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Using Landsat images to map habitat availability for waterbirds in rice fields

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Rice fields are an important habitat for waterbirds. Knowledge of the availability of this habitat is important since the reduction in the area of natural wetlands has converted rice fields into vital refuges. This paper presents a method for mapping habitat availability in rice fields according to different waterbirds' habitat preferences and examining its phenology during the crop cycle. Data from bird censuses carried out in the Doñana rice fields were analysed to determine the habitat preferences of 22 species of waterbird at different stages in the rice production cycle. Discriminant function analysis of seven Landsat images was used to classify paddy field stages. The phenology of habitat availability in rice fields during autumn and winter was examined. Waterfowl and waders preferentially used the 'flooded' and 'mudflats with water' paddy field stages, respectively, and the 'rice growing' and 'dry' stages were rejected by waterbirds. The area of preferred habitats within rice fields increased during autumn; subsequently, the area of the 'flooded' paddy fields decreased in January, whereas that of 'mudflats with water' remained available until March. The automatic classification of paddy field stages with Landsat images allowed habitat availability for different species of waterbirds to be monitored and provides relevant information for understanding behavioural and population responses in waterbirds that use rice fields. After examining the phenology of the availability of habitat and comparing it with dates of arrival and departure of migrant waterbirds, best crop practices could be defined to favour waterbirds (i.e. adjusting harvest, ploughing and flooding dates). Taking into account climatic change and loss of wetlands this method could help in the integration of agriculture and conservation, in particular in areas where there is no remaining natural wetland habitat.

Keywords: discriminant analysis, Doñana, shorebirds, waterfowl, wetland.

Worldwide, natural wetlands have been lost due to human action (Sánchez-Guzmán *et al.* 2007). However, the area of artificial wetlands has increased in many regions, providing alternative habitats for waterbirds (Elphick & Oring 1998, Elphick 2000, Tourenq *et al.* 2001, Ma *et al.* 2004). These man-made habitats, which are usually artificially flooded, could mitigate the current loss of natural wetland habitat. Rice fields are one of the main artificial wetlands in terms of their value for waterbirds. The importance of rice fields as an alternative habitat for waterbirds in different regions of the world is well documented (Fasola & Ruiz 1996, Elphick 2000, Maeda 2001, Czech & Parsons 2002, Sánchez-Guzmán *et al.* 2007, Toral & Figuerola 2010). Rice fields are particularly attractive to waterbirds during the autumn and early winter in the Mediterranean region, when invertebrate biomass levels peak in these habitats and temporary wetlands are usually dry (González-Solís *et al.* 1996, Marques & Vicente 1999). During this period, these habitats are of international importance in the western Mediterranean as

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stopover sites for migrating birds (Finlayson *et al.* 1992), although not all the stages of the crop cycle are attractive to waterbirds.

Between September and January, the habitat structure of rice fields in southern Europe changes quickly as rice fields are harvested and thus undergo a series of management processes. A few days after a paddy field (an individual parcel of cultivated rice) is harvested, usually at the end of September, it is ploughed up while still wet to favour the decomposition of the stubble and its admixture with the soil. Subsequently, the paddy field is flooded with a variable amount of water (depending on management decisions made by the farmer and the amount of rainfall) and stays flooded until it dries up, usually in December–January.

Changes in water levels and stubble management during the winter influence how birds use rice fields, as species can differentially select habitat with respect to the crop cycle (Elphick & Oring 1998, Lourenço & Piersma 2009). Habitat availability has an important impact on bird behaviour, resistance to disturbance, foraging behaviour, energy budget (Lombardini *et al.* 2001, Bolduc & Afton 2004) and, ultimately, survival and the decision to emigrate (Goss-Custard *et al.* 2006, Figuerola 2007).

Satellite-based remote sensing is a promising solution for evaluating habitat availability over large and/or isolated areas. In a recent review, Gottschalk *et al.* (2005) concluded that remote sensing imagery offers great potential to investigate habitat availability for birds. Satellite-based remote sensing could assist habitat evaluation, habitat modelling and monitoring programmes. This methodology has been used successfully to evaluate habitat availability for waterbirds using Landsat images (e.g. Boyle *et al.* 2004, Wade & Hickey 2008). Remote sensing has many advantages when classifying and monitoring wetlands (Ozesmi & Bauer 2002) and previous studies have used multitemporal remote sensing images to monitor the flooding of rice fields and to discriminate between different flooding stages in fields (Xiao *et al.* 2002, Alonso *et al.* 2005, Serra *et al.* 2007). There are also a small number of studies that have used remote sensing data to measure the area of flooded rice fields available to waterbirds (Spell *et al.* 1995, Fleskes *et al.* 2005).

