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Conservation implications of flooding rice fields on winter waterbird communities

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Abstract

The effects of flooding harvested rice fields on waterbird communities were studied during winter. Variation in the number of waterbird species, overall densities of all waterbirds, wading birds, waterfowl, and shorebirds, and a measure of conservation value that weighted species according to their relative abundance and population trends were examined. Each variable was tested for differences among: (a) flooded and unflooded fields; (b) flooded fields that received different rice straw manipulations; and (c) fields with different water depths. Flooded fields were used by waterbirds more than unflooded fields according to most criteria, although wading bird densities did not differ between flooded and unflooded fields. In terms of conservation value, flooded fields contributed considerably more to waterbird conservation than unflooded fields. The number of waterbird species, total waterbird density, and the density of wading birds differed significantly among straw management treatments, though in different ways. Water depth significantly affected all measures, but in all cases most of the variation went unexplained. Bird densities were explained best by asymptotic relationships, with shorebird densities greatest in shallow water and waterfowl and wading bird densities greatest in deeper conditions. Waterbird richness and conservation value both were greatest at depths of 10–15 cm. Intentionally flooding fields during winter significantly affected numerous aspects of the waterbird community. The method of flooding also influenced the waterbird community, although these effects often were small.

Keywords: California; Shorebird; Waterfowl; Wading birds; Agricultural wetland; Rice farming; Conservation value; Management

1. Introduction

One-third of the world's ice-free land area is used for agriculture and 11% is cultivated annually (Urban and Vollrath, 1984). Agricultural habitats often are concentrated in productive and biologically rich areas of the world. To stem the current rapid loss of biological diversity (World Conservation Monitoring Centre, 1992), we need to consider ways in which agricultural land and species conservation can be conducted simultaneously.

Every year, 140 000–180 000 ha of land are planted with rice in California, predominantly in the northern half of the Central Valley (Hill et al., 1992). Flooding rice fields offers great potential as surrogate habitat for wetland species and the importance of rice fields to waterbirds has been suggested repeatedly (Wright, 1959; McGinn and Glasgow, 1963; Fasola and Barbieri, 1978; Fasola, 1983; Miller, 1987; Miller et al., 1989; Remsen et al., 1991; Pain, 1994; Brouder

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and Hill, 1995; Fasola and Ruíz, 1996; Fasola et al., 1996; Lane and Fujioka, 1998; see also Tourenq et al., 2001). The Central Valley is thought to have supported more than 40 million waterfowl historically and, despite substantial declines in waterfowl populations, remains the primary wintering area for 20% of the waterfowl in North America (Heitmeyer et al., 1989; Banks and Springer, 1994; Reid and Heitmeyer, 1995). Less is known about other waterbirds, although a minimum of 200 000–375 000 shorebirds currently winter in the valley (Shuford et al., 1998).

Recently, legislation was introduced in California to improve air quality by reducing the area of rice stubble burned after harvest (Rice Straw Burning Act, AB 1378, 1991). This legislation has resulted in many rice farmers flooding fields during winter to increase straw decomposition (Brouder and Hill, 1995). Winter flooded fields provide habitat for many waterbird species, with planned flooding, straw management, and water depth affecting the occurrence of individual species (Day and Colwell, 1998; Elphick and Oring, 1998).

Although most conservation actions are directed at individual species, characteristics of the entire waterbird community also might influence the long term viability of winter flooding as a management option. Small-scale studies suggest that the presence of waterbirds in flooded fields enhances straw decomposition, and thus provides a direct economic benefit to farmers (Bird et al., 2000). Additionally, some farmers offset the costs of flooding fields by renting land to waterfowl hunters. Further benefits might be derived from birds that eat invertebrates and weed seeds and thus reduce the abundance of pest species (Jones, 1940; Smith and Sullivan, 1980; Fasola and Ruíz, 1997), or from the promotion of winter flooding as a form of agriculture with important conservation benefits.

Flooding rice fields during winter might benefit a diversity of waterbird species and provide substantial conservation gains (Brouder and Hill, 1995). Results from individual species support this idea (Elphick and Oring, 1998), but fully testing the supposition requires examination of measures that collectively describe the conservation value of the waterbird communities found in different fields. Day and Colwell (1998) have shown that species richness was greater in fields with standing water, but they did not distinguish between fields that were actively flooded as part of the management regime and those that were passively flooded.

Variation among rice fields in total waterbird density, species richness, and a measure that evaluates the contribution of sites to waterbird conservation were examined, based on three hypotheses: (1) waterbird use of fields flooded by farmers would differ from fields that were not intentionally flooded; (2) flooded fields receiving different straw management treatments would be used differently by waterbirds; and (3) waterbird use would be affected by water depth. In addition, differences were examined between the two winters of the study, which differed considerably in rainfall (Elphick and Oring, 1998), and among the geographic areas where data were collected.

2. Methods

2.1. Study area

Field work was conducted in the Sacramento Valley, California, during the winters of 1993/1994 and 1994/1995. The Sacramento drainage constitutes the northern half of the Central Valley and contains the majority of California's rice lands. Study fields were selected in three representative areas of the California rice-growing region: Richvale–Biggs, Sutter, and Princeton (Elphick and Oring, 1998). Thirty-seven flooded fields (total area = 797.2 ha; mean area ± S.E. = 21.5 ± 4.1 ha) and 16 unflooded fields (486.5 ; 30.4 ± 7.1 ha) were censused during the first winter of the study, and 25 flooded (699.3 ha; 28.0 ± 5.4 ha) and 15 unflooded fields (398.3 ha; 26.6 ± 6.4 ha) the following winter. Fifteen flooded fields and five unflooded fields were sampled in both winters to test for differences between winters. Only fields that were flooded intentionally to enhance straw decomposition, attract waterfowl, or both, were classified as flooded fields. Fields that were not intentionally flooded were defined as unflooded, even though they occasionally held standing water from rainfall or river flooding for a few days at a time.

