TECHNICAL NOTES

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THE IMPACT OF WATERFOWL FORAGING ON THE DECOMPOSITION OF RICE STRAW: MUTUAL BENEFITS FOR RICE GROWERS AND WATERFOWL

More and more NRCS conservationists in rice growing areas of California are assisting clients managing rice residues without burning to comply with the California Rice Straw Burning Reduction Act of 1991 and the state Air Resources Board's new Conditional Rice Straw Burning Permit Program. Growers are no longer allowed to burn rice residues unless it is certified that a disease is present and likely to cause significant yield losses.

The enclosed article is based on research performed by University of California-Davis soils specialist Stuart Pettygrove, Department of Land, Air and Water Resources, waterfowl specialist John Eadie, Department of Wildlife, Fish, and Conservation Biology, and graduate student Jeff Bird.

It describes how rice plots were flooded and either wet-rolled or left untilled after harvest. Mallard ducks were kept on half of each plot for 12 six-hour periods during February to approximate observed seasonal use. The ducks increased straw decomposition by 78 percent in the untilled plots and 18 percent in the wet-rolled plots compared to unforaged plots. The average straw diameter in foraged plots was reduced by one-third that of straw in unforaged plots.

The Sacramento and San Joaquin Valleys provide habitat for approximately 60 percent of the wintering waterfowl in the Pacific Flyway. Annual rice acreage averages 500,000 acres. The authors conclude that rice fields flooded 10-15 cm deep (4 to 6 inches deep) can provide important winter habitat for migratory waterfowl and their foraging can substantially increase straw decomposition. This may alleviate the grower's need and expense for tillage after harvest.

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The impact of waterfowl foraging on the decomposition of rice straw: mutual benefits for rice growers and waterfowl

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Summary

1. Recent legislation in California, USA, has restricted traditional open-field burning of rice straw residues, leading farmers to adopt alternative methods of straw disposal such as post-harvest flooding of rice fields. These changes may benefit wildlife because winter-flooded fallow rice fields provide foraging habitat to migratory waterfowl. In turn, the foraging activity of waterfowl may help to increase rice straw decomposition, providing a reciprocal benefit to farmers. We examined the effects of waterfowl foraging activity on straw decomposition and nitrogen mineralization following rice harvest in a fallow flooded soil.

2. Experimental plots ($25\,m^2$) were established on a silty clay soil and were subjected to two post-harvest treatments: wet-rolled or untilled. Mallard ducks *Anas platyrhynchos* were placed in one-half of the experimental plots, following a split-plot design, for a 3-week period, at a density equivalent to 33 birds ha^{-1} over a season of 180 days to approximate regional abundance data.

3. Waterfowl foraging activity increased residual surface straw decomposition by 78% in untilled plots and 18% in wet-rolled plots compared with the respective unforaged plots. Average straw diameter in foraged plots was reduced to one-third that of unforaged plots.

4. Waterfowl foraging and field tillage reduced nitrogen (N) concentrations in the surface straw residue remaining at the end of the winter fallow period. Below-ground organic residue was not affected by waterfowl foraging, indicating that ducks did not incorporate the straw. There were no apparent additions of carbon (C) or N to the soil as a result of waterfowl activity.

5. We conclude that waterfowl foraging can substantially increase straw decomposition in flooded, fallow, rice fields. Accordingly, rice producers should consider agronomic practices that attract waterfowl, such as winter flooding, to maximize the decomposition of rice straw residue. At the upper end of regionally observed waterfowl densities (at or near 33 birds ha^{-1} $season^{-1}$) waterfowl foraging activity may alleviate the need for autumn tillage. Shallow flooded rice fields will also provide important winter habitat to migratory waterfowl, aiding wetland management and conservation efforts in the Central Valley of California.

6. These results provide an example of how a mutually beneficial solution can be achieved that provides needed waterbird habitat while concomitantly alleviating an agricultural problem.

Key-words: agriculture, ducks, straw disposal, nitrogen, wetland management, winter habitat.

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Introduction

Production of rice *Oryza sativa* L. in the Central Valley of California, USA, ranges annually between

140 000 and 180 000 ha (Hill *et al.* 1992). A major by-product of this production is 8–10 t ha^{-1} of rice straw residue (Brandon *et al.* 1995). Traditionally, straw residue was disposed of by open-field burning. However, with the recent implementation of the California Rice Straw Burning Reduction Act (AB 1378 1991), intended to reduce air pollution in the region, farmers are now required to adopt alternative methods to reduce rice straw. Many farmers in the Central Valley are winter flooding fallow rice fields after autumn straw incorporation as an alternative to burning. An associated benefit of this practice has been the creation of wetland habitat for migratory waterfowl in the Pacific Flyway (Gilmer *et al.* 1982; Elphick & Oring 1998). Winter flooding significantly increases waterfowl use of fallow rice fields and may provide substantial habitat for waterbird populations in California (Elphick & Oring 1998; Day & Colwell 1998). Recently, it has been suggested that foraging waterfowl attracted to flooded rice fields may provide a reciprocal benefit to farmers by enhancing straw decomposition in winter-flooded fields (Burnham 1995). We initiated the present study to investigate this possibility.

Decomposition of straw residues is influenced mainly by cultural practices, environmental factors and soil properties, including soil moisture content, temperature and relative humidity (Pal & Broadbent 1975a, 1975b; Pal, Broadbent & Mikkelsen 1975; Sain & Broadbent 1977; Broadbent 1979). In California, rice straw typically has a period of 6 months (October–March) to decompose prior to the next crop of rice. In a laboratory study, rice straw added to soil mineralized 67–74% of its carbon (C) under optimum conditions of 60% soil water-holding capacity and a constant temperature of 22 °C (Pal, Broadbent & Mikkelsen 1975). However, with the cool winter temperatures (5–15 °C) and variable soil moisture content typical of winter in the Central Valley of California, this process is slowed considerably. Field experiments in California have shown more rapid rates of surface straw decomposition under conditions of shallow winter flooding than without winter flooding (Hill *et al.* 1999).

The role of waterfowl activity on rice straw decomposition has not been investigated previously. The Central Valley of California provides habitat for large numbers of migratory waterfowl during winter, including up to 20% of all waterfowl in North America and 60% of wintering waterfowl in the Pacific Flyway (Gilmer *et al.* 1982; Reid & Heitmeyer 1995). Historically, up to 40 million birds may have used this area, although numbers now range from 2 to 4 million. Currently, wetland habitat in California is scarce for migratory bird populations, with only 5–10% of wetland acreage available compared with that found in the 1780 s (Frayer, Peters & Pywell 1989; Dahl 1990; National Research Council 1992). Much of this habitat has been lost through draining of wetlands, primarily for agriculture (Frayer, Peters & Pywell 1989). Wetland conservation efforts in the Central Valley have focused on initiatives to enhance or restore wildlife habitat on private lands, particularly in the agricultural sector (Central Valley Habitat Joint Venture 1990). Recent research has demonstrated that flooded rice fields may provide valuable winter habitat for waterbirds, and thereby alleviate, in part, the loss of historic wetlands (Day & Colwell 1998; Elphick & Oring 1998). Accordingly, considerable potential exists for rice producers to play an important role in the stewardship of waterfowl resources. What has not been recognized until recently is that the presence of foraging waterfowl may also provide reciprocal benefits to rice farmers by accelerating straw decomposition. If waterfowl activity increases straw decomposition, as proposed, it could reduce considerably the need for autumn tillage operations, at a substantial saving to growers. These mutual benefits could greatly facilitate wetland conservation efforts in the Central Valley by increasing the likelihood that land management practices will change in a manner that benefits waterbird conservation.