In this study, we assessed the preference of different waterbird species for different flooding stages of rice fields and examined the capacity of Landsat satellite images to discriminate between paddy field stages. We used a GIS to monitor the availability of habitat for different bird groups in rice fields during the autumn and winter. This is the first study directly integrating remote sensing with the classification of birds' habitat preferences in relation to specific rice field conditions.

METHODS

Study area

Fieldwork was carried out in a large area (36 000 ha) of rice cultivation in Spain, situated in reclaimed marshland near the Doñana National and Natural Parks. This 105 000-ha wildlife reserve, lying to the north of the Guadalquivir estuary in Andalusia (SW Spain), includes 30 000 ha of seasonal freshwater marshes (Fig. 1). Doñana is the most important wintering site for migrating waterbirds in the Mediterranean (Rendón *et al.* 2008) and one of the main migratory stopover points for waterbirds using the East Atlantic flyway.

Waterbird census

To evaluate waterbird preference for different flooding stages of rice fields, censuses were carried out at four sites of known area in the area of rice cultivation during the periods September 2005–January 2006, September 2006–January 2007 and September 2007–December 2007. Waterbirds were counted every fortnight from a car using a telescope (20–60×) along four transects through 20 contiguous paddy fields, 10 on each side of the track. All waterbirds (gulls, terns, ducks, waders, herons, flamingos and spoonbills) present within the paddy fields were counted. The area of the surveyed rice fields was calculated using ArcGIS 9.2 (ESRI, Redlands, CA, USA). Census data used in the analyses were converted into densities (birds/ha).

In addition, data from censuses in natural marshes and rice fields from May 2005 to December 2007, carried out by the Doñana Biological Station as part of a monitoring programme (http://www-rbd.ebd.csic.es/Seguimiento/seguimiento.htm), were used to assess whether the distribution of birds in the rice fields and natural marshes was related to the availability of the different field stages. Census data were converted into densities (birds/ha) and monthly mean values were used.

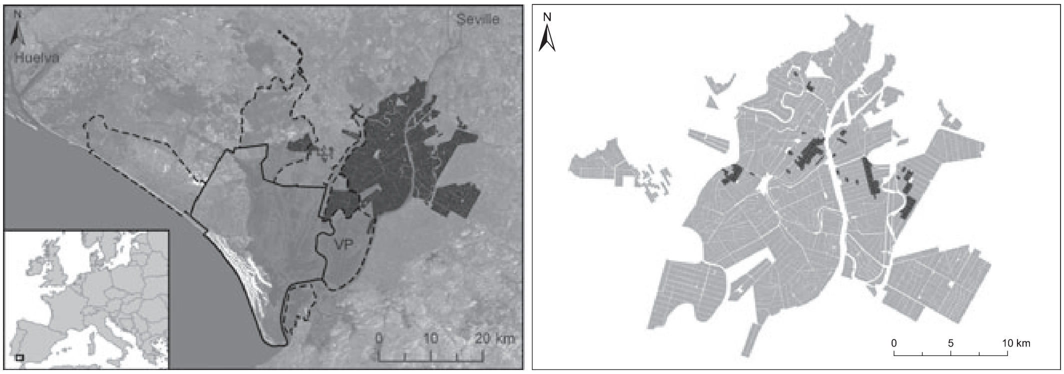

Figure 1. Location of the study area (image on the left) showing rice fields (dark shading) and the boundaries of the Doñana National Park (solid line) and Doñana Natural Park (dashed line), which also includes the fish ponds of Veta la Palma (VP). The location of the rice fields visited to collect data for comparison with Landsat satellite images (n = 114), including those where waterbird censuses were also carried out (four main groups of fields indicated in darker grey colour, n = 80), within the Doñana rice cultivation area are shown on the right.

Remote sensing

To map the availability of the different paddy field stages during the year, we developed a model using seven Landsat satellite images (those with ground-truthed data) taken on the following days: 20 September 2005 (Landsat 5), 6 October 2005 (Landsat 5), 23 November 2005 (Landsat 5), 18 January 2006 (Landsat 7), 10 November 2006 (Landsat 5), 20 October 2007 (Landsat 7) and 5 November 2007 (Landsat 7). All the images were geometrically and radiometrically corrected (Aragonés *et al.* 2005). To avoid spectral confusion with other land-cover categories (other crops, river, roads, etc.), a mask was derived from data from the cadastre that identified paddy field polygons. During preliminary analyses a mixed pixel effect was detected, giving better classification results when a buffer of 42 m (the diagonal length of a pixel in a Landsat image) was applied to all polygons representing rice fields. Thus, only interior pixels more than 42 m from the border of the polygons were used in the rest of the analyses.

