3% (0.3% of total), most as methane during the growing season (CA-ARB, 2014). State regulations enacted in the 1990s restricted the amount of allowable rice residue burning (Rice Straw Burning Reduction Act, AB 1378, 1991) resulting in an increase in the amount of rice that is flooded after harvest for residue (straw and stubble) decomposition (Miller et al., 2010). This reduction in burning for residue management post-harvest decreased air pollution, including CO₂, but increased annual GHG emissions (Fitzgerald et al., 2000; CA-ARB, 2003) because the by-product of straw fermentation via flooding is methane.

The state of California set a target of reducing GHG emissions to 1990 levels by 2020 (Global Warming Solutions Act of 2006, AB-32, 2006). Reducing GHG emissions from agriculture will be an important component of reaching those goals. California is considering adopting some GHG emission-reducing practices for rice agriculture in its Cap-and-Trade Program (CA-ARB, 2014). While mitigation measures may

help get California closer to its AB-32 goals, the practices used for mitigation could also reduce the ability of rice to provide surrogate wetland habitat for waterbirds, either by reducing the total amount of flooded habitat, or by reducing the fields' ability to provide habitat to certain groups of waterbirds (e.g., by reducing the availability of suitable water depths or other indicators of good quality habitat; see Strum et al., 2013).

We studied the response of waterbirds to rice management practices designed to reduce GHG emissions in the Sacramento Valley of California. Specifically, we compared waterbird density and other indicators of habitat quality (1) among four combinations of post-harvest management practices of flooding and baling during winter; and (2) between drill seeding and flooded fly-on seeding during spring.

2. Methods

2.1. Study area

The Sacramento Valley is the northern portion of the Central Valley of California (Fig. 1). Average annual rainfall is 51 cm and most rain falls between the months of October and February. The region historically flooded in late winter creating approximately 1.5 million ha of seasonal wetlands across the valley floor (Frayer et al., 1989). Over the last century, the majority of these historical wetlands have been converted to agriculture, with only 28,300 ha of managed wetlands remaining. Currently there are approximately 227,000 ha of rice grown in the Sacramento Valley (USDA, 2014) providing flooded habitat to spring migrants and breeding waterbirds. During winter, the amount of rice fields that are flooded decreases to approximately 107,000 ha (Garr, 2014) and provides important habitat for migratory and wintering waterbirds.

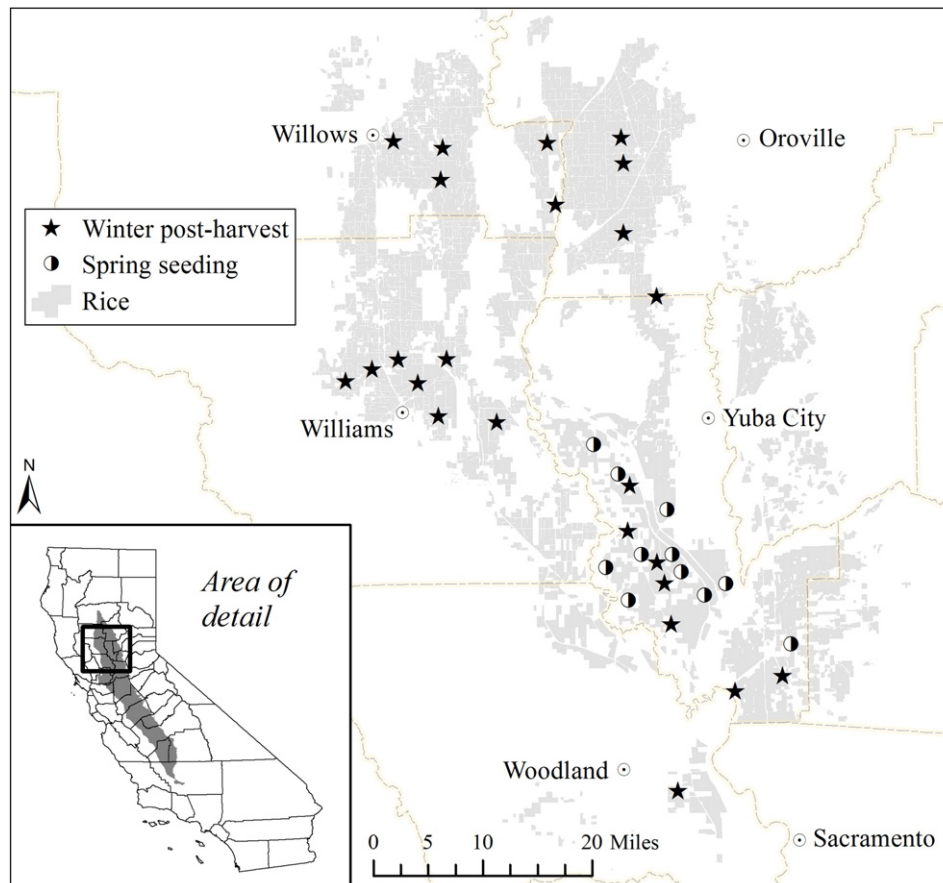


Fig. 1. Location of participating rice farms in the Sacramento Valley, California, USA for both the winter post-harvest and spring seeding studies of waterbird use of rice fields, 2011–2013.

2.2. Study species

We studied three waterbird groups commonly found in rice fields: dabbling ducks (Anseriformes), geese and swans (Anseriformes), and shorebirds (Charadriiformes; Table 1). These three groups represent the largest use of rice by waterbirds in the Sacramento Valley (Sterling and Buttner, 2011) and quantitative population objectives are established for these groups in conservation planning by the Central Valley Joint Venture (CVJV, 2006). Furthermore, these groups consume different food resources (seeds and invertebrates), and have different habitat requirements.

2.3. Post-harvest practices

Two GHG reducing practices were associated with field management after the rice was harvested: baling of rice straw and reduced winter flooding. We investigated four combinations of baling and winter flooding practices in order of decreasing methane emissions: non-baled/flooded, non-baled/non-flooded, baled/flooded, and baled/non-flooded.

Baling removes most of the rice residue (straw and stubble) from the field. After harvest, there was typically 0.3–1 m of standing stubble left in the rice fields. Baling removed most of this, but 7–15 cm of standing stubble typically remained. The remaining standing stubble in baled fields was either left “as-is” until spring, burned, or incorporated into the soil. Since most of the residue was removed from baled fields, neither flooding nor incorporation is typically required for residue decomposition.