Clearly, there is a need for a better understanding of the impact of waterfowl foraging on the decomposition of rice straw, especially under flooded conditions in temperate climates. Our objective in the present study was to determine the effects of waterfowl foraging activity, with and without field tillage, on rice straw decomposition and nitrogen mineralization, in a fallow winter-flooded soil in California.

Materials and methods

We initiated a 1-year field study following rice harvest in October 1995 at the University of California rice research facility in Davis, CA, USA. M-103, a very early medium-grain rice variety (California Cooperative Rice Research Foundation, Inc., Biggs, CA, USA) yielded approximately 6000 kg ha^{-1} on 23 October 1995. The remaining rice grain after harvest was approximately 400 kg ha^{-1}. The soil at the field site is a fine, smectitic, thermic, Chromo Haploxerert (Capay silty clay). Selected chemical and physical soil properties are shown in Table 1. Treatments were laid out on a split-plot design, replicated four times. The main plot treatments were wet-rolled or untilled. Split-plot treatments were presence or absence of waterfowl foraging. Each of the four treatment combinations was arranged as separate distinct field plots ($n = 16$) that were 25 m^2 in area (5 × 5 m) (Fig. 1). The term 'plot' used in this paper refers to the individual field plots ($n = 16$). The tillage treatment was carried out shortly after harvest in November 1995. The waterfowl treatment foraging period was applied from 1 to 18 February. This design allowed for an evaluation of tillage effects during the first period of the winter fallow,

Table 1. Selected chemical and physical properties of the fine, smectitic, thermic, Chromo Haploxerert soil (0–15 cm soil depth) present on the study site

Soil property	pH*	EC* (dS m^{-1})	SOM† (%)	Organic C (g kg^{-1})	Total N (g kg^{-1})	P‡ (mg kg^{-1})	K§ (mg kg^{-1})	Mg§ (mg kg^{-1})	Ca§ (mg kg^{-1})	CEC¶ (cmol kg^{-1})	Sand** (%)	Silt** (%)	Clay** (%)
Mean (n=16)	6.7	0.38	1.24	9.0	1.01	6	271	2517	2052	38	12	50	38
SE	0.1	0.01	0.03	0.15	0.01	0.2	4	11	16	0.2	0.2	0.2	0.1

*Saturated soil paste (Richards 1954).
†Potassium dichromate reduction of organic C and subsequent spectrophotometric measurement (modified Walkley–Black method as described by Nelson & Sommers 1982).
‡Sodium bicarbonate method described by Olsen & Sommers (1982).
§1 N ammonium acetate method described by Knudsen, Peterson & Pratt (1982) and Lanyon & Heald (1982), and subsequently levels were determined by atomic absorption/emission spectrometry.
¶Barium acetate saturation and calcium replacement (Rhodes 1982; Janitzski 1986).
**Soil suspension by hydrometer (Gee & Bauder 1979).

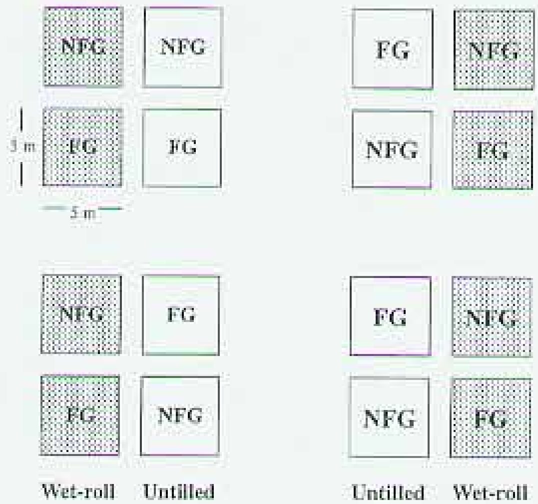

Fig. 1. Illustration of plot layout at University of California rice research facility. Each of the individual subplots ($n = 16$) was contained separately with levees and was 5×5 m. Main plot treatments were wet-rolled or untilled. Split-plot treatments were foraged (FG) or non-foraged (NFG) by waterfowl.

and the effect and interactions of waterfowl foraging in the second fallow period.

TILLAGE TREATMENT/FLOODWATER MANAGEMENT

On the plots designated as wet-rolled, straw was rolled on 7 November with a 7-m long open-cage style roller using two passes during flooded (8-cm water depth) conditions. All plots were temporarily flooded for 3 days during the wet-rolling period in November, drained, and reflooded to a depth of 10 cm on 17 January, after the construction of levees for each plot had been completed. Each plot was surrounded by its own levee and was irrigated with well water. Water depth was kept constant in each plot with a float valve on the water inlet pipe. Plots were drained on 11 March.

WATERFOWL TREATMENTS

Mallards *Anas platyrhynchos* Linnaeus were used for this study because they are one of the most common migratory waterfowl species in wetlands and rice fields in the Sacramento Valley during winter (Gilmer *et al.* 1982; Elphick & Oring 1998). Northern pintail *Anas acuta* L., green-winged teal *Anas creccal* L., American coots *Fulica americana* Gmelin and Northern shovelers *Anas clypeata* L. are also observed in high densities in flooded rice fields in California (Elphick & Oring 1998). The winter diet of mallards in the Central Valley consists mainly of rice and seeds, which they obtain primarily from the substrate surface and water column.

Fifty-eight mallard ducklings were raised at off-site locations and maintained until early January, when they were moved to a holding pen at the experimental site. Waterfowl foraging treatments were applied from 1 to 18 February using 5-month-old pinioned mallards. Five birds were placed in designated plots for 12 6-hour periods over the treatment period. This provided a total grazing intensity of 144 000 bird-hours ha^{-1} and was equivalent to 33 birds ha^{-1} over a season of 180 24-h days. We chose this density based on observations by Elphick & Oring (1998) and C.S. Elphick (personal communication) of waterfowl use of rice fields in the Sacramento Valley. They reported densities of waterfowl during day-time counts ranging from 0 to 38 birds ha^{-1} day^{-1}. We used densities at the upper end of this range for two reasons. First, we wanted to ensure that our waterfowl treatment was sufficiently large that, if an effect of waterfowl activity existed, we would be able to detect it in our experiments. Secondly, studies both in the Central Valley of California (Miller 1985) and in Texas (Anderson & Smith 1999) indicate that much of the foraging activity of waterfowl occurs at night. Birds rest in sanctuaries during the day and move to rice fields at dusk, where they feed intensively until dawn. Estimates of bird densities during diurnal periods (Day & Colwell 1998; Elphick & Oring 1998) may therefore significantly underestimate actual bird use. In fact, Anderson & Smith (1999) indicate that diurnal counts may underestimate abundance by as much as 10-fold. To ensure that the density of birds in our experiment was not too low, we used the upper range of values provided by C.S. Elphick (personal communication) for day-time counts.