Within the sample of flooded fields, six different straw management methods were represented: (1) flooded without straw management; (2) rolled to flatten straw and stubble and then flooded; (3) rolled after flooding to increase the extent that straw stuck in the mud; (4) flooded after chopping the straw to increase its surface area; (5) incorporated by ploughing to both cut straw up and partially bury it, and then flooded; (6) flooded after removing straw either by burning or baling. The first treatment controlled for the need to manipulate straw and the last for the presence of straw. Fields under different straw management treatments were spatially interspersed and distributed across geographic blocks.

Harvest method also can influence bird use with lower species richness in fields harvested using methods that strip seeds from the rice plant ("stripper-headers") than in those harvested by conventional means (Day and Colwell, 1998). All fields surveyed were harvested by conventional means, except two unflooded fields in the second year; excluding these fields did not alter our conclusions.

Surveys were made on foot, counting and identifying all species in the orders Podicipediformes, Ciconiiformes, Anseriformes, Gruiformes, and Charadriiformes seen within the boundary of the field, and including birds standing on the banks at the edges of fields and on internal earthen levees. Birds that were disturbed or that landed in a field during a survey were counted, but birds flying overhead were not.

Surveys were conducted at approximately 10-day intervals from mid-November until the end of March. Waterfowl hunting occurred throughout the region during the first half of this period and no attempt was made to avoid hunted fields. The order in which fields were visited was varied for each census and was determined by randomly selecting the order in which farms were visited, and then randomly selecting the field at which each farm's census began.

Most California rice fields are subdivided by narrow earthen levees to facilitate water depth management. To assess the effects of water depth, each subdivision was treated as a separate plot. Plot size ranged from 0.51 to 19.14 ha (mean ± S.E. = 6.64 ± 0.28 ha). Water depth varied little within each plot, but considerably among plots within a single field. On each census, plots were censused separately and water depth was measured at a stake placed in the deepest corner of the plot. Depths measured at these stakes were calibrated by taking randomly placed measurements throughout each plot and comparing the depth at the stake to the mean depth for the random points. Depth measurements were made for 116 plots in 1993/1994 and 51 plots in 1994/1995.

2.2. Community variables

Four measures were used to compare management methods:

1. Waterbird species richness = the mean number of waterbird species seen in each field on a census during a winter.
2. Total waterbird density = the mean density of waterbirds (total number of birds/ha) per field, areas being obtained from site-survey information provided by farmers, or calculated from 1:24 000 topographic maps.
3. Total density of each of three specific groups, wading birds (Ciconiiformes plus cranes), waterfowl (Anatidae), and shorebirds (Charadrii and Scolopaci).
4. Conservation value = a composite measure that reflected the contribution of fields to waterbird conservation. Each species was weighted according to its mean density in a particular field (D), its mean relative abundance across its North American range during winter (A), and its population trend (T). Relative abundance and population trends were as calculated from 30 years (1959–1988) of Christmas Bird Counts (CBCs) by Sauer et al. (1996; see Appendix A). These volunteer-based surveys involved counting all birds within a prescribed area, and are conducted during mid-winter across North America (Root, 1988; Butcher, 1990). Only CBC sites within the usual winter range of a species were used to calculate its relative abundance score. Sauer et al. (1996) calculated population trends with the route-regression method (Geissler and Sauer, 1990) using data for all of North America. Trend estimates were transformed so that declining populations received large weights and increasing populations small weights. For each field, values were summed for each species (i) to obtain a single measure of "conservation value":
$$\sum_{i=1}^{x}\left[e^{-T(i)}\frac{D(i)}{A(i)}\right].$$
This value can be interpreted as the sum of the species' densities relative to their distribution-wide

abundance, where the value for each species was weighted such that the more positive the population trend the smaller the influence of the species on the summed value. A worked example is given in Appendix B.

2.3. Data analysis

For each independent variable, three null hypotheses were tested: (1) no difference between intentionally flooded and unflooded fields; (2) no difference among flooded fields receiving different straw management treatments; and (3) no relationship with water depth. Analysis of variance (ANOVA) was used to examine the first two hypotheses and regression to evaluate the third. Levene's test (Levene, 1960; Milliken and Johnson, 1992) was used to test for heteroscedacity and, when the assumption of homogeneous variances was violated, data were transformed or non-parametric tests were used.

Results where $0.05 < P < 0.10$ were not dismissed as insignificant, because logistic constraints limited sample sizes. Differences with probabilities within this range, however, were given lower weight than those of higher magnitude when interpreting results. This decision decreased the risk of mistakenly concluding that no treatment effect existed (i.e., making a Type II error). Since perspectives on what constitutes a "significant" result vary, exact P-values are presented for all statistical tests, except in extreme cases ($P > 0.15$ or $P < 0.001$), allowing readers to draw their own conclusions as to the biological significance of the results.

Power of non-significant tests was calculated using Cohen (1988), with $\alpha = 0.10$. For non-parametric tests, sample sizes were adjusted following guidelines on power efficiency (Siegel and Castellan, 1988). Power greater than 0.8 was considered as evidence for no difference among treatments, and power was determined for small, medium and large effect sizes.

For tests of flooding and straw manipulation treatments, individual fields were considered experimental units and mean values calculated across dates were used. Analyses of water depth effects differed because depths varied among sampling dates and among plots within a field. To determine whether repeated samples of a plot were statistically independent, autocorrelation was tested for (Elphick, 1998; Elphick and Oring, 1998). For each variable, a random sample of 20 sites was examined. In all the cases, the number of sites for which there was significant autocorrelation was less than expected by chance (Chatfield, 1980; two out of 120 tests when all variables combined). Sample size and statistical power being relatively low, the correlation coefficients also were examined for evidence of autocorrelation. In general, coefficients clustered close to zero (Elphick, 1998), further suggesting no trend and that samples were statistically independent.