After harvest in non-baled fields, the 0.3–1 m of standing stubble was often chopped or mowed to break the standing stubble into shorter pieces, creating loose straw that lay horizontally, often on top of the remaining standing stubble. Many farmers then incorporated that straw and the remaining stubble into the soil through various methods such as disking, chiseling, or stomping, the latter of which was performed after they flooded using special equipment which smashed the straw into the mud. The amount of residue remaining on fields in this study varied, depending on the method of incorporation and the farmer's individual preference. Within the four practice combinations, the amount, timing, and method of incorporation varied across fields.

Generally, farmers flooded fields post-harvest sometime from late-October through early December, then maintained water levels of 8–25 cm throughout the winter and drained fields in February. Previous studies suggest that water can be applied a single time or continually added throughout the season (Strum et al., 2013). Both strategies

were represented in our sample. Given the complexity and constraints of working with many private landowners and their different preferences and capabilities, it was not possible to conduct a study where all the practice combinations were implemented with the exact same set of methods, timing, and equipment. However, we believe our sample is representative of the variation observed in farmer approaches to post-harvest management in the Sacramento Valley.

2.4. Seeding practices

During the growing season, we compared the widely used flooded fly-on seeding practice with a practice called drill seeding. Fly-on seeding involved rolling a rice field to create furrows then flooding the field 10–13 cm deep and distributing pre-germinated rice seed over the field by airplane. The rice seed then sinks into the furrows and begins to grow. These fields were generally left flooded after seeding. Drill-seeded fields in our study were not flooded prior to seeding. A seed drill was pulled over the field and sowed seeds below the surface of dry ground. Fields were then flooded in short pulses (water added every ~10 days) 2–3 times to germinate the rice seed. Eventually, both seeding methods were kept flooded at 10–13 cm for the remainder of the growing season.

2.5. Study design

Within farms, rice fields are divided into subunits called paddies that are separated by internal earthen levees. We considered the individual paddy to be the sample unit for both the post-harvest and the seeding studies.

2.5.1. Post-harvest practices

We contacted rice growers and identified 20 farms (year 1: $N = 11$, year 2: $N = 14$, both years: $N = 5$) where one or more of the four study practice combinations, hereafter “practices”, were implemented. We selected paddies from participating farms using Generalized Random Tessellation Stratified (GRTS) sampling methodology, which enabled the selection of spatially balanced random locations with respect to practice (Stevens and Olsen, 2004). In 2011–2012, we selected 233 paddies (45 baled/flooded, 74 baled/non-flooded, 54 non-baled/flooded, and 60 non-baled/non-flooded). In 2012–2013, we selected 246 paddies (65 baled/flooded, 39 baled/non-flooded, 72 non-baled/flooded, and 70 non-baled/non-flooded).

Table 1

Waterbird species observed during surveys of rice fields with different management practices in the Sacramento Valley, California, USA. “W” denotes species observed during winter study of four post-harvest rice practices (baled/flooded, baled/non-flooded, non-baled/flooded, and non-baled/non-flooded) surveyed from 2 December 2011–27 January 2012 and 3 December 2012–25 January 2013. “S” denotes species observed during spring study of two rice seeding practices (drill and fly-on) surveyed from 5–26 May 2012 and 18 April–24 May 2013. Species (or subspecies) of conservation concern are indicated by a “*.”

Shorebirds	Dabbling ducks	Geese and swans
Black-bellied plover (<i>Pluvialis squatarola</i>) – SW	Wood duck (<i>Aix sponsa</i>) – SW	Gr. White-fronted goose (<i>Anser albifrons</i>) – SW
Semipalmated plover (<i>Charadrius semipalmatus</i>) – S	Gadwall (<i>Anas strepera</i>) – SW	Snow goose (<i>Chen caerulescens</i>) – W
Killdeer (<i>Charadrius vociferus</i>) – SW	Eurasian wigeon (<i>Anas penelope</i>) – W	Ross's goose (<i>Chen rossii</i>) – W
Black-necked stilt (<i>Himantopus mexicanus</i>) – SW	American wigeon (<i>Anas americana</i>) – W	Canada goose (<i>Branta canadensis</i>) – W
American avocet (<i>Recurvirostra americana</i>) – S	Mallard (<i>Anas platyrhynchos</i>) – SW	Tundra swan (<i>Cygnus columbianus</i>) – W
Spotted sandpiper (<i>Actitis macularia</i>) – S	Cinnamon teal (<i>Anas cyanoptera</i>) – S	
Greater yellowlegs (<i>Tringa melanoleuca</i>) – SW	Northern shoveler (<i>Anas clypeata</i>) – SW	
Lesser yellowlegs (<i>Tringa flavipes</i>) – W	Northern pintail (<i>Anas acuta</i>) – W	
Whimbrel (<i>Numenius phaeopus</i>) – S	Green-winged teal (<i>Anas crecca</i>) – W	
*Long-billed curlew (<i>Numenius americanus</i>) – W		
Western sandpiper (<i>Calidris mauri</i>) – SW		
Least sandpiper (<i>Calidris minutilla</i>) – SW		
Dunlin (<i>Calidris alpina</i>) – SW		
Long-billed dowitcher (<i>Limnodromus scolopaceus</i>) – SW		
Wilson's snipe (<i>Gallinago delicata</i>) – W		
Wilson's phalarope (<i>Phalaropus tricolor</i>) – S		
Red-necked phalarope (<i>Phalaropus lobatus</i>) – S		

2.5.2. Seeding practices

Drill seeding is rare in the study area and requires specialized equipment. We worked with two growers who use drill-seeding with large farms located primarily in Sutter County (Fig. 1). On these large farms, we again selected paddies using GRTS sampling methodology. To increase our sample size of fly-on seeding, we selected additional rice fields that were close to our primary farms, accessible from public roads, and starting the seeding process at approximately the same time. Across these fly-on seeded fields, we used simple random sampling to select paddies. In 2012, we selected 150 paddies (80 drill, 70 fly-on). In 2013, we selected 131 paddies (69 drill, 62 fly-on).

2.6. Data collection

2.6.1. Waterbird surveys

During winter, habitat availability and bird abundance were relatively stable. We conducted waterbird surveys every ~10 days from 2 December 2011–27 January 2012 and 3 December 2012–25 January 2013. Selected paddies received approximately five visits each winter for a total of 509 unit surveys of bale/flood, 594 unit surveys of non-baled/flooded, 549 unit surveys of baled/non-flooded, and 609 unit surveys of non-baled/non-flooded. During the spring, habitat availability changed frequently as water was added and removed and bird abundance was more variable since waterbirds (particularly shorebirds) were migrating through the region. We conducted waterbird surveys twice weekly from 3–26 May 2012 and 18 April–24 May 2013, with a mean of six and eight visits, respectively, to selected paddies for a total of 1021 unit surveys of drill-seeding and 890 unit surveys of fly-on seeding. The earlier start to seeding in 2013 prompted our study to start earlier in 2013 than in 2012.