Ducks were kept on-site during the 4-week treatment period in a secure holding pen, and were herded into plots daily on a 2-day-on, 1-day-off pattern. Groups consisting of two male and three female mallards were selected randomly and placed in enclosed treatment basins at approximately 08.00 h, and removed at 14.00 h, on each of the 12 treatment days. Time budgets were determined for waterfowl while in the field plots using instantaneous scan sampling techniques (Martin & Bateson 1986) with 15-second sampling intervals. Observations were recorded daily for ducks in all treatments. On most days, observations were conducted in both the morning and afternoon.

SOIL AND PLANT RESIDUE SAMPLING

The amount of residual rice straw on the soil surface was estimated on 24 October, 4 January and 18 March by clipping at the soil surface, collecting, combining, washing and drying subsamples of surface straw from three 0·25-m^2 quadrats per plot. Additionally on 18 March, levels of below-ground organic residue were estimated by taking six soil cores (6-cm diameter to 14-cm depth) per plot, two from each quadrat area. Below-ground organic residues were separated from the soil by washing combined samples using a Gillison Root Washer (Gillison's Variety Fabrications, Inc., Benzonia, MI, USA) equipped with a 960-μm sieve. Additionally, soil samples (10 per plot) were taken from each plot on 4 January, 9 February, 16 February, 23 February and 8 March, to a 15-cm soil depth, for soil nutrient analyses. Soil samples were combined for each plot prior to processing and analysis. Floodwater samples (500 ml) were collected on 30 January, 11 February, 17 February, 24 February and 1 March from each plot.

SOIL AND PLANT RESIDUE PROCESSING

Surface straw residue and below-ground organic matter plant samples were dried at 55 °C for 72 h and ground using a Wiley plant grinding mill (A.H. Thomas Co, Philadelphia, PA, USA) to pass a 2000-μm sieve. Plant subsamples were taken and further ground to pass a 250-μm sieve for total C and nitrogen (N) determination. Fibre analysis was conducted on plant subsamples ground to pass a 420-μm sieve. Soil samples were refrigerated at 4 °C until analysis. Field-moist soil samples were mixed and subsampled for inorganic N and potentially mineralizable N determinations. Remaining soil samples were dried at 60 °C for 72 h. Soils were initially ground to pass a 2000-μm sieve for Olsen P, exchangeable K, Ca and Mg, particle size, cation exchange capacity (CEC), soil organic matter (SOM) and $CaCO_3$ equivalent. Soil subsamples were further ground to pass a 250-μm sieve for total N and C analysis. Floodwater samples were frozen at −11 °C until analysis for total N, organic C and inorganic N (NH_4^+ and NO_3^-).

Total C and N were determined for all plant samples using the Dumas dry combustion method–Carlo-Erba CHN gas analyser (Costech Analytical Technologies, Inc., Valencia California, formerly Fision Instruments S.p.A., Milan, Italy) (Dumas 1831). Lignin content was measured using the fibre analysis method described by Van Soest (1963). Field-moist soil samples were subsampled in triplicate and extracted with 2 N KCl using a 5 : 1 extractant : soil ratio. Inorganic N (NH_4^+ and NO_3^-) levels were determined by automated direct conductivity (Carlson 1986). Potentially mineralizable N levels were estimated by the 7-day, 40 °C, anaerobic incubation method (Waring & Bremner 1964). The resulting incubation extracts were quantified for NH_4^+ and NO_3^- levels as indicated previously. N and C levels are expressed on a dry soil basis. Total soil C and N were determined using the Dumas dry combustion method–Carlo-Erba CHN gas analyser

(Dumas 1831). Inorganic soil C ($CaCO_3$ equivalent) was measured gravimetrically by reaction with HCl using a saturated soil paste. Soil organic C was calculated by difference by subtracting inorganic soil C from total soil C. Total N in the floodwater samples were determined by the Kjeldahl digestion method and quantified conductimetrically (Nelson & Sommers 1982). Total organic C in the floodwater was measured by UV-persulphate oxidation using a Shimadzu Soluble Carbon Analyser (Shimadzu Scientific Instruments, Inc., Pleasanton, CA, USA). Suspended sediment concentrations in the floodwater samples were quantified gravimetrically by filtering a 20-ml aliquot of floodwater over number 42 Whatman filter paper.

STATISTICAL ANALYSIS

Main effects of tillage and waterfowl were tested using a general linear model (GLM) test designed for the split-plot design. The tillage by replicate error (3 degrees of freedom; d.f.) was used as the error term in the GLM for the untilled vs. wet-rolled treatment (1 d.f.). The replicate by waterfowl by tillage error (6 d.f.) was used as the error term in the GLM for the waterfowl vs. no waterfowl treatment (1 d.f.) and the tillage by waterfowl interaction (1 d.f.). When there was a significant tillage by waterfowl interaction, pairwise comparisons between individual treatment combinations were performed using adjusted Bonferroni t-tests and are indicated in the text when used. The effect of tillage without waterfowl was assessed by using Bonferroni t-tests after waterfowl treatments were applied. All data are expressed as least-squares means with standard errors of indicated treatments. F statistics and P-values are indicated in text and tables for all GLM procedures. A significance level of $P < 0{\cdot}05$ was set a priori as the α-level, and P-values are specified between 0·05 and 0·20 in tables and text to facilitate data interpretation. P-values greater than 0·20 are indicated simply as NS (non-significant) in the tables. Studentized t-tests were performed on the straw diameter data because only two of four replicates were sampled. Adjusted Bonferroni t-tests were performed on soil inorganic N and potentially mineralizable N data to compare values among sample dates within the sampling period. All statistical tests were performed using SYSTAT version 7.0 (SYSTAT 1997; SPSS Inc., Chicago, IL).

Results

RICE STRAW DECOMPOSITION

Rice straw residue remaining on the soil after harvest in October 1995 was 5428 kg ha^{-1} ($\pm$ 263) dry matter. Residual surface straw biomass was measured during the winter fallow period (Fig. 2). Initial surface straw biomass in October was not significantly different among the treatments (Table 2).

At the end of the initial non-flooded winter fallow period (October–January), less straw remained in wet-rolled plots compared with untilled (Fig. 2). From harvest to 4 January, wet-rolled plots lost over half (55%) of the residual surface straw compared with 27% lost in untilled plots (Table 3). Wet-rolling resulted in a lower N concentration and higher C/N ratio of straw residue remaining in January (Table 4).