For each dependent variable, differences between the two winters were tested using data from the 20 fields sampled in both seasons. If there was no difference ($P < 0.10$), data were pooled for subsequent analyses, randomly selecting one winter's data for those fields sampled twice. When the two winters differed significantly, data were analysed for each year separately. Geographic variation in dependent variables was another potential source of bias, because not all straw management methods were represented in every area, and so geographic area was incorporated as a blocking factor into the parametric analyses. When management treatment and geographic block effects could not be tested together, separate non-parametric tests of geographic differences were made. If these tests were significant, data were examined for each block separately to assess whether geographic differences alone explained differences among treatments.

In addition to linear correlations between dependent variables and water depth, three non-linear relationships were possible: an increase to a peak followed by a decline, an increase to a plateau, or a plateau followed by a decrease. To examine these relationships, quadratic and asymptotic relationships between each variable and water depth were tested after the transformation: $y = \log_{10}(x+1)$. Date (coded as the number of days since the first census of the winter) was incorporated in these models to control for temporal variation in each measure. Water depth and date were negatively correlated with each other ($r = -0.599$, $P < 0.001$; Elphick and Oring, 1998) raising concerns about the effects of multicollinearity. All regressions were, therefore, repeated with just depth terms to ensure the significance levels persisted when the potential for this problem was eliminated.

Most of the variables controlled for differences in the size of fields by dividing bird abundance by area. Species richness does not increase as a linear function of area (Gleason, 1922) and the relationship between species richness (S) and area (A) usually is described by the non-linear equation $S = cA^z$, where c and z are constants (Preston, 1960; Rosenzweig, 1995). To test for this non-linear relationship, this equation was $\log_{10}$ transformed and linear regression was used. Tests of management treatment effects on richness, interactions between area and treatment, and differences among geographic blocks, were conducted by adding these variables to the basic model.

3. Results

Mean waterbird species richness did not differ between years (paired-$t = 1.09$, df $= 19$, $P = 0.291$, $1 - \beta > 0.99$ for medium effect size, $d = 0.5$) and data were pooled for all analyses. When all fields were considered, the relationship between the mean number of species using a field and the field's area was highly significant, but left much of the variance unexplained ($t = 3.38$, df $= 73$, $P = 0.001$, $r^2 = 0.124$).

Fields that had been flooded intentionally were used by significantly more species than fields that were not ($F = 67.23$, df $= 1, 70$, $P < 0.001$) (Fig. 1A). The method of straw management used also affected waterbird richness ($F = 2.37$, df $= 5, 40$, $P = 0.057$). Richness was greatest in fields that had been rolled after flooding and lowest in fields where straw had been removed prior to flooding (Fig. 1B). In both analyses, field area had a highly significant effect on species richness ($F = 20.63$, df $= 1, 70$, $P < 0.001$ and $F = 10.84$, df $= 1, 40$, $P = 0.002$, respectively). There was no detectable interaction between area and management method in either model ($P > 0.15$ for both), nor effects of geographic block ($P > 0.45$ for both), so these terms were dropped from the final models. The combination of flooding treatment and field area explained 55.9% of the variance in waterbird richness across all fields. The method of straw manipulation combined with area explained 37.0% of the variability in richness found in flooded fields.

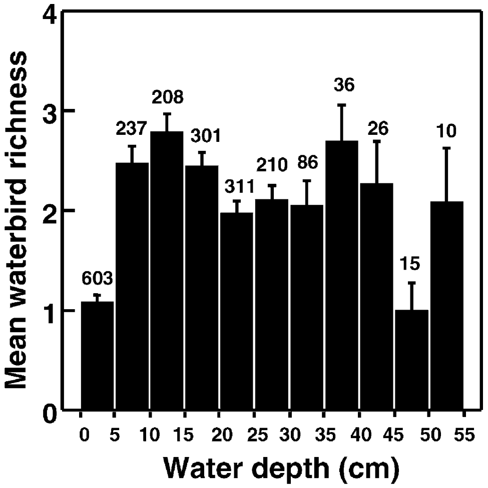

Fig. 2. Mean ± S.E. waterbird richness for 5 cm water depth categories. Sample sizes are given above each bar. All depth categories deeper than 55 cm had fewer than 10 observations and were omitted.

Waterbird richness also varied with water depth, with peaks at depths of 10–15 cm and 35–40 cm (Fig. 2). After controlling for a significant area effect,

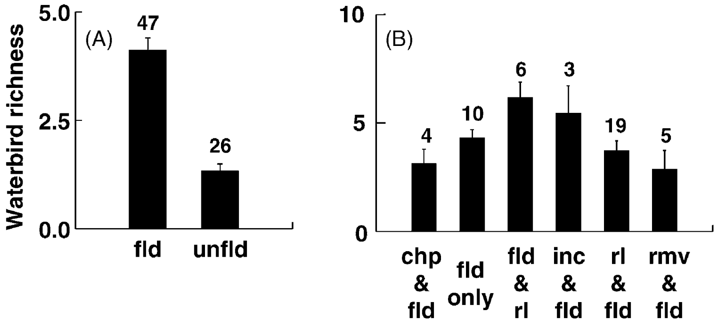

Fig. 1. Mean ± S.E. species richness in different management treatments. (A) Flooded (fld) vs. unflooded (unfld) fields. (B) According to straw treatment: chopped then flooded (chp and fld), just flooded (fld only), flooded then rolled (fld and rl), incorporated into soil then flooded (inc and fld), rolled then flooded (rl and fld), and removed then flooded (rmv and fld). Sample sizes are given above each bar.

richness varied as an inverse quadratic function of both water depth and date, with peaks at intermediate depths and mid-winter. All terms were highly significant ($P < 0.001$), although the entire model explained only 15% of the variance in species richness.