We conducted surveys from the edge of each randomly selected rice paddy and used a 200-m fixed-radius and the internal levees separating paddies (whichever was closer) to define the survey area. Where possible, we varied the order in which we visited survey areas during daylight hours to avoid bias in counts due to the effects of time of day. We identified all waterbirds to species and counted all individuals. All survey areas were scanned for at least 2 min. There was no maximum time limit for completing a count, though they ranged from 2–15 min, with a median of 3 min. We only counted waterbirds using the survey area, and did not count birds that flew over. Surveys were not conducted in inclement weather, i.e. winds ≥ 40 kph, heavy fog, or rain.

2.6.2. Habitat characterization

During each survey, we visually estimated percent cover of several metrics to characterize vegetation structure and the degree to which soil was wetted in the survey area. These included the proportion of the survey area with standing rice stubble (if flooded, this was emergent stubble only), as well as the proportion of survey area flooded (completely covered in water), saturated (no standing water but soil appearing with a sheen), moist (wet areas visible in soil but no sheen), and dry (no moisture visible in soil). For the post-harvest study, we also recorded water depth in each survey area using two wooden stakes placed at 50 m and 200 m in the center of the paddy marked with 5-cm depth increments.

2.7. Data analysis

2.7.1. Waterbird density

We calculated the area (ha) surveyed for waterbirds at each sample point using ArcMap Version 9.3.1 (© 1999–2009 ESRI Inc.). We compared waterbird densities, calculated for dabbling duck, goose and swan, and shorebird groups, among practices and years using the average of the pooled mean density (birds/ha) from each survey location in each year and 95% confidence intervals (95% CI). Due to the large number of zeroes (50–90%) and non-normal distribution of bird counts and subsequently bird density estimates, we used bootstrapping and the

percentile method to estimate the 95% CI for the mean density estimates of each waterbird group (Manly, 2007). We chose to use this non-parametric bootstrap approach because we believe it was better able to characterize the mean and variance in bird abundance by practice than a parametric regression model which assumes a single specific distribution, irrespective of treatment, which our count data struggled to achieve. To calculate the confidence intervals, we generated 1000 bootstrap iterations (random resample with replacement) from the original data set, and then calculated the mean for each bootstrap replicate. To account for spatial and temporal correlation from repeated visits to the same survey area each year, we sampled with replacement from each survey area, averaged those values within survey area and then averaged across survey areas in each bootstrap iteration. We calculated density estimates for both years combined and independently for the first and second year of the study to assess year to year variation.

2.7.2. Habitat characterization

The non-parametric bootstrap approach would not work to compare the effects of continuous covariates, so we used zero-inflated negative binomial regression models (Zuur et al., 2009) to examine survey area characteristics (e.g. proportion flooded or proportion covered in vegetation) that could be considered mechanisms driving the observed differences in waterbird density among practices. We used the zero-inflated negative binomial distribution over the zero-inflated Poisson, similar to Strum et al. (2013), because our preliminary assessment of the variance-to-mean ratio of bird counts was dramatically larger than one, which violates the assumptions of the zero-inflated Poisson; highlighting the need for the overdispersion parameter from the negative binomial. Because correlated mechanism covariates could confound inference from our models, we considered only univariate models; although a quadratic form of a water-depth model was evaluated. To assess the relative influence of our selected survey area characteristics as mechanisms influencing abundance of waterbird groups, we ranked the univariate models using Akaike's Information Criterion (AIC; Burnham and Anderson, 2002) and considered models within 2 AIC units of the model with the lowest AIC as part of the top model set. We used the count of waterbirds of the different groups summed across all visits to a survey area as the response variable and included an offset term equal to the natural logarithm of the area (ha) of the survey area in the paddy multiplied by the number of visits to account for variation in the size of survey areas and the number of visits (Zuur et al., 2009). We pooled counts across visits to remove autocorrelation due to repeated visits to the same survey area through the year and to reduce zero-inflation in the data. To match the pooled response data, we used the average of our covariate values across all visits to a survey area in the model.

For the post-harvest practices, we examined the effect of whether a survey area was incorporated (disked, chiseled, stomped) or not by combining all the different methods of incorporation. We expected waterbird groups with large granivorous components of their diet, such as geese and ducks, to have higher use of non-incorporated paddies since the waste grain should be on the surface and more accessible (Miller et al., 1989), though Elphick and Oring (1998) showed no effect of straw management practices on these groups. We expected waterbird groups that feed on invertebrates, such as most shorebirds and some ducks, to have higher use of incorporated paddies due to the increase in overall decomposition. Some species of smaller shorebirds have been shown to be positively associated with incorporation (Elphick and Oring, 1998) although the mechanism for this remained unknown, but could be due to incorporated paddies having more variation in water depth (Elphick et al., 2010) or a lower probability of standing stubble (Strum et al., 2013). We also examined the effect of the proportion of the survey area that was flooded (having standing water) and the effect of water depth in both linear and quadratic forms, as both shorebirds and ducks have been shown to have optimal depth range preferences (Strum et al., 2013). We found it difficult to assign an

optimal depth range to geese since they use both flooded and unflooded fields (Elphick and Oring, 1998; Ackerman et al., 2006). Lastly, we quantified the effect of the proportion of the survey area with standing stubble (only emergent stubble if flooded) since previous studies have found some species, which use visual detection and flight as a means of escaping predators, may avoid habitats with tall structure (e.g. stubble) which can obstruct their view of approaching predators (Cresswell, 1996; Ydenberg et al., 2002; Whittingham and Evans, 2004).

For the post-harvest practices, we also examined the probability that a practice provided suitable water depths for shorebirds and dabbling ducks following methods outlined in Strum et al. (2013). They defined suitable water depth for shorebirds to be between mudflat and 16 cm and suitable water depth for dabbling ducks to be greater than 16 cm. Geese use a wide range of water depths from dry fields to fields flooded to greater than 16 cm, so were not assigned a suitable depth range. We also compared the probability of incorporation (all methods combined) among practices. We used mixed-effects logistic regression models to estimate the mean and 95% CI of the probability of suitable water depth or incorporation by practice (Zuur et al., 2009). The response variable for the models was a 1 or 0 indicating whether or not the survey was of suitable depth or incorporated during each visit. To account for autocorrelation in the data due to repeated visits to the same survey area through the year we included survey area as a random effect in these models.