Due to technical problems with the Scan Line Corrector of Landsat 7 (see http://landsat.usgs.gov/products_slcoffbackground.php), we lacked information for a small number of pixels in some of the images and so they were excluded from the analyses. The final size of the area representing each paddy field in the Landsat images ranged from five to 123 pixels (pixel size was 30 × 30 m). Reflectance values for all the bands (except the thermal band) were obtained from each image using the software IDRISI (Kilimanjaro version; Clark University, Worcester, MA, USA). The mean values of the reflectance of each band of pixels selected from each paddy field were used for the analysis. Paddy fields that were not sown in a particular season due to water shortage were excluded from the analysis.

We ground-truthed 114 paddy fields by visiting them periodically to record the cultivation stage of each (Fig. 1). Taking into account only visits made during a period of < 4 days either side of the date of the seven satellite images, we were able to use a total of 443 visits to build the models. Five paddy field stages were distinguished during fieldwork: (i) 'growing rice' (paddy fields with rice growing and vegetation covering the water); (ii) 'harvested' (paddy fields that had been harvested but in which the rice stubble was still present); (iii) 'mudflats with water' (harvested paddy fields in which the stubble had been ploughed into the soil and 10–80% of the surface area was flooded); (iv) 'flooded' (100% of the paddy field was flooded and little or no green vegetation was observed) and (v) 'dry' (dry paddy field with bare soil and little or no green vegetation).

Statistical analysis

Distribution patterns of waterbirds were explored using principal components analysis (PCA) and redundancy ordination analysis (RDA). We used a multivariate approach instead of single species analyses because we wanted to describe a useful method to map the habitat availability for groups of species that could be applied in other rice-growing regions with similar or closely related species instead of a method focused on a particular species. A linear-based instead of a unimodal approach (detrended correspondence analysis and canonical correspondence analysis) was chosen due to the presence of many zero observations in our data (rice paddy fields with no birds) (Lepš & Šmilauer 2003). We used PCA to summarize the community variation and RDA, which is a constrained linear form of PCA, to explain this variance via explanatory variables. Species scores were standardized after extraction of the axes to avoid the influence of species with a large variance, so the ordination diagrams display correlations instead of covariances (Ter Braak & Šmilauer 2002, Lepš & Šmilauer 2003). Zuur *et al.* (2010) discuss the problem of the presence of double-zeros (when two species are jointly absent) in the data when using PCA and suggest using alternative multivariate analyses that ignore double-zeros. However, calculations using alternative analyses such as non-metric multidimensional scaling are time-consuming for larger datasets, even on fast computers (Zuur *et al.* 2007), and results are not always easier to interpret. Spatial (sites) and environmental variables (paddy field stage) were binary coded as dummy variables to be used in the redundancy analysis (Lepš & Šmilauer 2003). The significance of both effects on the waterbird species composition of each paddy field was assessed by means of a Monte Carlo permutation test (499 permutations) with blocks (transects and paddy fields) taken into account as covariates. Analyses were performed with CANOCO for Windows 4.5 (Microcomputer Power 113; Ithaca, NY, USA).

Discriminant analysis is a useful statistical tool for classifying remote sensing data (Treitz & Howarth 2000). In this study, a supervised classification process using linear combinations of the independent variables (reflectance of TM and ETM + bands) in a discriminant analysis was applied to classify each paddy field according to the identified stages. This method has already been successfully used by Serra *et al.* (2007) to differentiate successfully between eight different flooding stages of rice fields of the Ebro Delta (Catalonia, northeast Spain) with an accuracy higher than 90%.

Due to their similarities, sown and harvested paddy fields were combined into a single category ('vegetation') during the discriminant analysis to improve its classification. 'Growing rice' and 'harvested' paddy fields were later discriminated using normalized difference vegetation index (NDVI) values. Values of NDVI were calculated for all ground-truthed paddy fields. 'Harvested' paddy fields showed lower NDVI values (mean 0.29 ± 0.085 se) compared with 'growing rice' paddy fields (mean 0.52 ± 0.084 se). 'Vegetation' paddy fields with an NDVI < 0.38 were classified as 'harvested', whereas those with higher values were classified as 'growing rice'. Applying this threshold on ground-truthed paddy fields, 8% of 'vegetation' paddy fields were misclassified as 'harvested' paddy fields, and 13% of 'harvested' paddy fields were misclassified as 'vegetation' paddy fields. Values of NDVI were not used in the discriminant analyses because they did not improve the accuracy of the classification when considering the five stages of cultivation (preliminary analyses not shown). The model obtained was tested using the 'jacknife method' method: each of the seven images was classified with a model using the other six images. The Kappa statistic (Titus *et al.* 1984) was used to evaluate the results of the classifications obtained from the discriminant analyses (results from the 'jacknife method' method were pooled to calculate the resulting Kappa). A Kappa of zero indicates that no improvement over chance is provided by the discriminant analysis; a Kappa of one occurs only in the case of perfect agreement. To map the changes of the different flooded stages of rice fields during the whole crop season, Fisher's classification functions obtained from the discriminant analysis were applied to obtain the classification maps for 10 Landsat images from the crop season of 2005/2006 (from May 2005 to April 2006), including four of the seven images used to develop the model (images from 20 September 2005, 6 October 2005, 23 November 2005 and 18 January 2006). Analyses were performed with SPSS for Windows 16.0 (IBM, Chicago, IL, USA). Maps and area calculations were derived in ArcGIS 9.2.