During the second period of the winter fallow (January–March), the waterfowl treatment was applied. The foraging activity of waterfowl signifi-

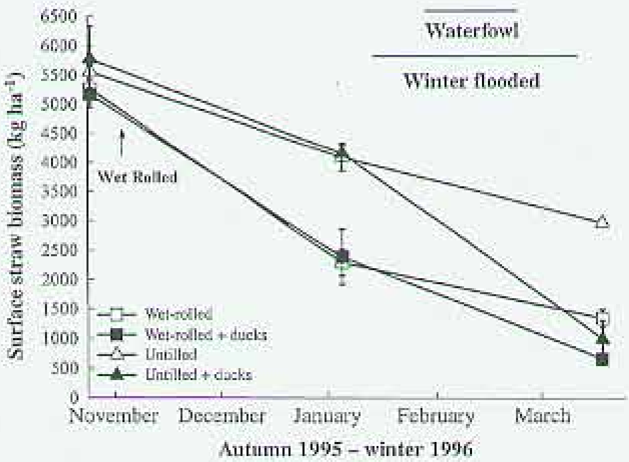

Fig. 2. Effects of tillage and waterfowl activity on surface straw biomass after harvest, October 1995 (dry matter). Least-squares means and standard errors are shown ($n = 4$). The period of waterfowl foraging was from 1 to 18 February and plots were continuously flooded from 17 January to 11 March to a 10-cm depth. Time labels refer to the first of each month.

Table 2. Statistical effects of tillage and waterfowl foraging on rice straw biomass during the winter fallow period 1995–96

		Surface straw biomass		
Effect	*F* statistic/*P*-value	24 Oct	4 Jan	18 Mar
Waterfowl (W)	*F*	0.1	–	219.0
	P	NS	–	< 0.001
Tillage (T)	*F*	2.9	51.1	48.2
	P	NS	0.006	0.006
W x T	*F*	0.6	–	51.4
	P	NS	–	0.001

Table 3. Effects of tillage and waterfowl foraging on surface straw percentage loss during the winter fallow period 1995–96. Percentage surface straw loss figures were calculated as loss from that remaining at the start of the period indicated (dry matter). Least-squares means and standard errors are given in parentheses ($n = 4$)

		Surface straw residue loss (%)		
Waterfowl	Post-harvest tillage	Oct–Jan	Jan–Mar	Oct–Mar
None	Wet-rolled	56 (4)	41 (6)	74 (2)
None	Untilled	26 (5)	27 (5)	46 (1)
Waterfowl	Wet-rolled	54 (8)	72 (2)	87 (2)
Waterfowl	Untilled	28 (2)	76 (2)	82 (3)
F statistic/*P*-value				
Waterfowl (W)	*F*	–	101.6	231.1
	P	–	< 0.001	< 0.001
Tillage (T)	*F*	38.3	0.8	39.2
	P	0.008	NS	0.008
W x T	*F*	–	5.1	51.6
	P	–	0.065	< 0.001

cantly reduced residual surface straw biomass in the untilled and wet-rolled plots (Fig. 2 and Table 2). Waterfowl foraging had a significantly greater effect on straw loss in untilled plots compared with wet-rolled, as indicated by a significant waterfowl by tillage interaction for biomass and percentage loss (Tables 2 and 3). From October–March in wet-rolled plots, surface straw loss was greater in foraged (87%) than in unforaged plots (74%; $P = 0{\cdot}008$; Table 3). Waterfowl foraging had an even greater effect in untilled plots, with 82% surface straw loss in foraged plots compared with 46% loss in unforaged plots from October–March ($P < 0{\cdot}001$). Additionally, untilled foraged plots (82%) lost slightly more straw than unforaged wet-rolled plots (74%; $P = 0{\cdot}073$). Surface straw loss was similar in foraged wet-rolled plots (87%) and foraged untilled plots (82%; $P = 0{\cdot}468$; Table 3).

Table 4. Effect of tillage on chemical composition of surface straw 6 weeks after tillage at 4 January 1996. Averages presented are for non-foraged plots. Least-squares means and standard errors are given in parentheses ($n = 4$)

	Chemical composition (g kg^{-1})				
Post-harvest tillage	C	N	Lignin	C/N	L/N
Wet-rolled	358 (2)	5.4 (0.2)	53 (1)	67 (2)	9.9 (0.3)
Untilled	358 (2)	6.1 (0.3)	54 (1)	60 (2)	9.1 (0.5)
F statistic/*P*-value					
Tillage (T) *F*	< 0.1	9.1	< 0.1	10.6	2.9
P	NS	0.057	NS	0.047	NS

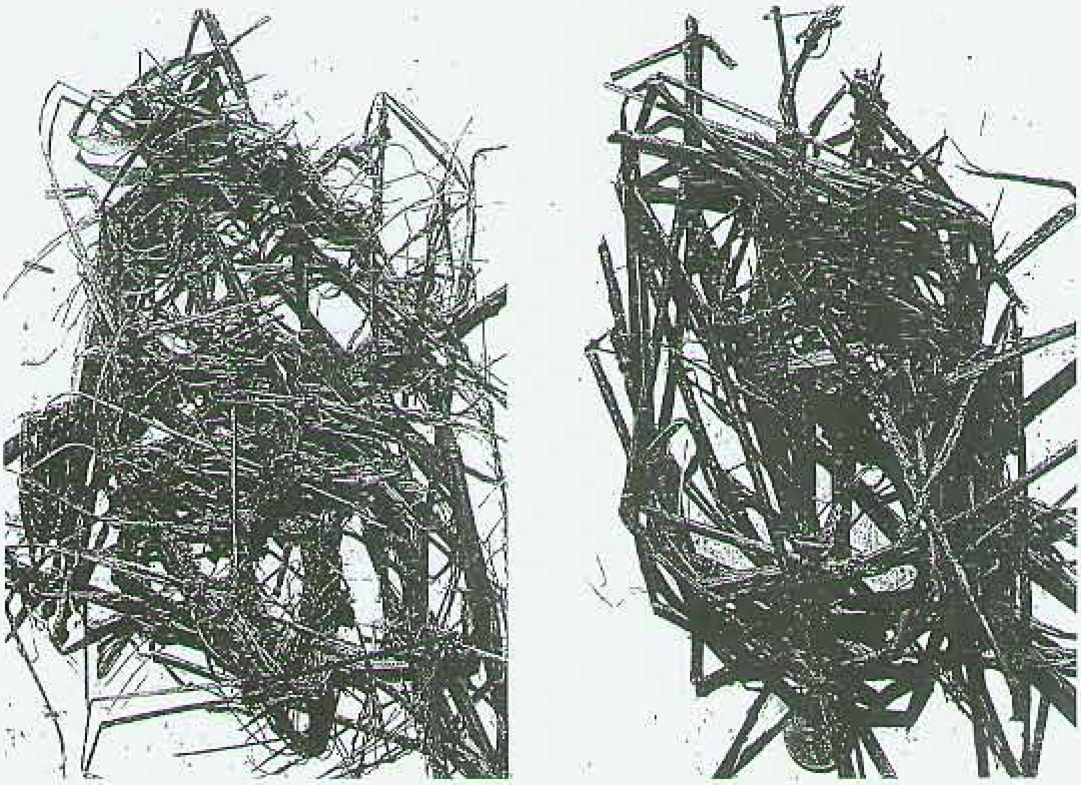

Fig. 3. Surface straw from the waterfowl foraged plot (left) and unforaged plot (right). Both samples from the untilled treatments were sampled in March 1996 at the end of the winter fallow period.

