REPORT

Waterfowl foraging in winter-flooded ricefields: Any agronomic benefits for farmers?

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Abstract Winter-flooding of ricefields provides foraging habitat to waterfowl, which in return may bring agronomic benefits to farmers. Our study experimentally tested the effect of mallards (*Anas platyrhynchos*) on the standing stalks and weed seed bank in the Camargue (France), both of which present major challenges for farmers. Three duck densities were tested: (D1) 5 ducks ha⁻¹ (historical nocturnal density), (D2) 23 ducks ha⁻¹ (present nocturnal density), and (D3) 300 ducks ha⁻¹ (Asian rice-duck farming density). The ducks reduced the stalks significantly: -27 % (D1), -52 % (D2), and -91 % (D3). Conversely, they decreased the number of seeds by only 3 % (D3) and the seed mass by about 21 % (D1 and D3), which was not significant. Besides they had no effect on seed species richness. This study clearly demonstrates that the winter-flooding effect on straw decomposition can be enhanced by waterfowl foraging, hence showing an agronomic benefit from ducks to farmers. However, there was no clear effect in terms of seed bank reduction.

Keywords Rice · Straw disposal · Waterfowl · Weeds · Winter-flooding

INTRODUCTION

Waterbirds provide important ecosystem services, both cultural (e.g., birdwatching, leisure hunting) and provisioning (meat, eggs, feathers, etc.). They can also contribute to maintaining wetlands' biodiversity through dispersal of aquatic organisms and seeds, grazing, or pest control (Green and Elmberg 2014). Agroecology highlights the importance of creating agricultural systems that build on natural ecosystems for sustainability (Gliessman 2007),

hence largely relying on existing services provided by some elements of these ecosystems.

Associating rice (*Oryza sativa*) and duck farming is a traditional Chinese practice, recently formalized as “Integrated Rice Duck Farming” and widely spread throughout Asia (IRDF, Furuno 2001). IRDF is a synchronic farming system: interactions between crops and livestock are promoted within the same space, at the same time. One-week-old ducklings are introduced at a density of 150–300 ducks ha⁻¹ in fenced paddy fields one week after planting the rice seedlings, or about 23 days after direct sowing. The rice and the ducks grow together in the field in a mutually beneficial way: the rice field provides (1) food resources in the form of waste rice and weeds (fodder and seeds), rice pests and other aquatic organisms, (2) water habitat, and (3) shelter to the ducks. In return, the ducks provide (1) weeding, (2) pest control, (3) nutrients, (4) ploughing and muddying, and (5) physical stimulation of the plant resulting in growth hormone production (Furuno 2012). Traditionally, ducks were also introduced into ricefields after harvest to feed on waste rice (Suh 2014a). IRDF differs from conventional rice cultivation as the ducks perform some tasks that usually require chemical addition, while here resource utilization is maximized in a low input strategy (Furuno 2012). Adaptations of this ancestral approach to farming now exist throughout Asia (Hossain et al. 2005; Rutz and Zingerli 2009), although local constraints (climatic, labor, species-related, or sanitary concerns such as fear of Avian Influenza Viruses) may hinder its actual spread (Gilbert et al. 2007; Suh 2014b).

Waterfowl and rice farming are also linked in North America, albeit in a different context since it is driven by concern for wild waterfowl conservation and the threat of loss of their habitat. Natural wetlands are drastically disappearing; more than 50 % of the world's wetlands were