For the seeding practices, we considered the proportion of the survey area that was flooded, saturated, moist, and dry in univariate models to examine possible mechanisms driving bird use. We assessed these gradients in soil moisture because water characteristics were variable and dynamic in fields during planting while other aspects of the fields were similar across farms and practices, such as presence of vegetation or stubble, of which there was generally none.

We considered estimates (of density, coefficients, etc.) to be significantly different if their 95% CI did not overlap. We recognize that this is a strict measure of significance and represents $\sim P = 0.01$ (Gardner and Altman, 1986) but wanted to set a high burden of proof. We assessed the fit of our models by evaluating residual plots for evidence of autocorrelation or deviance from normality as well as fitting an intercept only model for inclusion in model comparisons. We specifically assessed spatial autocorrelation by plotting model residuals against farm and calculating Moran's I (Moran, 1950). We used R v.3.0.2 (©2013 The R Foundation for Statistical Computing) for all statistical analyses, specifically the 'boot' package version 1.3-11 for bootstrapping analyses (Canty and Ripley, 2015), the 'pscl' package version 1.4.9 for the zero-inflated negative binomial analyses (Zeileis et al., 2008), and the lme4 package version 1.0-4 for mixed-effects logistic regression analyses (Bates et al., 2015).

3. Results

3.1. Post-harvest practices

We observed 36 species of waterbirds, for a total of 32,497 birds in 2011–2012 and 18,440 birds in 2012–2013. The most numerous species were American coot (*Fulica americana*), mixed goose flocks (*Chen/Anser* spp.), northern pintail (*Anas acuta*), and dunlin (*Calidris alpina*). The two flooded practices, bale/flooded and non-baled/flooded, had almost twice the waterbird species richness ($N = 29$ and $N = 30$, respectively) compared to non-flooded practices ($N = 17$).

3.1.1. Waterbird densities by practice

With both years combined, we found dabbling duck mean density to be significantly higher in the non-baled/flooded practice than the baled/flooded practice (Fig. 2). The difference between non-baled and baled was not significant in the first year but was significant in the second year of the study. We found no dabbling ducks in the two non-flooded practices. Shorebird mean density was significantly higher in the non-baled/flooded practice than in the other three practices (Fig. 2),

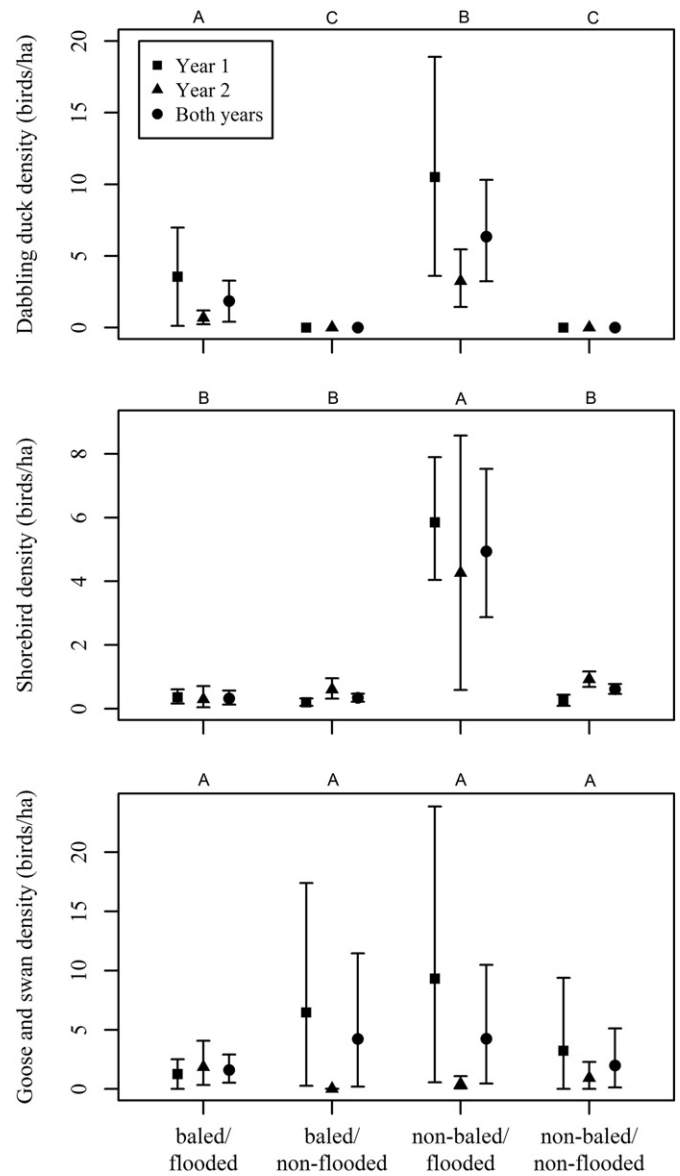


Fig. 2. Mean waterbird density (birds/ha) and 95% confidence intervals (CIs) in four post-harvest rice practices, baled/flooded, baled/non-flooded, non-baled/flooded, and non-baled/non-flooded. Surveys conducted from 2 December 2011–27 January 2012 (Year 1) and 3 December 2012–25 January 2013 (Year 2) in the Sacramento Valley, California, USA. Means (for both years combined) with different letters are significantly different (95% CIs do not overlap).

although we found more variation around the mean density for non-baled/flooded in the second year; this led to a small amount of overlap of the 95% CIs with the other practices. Our data suggested no significant differences among the post-harvest practices for geese though we recorded some very large flocks of geese in the first year which resulted in the large 95% CIs (Fig. 2).

3.1.2. Waterbird densities and habitat characterization

Water variables were important for dabbling ducks and shorebirds while we were not able to tease out any significant effects for geese. For dabbling duck and shorebird density, we found water depth and proportion of survey area flooded had significant positive effects while proportion of area with stubble had a significant negative effect; however none of the covariates had a significant effect on goose density (Table 2). Additionally, incorporation of rice residue in a survey area had a significant positive effect on shorebird density. For shorebirds, the quadratic water depth model had the lowest AIC and was >2 AIC

Table 2
Summary of zero-inflated negative binomial regression models evaluating habitat characteristics as mechanisms influencing waterbird use of four post-harvest rice practices surveyed from 2 December 2011–27 January 2012 and 3 December 2012–25 January 2013 in the Sacramento Valley, California, USA. In addition to covariates listed, all models included an intercept, an overdispersion parameter, and a zero-inflation parameter.