Over the entire fallow season (October–March), surface straw loss in unforaged wet-rolled plots (74%) was significantly greater than in unforaged untilled plots (46%; $P < 0{\cdot}001$). During the second half of the winter fallow (January–March), unforaged wet-rolled plots lost more of the straw remaining from January (41%) than the unforaged untilled plots (27%); however, these means were not significantly different ($P = 0{\cdot}296$; Table 3).

The surface straw collected in March from the plots grazed by waterfowl had a smaller mean diameter ($1{\cdot}3 \pm 0{\cdot}1$ mm) than from plots without waterfowl ($3{\cdot}7 \pm 0{\cdot}2$ mm) ($t = 14{\cdot}72$; $P < 0{\cdot}001$). This significant difference is further illustrated in Fig. 3. In March, straw diameter in wet-rolled and untilled was similar ($t = 0{\cdot}79$; $P = 0{\cdot}70$).

Waterfowl foraging affected the chemical composition of the remaining surface straw (Table 5),

Table 5. Effects of tillage and waterfowl foraging on chemical composition of surface straw at 18 March 1996. Least-squares means and standard errors are given in parentheses ($n = 4$)

		Chemical composition (g kg^{-1})				
Waterfowl	Post-harvest tillage	C	N	Lignin	C/N	L/N
None	Wet-rolled	367 (1)	6.6 (0.2)	68 (4)	55 (1)	10.3 (0.7)
None	Untilled	361 (2)	7.5 (0.1)	70 (4)	48 (1)	9.3 (1.1)
Waterfowl	Wet-rolled	317 (4)	5.4 (0.2)	64 (5)	59 (2)	11.0 (0.9)
Waterfowl	Untilled	347 (5)	5.8 (0.3)	62 (3)	60 (3)	10.6 (1.0)
F statistic/*P*-value						
Waterfowl (W)	*F*	88.3	270.4	9.0	32.6	12.2
	P	< 0.001	< 0.001	0.024	0.001	0.013
Tillage (T)	*F*	26.9	52.7	0.3	7.4	4.9
	P	0.014	0.005	NS	0.073	0.110
W x T	*F*	27.4	5.3	0.6	8.7	0.1
	P	0.002	0.062	NS	0.025	NS

Table 6. Effects of tillage and waterfowl foraging on below-ground organic residue biomass and its chemical composition, March 1996 (dry matter). Least-squares means and standard errors are given in parentheses ($n = 4$)

Waterfowl	Post-harvest tillage	Yield (kg ha^{-1})	Chemical composition (g kg^{-1}) C	N	Lignin	C/N	L/N
None	Wet-rolled	4275 (275)	341 (16)	12.7 (0.5)	146 (2)	27 (1)	11 (1)
None	Untilled	4031 (723)	338 (22)	13.3 (0.5)	154 (5)	26 (2)	12 (1)
Waterfowl	Wet-rolled	3969 (145)	367 (3)	12.2 (0.2)	154 (3)	30 (1)	13 (1)
Waterfowl	Untilled	4185 (351)	354 (7)	12.3 (0.6)	137 (7)	29 (1)	11 (1)
F statistic/*P*-value							
Waterfowl (W)	*F*	2.3	0.3	1.9	0.9	6.1	0.3
	P	NS	NS	NS	NS	0.049	NS
Tillage (T)	*F*	<0.1	0.1	3.3	1.5	1.1	2.0
	P	NS	NS	0.169	NS	NS	NS
W x T	*F*	0.2	0.2	0.1	14.7	<0.1	1.8
	P	NS	NS	NS	0.009	NS	NS

resulting in a lower N and C concentration and a greater C/N and lignin/N ratio of the remaining residue in the spring in both foraged untilled and wet-rolled plots. Foraged wet-rolled plots were more depleted in C and N than foraged untilled plots, resulting in a significant waterfowl by tillage interaction for C ($P = 0{\cdot}002$) and C/N ratio ($P = 0{\cdot}025$); a similar trend but non-significant interaction was present for N ($P = 0{\cdot}062$).

The effects of tillage and waterfowl were not evident in the below-ground organic residue yields, and values were similar in the top 14 cm of the soil in March (Table 6). Below-ground organic residue yield was 4115 ($\pm$ 195) kg ha^{-1} in March. Additionally at the end of the winter fallow period, C and N content in the below-ground organic residue was similar and averaged 353 g kg^{-1} total C and 12·7 g kg^{-1} total N for all treatments (Table 6). A slightly lower C/N ratio, however, was observed in below-ground organic residue remaining in the unforaged plots at the end of the winter fallow period ($P = 0{\cdot}049$).

FLOODWATER: SUSPENDED SEDIMENT, N AND C

Waterfowl foraging activity suspended organic particles and sediment in the floodwater. On two dates of five during the foraging period (11 and 17 February), suspended sediment and organic C concentrations were higher in floodwater sampled from foraged plots than control plots at a $P < 0{\cdot}05$ significance level (Table 7). Organic C was also slightly higher in floodwater in foraged plots on 24 February ($F = 3{\cdot}7$; $P = 0{\cdot}103$). Five days after the end of the foraging period, no differences in suspended sediment levels were detected among the flooded treatments, even though the floodwater in the duck plots remained visibly cloudy. Nitrogen concentrations in the surface water averaged 2·95 ($\pm$ 0·13) mg l^{-1} total N, 0·40 ($\pm$ 0·01) mg l^{-1} NH_4-N and 0·02 ($\pm$ 0·001) mg l^{-1} NO_3-N. Nitrogen levels were similar in all treatments for each form of nitrogen measured.

SOIL N AND C

Soil organic C, total N, exchangeable NH_4-N and NO_3-N were monitored to a 15-cm soil depth throughout the study. Total soil extractable inorganic N concentrations (NH_4^+ and NO_3^-) ranged from 3·9 to 9·9 mg N kg^{-1} throughout the winter sampling period (Fig. 4). Levels of extractable inorganic N were higher prior to winter flooding on 4 January (8·15 mg N kg^{-1}) than after winter flooding on 9 February (4·61 mg N kg^{-1}; $t = 5{\cdot}96$; $P < 001$).