RESULTS

Waterbird habitat selection

We recorded a total of 39 waterbird species in the rice fields, of which the 22 species with at least 10 positive censuses were considered for further analysis. In 69.6% of visits to a paddy field there were no birds (*n* = 2020). The first two axes of the PCA (Fig. 2a) explained 42.8% of the variation in the

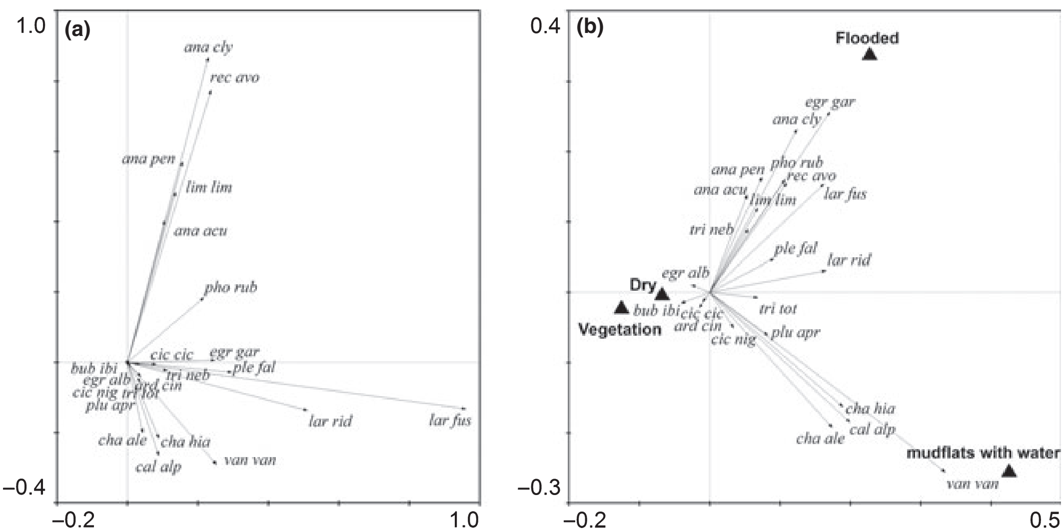

Figure 2. (a) Axes 1 and 2 of principal component analysis (PCA) showing waterbird species distribution in Doñana rice fields based on censuses during the autumns (September–January) of 2005⁄2006 and 2006⁄2007. (b) Axes 1 and 2 of redundancy analysis (RDA) showing waterbird species distribution in Doñana rice fields in relation to paddy field stages based on the same census data. ana cly (*Anas clypeata*), rec avo (*Recurvirostra avosetta*), ana pen (*Anas penelope*), lim lim (*Limosa limosa*), ana acu (*Anas acuta*), pho rub (*Phoenicopterus ruber*), egr gar (*Egretta garzetta*), cic cic (*Ciconia ciconia*), ple fal (*Plegadis falcinellus*), bub ibi (*Bubulcus ibis*), egr alb (*Ardea alba*), tri neb (*Tringa nebularia*), ard cin (*Ardea cinerea*), lar fus (*Larus fuscus*), lar rid (*Larus ridibundus*), cic nig (*Ciconia nigra*), tri tot (*Tringa tetanus*), plu apr (*Pluvialis apricaria*), cha ale (*Charadrius alexandrinus*), cha hia (*Charadrius hiaticula*), cal alp (*Calidris alpina*), van van (*Vanellus vanellus*).

species data. The vertical axis indicated a gradient with the group formed by waterfowl species and other species with a preference for flooded habitat (such as Pied Avocet *Recurvirostra avosetta* and Black-tailed Godwit *Limosa limosa*), in contrast to the waders, which prefer 'mudflats with water'. The horizontal axis was dominated by the two common species of gull, Lesser Black-backed Gull *Larus fuscus* and Black-headed Gull *Larus ridibundus*, indicating that their presence was poorly correlated with the presence of the species aligned with the vertical axis.