Total waterbird densities did not differ between 1993/1994 and 1994/1995 (Wilcoxon test, $z = 0.187$, $P = 0.852$). Similarly, there were no differences in the densities of waterfowl or wading birds in the two winters ($z = -0.411$, $P = 0.681$ and $z = -0.448$, $P = 0.654$, respectively). Power for these tests was high for a large effect size ($d = 0.8$; $1 - \beta = 0.92$–0.98), but not for a medium effect size ($d = 0.5$; $1 - \beta = 0.66$–0.72). Total shorebird densities did differ, with higher densities in the drier winter of 1993/1994 ($z = -2.539$, $P = 0.011$). Shorebird data were analysed, hence, for the two winters separately.

Densities of waterfowl, shorebirds, and all waterbirds combined were significantly higher in flooded fields than in unflooded fields (Fig. 3). Wading bird density ranks did not differ between the two habitats (Fig. 3A); power was 0.93 for a large effect size ($d = 0.8$; 0.63 for a medium effect size of 0.5). Significant differences among flooding treatments were found for the total numbers of waterbirds and total wading birds (Table 1). When all species were grouped, density ranks were significantly higher in fields that had been either flooded with no straw manipulation or rolled prior to flooding, than in fields where straw had been removed. Wading birds used fields that had only been flooded significantly more than several other treatments. In 1994/1995, shorebirds used fields where straw had been incorporated by ploughing significantly more than fields where the straw was chopped before flooding. These treatments were not present in the 1993/1994 sample, when no difference was found (Table 1). Waterfowl use of flooding treatments did not differ significantly. For both of these non-significant results, power was too low to conclude no difference ($1 - \beta = 0.57$ and 0.59, respectively, assuming a large effect size of $d = 0.4$).

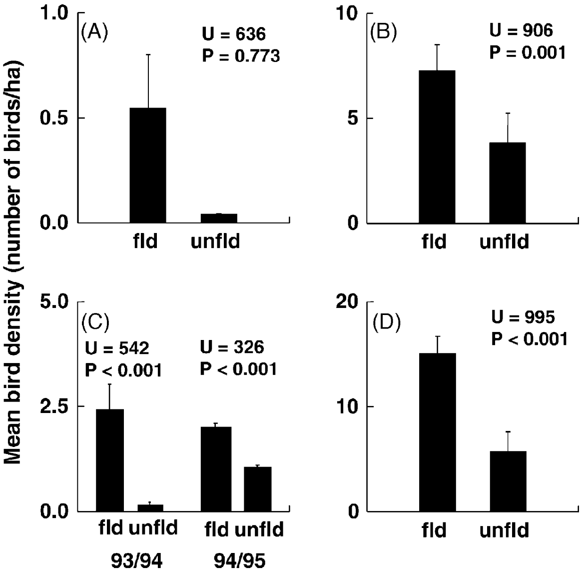

Fig. 3. Mean ± S.E. densities of birds in flooded and unflooded fields (number of birds/ha). (A) Wading birds, (B) waterfowl, (C) shorebirds, (D) all waterbirds combined. Sample sizes for flooded and unflooded fields, respectively, were: 37 and 16 (1993/1994), 25 and 15 (1994/1995), 47 and 26 (both years combined). Significance statistics are for Mann–Whitney tests, after rank transformation.

Geographic differences were found only in the total numbers of waterbirds and in the numbers of shorebirds in 1994/1995 (Kruskal–Wallis tests, $H = 5.39$, $P = 0.068$, and $H = 7.27$, $P = 0.026$, respectively; $P > 0.2$ for all other tests). When all species were pooled, there were significantly more birds at the Princeton sites than at the Sutter sites. When shorebirds alone were considered, the difference resulted from greater numbers at Princeton sites than at Richvale–Biggs sites. The geographic and straw treatment differences in shorebird abundance were confounded because all fields where straw was incorporated by ploughing were in the Princeton area and most fields where straw was chopped were in the Richvale–Biggs area. Differences in total waterbird use of straw treatments were not confounded with geographic differences and persisted when the geographic effect was removed by dropping Sutter sites from the analysis.

Bird densities were related significantly to water depth and date for all waterbird groups considered. Densities of wading birds, waterfowl, and all waterbirds combined, rose to an asymptote as depth increased, while shorebird densities decreased towards zero. None of the models, however, explained more than 17% of the variance in bird densities. Flooded plots that were occupied by any waterbird, waterfowl or wading birds were significantly deeper than sites without these birds. In contrast, sites that were used

Table 1
Mean ± S.E. bird densities (numbers of birds/ha) in flooded fields receiving different straw management[a]

	Treatment						*H*	*P*
	Flood only	Roll and flood	Flood and roll	Chop and flood	Incorporate and flood	Remove and flood		
n	8, 7, 10	21, 4, 19	4, 4, 6	0, 4, 4	0, 3, 3	3, 3, 5		
Wading birds	2.40 ± 1.04 a	0.05 ± 0.02 b	0.05 ± 0.02 a,b	0.02 ± 0.00 b	0.03 ± 0.03 b	0.07 ± 0.03 a,b	18.37	0.003
Waterfowl	8.60 ± 3.22	9.58 ± 2.29	5.98 ± 1.86	3.61 ± 2.07	3.61 ± 1.46	2.73 ± 1.34	5.82	0.324
Shorebirds (1993/1994)	2.54 ± 0.94	2.67 ± 0.97	2.22 ± 1.73	–	–	0.33 ± 0.02	3.57	0.311
Shorebirds (1994/1995)	1.01 ± 0.44 a,b	0.29 ± 0.04 a,b	0.42 ± 0.10 a,b	0.18 ± 0.10 b	12.94 ± 6.60 a	0.30 ± 0.17 a,b	10.52	0.062
All waterbirds	19.61 ± 3.86 a	17.77 ± 2.49 a	9.05 ± 2.28 a,b	9.10 ± 5.78 a,b	19.13 ± 9.48 a,b	4.98 ± 1.57 b	12.35	0.030

[a] Treatments with different letters were significantly different (Kruskal–Wallis tests, using Dunn's post-hoc comparisons; Zar, 1984). Sample sizes are for 1993/1994, 1994/1995, and both years combined, respectively.