Table 7. Effect of waterfowl foraging on suspended sediment and organic carbon in floodwater. Least-squares means and standard errors are given in parentheses ($n = 8$)

Waterfowl	Sediment (mg L^{-1}) 31 Jan	11 Feb	17 Feb	24 Feb	1 Mar	Organic C (mg L^{-1}) 31 Jan	11 Feb	17 Feb	24 Feb	1 Mar
None	558 (36)	622 (39)	512 (16)	616 (51)	611 (31)	4.5 (0.3)	5.0 (0.3)	5.5 (0.5)	4.3 (0.3)	3.7 (0.3)
Waterfowl	588 (46)	763 (72)	669 (24)	636 (42)	669 (60)	4.3 (0.2)	6.9 (0.4)	8.5 (0.8)	5.3 (0.3)	3.2 (0.3)
F statistic/*P*-value										
F	0.6	6.6	16.0	1.6	1.4	0.2	19.0	10.6	3.7	3.1
P	NS	0.043	0.008	NS	NS	NS	0.007	0.017	0.103	0.130

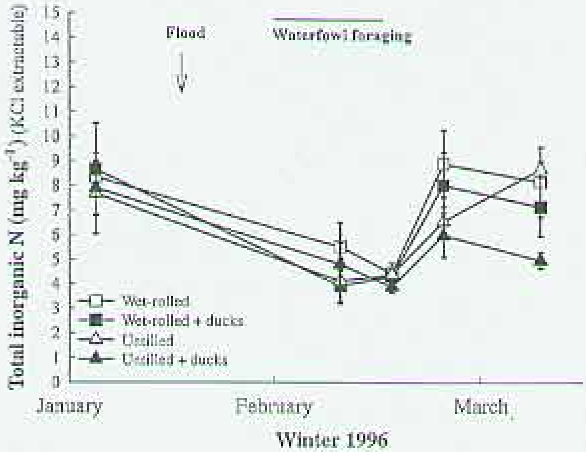

Fig. 4. Total soil extractable inorganic N (NH_4-N and NO_3-N) during the winter fallow period. Soil 0–15 cm depth. Least-squares means and standard errors are shown ($n = 4$). The period of waterfowl foraging was from 1 to 18 February and plots were continuously flooded from 17 January to 11 March to a 10-cm depth. Time labels refer to the first of each month.

Inorganic N concentrations were higher again by late February, ranging from 4·26 mg N kg^{-1} on 16 February to 7·38 mg N kg^{-1} on 23 February ($t =$ 5·16; $P = 0{\cdot}001$) and 7·24 mg N kg^{-1} on 8 March ($t = 5{\cdot}06$; $P = 0{\cdot}001$). Soil extractable inorganic N concentrations were similar during most of the study in the foraged and unforaged plots (Table 8). Early in the waterfowl treatment period a significant interaction was present in extractable inorganic N ($P =$ 0·043; Table 8). This initial interaction was slight and was not found later in the study. Two weeks after the end of the waterfowl treatments, foraged treatments had lower extractable N concentrations in the respective tillage treatments ($P = 0{\cdot}023$). Wet-rolling did not significantly affect extractable inorganic N (Table 8).

The level of potentially mineralizable soil N varied little throughout the winter sampling period but declined slightly as inorganic N concentrations rose in late February (Fig. 5). Potentially mineralizable N was significantly lower on 23 February than on 16 February ($t = 4{\cdot}49$; $P < 0{\cdot}004$) and measurements made prior to this date. Potentially mineralizable N measured on 8 March was not significantly different from each of the other sampling dates. Potentially mineralizable soil N was not significantly affected by tillage but was lower in the waterfowl foraged treatments during the waterfowl treatment period on 9

Table 8. Statistical effects of tillage and waterfowl foraging on soil extractable inorganic N (NH_4-N and NO_3-N) and potentially mineralizable N during the winter fallow period 1995–96. Soil 0–15 cm depth

		Sample date				
Effect	*F* statistic/*P*-value	4 Jan	9 Feb	16 Feb	23 Feb	8 Mar
Soil extractable inorganic N						
Waterfowl (W)	*F*	-	1.0	1.0	1.7	9.2
	P	-	NS	NS	NS	0.023
Tillage (T)	*F*	0.5	0.7	1.2	4.3	0.6
	P	NS	NS	NS	0.13	NS
W x T	*F*	-	6.6	0.4	< 0.1	3.0
	P	-	0.043	NS	NS	0.133
Soil mineralizable inorganic N						
Waterfowl (W)	*F*	-	7.8	3.7	< 0.1	< 0.1
	P	-	0.050	0.102	NS	NS
Tillage (T)	*F*	0.9	5.7	0.2	0.3	< 0.1
	P	NS	0.097	NS	NS	NS
W x T	*F*	-	3.1	< 0.1	< 0.1	1.9
	P		0.155	NS	NS	NS

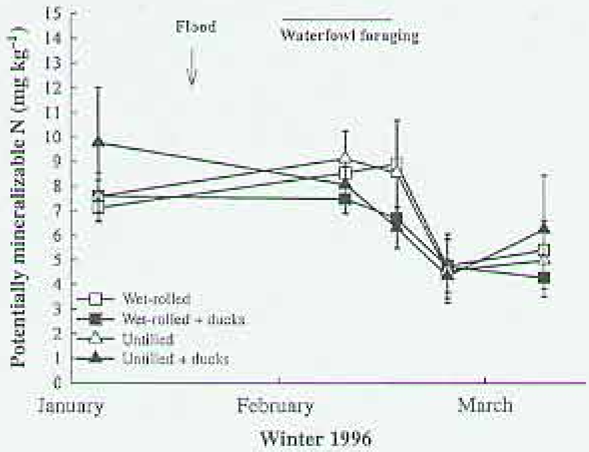

Fig. 5. Potentially mineralizable N during the winter fallow period. Soil 0–15 cm depth. Least-squares means and standard errors are shown ($n=4$). Period of waterfowl foraging was from 1 to 18 February and plots were continuously flooded from 17 January to 11 March to a 10-cm depth. Time labels refer to the first of each month.

February (Table 8). All plots had similar total soil N and organic C (Table 9).

WATERFOWL TIME BUDGETS

Time budgets of mallards on all plots were similar to those reported elsewhere for mallards during winter (Jorde 1981). The birds spent much of their time feeding (40–55%), alert (7–13%), moving (9–13%) or in maintenance activities (20–35%; Table 10). A diurnal pattern in activity was evident (active feeding in the morning, loafing and preening in the afternoon). Aggression was slight (< 1%) and the birds spent some time in courtship (< 1%), indicating that they had acclimated to the experimental situation.

Straw treatment (wet-rolled vs. tilled) in flooded plots had few effects on mallard time budgets (Table 10). None of the behaviour categories differed significantly between treatments, although there was a trend for courtship to be slightly higher on untilled plots (Table 10). However, as courtship was generally rare (< 1%), this difference was probably not meaningful. During the waterfowl treatment period, the amount of time spent foraging by mallards initially increased (acclimation to the experimental plots) and then decreased (J.M. Eadie, unpublished data). This suggests that birds may have consumed most of the available rice and invertebrates in the plots by the end of the study. Nonetheless, the proportion of time spent foraging never dropped below 35%, ranging from 35% to 80% of daily time budgets over the treatment period.