In the redundancy analysis (RDA), the first two ordination axes together explained 6% of the total variability in the species data and 97.9% of the species–environment variation. Both the first canonical axis ($F = 79.7$; $P = 0.002$) and all the canonical axes ($F = 44.0$; $P = 0.002$) were found to be significant with the Monte Carlo permutation test (499 permutations). The RDA biplot (Fig. 2b) shows associations of species that were similar to the patterns of variation observed in the PCA, but now related to the measured environmental variables (paddy field stages). The group formed by waterfowl species and other species with a preference for flooded habitat were related to 'flooded' rice paddy fields, whereas another group consisting of waders such as Kentish Plover *Charadrius alexandrinus*, Common Ringed Plover *Charadrius hiaticula* and Dunlin *Calidris alpina* was related to the 'mudflats with water' stage. Grey Heron *Ardea cinerea*, Cattle Egret *Bubulcus ibis*, White Stork *Ciconia ciconia* and Great Egret *Ardea alba* were the only species whose distribution was associated with the 'vegetation' and 'dry' stages ('growing rice', 'harvested' and 'dry' paddy fields). However, since the size of the vectors in the ordination graph indicates how well the species fit the analyses (Lepš & Šmilauer 2003), this last group of species showed no strong preference for any particular paddy field stage.

Classification of paddy field stages with satellite images

The first two canonical discriminant functions summarized 93.7% of the total variance. The third canonical discriminant function was also significant, but only summarized 6.3% of the total variance. Function 1 discriminated categories according to vegetation cover: values > 0 corresponded to paddy fields in the 'harvested' and 'growing rice' stages (grouped in the analysis under the 'vegetation' stage), whereas values < 0 corresponded to 'mudflats with water', 'flooded' and 'dry' paddy fields (Fig. 3). Function 2 separated categories according to their wetness: values < 0 corresponded to 'flooded' and 'mudflats with water' paddy fields (but also some 'harvested' and 'growing rice' paddy fields), and values > 0 corresponded mainly to 'dry' paddy fields (Fig. 3). Fisher's classification functions (see Table 1) were used to classify each paddy field in the 10 Landsat images from the crop season of 2005/2006.

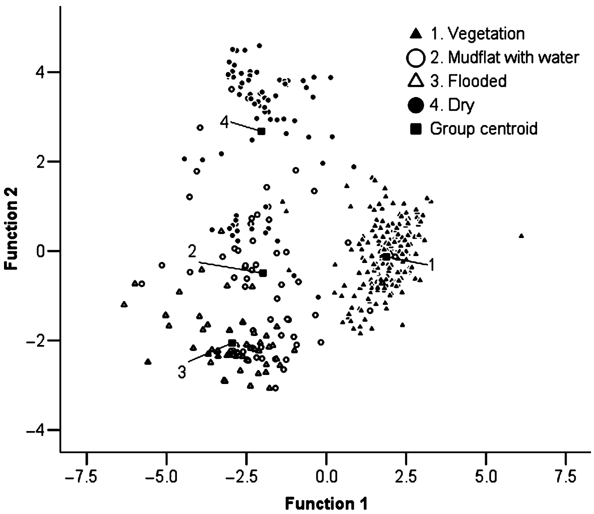

Figure 3. Canonical discriminant functions 1 and 2. Classification of Doñana rice fields into four different paddy field stages based on reflectance data from seven Landsat images from the autumn and winter of 2005, 2006 and 2007.

Table 1. Coefficients of Fisher's classification functions obtained from the discriminant analysis based on seven Landsat images. Each of the four Fisher's classification functions resulting from combining the coefficients with the corresponding averaged values of the reflectance bands extracted from the pixels of each paddy field (e.g. Vegetation value = 0.116 × B1 − 0.379 × B2 + 0.463 × B3 + 0.260 × B4 − 0.764 × B5 + 0.899 × B7 − 15.770) should be applied to classify the paddy field. The stage of the paddy field corresponds to the formula with the higher value. 'Mudflats' corresponds to the paddy field stage 'mudflats with water'.

	Paddy field stage			
Reflectance band	Vegetation	Mudflats	Flooded	Dry
B1	0.116	0.182	−0.174	0.242
B2	−0.379	−0.174	0.523	0.254
B3	0.463	0.545	0.224	−0.049
B4	0.260	0.256	0.114	0.109
B5	−0.764	−0.729	−0.434	−0.150
B7	0.899	0.551	0.216	0.096
Constant	−15.770	−28.616	−23.949	−28.337

The model using all seven Landsat images correctly classified the ground-truthed paddy fields in 91% of cases, with a Kappa of 0.86 ($P < 0.001$). The classification results for the 'jacknife method' analysis are given in Table 2 (results from the seven images are pooled). The resulting Kappa value was 0.74 ($P < 0.001$). The two paddy field stages with the best classification results in the 'jacknife method' analysis were 'vegetation' (97% of the cases correctly classified) and 'flooded' (93%), and the two stages with the lowest values for correctly classified cases were 'mudflats with water' (53%) and 'dry' paddy fields (59%).