lost during the twentieth century and 56–65 % of these were converted to agricultural land in North America and Europe (Finlayson and Davidson 1999). Flooded ricefields can play an important role in supplementing natural wetland resources as foraging grounds for waterfowl (Elphick and Oring 2003). In North America, ricefields are flooded during the winter period to attract waterfowl as part of a habitat management scheme (Eadie et al. 2008). In California, more than 40 % of ricefields are flooded during winter (Miller et al. 2010). The post-harvest practice in this state was encouraged by the prohibition of rice straw burning (California Rice Straw Burning Reduction Act, Bird et al. 2000a). Winter flooding contributes to (1) increasing straw decomposition rate; (2) decreasing weed seed viability by inhibiting their germination and postponing their winter growth; (3) limiting soil erosion; (4) retaining sediments and nutrients; (5) improving soil and water quality; and (6) reducing need for spring tillage (Manley et al. 2005; Anders et al. 2008). Moreover, the waterfowl attracted by flooding can further enhance the benefits triggered by implementing this post-harvest practice. Their trampling and foraging can lead to increased straw decomposition (Bird et al. 2000a; Manley et al. 2005), as well as decreased weed biomass in spring (van Groenigen et al. 2003; Manley et al. 2005).

Indeed, disposal of rice straw is a challenge because of its high silica content which makes it resistant to decomposition and abrasive, resulting in increased wear and tear of machinery (Monier et al. 2009). Straw incorporation produces a greater pool of soil organic nitrogen (Bird et al. 2000b) and winter flooding has been proven to further increase crop nitrogen uptake, possibly reducing the need for fertilization (Eagle et al. 2000). Weeds are also a challenge for rice farmers as they represent a major cause of yield loss (ca. 10 % of total loss on average, Oerke 2006), and thus are one of the main obstacles to conversion to organic farming (Mailly et al. 2013).

In the Camargue Rhône Delta (Southern France), 75 % of the residual rice straw still undergoes burning. This practice is currently tolerated, but a change of policy may occur in the future due to the air pollution it causes (Monier et al. 2009). Up until now, winter flooding after rice harvest is done mainly to attract waterfowl for hunting and thus is used relatively little at the regional scale (ca. 9 % of rice area, Pernollet et al. 2015) in spite of the opportunities that this practice could represent in terms of biodiversity and agronomic issues.

The general objective of this research was to assess the agronomic benefits that French farmers might expect from the use of wild waterfowl on their winter-flooded ricefields. Indeed, no comparable study to those conducted in North America has been carried out in Europe so far to determine the possible effects of ducks. The climatic conditions, the

use of different rice varieties over somewhat different soils, the differences in weed species, the fact that the landscape is more fragmented in the Camargue, and that the waterfowl use the ricefields mainly as nocturnal foraging grounds may all potentially lead to different conclusions. Additionally, previous studies may have underestimated total waterfowl use of ricefields since surveys were made during the day-time (e.g., Tourenq et al. 2001 for Europe; Elphick and Oring 2003 for the US). In particular, we aimed at quantifying (1) the trampling effect of ducks on the density of standing stalks and; (2) the foraging effect of ducks on seed abundance and species richness, considering both rice leftovers and weeds. Our predictions were that ducks would significantly reduce the number of standing stalks per experimental plot, especially at high density, and we expected they could significantly reduce the seed bank, especially for the larger seeds (>1.5 mm) which dabbling ducks normally prefer (Guillemain et al. 2002).

MATERIALS AND METHODS

Experimental plots

The research was carried out in the Camargue, the delta of the Rhône River, in Southern France. This region of about 145 000 ha comprised 60 000 ha of wetlands (Tamisier and Dehorter 1999) and 15 300 ha of cultivated rice in 2011, which represents 62 % of the agricultural area, the rest being dry crops and pastures (Regional Nature Park of the Camargue 2013). This combination of habitats makes this territory a very important site for waterfowl, especially during winter. The Camargue is the most important winter quarter at the national scale for four of the seven European dabbling duck species (i.e., mallard *Anas platyrhynchos*, common teal *A. crecca*, Eurasian wigeon *A. penelope* and Gadwall *A. strepera*, Heath and Evans 2000). The Camargue is almost the only area in France where rice is cultivated, owing to the climatic requirements of this culture. Ricefields are traditionally flooded between seeding and harvest, i.e., from April to September, then kept dry either in stubble, early disked, or ploughed during winter.