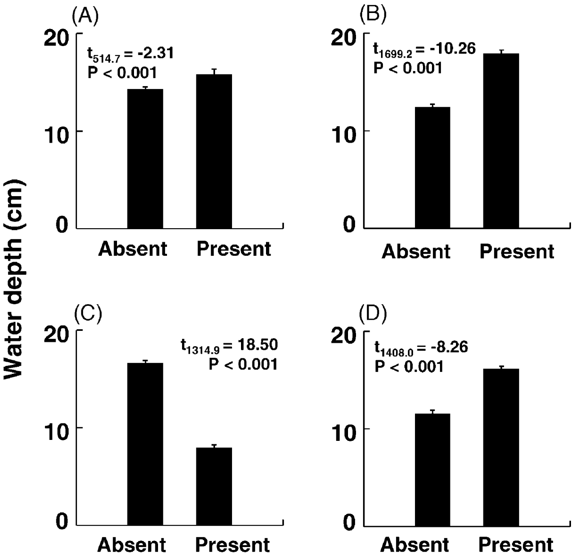

Fig. 4. Mean ± S.E. water depth of plots in which birds were absent and present. (A) Wading birds, (B) waterfowl, (C) shorebirds, (D) all waterbirds combined. Significance statistics are for separate-variance *t*-tests.

by shorebirds were significantly shallower than sites that were not used (Fig. 4).

No significant difference was found between years in terms of conservation value of fields (Wilcoxon test, $z = 0.485$, $P = 0.627$) and data were combined for the 2 years in subsequent analyses. Power of this test was 0.98 for a large effect size ($d = 0.8$; 0.74 for a medium effect size of 0.5). Flooded fields received significantly higher conservation value scores than unflooded fields (Mann–Whitney test, $U = 1079$, $P < 0.001$), but no difference was found among flooded fields receiving different straw manipulations (Kruskal–Wallis test, $H = 8.51$, $P = 0.130$). We could not, however, conclude that there was no difference among straw manipulations in flooded fields, even for a large effect size ($d = 0.4$; $1 - \beta = 0.59$). No difference among geographic areas was detected ($H = 0.097$, $P = 0.953$).

The conservation value of fields increased with water depth to a peak between 10 and 15 cm, then declined (Fig. 5). In the best regression model, conservation value varied significantly with water depth after log $(x+1)$ transformation, climbing to an asymptote as water depth increased. In addition, there was a quadratic relationship with date, with a mid-winter peak. This model explained 11% of the variance in conservation value.

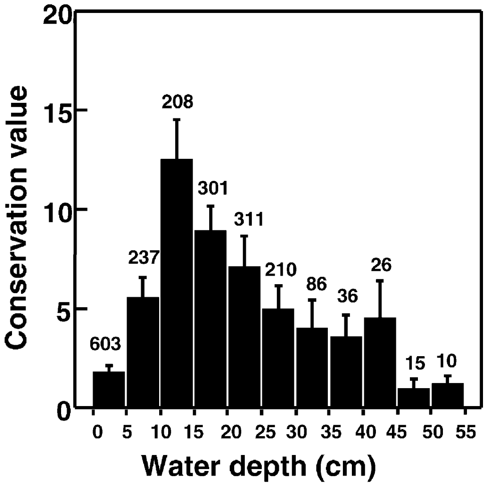

Fig. 5. Mean ± S.E. conservation value scores for 5 cm water depth categories. Sample sizes are given above each bar. All depth categories deeper than 55 cm had fewer than 10 observations and were omitted.

4. Discussion

Flooding harvested rice fields in winter significantly increased waterbird species richness, densities, and the conservation value of fields to waterbirds. The present results confirmed that differences were attributable to active water containment, and not simply passive flooding. Changes in management practices can be expected to have conservation benefits that are not limited to species of relatively low conservation interest. There was no difference in the density of wading birds, a group for which mixed results were recorded for individual species (Elphick and Oring, 1998).

Differences among flooding treatments were less clear. Species richness was greatest in fields that were flooded and then rolled. Total waterbird density was greatest in fields that were flooded with no straw manipulation. Shorebird density, in contrast, peaked in fields where straw had been incorporated by ploughing before flooding. This final result, however, was confounded with geographic variation in abundance, and also could be a consequence of especially shallow water in incorporated fields (Elphick and Oring, 1998).

In all the cases, differences among means were small, and statistical significance was attributable only to the differences between the treatments with extreme values. No treatment ranked highest for all measures, although flooding alone or flooding in combination with rolling the straw typically were ranked high, while removing or chopping the straw before flooding generally ranked low.

Water depth significantly affected all measures, although the nature of the relationships varied. Waterfowl and wading bird densities increased initially with increasing depth, but after a point densities levelled off. The opposite was true for shorebirds and, consequently, the number of waterbird species peaked at intermediate depths. After correcting for other variables the conservation value followed the pattern for total waterbird density by increasing with water depth, but at a decreasing rate in deeper conditions. This result suggests that waterfowl, wading birds, or both, influenced the conservation measure more than shorebirds. Two factors contributed to this effect. Waterfowl species tended to have less positive population trends than other species (Appendix A; Sauer et al., 1996), and, therefore, contributed more to the conservation value. In addition, there were more species of waterfowl than other groups and their cumulative effect was greater than that of the other two groups.