Group	Model covariate	AIC ^a	DeltaAIC ^b	LL ^c	K ^d	Estimate ^e	95% low ^f	95% up ^g	EstQ ^h	95% low	95% up
Dabbling ducks	Depth ⁱ + Depth ^{2j}	948.52	0.00	−469.26	5	0.96	0.56	1.36	−0.02	−0.04	−0.01
	Flood ^k	950.20	1.68	−471.10	4	6.19	4.24	8.15			
	Depth	963.77	15.25	−477.89	4	0.19	0.08	0.30			
	Stubble ^l	965.83	17.31	−478.92	4	−7.45	−10.79	−4.12			
	Intercept ^m	976.07	27.56	−485.04	3						
	Incorporation ⁿ	977.12	28.60	−484.56	4	0.83	−0.52	2.19			
Geese	Intercept	817.72	0.00	−405.86	3						
	Stubble	818.70	0.98	−405.35	4	0.96	−1.01	2.93			
	Flood	818.75	1.04	−405.38	4	−1.20	−3.41	1.00			
	Depth	819.48	1.76	−405.74	4	−0.02	−0.11	0.06			
	Depth + Depth ²	821.46	3.75	−405.73	5	−0.04	−0.29	0.21	0.00	−0.01	0.01
	Incorporation	822.26	4.54	−407.13	4	−0.38	−2.12	1.35			
Shorebirds	Depth + Depth ²	2065.84	0.00	−1027.92	5	0.41	0.30	0.53	−0.02	−0.02	−0.01
	Incorporation	2083.58	17.74	−1037.79	4	2.13	1.49	2.77			
	Flood	2099.84	33.99	−1045.92	4	1.89	0.86	2.91			
	Stubble	2104.30	38.46	−1048.15	4	−2.00	−3.16	−0.84			
	Intercept	2111.21	45.37	−1052.61	3						
	Depth	2112.10	46.26	−1052.05	4	0.03	−0.03	0.09			

^a Akaike's Information Criterion.

^b Difference from model with lowest AIC.

^c Log likelihood.

^d Number of parameters in model.

^e Parameter estimate for model covariate.

^f Lower 95% confidence bound.

^g Upper 95% confidence bound.

^h Parameter estimate for quadratic term of water depth model (Depth²).

ⁱ Average water depth (cm).

^j Quadratic term for water depth.

^k Proportion of the survey area that was flooded.

^l Proportion of the survey area with standing stubble.

^m Intercept-only model.

ⁿ Whether a field was incorporated post-harvest.

units less than the next best supported model which included the variable indicating whether residue incorporation had occurred. Similarly, the quadratic depth model was best supported by AIC for dabbling ducks; however the model including the proportion flooded was within 2 AIC units of the top dabbling duck model, further emphasizing that water is essential for dabbling duck use. All models for shorebirds and all models except the incorporation model for ducks were a significant improvement, based on AIC, over the intercept-only model. However, for geese, the intercept-only model was best supported, further substantiating that none of the covariates or practices considered had a significant effect on goose density.

Our assessment of the residuals of univariate models used to evaluate the effects of survey area characteristics as mechanisms influencing waterbird density suggested reasonable model fit to the data and largely non-significant spatial autocorrelation. Residual spatial correlation was generally higher for dabbling duck models than for shorebirds or geese and in models that were ranked lower than an intercept only model by AIC. Assessment of residuals suggested reasonable fit of our models and no pattern in residuals when plotted against farm, indicating limited or no residual spatial autocorrelation.

Differences in survey area characteristics influencing waterbirds were often associated with the four practices (Fig. 3) and consequently may help explain the observed variation in waterbird use. Predictably, water was more prevalent and deeper in flooded practices than in the non-flooded practices. Water depth was not significantly different between the two flooded practices. The probability of water being at shorebird depth was significantly higher in both baled/flooded (0.21; 0.15–0.29 95% CI) and non-baled/flooded (0.29; 0.19–0.49 95% CI) than in baled/non-flooded (0.08; 0.05–0.14 95% CI). However there was considerable uncertainty in our estimate of the effect of non-baled/non-flooded on water depth resulting in a large 95% CI (0.13; 0.08–0.61 95% CI) despite a low probability for shorebird depth. There

also was not a significant difference in the probability of water of suitable depth for dabbling ducks between the two flooded practices, baled/flooded (0.78; 0.68–0.87 95% CI) and non-baled/flooded (0.65; 0.48–0.79 95% CI) but both non-flooded practices had zero probability of providing water depth suitable for dabbling ducks. Standing stubble was strongly associated with non-flooded practices which may be related to water obscuring the substrate of the field when flooded. Where visible in dry practices, baled/non-flooded had a higher average proportion standing stubble than non-baled/non-flooded which, in part, may be explained by the higher frequency of incorporation in our sample of non-baled practices resulting in lower amounts of standing stubble in that practice (Fig. 3). There was a significantly lower probability of incorporation in baled practices in our study, baled/flooded (0.52; 0.46–0.58 95% CI) and baled/non-flooded (0.35; 0.28–0.42 95% CI), than in non-baled practices, non-baled/flooded (0.90; 0.86–0.93 95% CI) and non-baled/non-flooded (0.83; 0.78–0.98 95% CI).

Our results suggested that shorebird density was significantly associated with whether or not the straw was incorporated and that straw was more likely to be incorporated if the field was non-baled. Post-hoc we further examined whether differences in incorporation was the mechanism driving the difference in use between baled and non-baled fields by filtering the dataset to control for flooding and incorporation. We performed bootstrapping according to the methods described above, separately for baled and non-baled fields that were incorporated and non-incorporated. For shorebirds, non-baled and incorporated paddies still had significantly higher densities than any other combination of practices, and particularly than baled and incorporated paddies (Table 3). Our mechanism models did not indicate straw incorporation was important for ducks, or geese and swans, which is supported to some extent by other research (Elphick and Oring, 1998), thus we feel our initial comparison of means by practices is robust to differences in incorporation rates between baled and non-baled practices.