The experiments were carried out in a 2.7 ha rice field located at the center of the delta (Le Sambuc: 43°32'N, 4°43'E). This area corresponds to the mean size of ricefields in Camargue (2.5 ha, Mouret, pers. comm.). This field is cultivated conventionally (the preponderant method, as only 6 % of the Camargue rice is organic), with straw being crushed after harvest. It was experimentally flooded from mid-November 2013 to mid-February 2014 (average water depth: 15.5 cm) and was not hunted. The year preceding the experiment (winter 2012–2013), this field was under organic cultivation, it was dried at the

beginning of October and the straw was burnt after harvest. The field is close to major duck day-roosts in the Tour du Valat Nature Reserve (1.7 km flight distance, Guillemain et al. 2010), and weekly nocturnal counts during the same winter demonstrated that it was used by wild dabbling ducks as a nocturnal foraging ground. This experimental field was thus considered as representative of a typical Camargue rice field.

Experimental protocol

The tests were performed from January 21st to February 19th 2014, i.e., when wintering ducks are close to their maximum seasonal numbers in Camargue (Tamisier and Dehorter 1999). We used wing-clipped domestic mallards to mimic the effect of wintering wild ducks. In addition to the pre-treatment situation in each case (density D0, no ducks in the enclosure yet), three densities of ducks were used to represent three field situations. Two of the densities are nocturnal densities found naturally in Camargue during the winter: (1) 5 ducks ha⁻¹, the historical density recorded in the Camargue by Pirot (1981), (2) 23 ducks ha⁻¹, the nocturnal density presently observed in the Camargue ricefields (mean value recorded during nocturnal surveys on 32 post-harvest flooded ricefields between November 2013 and January 2014, Pernollet et al., unpubl.). The third density corresponds to the artificial density of ducks introduced in ricefields during the growing season as part of the Asian cultivation technique: (3) 300 ducks ha⁻¹, as is practiced in IRDF (Furuno 2012).

For this purpose, the number of ducks introduced to the experimental plots for each of the three above densities was determined using the formula: $N = (F \times D \times A) / (10\,000T)$, where N is the number of experimental ducks to release on the plot; F is the time the wild ducks normally spend foraging during a complete winter (in hours); D is the density tested (in ducks per hectare, transformed into ducks per m²); A is the area of the experimental plot (in m²); and T is the time the experimental ducks were left in the enclosure (in hours).

Considering that in the Camargue wintering wild ducks forage for ca. 10 h per 24 h, almost exclusively at night (Tamisier and Dehorter 1999), that the wintering season spans from November to February (the period during which the ducks are present in Camargue and the ricefields are available for foraging i.e., between rice harvest and ploughing), the total time spent foraging in a given rice field is $F = 10 \text{ h} \times 30 \text{ days} \times 4 \text{ months} = 1200 \text{ h}$. To measure the impact that the IRDF density would have if practiced in the Camargue, we considered that similarly the ducks would forage 10 h per 24 h and so 1200 h over the whole season.

The size of the experimental plots was set at $A = 9 \text{ m}^2$. The time that the ducks were left on the plots was set at: $T = 2 \text{ h}$ for the first two densities and $T = 20 \text{ h}$ for the IRDF

Table 1 Experimental settings specifying the duration of the experiment and the number of ducks for each density

Real duck density	Duration of the experiments	Number of ducks in enclosure
D0 = 0 ducks ha ⁻¹	T0 = 0 h	N0 = 0 ducks
D1 = 5 ducks ha ⁻¹	T1 = 2 h	N1 = 3 ducks
D2 = 23 ducks ha ⁻¹	T2 = 2 h	N2 = 12 ducks
D3 = 300 ducks ha ⁻¹	T3 = 20 h	N3 = 16 ducks

density (so as to limit the number of experimental ducks used in a limited area). The number of ducks in the enclosure and the duration of the experiments are given in Table 1.