Seasonal changes in habitat availability and bird densities

Figure 4(a) (15 May 2005) corresponds to the beginning of the crop season, with flooded paddy fields ready for the sowing of the rice. Some of the paddy fields that were not yet flooded were classified as 'harvested', probably due to the presence of dry vegetation. The maps from 3 August 2005 and 4 September 2005 (Fig. 4b,c) correspond to the growing period. Figure 4(d) (20 September 2005) corresponds to the beginning of the harvest, which is almost complete in Figure 4(e) (6 October 2005), at which point some paddy fields are classified as 'mudflats with water' and others as 'flooded' due to the post-harvest ploughing of the stubble into the soil and water before the paddy fields are flooded once again. On 23 November 2005 (Fig. 4f) the whole area consisted of a mosaic of 'flooded paddy fields', but there were also some paddy fields classified as 'harvested', 'mudflats with water' and 'dry'. On 18 January 2006 (Fig. 4g)

Table 2. Classification results for the 'jacknife method' analysis of the discriminant model. 'Mudflats' corresponds to the paddy field stage 'mudflats with water'.

	Predicted group membership			
Observed stage	Vegetation	Mudflats	Flooded	Dry
Vegetation	237	4	0	4
Mudflat	7	30	8	12
Flooded	1	4	62	0
Dry	17	11	2	44