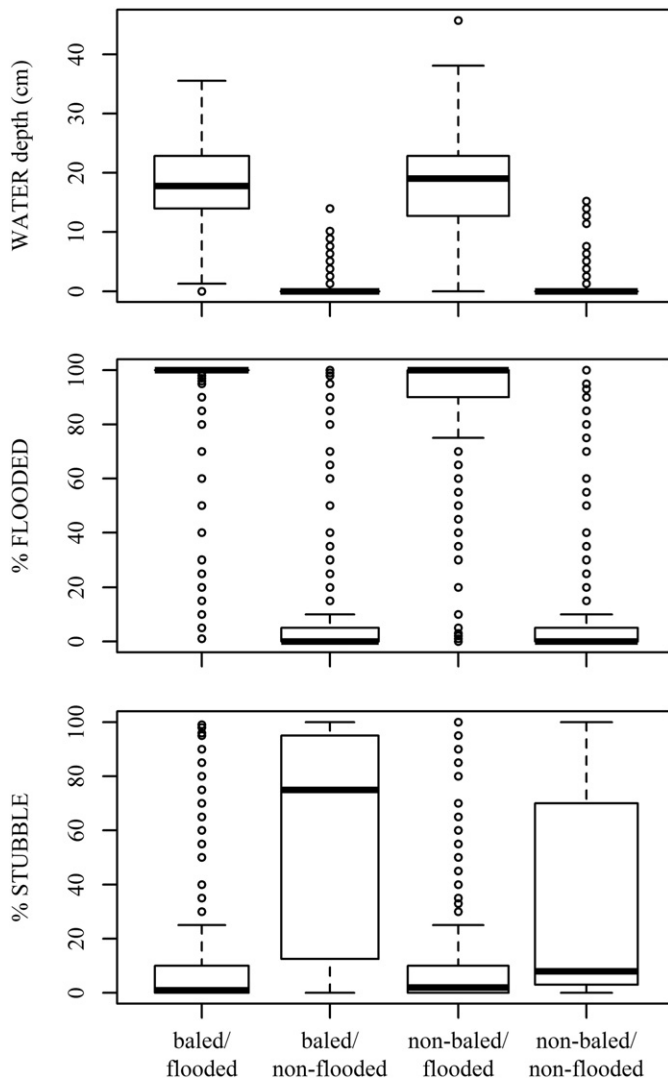


Fig. 3. Distribution of observed paddy characteristics in four post-harvest rice practices, baled/flooded, baled/non-flooded, non-baled/flooded, and non-baled/non-flooded. Surveys were conducted from 2 December 2011–27 January 2012 and 3 December 2012–25 January 2013 in the Sacramento Valley, California, USA. Boxes represent the median (center line), the lower quartile (bottom) and the upper quartile (top) of the observed data. Whiskers represent the range of values based on adding or subtracting 1.5 times the interquartile range. The hollow circles are values observed in the data outside of this range.

3.2. Seeding practices

3.2.1. Waterbird densities by practice

We observed 29 species of waterbirds for a total of 1441 birds in 2012 and 3573 birds in 2013. The most numerous species were mallard (*Anas platyrhynchos*; over 99% of the ducks observed on surveys were

Table 3

Mean shorebird densities and 95% CIs in the two flooded post-harvest rice practices, baled/flooded and non-baled/flooded, with incorporated and non-incorporated straw separated for each practice. Surveys were conducted from 2 December 2011–27 January 2012 and 3 December 2012–25 January 2013 in the Sacramento Valley, California, USA.

Flooded practices only	n ^a	Mean	95% CI
Baled, incorporated	59	0.48	0.13–0.99
Baled, non-incorporated	51	0.12	0.08–0.17
Non-baled, incorporated	114	5.33	2.96–8.05
Non-baled, non-incorporated	14	1.05	0.30–2.07

^a n is the number of surveyed paddies in each group.

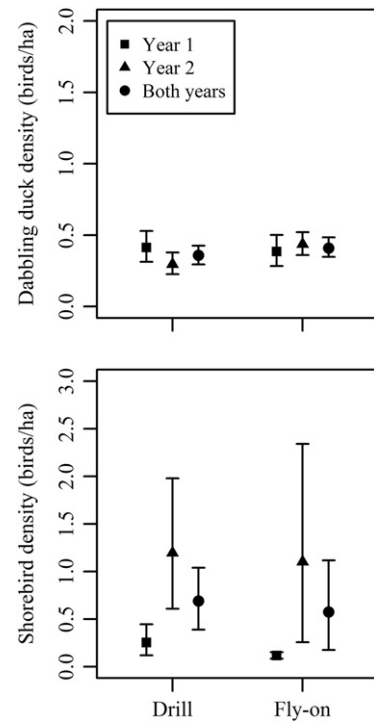


Fig. 4. Mean waterbird density (birds/ha) and 95% confidence intervals in two seeding practices, drill and fly-on seeding from surveys conducted from 5–26 May 2012 (Year 1) and 18 April–24 May 2013 (Year 2) in the Sacramento Valley, California, USA. We found no significant difference between seeding practices.

mallards), western sandpiper (*Calidris mauri*), white-faced ibis (*Plegadis chihi*), and American coot. We had sufficient data for analysis of 15 species of dabbling ducks and shorebirds (Table 1). However, geese (all greater white-fronted geese; *Anser albifrons*) were only recorded twice during this study, and both times in small groups.

We found no significant difference in mean dabbling duck or shorebird densities between the two seeding practices (Fig. 4). Shorebirds showed significantly higher densities and more variation in the second year of the study. We attribute this to the seeding period starting almost two weeks earlier in 2013, resulting in more use of the rice fields by flocks of migrating shorebirds. Breeding waterbird species recorded during this study that regularly breed in or near rice paddies include mallard and a subset of the shorebirds including black-necked stilt (*Himantopus mexicanus*), American avocet (*Recurvirostra americana*), Wilson’s phalarope (*Phalaropus tricolor*), and killdeer (*Charadrius vociferous*).

3.2.2. Waterbird densities and habitat characterization

Models used to evaluate the effects of survey area characteristics as mechanisms influencing waterbird density suggested that both shorebirds and dabbling ducks had significant negative associations with the proportion of the survey area that was dry (Table 4) and, conversely, a significant positive association with the proportion of the survey area that was flooded. The proportion of dry area was the best supported model based on AIC for both groups. Shorebirds were also positively associated with proportion of the survey area that was saturated with water.

Overall the average proportion of the survey area that was flooded was higher and less variable in the fly-on (0.86) than in the drill seeding (0.33; Fig. 5) practice while the opposite was true for the proportion of the survey area that was dry. However, the proportion of the survey area that was saturated and moist was, on average, higher in the drill seeding practice.

Table 4
Summary of zero-inflated negative binomial regression models evaluating habitat characteristics as mechanisms influencing waterbird use of two rice seeding practices, surveyed from 5–26 May 2012 and 18 April–24 May 2013 in the Sacramento Valley, California, USA. In addition to covariates listed, all models included an intercept, an overdispersion parameter, and a zero-inflation parameter.