For each of the three duck densities, the following protocol was applied: first, a new 9 m² enclosure was set up in a previously unused part of the winter-flooded ricefield. Enclosures were scattered uniformly over the field. Replicates for D1 and D2 were performed simultaneously within a single 2 h period in two separate enclosures. Each D3 trial was performed over two periods of 10 h during two consecutive days. The ducks were locked in overnight and did not receive supplementary feeding. Behavioral observations confirmed they were as a consequence actively foraging during our experimental tests. We alternated D1/D2 and D3 replicates, the latter being initiated at 3-day intervals. Once the enclosure was set up, seed bank samples were taken from nine soil cores (4.5 cm-diameter to 4 cm-depth) uniformly spread across the plot in a grid shape [at least 30 cm away from the edge and 80 cm ($\pm 10 \text{ cm}$) away from each other]. The number of standing stalks was recorded in a 25 × 25 cm quadrat randomly thrown ten times in the enclosure. These pre-treatment measurements correspond to density D0 (no ducks). N1, N2, or N3 ducks were then introduced for T1, T2, or T3 h. Because the ducks needed some time to adapt to their new environment, the experiment started when the ducks started to behave in a consistent way, i.e., initiated foraging or preening rather than swimming along the fences. To make sure the ducks were feeding, we observed them directly at a safe distance and also video-recorded the experiments during the first week. At the end of each trial, nine new soil samples were taken following the same protocol as above. Each post-duck soil sample was taken within a 10 cm radius of the associated pre-duck sample marked by a wooden stick. Soil samples were later sieved to 300 μm and dried at 70°C; seeds were then identified and counted per species using a binocular magnifier (W-PI 10×/23) and reference literature (Cappers et al. 2006). Weedy rice and cultivated rice were not differentiated. The number of remaining standing stalks in the plot was also recorded after the ducks were removed, with the same protocol as before duck introduction. The general aspect of the straw pre- and post-duck treatment was also captured by taking

photographs. The same experiment was repeated six times for each duck density.

An associated control plot, without any introduction of ducks, was set up beside each enclosure to assess representativeness of our plots in terms of stalk samples.

Statistical analyses

We first tested whether our experimental plots were representative of the whole field in terms of stubble density by comparing the number of standing stalks per quadrat in the enclosures to the number in the associated control plot with a pairwise Student *t* test. This yielded a non-significant result ($t_{179} = 0.51$, $p = 0.61$), indicating no statistically significant difference of means. We then proceeded with the analyses by testing for an effect of density of ducks on the number of standing stalks in the enclosures, using a generalized linear mixed model (GLMM) with a negative binomial distribution (package *glmmADMB*, *glmmadmb* function), after having checked for overdispersion ($\mu = 17.8$, $\sigma^2 = 171.2$). The data used for the analysis consisted of 360 (3 duck densities $\times$ 10 quadrats/plot $\times$ 2 pre- and post-treatments $\times$ 6 replicates) measures of the number of standing stalks. Density was included as a four level fixed factor (D0 corresponding to the pre-treatment, D1, D2, and D3 corresponding to the post-treatments), and plot (i.e., 1–18 since we did 6 replicates for each of the three duck densities) was included as a random factor. The fit of the model to the data was checked by performing an analysis of variance (package *car*, *anova* function) comparing it to the null model. Post hoc pairwise tests (package *multcomp*, *glht* function, Tukey test) were performed to compare the mean number of stalks among the three pre-treatment situations (the three D0 later associated with different densities of ducks) and among the post-treatment situations, i.e., D1, D2, and D3.

To determine if there was an effect of density of ducks (D1, D2, and D3) on the seed bank, we similarly compared seed abundance and richness before and after the introduction of the ducks for each density tested. We used a GLMM with a negative binomial distribution on the number of seeds after having checked for overdispersion ($\mu = 70.3$, $\sigma^2 = 1645.4$). Since there was no overdispersion ($\mu = 6.5$, $\sigma^2 = 4.0$) for the number of species, we performed a GLMM with a Poisson distribution. The data used for the analysis consisted of 324 measures (3 duck densities $\times$ 9 cores/plot $\times$ 2 pre- and post-treatments $\times$ 6 replicates) of the seed bank. The same mixed factors were chosen as for the stalks.