Discussion

The primary post-harvest objective of rice producers is to eliminate residual rice straw efficiently over the

Table 9. Effects of tillage and waterfowl foraging on soil total N, organic C and C/N ratio, March 1996. Least-squares means and standard errors are given in parentheses ($n=4$). Soil 0–15 cm depth

Waterfowl	Post-harvest tillage	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	C/N
None	Wet-rolled	8.3 (0.5)	0.92 (0.04)	9.0 (0.2)
None	Untilled	8.5 (0.3)	0.97 (0.01)	8.8 (0.3)
Waterfowl	Wet-rolled	8.5 (0.5)	0.94 (0.04)	9.0 (0.1)
Waterfowl	Untilled	8.2 (0.5)	0.92 (0.05)	9.1 (0.1)
F statistic/*P*-value				
Waterfowl (W)	*F*	0.1	0.9	0.6
	P	NS	NS	NS
Tillage (T)	*F*	0.1	0.1	0.4
	P	NS	NS	NS
W x T	*F*	1.3	3.3	0.6
	P	NS	0.120	NS

Table 10. Comparison of time budgets (percentage of time in each activity) of mallards in wet-rolled and untilled treatment plots. Means (SE)

Behaviour	Treatment: Wet-rolled ($n = 59$)	Untilled ($n = 61$)	t*	P†
Feeding	53·4 (2·5)	51·8 (3·3)	0·29	> 0·75
Maintenance	26·5 (2·6)	26·0 (2·8)	0·43	> 0·65
Alert	9·5 (1·0)	11·6 (1·2)	1·23	> 0·20
Motion	10·5 (0·8)	10·4 (1·2)	0·72	> 0·45
Courtship	0·3 (0·1)	0·9 (0·3)	2·13	0·035
Aggression	0·2 (0·1)	0·2 (0·1)	0·62	> 0·50

**t*-test based on arcsine (square-root) transformed data.
†Significant alpha value after Bonferroni correction $\alpha = 0{\cdot}008$.

winter fallow period before spring field preparation begins. We found that wet-rolling with winter flooding significantly increased surface straw loss by 28% compared with untilled unforaged plots. This result was expected, as tillage and flooding have been shown to hasten surface straw loss (Hill *et al.* 1999). In untilled plots, over half of the straw remained (2974 kg ha^{-1}) in March. Depending on straw yields and the time available for spring field preparation, untilled unforaged winter fallow fields would probably result in a number of agronomic problems for rice producers. Wet-rolling with winter flooding, in contrast, led to a loss of 74% of the straw from harvest by March; wet-rolling has caused no yield effects in recent trials in California (Hill *et al.* 1999). Wet-rolling did not reduce average straw diameter or incorporate straw into the soil. The result of wet-rolling appeared to be flattening of a portion of the straw onto the surface of the soil and cracking of some of the straw and crowns. The effect of the mechanical manipulation of the residual surface straw due to wet-rolling may have increased decomposition by providing more soil contact and greater accessibility of straw/crown interior tissue to microbial decomposers. This is supported by the lower N content of the residual straw in wet-rolled plots compared with that in the untilled plots. Wet-rolling is clearly an effective tool to reduce residual surface straw.

Large populations of migratory waterfowl inhabit flooded rice fields during the winter-fallow period and forage for grain, weeds and invertebrates (Day & Colwell 1998; Elphick & Oring 1998). We found that waterfowl foraging activity significantly affected the amount, composition and physical condition of surface straw residue in both the untilled and wet-rolled plots over the January–March period (i.e. the period when waterfowl were present on the plots).

Waterfowl foraging increased straw loss from January to March by a factor of three in the untilled plots and by a factor of 1·75 in the wet-rolled plots, compared with loss rates in the respective unforaged plots. The enhanced decomposition effect of waterfowl in the untilled plots compared with the wet-rolled plots may be due to the fact that, in the wet-rolled plots, there was 25% less straw, the remaining straw had less N, and it had been physically disturbed by the time waterfowl foraging began. In essence, the greater waterfowl effect in the untilled plots may have already been accomplished by the tillage in the wet-rolled plots.

The extent of surface straw decomposition in foraged wet-rolled plots (87%) and foraged untilled plots (82%) indicates that both treatments were highly effective at reducing surface straw, resulting in less than 1000 kg ha^{-1} dry matter. No additional benefit in straw loss was apparent statistically when combining wet-rolling and waterfowl foraging compared with waterfowl foraging alone. Only a slightly greater increase in loss over the winter fallow period (5%) difference was seen when both wet-rolling and foraging were applied compared with foraging alone. The remaining straw C content was reduced slightly when wet-rolling and waterfowl foraging were both employed, compared with foraging alone; however, the straw N concentration was similar in both foraged untilled and wet-rolled plots. From a practical perspective, both tillage options examined in conjunction with waterfowl foraging provide adequate reduction of surface straw, because they reduced residual levels to an amount equal to or less than wet-rolling alone.

Waterfowl visibly shredded the surface straw during foraging. Mallards crushed and tore the straw residue in their bills while searching for invertebrates and residual grain. This mechanical effect was apparent not only in the differences seen in the amount of remaining straw, but also in the much smaller average diameter of the residual straw after foraging. The foraged residue was dissimilar in both texture and appearance (Fig. 3). Finer textured remaining straw may ease spring tillage operations.

Our results differ from those reported by Sain & Broadbent (1977), who found no effect of straw particle size on rice straw decomposition when residues were left on the soil surface. In contrast to our study, Sain & Broadbent (1977) examined the decomposition of rice straw in mesh bags enclosed in cheesecloth, which minimized straw–soil contact. By minimizing soil contact with the straw residue, the critical effect of decomposer access to the residues was decreased, possibly resulting in no effect of straw particle size.

Below-ground organic residue yield was unaffected by waterfowl foraging, indicating that waterfowl did not incorporate the straw in the top 14 cm of soil. A similar C and N content was found in the below-ground organic residue, although there was a slight increase in the C/N ratio of the remaining straw in the foraged plots; this may indicate more decomposed straw residue in the soil. Suspended sediment and organic C levels in the floodwater were increased during waterfowl foraging, illustrating the agitation of the straw and soil caused by feeding activity. From the data gathered, it appears that the effects on straw decomposition for both waterfowl and wet-rolling occurred mostly at or above the soil surface and in the floodwater.

While N content in the residual surface straw was significantly less in the foraged and tilled treatments, there was little evidence of differences in soil N cycling over the winter fallow period due to these treatments. Nitrogen concentrations in below-ground organic residue were not significantly affected by treatment. Concentrations of total soil N, floodwater total N, soil extractable inorganic N, and potentially mineralizable soil N were similar throughout the winter. Levels of extractable inorganic N decreased after winter flooding but increased again by late February. At the same time, potentially mineralizable soil N decreased. This may indicate a turnover of the microbial biomass due to the onset of flooding. At the end of the waterfowl treatment period, foraged plots had slightly less extractable inorganic N, a result that may indicate N immobilization due to greater available C. Potentially mineralizable soil N was not affected by tillage but was lower in the waterfowl-foraged treatments near the end of the waterfowl treatment period. N from decomposing straw may have been lost to the atmosphere via denitrification or immobilized by micro-organisms at the soil surface.