Group	Model/covariate	AIC ^a	DeltaAIC ^b	LL ^c	K ^d	Estimate ^e	95% low ^f	95% up ^g
Dabbling ducks	Dry ^h	1744.18	0.00	−867.09	5	−1.60	−2.30	−0.90
	Flood ⁱ	1753.30	9.12	−871.65	5	0.79	0.30	1.27
	Intercept ^j	1761.69	17.51	−877.84	3			
	Saturated ^k	1762.68	18.50	−876.34	5	−0.41	−1.52	0.71
	Moist ^l	1763.17	18.99	−876.58	5	0.10	−1.34	1.54
Shorebirds	Dry ^h	1421.68	0.00	−705.84	5	−3.34	−4.64	−2.04
	Saturated ^k	1431.99	10.31	−711.00	5	4.53	1.41	7.65
	Flood ⁱ	1435.92	14.24	−712.96	5	1.39	0.25	2.53
	Moist ^l	1439.39	17.71	−714.69	5	−1.91	−4.51	0.68
	Intercept ^j	1460.87	39.19	−727.43	3			

^a Akaike's Information Criterion.

^b Difference from model with lowest AIC.

^c Log likelihood.

^d Number of parameters in model.

^e Parameter estimate for model covariate.

^f Lower 95% confidence bound.

^g Upper 95% confidence bound.

^h Proportion of survey area that was dry.

ⁱ Proportion of survey area that was flooded.

^j Intercept-only model.

^k Proportion of survey area that was saturated.

^l Proportion of survey area that was moist.

4. Discussion

4.1. Post-harvest practices

Our study documented significant differences in densities of shorebirds and dabbling ducks in rice fields in winter depending on the

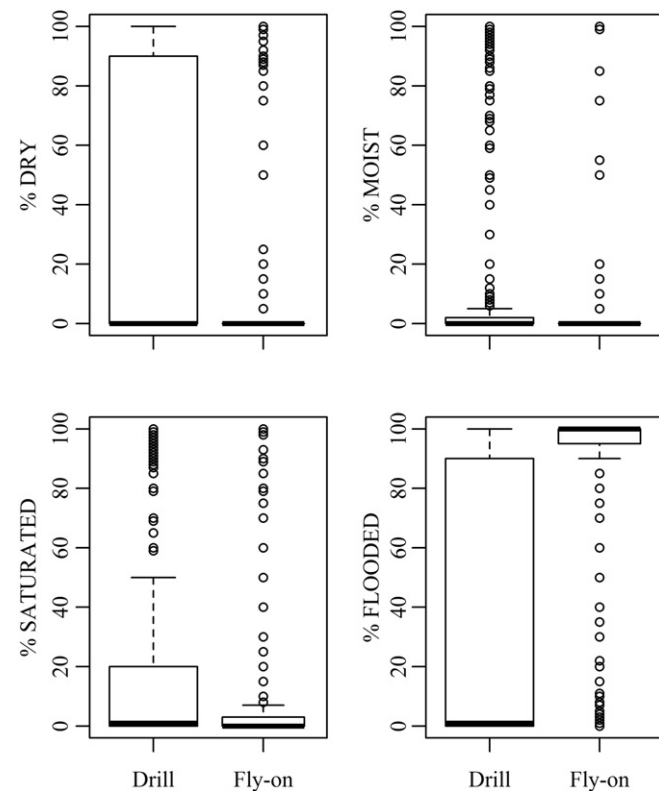


Fig. 5. Distribution of observed soil moisture characteristics in rice paddies in two seeding practices, drill and fly-on seeding from surveys conducted from 5–26 May 2012 and 18 April–24 May 2013 in the Sacramento Valley, California. Boxes represent the median (center line), the lower quartile (bottom) and the upper quartile (top) of the observed data. Whiskers represent the range of values based on adding or subtracting 1.5 times the interquartile range. The hollow circles are values observed in the data outside of this range.

post-harvest practices. The flooded practices had significantly higher waterbird numbers than non-flooded practices, as has been found in other studies in California (e.g., Day and Colwell, 1998; Elphick and Oring, 1998; Strum et al., 2013) and in other rice growing regions of the world (Lourenço and Piersma, 2009; Tajiri and Ohkawara, 2013; Pernellet et al., 2015). Non-flooded practices received use by geese and other studies also found geese to use both flooded and non-flooded fields (Elphick and Oring, 1998; Ackerman et al., 2006; Nam et al., 2015). Compared to a recent study in the same area using the same protocol, our flooded and non-flooded practices had comparable but lower density estimates for dabbling ducks and slightly higher density estimates for shorebirds (Strum et al., 2013). Elphick and Oring (1998) found generally lower densities for all the waterbird groups than observed in our study. This may be due, at least partially, to an increase in waterfowl densities in the Sacramento Valley in the 18 years between studies (Olson, 2014). The increase in waterfowl in the Sacramento Valley tracks increases in availability of winter flooded habitat (Fleskes et al., 2005). There are no data on population trends of shorebirds in the Sacramento Valley, but it stands to reason they could show a similar pattern to waterfowl.

Few studies have examined waterbird response to baling, or the removal, of rice straw. Of the two non-flooded practices, we did not find a significant difference in densities in baled versus non-baled paddies for all three waterbird groups. Nam et al. (2015) found a mixed response from geese, with higher densities of greater white-fronted geese in non-baled fields compared to baled fields (either incorporated or not) while bean goose (*Anser fabalis*) had higher densities in baled fields. The same study also found that within non-incorporated fields, non-baled fields had higher densities of waste rice compared to baled fields. Of the two flooded practices, we found significantly higher densities of shorebirds and dabbling ducks in the non-baled/flooded than baled/flooded practice. Mean duck densities were three times larger and mean shorebird densities were fifteen times larger in non-baled/flooded than baled/flooded paddies. Elphick and Oring (1998) found no evidence that baling affected density for most species of ducks, geese, and shorebirds.

Elphick and Oring (1998) found that four species of smaller shorebird were most abundant in incorporated fields, although their results were confounded by geographic variation in abundance and their incorporated fields were shallower than their non-incorporated fields. Mean water depths of our flooded practices were not significantly different

between baled and non-baled ($t = -0.02, P = 0.99$), however there is inherently more fine-scale variation in depth in a field that is incorporated. About half of our baled/flooded fields were not incorporated, leaving more emergent stubble compared to non-baled/flooded fields of which about 90% were incorporated, which makes incorporation and non-baled/flooded fields correlated to a higher degree than baled/flooded fields. We found shorebirds to be significantly associated with incorporation and even after controlling for incorporation, shorebird density was still significantly higher in non-baled compared to baled paddies. These results further support the higher value of non-baled/flooded fields compared to baled/flooded fields for shorebirds.