Using a reference publication complemented by unpublished Camargue data (Arzel et al. 2007; Brochet and Mouronval, unpubl.), we computed the mean mass of each

seed species per core from the number of seeds. We log-transformed the seed mass and added a constant (constant value = 2) to attain a normal distribution, then performed a GLMM with a Gaussian distribution to test for potential differences in mean seed mass, with the same mixed factors as before.

Finally, we renewed the three previous analyses (on seed abundance, specific richness and mean seed mass) taking out the seeds under 1.5 mm in size, as mallards may avoid such small seeds (Guillemain et al. 2002). The mean size of each seed species was found in the literature (Cappers et al. 2006).

All statistical analyses were performed using R software (R version 3.1.0 beta, R development Core Team 2014). Results are expressed as mean $\pm$ standard deviation (SD) throughout the text, and the impact of ducks on stalks and the seed bank was expressed in percentage. Mean values pre- and post-treatment (as well as their SD) stand for the averages computed over $n = 6$ trials in each situation, each trial value being the mean of all 10 stalk counts or 9 core samples.

RESULTS

Stalks

The GLMM showed that duck activity had a significant effect on the number of standing stalks. Indeed the comparison to the null model proved significant (deviance = 280, $df = 3$, $p < 0.001$). The analyses of effect sizes indicated significant differences ($p < 0.001$) between each duck density and D0 (Table 2), i.e., duck activity reduced the density of standing stalks. The post hoc Tukey tests indicated no significant difference in mean number of standing stalks before treatment among the three duck densities (i.e., the three sets of D0 values), but showed a significant difference ($p < 0.001$) between the three post-treatment situations D1, D2, and D3 (Fig. 1).

When expressed in percentages, the mean decrease in number of standing stalks was of -27% ($\pm 16\%$) for D1 compared to its associated D0, -52% ($\pm 15\%$) for D2, and -91% ($\pm 3\%$) for D3. The impact of the ducks was clearly visible on the number of standing stalks in the experimental plots (Fig. 2).

Weeds

The core samples revealed the presence of 36 different weed species in addition to rice in the experimental plots. At least five species of five genera occurred in more than 50 % of the samples (Table 3).

Table 2 Generalized linear mixed model (negative binomial distribution) testing the effect of duck density (D0, D1, D2, and D3) on the mean number of stalks per 175 cm². In each model, the plot (3 densities × 6 replicates = 18 plots) was included as a random factor. See text for statistics of the complete model. The table here shows the effect sizes, which correspond to comparisons of mean density values for D1, D2, and D3 to the mean value for D0, i.e., stalks density pre-duck treatment

Fixed effects	Estimate	SE	<i>p</i> value
Model : Number of stalks ~ duck density + (1 plot), family = negative binomial			
Intercept (D0)	3.2	0.05	<i>p</i> < 0.001
Density 1	−0.4	0.09	<i>p</i> < 0.001
Density 2	−0.7	0.09	<i>p</i> < 0.001
Density 3	−2.4	0.12	<i>p</i> < 0.001

Fig. 1 Number of stalks per quadrat before and after duck treatment for each duck density (D1 = 5 ducks ha^{−1}, D2 = 23 ducks ha^{−1}, D3 = 300 ducks ha^{−1}). For each density before and after duck treatment, the figure represents the minimum, the first quartile, the median, the third quartile, and the maximum. Boxes with different letters differed significantly after post hoc Tukey tests

The GLMM showed no significant effect of the ducks' foraging on the number of seeds (deviance = 2.3, df = 3, *p* = 0.51). At density D3, the mean number of seeds only showed a non-significant 3 % (±32 %) decrease after the duck treatment compared to the initial situation.

There was a decrease of the mean seed mass before and after the ducks for D1 and D3: respectively, −17 % (±68 SD) and −25 % (±51). Concerning D2, the tendency was an increase of the seed mass, although with a very high SD: 81 % (±211). However, the linear mixed model showed no significant effect of density on the mean seed mass (deviance = 4.2, df = 3, *p* = 0.24).