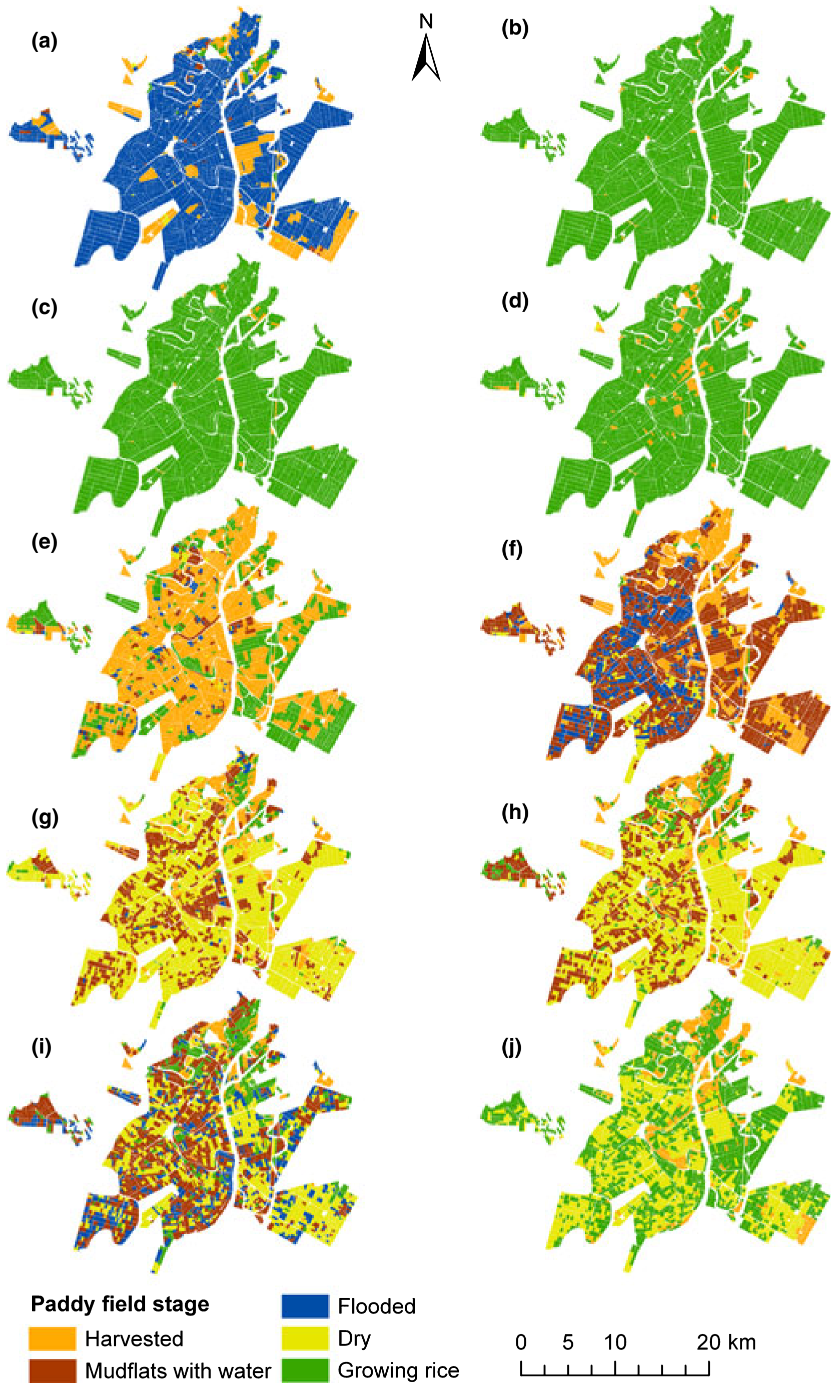

Figure 4. Habitat availability maps of Doñana rice fields based on Landsat images from May 2005 to April 2006. Dates of the images: (a) 15 May 2005, (b) 3 August 2005, (c) 4 September 2005, (d) 20 September 2005, (e) 6 October 2005, (f) 23 November 2005, (g) 18 January 2006, (h) 11 February 2006, (i) 27 February 2006, (j) 8 April 2006.

most of the area was 'dry' and only a few 'flooded' paddy fields remained, as by then many had reached the 'mudflats with water' stage. In the maps from 11 and 27 February 2006 (Fig. 4h,i), the paddy fields were mostly 'dry', although there were still many at the 'mudflats with water' stage or freshly 'flooded', probably due to rainfall or management for hunting purposes. Figure 4(j) (8

April 2006) shows the 'dry' paddy fields waiting to be flooded at the beginning of the new crop season. In the last three maps some paddy fields were classified as 'growing rice', possibly due to the presence of some green vegetation.

The area of 'harvested' paddy fields increased quickly during October and then decreased after reaching its peak (Fig. 5). During October and November the area occupied by 'mudflats with water' and 'flooded' paddy fields increased as the harvested paddy fields were ploughed and then flooded (Fig. 5).

The density of the group of species with preferences for the 'mudflats with water' stage increased in the paddy fields from September to January and then decreased from January to March (Fig. 6a), although throughout this period it was higher than in the natural marshlands. In the natural marshes, the density of this group of species increased from March to May, when it reached a maximum, and then decreased to its low point in June. The density of the group of species with preference for flooded paddy fields reached a peak in January but was always higher in the natural marshland (Fig. 6b).

DISCUSSION

Evaluating the potential role of man-made habitats relative to natural habitats is a key issue in conservation biology (Elphick 2000). Many studies have suggested that artificial wetlands may be suitable habitats for waterbirds (e.g. Acosta *et al.* 1996, Elphick & Oring 1998, Froneman *et al.* 2001). In particular, once wetlands have been drained in a region, rice fields can provide suitable alternative habitat (Elphick 2010) and rice is considered the world's most important agricultural crop for waterbirds (King *et al.* 2010). The area of marshland in Doñana that floods every autumn and winter is extremely variable (Kloskowski *et al.* 2009) and has been drastically reduced in extent due to anthropogenic activities (García-Novo & Martín-