Although relationships between depth and many of the measures were significant, most of the variance went unexplained (>83% in all cases). Determining the cause of the remaining variance would provide greater insight into the relative importance of water depth. The propensity for many waterbird species to flock, creates clumped distributions that inevitably cause high variance in bird densities. Incorporating the effects of individual species behaviour into explanatory models, therefore, would seem to be essential. Our data support the notion that intermediate depths maximise the value of rice fields to waterbird conservation. Both waterbird richness and conservation value were greatest at depths of 10–15 cm (Figs. 2 and 5), with the peak in richness at slightly lower depths than predicted from examination of depths used by individual species (Elphick and Oring, 1998). Nonetheless, the statistical analyses suggest that differences in conservation value among depths are statistically insignificant at greater depths, and data from individual species show that a diversity of depths must be maintained throughout the rice-growing region to avoid the exclusion of certain species (Elphick and Oring, 1998).

Water depth decreased significantly during winter. Bird use of fields also varied over time due to migratory behaviour or food availability and it is possible that collinearity between depth and date influenced the analyses. All significant results between depth and bird use persisted after the effect of date was removed, however, verifying that correlations existed. Determining whether these correlations indicate a causal relationship between depth and bird use will require experiments that separate the date and depth variables.

Waterbirds are extremely mobile during winter, and their use of individual fields is influenced by features of the landscape up to at least 10 km away (Elphick, 1998). To ensure that samples are independent, pairwise distances among all sites would need to exceed this distance, which would be impossible to achieve. Any spatial bias, therefore, was minimised by blocking the sampling design by geographic region.

Weighting species by their probability of extinction would provide an objective measure for ensuring that the most vulnerable species receive greatest attention without neglecting other species completely. Unfortunately, extinction probabilities are generally unknown and can be estimated only in rare cases (Boyce, 1992). The abundance of each species in a field relative to other sites they occur at during winter, and population trend were used to weight species in this study instead. As with all indices of conservation value, this one has its limitations. For example, it does not distinguish among species with different total population sizes or life-histories. It does, however, incorporate more of the information of interest to conservationists than do common community descriptors such as species richness.

All composite measures are intended to summarise large numbers of variables and hence simplify complex situations. Management prescriptions based on composite measures relate only to those measures and certain species may respond differently. No management method will benefit all species and exceptions may need to be catered for separately. For instance, in the California rice-growing region it may be necessary to ensure that sufficient unflooded habitat is available for Sandhill Cranes *Grus canadensis* (Elphick and Oring, 1998).

5. Conclusions

There are conservation benefits of flooding rice fields during winter in terms of overall waterbird richness, abundance, and conservation value. Increased waterbird abundance is particularly important to rice farmers because the density of foraging waterfowl has been linked with straw decomposition. In a small-scale experimental setting, high densities of ducks (Mallards *Anas platyrhynchos*) were found to increase straw decomposition, apparently through their foraging activity (Bird et al., 2000). Data presented here suggest that average waterbird densities in intentionally flooded fields are about half those used in this decomposition experiment (Fig. 3). Waterfowl constitute only about half the waterbirds found in flooded fields. American Coots *Fulica americana* constitute the bulk of the remaining birds (Elphick and Oring, 1998). Since this species is vegetarian and is far less affected by the activities of hunters and other disturbances, it may play an important role in the decomposition of straw. High total waterbird densities could also be important to farmers because waterbird activity may help reduce the abundance of pest species (Jones, 1940; Smith and Sullivan, 1980; Fasola and Ruíz, 1997) or provide alternative sources of revenue. Manipulation of flooding conditions may provide a mechanism for increasing the number of birds in a field. Straw manipulation may influence the overall abundance of waterbirds, with highest densities in fields that had been flooded with no other manipulation and in those that had been rolled prior to flooding. Fields from which straw had been removed had very low waterbird densities. Water depth also influenced bird use of fields, although there was much variance and it would be difficult to predict bird densities from water depth alone.

Farmers may accrue additional benefits by developing ways of increasing the area of flooded rice without using more water. For much of the winter, fields are flooded deeper than necessary to maximise bird densities. The presence of deeper water early in the winter may reflect a common belief among hunters that ducks prefer deeper water. Constraints on the availability of water during the latter half of the winter also require farmers to flood fields deeply in order to ensure that they stay inundated until spring. There is no evidence that current deep conditions are required for effective straw decomposition, and reducing water depths, therefore, may increase bird use without affecting decomposition. Assuming that water is available throughout the winter so that evaporated water can be replaced, reducing average depths would enable farmers to flood larger areas without needing more water. Another option for increasing the flooded area is to block off field drainage outlets to retain rainwater in fields. Rainfall may not be sufficiently reliable for farmers to use this method alone to dispose of rice straw. It may be helpful, however, in speeding up decomposition in fields where other methods (e.g. ploughing) have been used. Moreover, for very little cost or inconvenience to growers, even very shallow flooding could have considerable benefits for some waterbird species.

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Appendix A

Mean relative abundance and 30-year population trend for bird species found in rice fields as were used to calculate an index of conservation value for each field. Data obtained from CBC (Sauer et al., 1996).