As with seed mass, the GLM showed no significant effect of the ducks on the species richness of the samples, for the three duck densities tested (deviance = 1.3, df = 3, *p* = 0.73).

The same analyses performed on a subset of the data without the smaller seeds (<1.5 mm) yielded the same results (not shown).

DISCUSSION

Ducks had a very clear effect on the standing stalks, most likely due to their trampling, while the consequence of their foraging on the seed bank of weeds and rice leftovers was not significant.

The ducks particularly reduced the amount of standing stalks when they were at higher densities. Their impact was almost doubled between the historical (5 ducks ha^{−1}), and the natural density (23 ducks ha^{−1}), respectively, −27 and −52 %, and again from the natural density to the IRDF density (−91 %). Therefore, foraging of wild ducks on winter-flooded ricefields can greatly contribute to getting rid of standing stalks. High densities of ducks may reduce stubble because the trampling pushes the straw underwater, leading to its incorporation into the soil and increased decomposition (Bird et al. 2000a).

The present results are novel, since stalks have not been targeted in previous studies, which have concentrated more on lying residual straw. Indeed the latter was shown to decrease by 27–41 % in flooded ricefields compared to unflooded (Bird et al. 2000a), and up to 41–68 % after disking plus flooding (Manley et al. 2005). In addition to submersing the stalks, the trampling of the ducks has a direct effect on the straw by flattening and cracking it, resulting in an increased soil contact and greater accessibility for microbial decomposers (Bird et al. 2000a). These authors quantified the additional effect of waterfowl (with a density of 33 birds ha^{−1} over a 180-day-long season) as a 78 % increase in straw decomposition in untilled plots and a 18 % increase in wet-rolled compared to fields without waterfowl. There is little information on the impact of ducks on post-harvest residual straw in Asia, since the interest there is focused on duck benefits during the growing season (Furuno 2012; Suh 2014b).

Winter flooding by combining the action of standing water and waterfowl activity could provide economic benefits to farmers, which has been evaluated in the US. Savings in the form of reduced tillage requirements and preparation costs for seeding (Bird et al. 2000a; Manley et al. 2005) can reach up to US \$22–63 ha^{−1} (Stafford et al.

Fig. 2 Standing stalks before (*left*) and after (*right*) duck treatment at the three duck densities D1 = 5 ducks ha⁻¹ (*top*), D2 = 23 ducks ha⁻¹ (*middle*), D3 = 300 ducks ha⁻¹ (*bottom*) (Photos by Anne Brogi)

2010). Moreover, US \$34.22 ha⁻¹ could be saved by eliminating two disking passes in autumn (Manley et al. 2005). Getting rid of residual straw after harvest by chopping, ploughing or disking can cost up to US \$125 ha⁻¹ (Bird et al. 2000b). Such savings could potentially also be made in Europe. An estimate of the financial benefits that ducks can provide farmers in France needs to take into account the high cost of pumping for flooding and

draining into the river, which has never been done before. A detailed cost-benefit analysis is underway to assess whether this represents an economically realistic option for Camargue rice farmers (Pernollet et al., unpubl.).

In Camargue, 40 weed species are commonly recorded in ricefields (Marnotte et al. 2006). Out of the 36 weeds found here, four of the most frequent ones are considered to be major weeds of ricefields in the area (*Heteranthera*

Table 3 Seed species found in the samples, with occurrence (% of core samples containing a given species), relative abundance (%), and relative dry mass (%) as computed from seed numbers and reference seed masses