Our results demonstrate that foraging mallards can substantially increase straw decomposition in a fallow, flooded, rice field. However, several questions remain for further study. For example, we focused only on the effects of waterfowl foraging in flooded rice fields. While the presence of floodwater may enhance the impact of waterfowl by attracting large numbers of birds (Day & Colwell 1998; Elphick & Oring 1998), dry fields may benefit as well. Large numbers of geese, as well as American coots, northern pintails, mallards and American wigeon *Anas americana* Gmelin, feed in unflooded fields and may enhance straw decomposition. Nonetheless, Elphick & Oring (1998) and Day & Colwell (1998) found that both density and diversity of waterbird species was significantly higher in flooded rice fields, indicating that the maximum impact of waterfowl would be obtained by winter flooding. Floodwater depth, held constant for this study at 10 cm, may further influence these results. Water depths can significantly influence the density and species composition of waterbirds in rice fields (Day & Colwell 1998; Elphick & Oring 1998), although depths of 15–20 cm appear to attract the greatest number of birds (Elphick & Oring 1998). The greatest impact of waterfowl foraging might be achieved by maintaining depths of flooded fields in this range.

Waterfowl may provide benefits to farmers in addition to enhancing straw decomposition. For example, foraging ducks may reduce insect and weed pest populations. Preliminary data from our study indicate that foraging mallards removed much of the invertebrate biomass (mostly Diptera) in the flooded rice plots (J.M. Eadie, unpublished data). We did not examine the effects of waterfowl foraging on weed seeds but studies are currently underway. Research is also needed on the impacts of different species of waterfowl on rice straw decomposition. Foraging behaviour varies considerably among species of ducks and geese and it is possible that mixtures of species will yield different (and perhaps additive) impacts on straw decomposition.

Perhaps the greatest single research need is to determine the density of waterfowl that must be attracted to, or maintained on, flooded rice fields to achieve the greatest effect on straw decomposition. The densities used in this experiment (equivalent to 33 birds ha^{-1} over a 180-day season) were within the range of regionally observed values, although at the upper end of the reported range. However, because all studies of waterbird use of rice fields in California have been based on diurnal surveys (Day & Colwell 1998; Elphick & Oring 1998), and because these values may underestimate actual bird density by a factor of 10 when nocturnal use is considered (Anderson & Smith 1999), we may have, in fact, used densities that were on the low side of actual densities. The true impact of waterfowl foraging on rice straw decomposition could be even greater than we report.

We recognize that the size of plots (5 × 5 m) used in this study are much smaller than the average size of rice fields (4–10 ha) in California. Although it is clearly desirable to test our results at a larger scale, the fact that the mallards in our study behaved similarly to that expected under natural conditions suggests that our findings should be reproducible (i.e. the small size of our plots did not introduce abnormalities or artefacts). We also note that our waterfowl treatments were concentrated in time (i.e. applied over a period of 18 days). However, this probably mimics the actual use of rice fields by waterfowl in the Central Valley of California. Typically, large flocks of waterbirds occupy rice fields for relatively short periods, during which time they presumably deplete the food supply, and then move on to other fields. Short concentrated use of rice fields, rather than low levels of extended use for the entire winter, are characteristic of California and our experimental design therefore represents realistic conditions.

If the results of our study are representative of patterns in the Central Valley (i.e. 'scale-up' to the landscape level), there are several important management applications. First, by attracting waterfowl to flooded fallow rice fields, growers might realize a substantial agronomic advantage by using waterfowl to accelerate decomposition of residual rice straw after harvest. Indeed, the magnitude of the waterfowl effect that we observed in our study suggests that the need for autumn tillage could be reduced or even eliminated when flooded fields are used by waterfowl at densities comparable to those observed regionally. No additional benefit of combining wet–rolling and waterfowl foraging was measured, suggesting that the reduction in residual rice straw could be accomplished by waterfowl alone. If so, farmers could realize considerable savings in time and money; for example, estimates of the cost of chopping, ploughing or disking residual rice straw range from \$25 to \$125 ha^{-1} (Blank *et al.* 1993). Rolling may be cheaper (\$9 to \$15 ha^{-1}) but still represents a significant cost to a grower over a large acreage. The cost of water for winter flooding needs to be considered to evaluate fully the economic advantages of this approach, although many farmers currently flood rice fields post-harvest in addition to tilling operations.

A second important management application of our work is that agronomic advantages of attracting waterfowl to rice fields post-harvest could provide a compelling incentive for rice farmers to flood fallow rice fields during winter. In doing so, farmers would help to provide critical wetland habitat for the large numbers of migratory waterfowl and other waterbirds. Wetland habitat loss, as a consequence of agricultural conversion, has been extensive in North America (Dahl 1990), as well as in the rest of the world (Duncan *et al.* 1999). In California wetland loss has been reduced at a greater rate than anywhere in the rest of the USA (Frayer, Peters & Pywell 1989) yet over 20% of all waterfowl in North America depend on these areas during winter (Gilmer *et al.* 1982; Reid & Heitmeyer 1995). Wetland conservation and restoration efforts in the Central Valley have focused on developing innovative solutions to enhance wildlife habitat on agricultural lands (Central Valley Habitat Joint Venture 1990). Recent research indicates that flooding rice fields during winter can play an important role in these programmes by providing valuable wetland habitat (Day & Colwell 1998; Elphick & Oring 1998). Our work is the first to demonstrate empirically that reciprocal benefits may accrue to growers, thereby helping to promote changes in land management practices that will ultimately benefit waterbird conservation in the agricultural landscape.

Management recommendations

While we feel that our methods represent realistic conditions found in northern California, future studies should consider the effects of additional species of waterfowl, different densities of birds and a wider temporal and spatial scale of experiments. Several research projects are currently underway in California to address these issues. Given our current understanding of waterfowl effects on rice straw decomposition, we recommend the following.

1. Rice producers should consider agronomic practices that attract waterfowl, such as winter flooding to maximize the decomposition impact of foraging waterfowl. Water depths of 10–15 cm are most likely to attract the greatest numbers and diversity of foraging waterfowl.
2. At the upper end of regionally observed waterfowl densities, at or near 33 birds ha^{-1} 180-day $season^{-1}$, waterfowl foraging activity may alleviate the need for autumn tillage. Farmers should evaluate the potential cost savings of reduced or eliminated autumn tillage operations, relative to the cost and benefits of winter flooding.
3. Soil N pools did not appear to be affected by waterfowl foraging over the course of our experiment. While these studies should be repeated at larger scales and over longer time periods, our results suggest that changes in fertilizer N needs currently are not warranted. Future research will be required to determine if waterfowl use of rice fields affects soil N cycles over multiple years.

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