Species	Mean relative abundance (*A*)	Population trend (*T*)
Pied-billed Grebe (*Podilymbus podiceps*)	1.97	1.4
American Bittern (*Botaurus lentiginosus*)	0.12	−0.9
Great Blue Heron (*Ardea herodias*)	2.76	2.2
Great Egret (*A. alba*)	3.52	1.7
Snowy Egret (*Egretta thula*)	7.45	2.4
Black-crowned Night-Heron (*Nycticorax nycticorax*)	1.67	2.2
White-faced Ibis (*Plegadis chihi*)	4.94	6.4
Tundra Swan (*Cygnus columbianus*)	14.74	3.4
Greater White-fronted Goose (*Anser albifrons*)	15.97	7.5
Snow Goose (*Chen caerulescens*)[a]	85.59	−2.3
Ross's Goose (*C. rossii*)[a]	4.31	6.3
Canada Goose (*Branta canadensis*)	289.31	1.7
Wood Duck (*Aix sponsa*)	1.77	0.5
Green-winged Teal (*Anas crecca*)	13.64	3.2
Mallard (*A. platyrhynchos*)	597.67	−6.7
Northern Pintail (*A. acuta*)	134.02	−5.2
Cinnamon Teal (*A. cyanoptera*)	0.73	1.7
Northern Shoveler (*A. clypeata*)	21.19	3.3
Gadwall (*A. strepera*)	13.64	3.2
American Wigeon (*A. americana*)	88.36	−1.2
Canvasback (*Aythya valisineria*)	12.93	−1.0
Redhead (*A. americana*)	53.56	−3.4
Ring-necked Duck (*A. collaris*)	10.74	−1.1
Bufflehead (*Bucephala albeola*)	8.32	0.6
Common Merganser (*Mergus merganser*)	25.89	1.3
Ruddy Duck (*Oxyura jamaicensis*)	23.85	−0.1
Sora (*Porzana carolina*)	0.21	0.2
Common Moorhen (*Gallinula chloropus*)	1.71	4.5
American Coot (*Fulica americana*)	111.08	−1.1
Sandhill Crane (*Grus canadensis*)	143.29	0.7
Black-bellied Plover (*Pluvialis squatarola*)	6.00	0.5
Killdeer (*Charadrius vociferus*)	6.53	0.0
Black-necked Stilt (*Himantopus mexicanus*)	3.77	11.4
American Avocet (*Recurvirostra americana*)	11.86	−1.1
Greater Yellowlegs (*Tringa melanoleuca*)	0.87	0.6
Lesser Yellowlegs (*T. flavipes*)	0.49	1.3
Long-billed Curlew (*Numenius americanus*)	4.4	0.0
Western Sandpiper (*Calidris mauri*)	13.91	−0.7
Least Sandpiper (*C. minutilla*)	5.44	−0.2
Dunlin (*C. alpina*)	32.70	−1.9
Long-billed Dowitcher (*Limnodromus scolopaceus*)	6.10	9.2
Common Snipe (*Gallinago gallinago*)	1.37	−1.2
Ring-billed Gull (*Larus delawarensis*)	57.06	3.2
California Gull (*L. californicus*)	10.85	3.3
Herring Gull (*L. argentatus*)	46.83	0.1

[a] Since "white" geese were not distinguished during surveys, these species had to be omitted from conservation value calculations.

Appendix B

Worked example demonstrating the calculation of the conservation index used in this study.

Suppose that two 1 ha fields were surveyed. Field 1 contained 100 Northern Pintail and 50 Mallards, while Field 2 contained 10 Snowy Egrets, 1000 Greater White-fronted Geese, 10 Gadwall and 20 Ring-billed Gulls. Using data given in Appendix A, the conservation values for each of these fields are given as follows:

$$\begin{aligned}\text{Field 1}: \quad & e^{5.2}\,(100/134.02) + e^{6.7}\,(50/597.67)\\ & = 135.257 + 67.964 = 203.22\end{aligned}$$

$$\begin{aligned}\text{Field 2}: \quad & e^{-2.4}\,(10/7.45) + e^{-7.5}\,(1000/15.97)\\ & \quad + e^{-3.2}\,(10/13.64) + e^{-3.2}\,(20/57.06)\\ & = 0.1218 + 0.0346 + 0.0299 + 0.0143\\ & = 0.20\end{aligned}$$

Under this scenario, Field 1 is viewed as having higher conservation value than Field 2, even though both species richness and total number of birds are higher in Field 2. This is because the species found in Field 1 have extremely negative population trends, while the species in Field 2 all have positive trends.

References

Banks, R.C., Springer, P.F., 1994. A century of population trends of waterfowl in western North America. In: Jehl Jr., J.R., Johnson, N.K. (Eds.), A Century of Avifaunal Change in Western North America. Stud. Avian Biol. 15, 134–146.

Bird, J.A., Pettygrove, G.S., Eadie, J.M., 2000. The impact of waterfowl foraging on the decomposition of rice straw: mutual benefits for rice growers and waterfowl. J. Appl. Ecol. 37, 728–741.

Boyce, M.S., 1992. Population viability analysis. Ann. Rev. Ecol. Syst. 23, 481–506.

Brouder, S.M., Hill, J.E., 1995. Winter flooding of ricelands provides waterfowl habitat. Calif. Agric. 49, 58–64.

Butcher, G.S., 1990. Audubon Christmas Bird Counts. In: Sauer, J.R., Droege, S. (Eds.), Survey Designs and Statistical Methods for the Estimation of Avian Population Trends. Biological Report 90 (1). US Fish and Wildlife Service, Washington, DC, pp. 5–13.

Chatfield, C., 1980. The Analysis of Time Series: An Introduction. Chapman & Hall, London.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, 2nd Edition. Lawrence Erlbaum, Hillsdale, NJ.

Day, J.H., Colwell, M.A., 1998. Waterbird communities in rice fields subjected to different post-harvest treatments. Colonial Waterbirds 21, 185–197.

Elphick, C.S., 1998. Waterbird conservation and ecology: the role of rice field management in habitat restoration. Unpublished Ph.D. Dissertation. University of Nevada, Reno, NV.

Elphick, C.S., Oring, L.W., 1998. Winter management of California rice fields for waterbirds. J. Appl. Ecol. 35, 95–108.

Fasola, M., 1983. Nesting populations of herons in Italy depending on feeding habitats. Bollettino di Zoologia 50, 21–24.

Fasola, M., Barbieri, F., 1978. Factors affecting the distribution of heronries in northern Italy. Ibis 120, 537–540.