Species	Occurrence (%)	Relative abundance (%)	Relative mass (%)
<i>Chara</i> sp. ^a	99	84	12
<i>Heteranthera limosa</i>	87	5.9	1
<i>Ranunculus sceleratus</i>	70	2.5	3
<i>Scirpus maritimus</i>	68	1.9	29
<i>Phragmites australis</i>	52	1.5	1
<i>Ranunculus baudotii</i>	35	0.7	0.6
<i>Cyperus fuscus</i>	33	1.1	0.03
<i>Eleocharis uniglumis</i>	18	0.3	0.7
<i>Echinochloa crus galli</i>	17	0.3	3
<i>Scirpoides holoschoenus</i>	16	0.3	0.4
<i>Trifolium campestre</i>	15	0.2	0.4
<i>Potamogeton pusillus</i>	10	0.2	0.5
<i>Najas indica</i>	9	0.2	0.2
<i>Suaeda fruticosa</i>	9	0.1	0.2
<i>Oryza sativa</i>	8	0.4	46
<i>Carex vulpina</i>	8	0.1	0.5
<i>Chenopodium album</i>	6	0.1	0.3
<i>Ranunculus sardous</i>	6	0.1	0.7
<i>Lolium perenne</i>	5	0.1	0.02
<i>Salicornia europaea</i>	5	0.1	0.1
<i>Trifolium repens</i>	3	0.1	0.1
<i>Rubus fruticosus</i>	3	0.05	0.5
<i>Zannichellia palustris</i>	2	0.04	0.1
<i>Arthrocnemum glaucum</i>	2	0.03	0.03
<i>Poaceae</i> sp. ^a	2	0.04	0.2
<i>Melilotus albus</i>	2	0.03	0.1
<i>Juncus effusus</i>	1	0.01	0.001
<i>Polygonum aviculare</i>	1	0.01	0.1
<i>Alisma</i> sp. ^a	1	0.01	0.01
<i>Baldellia ranunculoides</i>	1	0.01	0.01
<i>Euphorbia helioscopia</i>	1	0.01	0.1
<i>Galium palustre</i>	0.3	0.005	0.01
<i>Leersia oryzoides</i>	0.3	0.005	0.03
<i>Rumex crispus</i>	0.3	0.005	0.01
<i>Schoenoplectus mucronatus</i>	0.3	0.005	0.02
<i>Schoenoplectus tabernaemontani</i>	0.3	0.005	0.04
<i>Scirpus lacustris</i>	0.3	0.005	0.01

^a Seeds of *Chara*, *Alisma* and *Poaceae* could not be identified to species, but a single species in each genera/family appeared to dominate in our samples

limosa, *Phragmites australis*, *Scirpus maritimus*, and *Echinochloa crus galli*), and two as secondary ones (*Ranunculus sceleratus* and *Cyperus fuscus*, Marnotte et al. 2006). The 11 most frequent seeds we found were proven to be part of duck diet in the Camargue (Brochet et al. 2012). Moreover, nocturnal duck counts carried out during

the same winter as our tests (November 2013–February 2014) demonstrated that this experimental field was used by dabbling ducks as a nocturnal foraging ground: we observed a total of 348 mallards and 54 teal during the 13 weekly nocturnal counts, with a mean density of 12 (± 20) ducks $\text{ha}^{-1} \text{night}^{-1}$ (Pernollet et al., unpubl.). The seed bank we recorded was therefore attractive to wild birds. With the knowledge that dabbling ducks are mainly granivorous during winter (Guillemain et al. 2002), we were confident it would be used by the ducks, while at the same time being a problem for the farmer as a source of weeds. Prior to the test period, the bred ducks we used had been fed with wheat seeds and had free access to partly flooded grassland where they could feed on seeds. Consequently, they would have been able to identify seeds as potential food and were observed eating in the plots during the experiment. It is possible that the ducks were in fact partly eating macroinvertebrates; however we did not measure the availability of these in our samples and we do not have any conclusive data for Camargue winter-flooded ricefields in January. In any case, whatever the reason behind this pattern, our results clearly show that despite their active foraging the ducks at the density we used were not able to significantly deplete the seed bank.