We did not find waterfowl to be significantly associated with incorporation (positively or negatively), and similarly Elphick and Oring (2003) found no evidence that granivores avoid fields where the straw had been incorporated. However, Tajiri and Ohkawara (2013) found incorporating fields via plowing had a negative effect on duck densities and on availability of waste rice. Our results are somewhat contrary to the hypothesis that granivores prefer non-incorporated fields, although the dabbling duck group in our analysis includes both granivores and species that forage on a mix of seeds, invertebrates, and vegetation.

Our study of post-harvest rice included two species of conservation concern; the tule greater white-fronted goose (*Anser albifrons elgasi*; California Species of Conservation Concern) which we included in the goose and swan group, and long-billed curlew (*Numenius americanus*; Federal Bird Species of Conservation Concern), which we included in the shorebird group. We did not differentiate subspecies of greater white-fronted goose, although based on our study area, we likely detected them but to an unknown degree (Deuel and Takekawa, 2008). We detected long-billed curlews in all four post-harvest practices we studied, however their sample size was too low to analyze separately.

4.2. Seeding practices

Our novel study on the use of rice fields during planting suggests that drill seeding and its pulse flooding strategy for irrigation, provide comparable habitat for shorebirds and dabbling ducks to traditional and more widely used fly-on seeding. Fly-on seeding had a slightly greater proportion flooded, but drill seeding provided more saturated and moist soil habitat for shorebirds. These findings provide evidence that drill seeding may be a viable option for reducing GHGs while supporting non-breeding waterbirds. Currently, drill seeding is only practiced by a small number of farmers in the study area and involves specialized seeding equipment, thus is unlikely to become widespread in the near future unless heavily incentivized to reduce costs.

During seeding, there are two major lifecycle stages to consider for waterbirds when assessing results and making decisions about seeding practices: spring migration for shorebirds and the beginning of the breeding season for species of shorebirds and waterfowl that nest in the Central Valley (e.g., mallard, black-necked stilt). The timing of rice planting varies annually in response to suitable weather conditions for field preparation (2012 was a late year for planting). Waterbird use of rice fields in spring likely varies annually as well, in response to variation in the timing of flooding and migration. Migration and variability in timing was apparent in our data as western sandpiper was the second most abundant shorebird species in this study, yet they were only present through 18 May in 2012 and 3 May in 2013. Dunlin, semipalmated plover (*Charadrius semipalmatus*), whimbrel (*Numenius phaeopus*), and dowitchers (*Limnodromus* spp.) were all present throughout the seeding study window with numbers decreasing during the course of our surveys, making it more difficult to assess differences between the seeding practices. Matching the timing of rice seeding with migration of waterbirds, when possible, would ensure maximum benefit of the water for agriculture and wildlife.

Rice planting occurs at the beginning of the breeding season for many locally breeding waterbirds. Species that breed directly in or

adjacent to rice fields may perceive the drier drill-seeded fields as less suitable when they are prospecting for nesting sites. Nest initiation in mallards is well underway by the time seeding occurs (McLandress et al., 1996) so the seeding practice may not affect nesting decisions and we did not find a significant difference in use. For black-necked stilts and American avocets, nest site selection typically occurs in May (Shuford et al., 2007), so their nesting decisions are more likely to be affected by the drill seeding practice. During our study, sample sizes for stilts ($N = 46$) and avocets ($N = 21$) were not sufficient to assess differences between the seeding practices. Black terns are another important waterbird that regularly breed in rice fields in the Sacramento Valley (Shuford et al., 2001) and are a species of special concern in California (Shuford, 2008). Nest site selection for black terns in most years occurs in May, so terns, like shorebirds, may perceive drier drill-seeded fields as less suitable. Sample size in this study for black terns ($N = 19$) was not sufficient to assess differences between the seeding practices. Further evaluation of the effects of these two seeding practices on breeding species (i.e. nest success, productivity) is needed.

5. Conclusions

Our study provides evidence that some post-harvest practices (reduced winter flooding, baling of rice straw) designed to reduce GHG emissions from rice agriculture, reduce use by waterbirds. The benefits of the GHG reducing practices must be evaluated against this trade-off of reduced habitat for waterbirds and other wildlife (EDF, 2011). While baling of straw and not flooding results in the largest decrease in methane emissions (approximately 32% from current baseline practices), our data suggest not flooding would significantly reduce use of rice fields by waterbirds, especially ducks, which did not use non-flooded fields at all. Our data also suggest that, on average, densities in baled and flooded fields would be 94% lower for shorebirds and 71% lower for dabbling ducks, than fields that are non-baled and flooded. Meanwhile, there is only a reduction of 23% in methane emissions when baling fields prior to flooding rather than not baling (EDF, 2011). Our study provides the essential data to rigorously evaluate these trade-offs between GHG and wildlife habitat in order to make optimal management decisions.

Currently, baling is more expensive than flooding and there are limited markets for the straw (EDF, 2011). However, if there were incentives to baling such as the possible inclusion of the practice into California's Cap and Trade Program, it may become increasingly popular. Water supplies in California are under increasing pressure, even before the record-breaking drought of 2013–2015, and farmers are increasingly turning to dry incorporation to decompose rice straw (Petrie et al., 2014). In the Central Valley, rice provides nearly half of all the food energy available to dabbling ducks from flooded habitat and over seventy percent of all food energy for snow (*Chen caerulescens*) and Ross's geese (*Chen rossii*; Petrie et al., 2014). Changes in post-harvest practices that reduce availability to waste grain, such as baling and decreased flooding, could have a significant impact on waterfowl populations in the Pacific Flyway, especially given that other important stopovers in the flyway, such as the Klamath Basin, are also struggling with water availability (Petrie et al., 2014). There is evidence that shorebirds which prefer to use flooded rice, retreat to nearby wetlands as post-harvest flooded rice fields dry up in late-winter, and eventually leave the Sacramento Valley entirely (Barbaree et al., 2015).

When considering possible mechanisms to reduce GHG while still providing habitat for waterbirds, maintaining food resources and flooding is critical. Additional analyses are needed that focus on the net trade-offs between waterbird populations and total GHG reductions of these practices to help gauge the best approach for potential implementation. An optimization study (e.g. Starfield and Bleloch, 1991) could identify the combination of rice management strategies that would minimize total GHG emissions while still providing enough habitat to meet waterbird population objectives for the Central Valley

(CVJV, 2006). While reducing GHG is globally necessary to minimizing the impacts of climate change, this study shows that some practices may negatively impact waterbirds in an area of hemispheric importance. This tradeoff needs to be acknowledged in future decision-making to successfully guide the balancing of multiple competing benefits.

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