Fasola, M., Ruíz, X., 1996. The value of rice fields as substitutes for natural wetlands for waterbirds in the Mediterranean region. In: Crivelli, A.J., Hafner, H., Fasola, M., Erwin, R.M., McCrimmon, D.A. (Eds.), Ecology, Conservation and Management of Colonial Waterbirds in the Mediterranean Region. Colonial Waterbirds 19 (special publication No. 1), 122–128.

Fasola, M., Ruíz, X., 1997. Rice farming and waterbirds: integrated management in an artificial landscape. In: Pain, D.J., Pienkowski, M.W. (Eds.), Farming and Birds in Europe: the Common Agricultural Policy and its Implications for Bird Conservation. Academic Press, San Diego, CA, pp. 210–235.

Fasola, M., Canova, L., Saino, N., 1996. Rice fields support a large portion of herons breeding in the Mediterranean region. In: Crivelli, A.J., Hafner, H., Fasola, M., Erwin, R.M., McCrimmon, D.A. (Eds.), Ecology, Conservation and Management of Colonial Waterbirds in the Mediterranean Region. Colonial Waterbirds 19 (special publication No. 1), 129–134.

Geissler, P.H., Sauer, J.R., 1990. Topics in route-regression analysis. In: Sauer, J.R., Droege, S. (Eds.), Survey Designs and Statistical Methods for the Estimation of Avian Population Trends. Biological Report 90 (1). US Fish and Wildlife Service, Washington, DC, pp. 54–57.

Gleason, H.A., 1922. On the relation between species and area. Ecology 3, 158–162.

Heitmeyer, M.E., Connelly, D.P., Pederson, R.L., 1989. The Central, Imperial, and Coachella valleys of California. In: Smith, L.M., Pederson, R.L., Kaminski, R.H. (Eds.), Habitat Management for Migrating and Wintering Waterfowl in North America. Texas Tech University Press, Lubbock, TX, pp. 475–505.

Hill, J.E., Robert, S.R., Brandon, D.M., Scardaci, S.C., Williams, J.F., Wick, C.M., Canevari, W.M., Weir, B.L., 1992. Rice Production in California, Publication 21498. Cooperative Extension, University of California, Davis, CA.

Jones, J., 1940. Ducks and the rice industry: a supplementary note. Emu 39, 206–209.

Lane, S.J., Fujioka, M., 1998. The impact of changes in irrigation practices on the distribution of foraging egrets and herons (Ardeidae) in rice fields of central Japan. Biol. Conserv. 83, 221–230.

Levene, H., 1960. Robust tests for equality of variance. In: Olkin, I., Gharge, S.G., Hoeffding, W., Madow, W.G., Mann, H.B. (Eds.), Contributions to Probability and Statistics. Stanford University Press, Palo Alto, CA, pp. 278–292.

McGinn, L.R., Glasgow, L.L., 1963. Loss of waterfowl foods in ricefields in southwest Louisiana. In: Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners, Vol. 17, pp. 69–79.

Miller, M.R., 1987. Fall and winter foods of northern pintails in the Sacramento Valley, California. J. Wildl. Manage. 51, 405–414.

Miller, M.R., Sharp, D.E., Gilmer, D.S., Mulvaney, W.R., 1989. Rice available to waterfowl in harvested fields in the Sacramento Valley, California. Calif. Fish Game 75, 113–123.

Milliken, G.A., Johnson, D.E., 1992. Analysis of Messy Data, Vol. I, Designed Experiments. Van Nostrand Reinhold, New York.

Pain, D., 1994. Case Studies of Farming and Birds in Europe: Rice Farming in Italy. Studies in European Agriculture and Environmental Policy, No. 8. RSPB, Sandy.

Preston, F.W., 1960. Time and space and the variation of species. Ecology 41, 611–627.

Reid, F.A., Heitmeyer, M.E., 1995. Waterfowl and rice in California's Central Valley. Calif. Agric. 49, 62.

Remsen Jr., J.V., Swan, M.M., Cardiff, S.W., Rosenberg, K.V., 1991. The importance of the rice-growing region of south-central Louisiana to winter populations of raptors, waders, and other birds. J. Louisiana Ornithol. 1, 35–47.

Root, T., 1988. Atlas of Wintering North American Birds: An Analysis of Christmas Bird Count Data. University of Chicago Press, Chicago, IL.

Rosenzweig, M.L., 1995. Species Diversity in Space and Time. Cambridge University Press, Cambridge.

Sauer, J.R., Schwartz, S., Hoover, B., 1996. The Christmas Bird Count Home Page. Version 95.1. Patuxent Wildlife Research Center, Laurel, MD.

Shuford, W.D., Page, G.D., Kjelmyr, J.E., 1998. Patterns and dynamics of shorebird use of California's Central Valley. Condor 100, 227–244.

Siegel, S., Castellan Jr., N.J., 1988. Nonparametric Statistics for the Behavioral Sciences, 2nd Edition. McGraw-Hill, New York.

Smith Jr., R.J., Sullivan, J.D., 1980. Reduction of red rice grain in rice fields by winter feeding of ducks. Arkansas Farm Res. 29, 3.

Tourenq, C., Bennetts, R.E., Kowalski, H., Vialet, E., Lucchesi, J.-L., Kayser, Y., Isenmann, P., 2001. Are ricefields a good alternative to natural marshes for waterbird communities in the Camargue, southern France? Biol. Conserv. 100, 335–343.

Urban, F., Vollrath, T., 1984. Patterns and trends in world agricultural land use. Foreign Agricultural Economic Report No. 198. International Economics Division, Economic Research Service, US Department of Agriculture, Washington, DC.

World Conservation Monitoring Centre, 1992. Global Biodiversity: Status of the Earth's Living Resources. Chapman & Hall, London.

Wright, T.W., 1959. Winter foods of mallards in Arkansas. In: Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners, Vol. 13, pp. 291–296.

Zar, J.H., 1984. Biostatistical Analysis, 2nd Edition. Prentice-Hall, Englewood Cliffs, NJ.