Flooding itself can affect the seed bank by increasing the decomposition rate of some seeds (Stafford et al. 2005). The decaying of seeds is triggered by a combination of high moisture content and alternate low and high temperatures (Fogliatto et al. 2010). It has been demonstrated that winter flooding is highly effective in controlling some weeds such as weedy rice (*Oryza sativa* L., Fogliatto et al. 2010) and in inhibiting dormancy break of other seeds such as the exotic *Heteranthera limosa* (Baskin et al. 2002). Greer et al. (2009) attributed 44–47 % of waste rice seed loss over the winter to deterioration due to flooded conditions. Another factor of seed bank decrease may potentially be waterfowl foraging. However, we did not detect any significant effect of the ducks on the weed seed bank. These results are in contrast to previous studies: Li et al. (2012) found a decline of the number of weed species (from 38 to 21) and of the weed seed bank density of more than 90 % which they attributed to foraging by ducks. Other studies have either measured the effect of waterfowl on waste rice seeds available after harvest or on the grassy weed biomass of the next growing season. Measuring the weed seed bank, we expected greater effects, since not all the seeds present in winter will germinate during the subsequent growing season. Greer et al. (2009) estimated that wild waterfowl consumed between 25 and 48 % of waste rice seeds. Concerning weed biomass, the estimated decrease was of 48 % with a medium waterfowl activity (0–21.3 birds ha^{-1}) during the winter (van Groenigen et al. 2003). When ducks are released at high densities in

ricefields during the growing season in Asia (IRDF), their estimated effect on the weed biomass varies from a 58 to 98 % reduction (Hossain et al. 2005; Yu et al. 2008). The mallards we used were approximately the same size as the ducks in IRDF which normally uses “Aigamo” ducks, a crossbreed between mallards and pacific black ducks (*Anas superciliosa*), although some farmers may use larger ducks such as white pekin ducks (*Anas platyrhynchos domestica*). Contrary to Guillemain et al. (2002), we did not detect any difference when focusing on seeds over 1.5 mm, which should be preferably consumed by mallards (Brochet et al. 2010).

The lack of significant effects of the ducks on the seeds may be due to the very patchy distribution of the seeds in the ricefields, resulting in a highly variable number of seeds per core sample. Such a high intra-field variability in seed distribution may have prevented us from detecting any potential effect of the ducks if this was of limited magnitude, given the limited number of replicates that could practically be performed.

There was an overall low abundance of seeds in the field chosen for the study (11 g m^{-2}), which was only half of the mean winter seed biomass of 21.2 g m^{-2} found in Camargue by Tamisier (1971). More recent studies in Spain have shown that similarly crushed and flooded fields have a waste rice density of 24.5 g m^{-2} (Toral 2011), while in North America the values range from 6.6 to 67.2 g m^{-2} (Stafford et al. 2010). In any case, we found an abundance of seeds well above the giving-up density of 5 g m^{-2} , under which waterfowl are considered to cease foraging (Reinecke et al. 1989; Greer et al. 2009). Therefore, ducks should have considered the experimental plots as a valuable feeding habitat.

It may seem surprising that ducks had such a limited effect on the seed bank at densities as high as practiced in IRDF ($300 \text{ ducks ha}^{-1}$), which is much greater than the historical and the natural densities recorded in France (5 and 23 ducks ha^{-1} , respectively). It is likely that the ducks are more efficient in Asian IRDF because they are put in the ricefields during the growing season, as opposed to winter here. During the growing season, the ducks have a greater impact on the weeds since they have a triple action: they prevent the seeds from germinating by provoking water turbidity, they trample the plantlets, and they feed on the seedlings (Zhang et al. 2009; Furuno 2012), hence directly acting on grassy weeds that are competing with the cultivated rice.

CONCLUSION

The present study suggests that waterfowl may not always have a significant effect on the weed seed bank during the winter. Therefore, they may not significantly impact the

weeds, which are a major limiting factor of rice cultivation and conversion to organic agriculture. However, the ducks provide a significant effect in terms of stubble reduction, which is also an important issue for rice cultivation, even more so if straw burning becomes banned in the future. Flooding ricefields during winter, to make them available to waterfowl, could thus be a way of combining conservation of biodiversity and provision of agronomic benefits to farmers, and should be promoted.

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