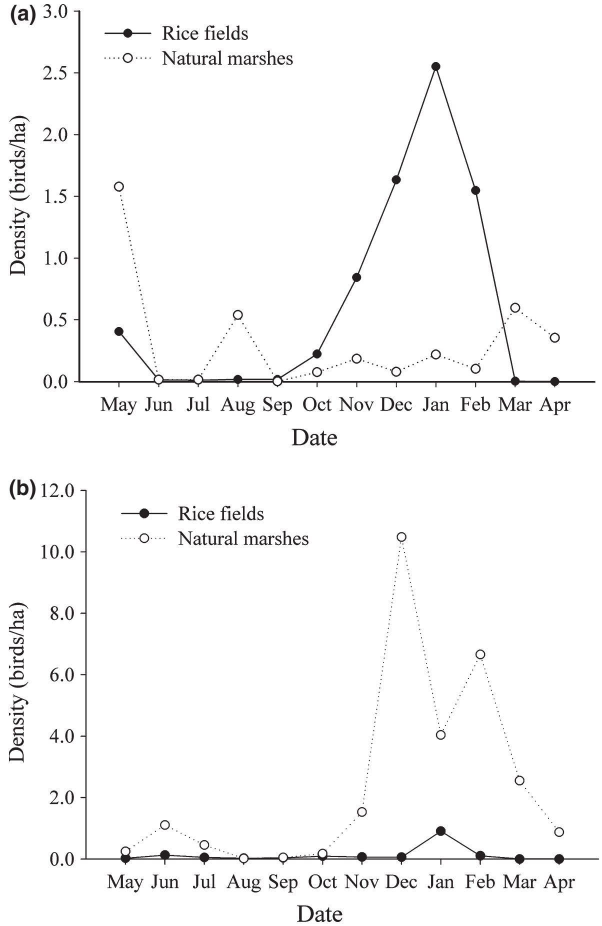

Figure 6. (a) Changes in the mean density of waterbird species preferring 'mudflats with water' in rice fields to natural marshes (mean of the sum of the density of *Calidris alpina*, *Charadrius alexandrinus*, *Charadrius hiaticula* and *Vanellus vanellus*). (b) Changes in the density of waterbird species preferring flooded paddy fields in rice fields to natural marshes (mean of the sum of the density of *Anas clypeata*, *Anas penelope*, *Anas acuta*, *Egretta garzetta*, *Recurvirostra avosetta* and *Limosa limosa*). Densities were calculated based on 4620 ha of rice fields and 3373 ha of natural marshes monitored by the Equipo de Seguimiento from Doñana Biological Station between May 2005 and December 2007.

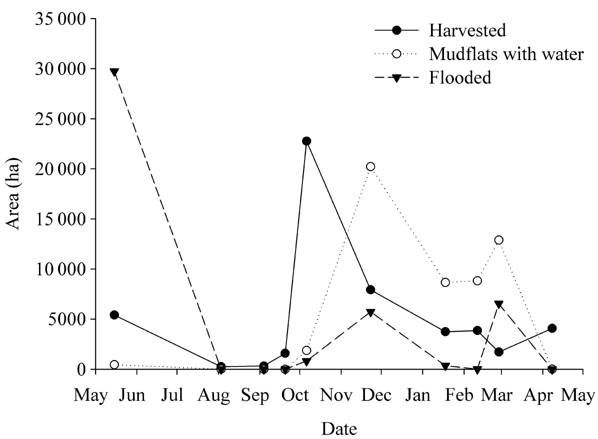

Figure 5. Changes in the area of the different paddy field stages during the 2005⁄2006 season obtained from the analysis of 10 Landsat images from May 2005 to April 2006.

Cabrera 2005). Given this variation in the natural habitat available to waterbirds, managed alternative habitats seem to have become essential for the large numbers of waterbirds that cross or stay in the Doñana wetlands every autumn and winter (Kloskowski *et al.* 2009).

In this study we describe an efficient and inexpensive method based on satellite telemetry that evaluates habitat availability for two groups of waterbird species with contrasting habitat preferences that frequent rice fields in southern Europe during autumn and winter. The distribution of the species that use rice fields was related to paddy field management. Although the percentage of the total variability of the species explained by redundancy analysis seemed to be very low (6%), obtaining low values is common in this type of ordination analysis (Ter Braak & Šmilauer 2002) and in our case could be due to the high percentage of empty cells (paddy fields with no birds) in the data matrix.

Of the different stages, 'growing rice' and 'dry' paddy fields were not attractive habitats for the majority of waterbirds due to the height of the rice in the first case and a scarcity of food in the second. Two of the main paddy field stages ('flooded' and 'mudflats with water') were preferred by waterfowl and waders, respectively. The habitat preferences of these species in Doñana are consistent with previous studies carried out in rice fields in Portugal (Lourenço & Piersma 2009) and California (Elphick & Oring 1998, 2003), where waterbirds were most abundant and diverse in flooded paddy fields and small waders were commonest in ploughed paddy fields. Some species did not show a clear preference for any particular paddy field stage; in the Cattle Egret this could be because it is a generalist species (Lourenço & Piersma 2009), which could also be applicable to other species in the analyses, such as Great Egret or Grey Heron, that use several different paddy field stages. Previous work carried out in rice fields of California by Elphick and Oring (1998) also found that the Great Egret and Blue Heron *Ardea herodias* (a close congener of the Grey Heron) did not show a significant preference for flooded or not flooded habitats. The agreement in the results discussed in those works suggests that our results could be generalized to other temperate rice-growing regions.

Several studies have successfully used remote sensing data to estimate the area of winter flooded rice fields available for waterbirds (Spell *et al.* 1995, Fleskes *et al.* 2005). The results obtained using this methodology would be useful to understand local changes in the distribution of waterfowl and other waterbird species (Fleskes *et al.* 2005). However, their winter flooding estimates are based upon a single, midwinter satellite image, and while representative of conditions during midwinter, they overlook any differences in flooding occurring during early and late winter. Serra *et al.* (2007) monitored winter flooding of rice fields in the coastal wetland of the Ebro Delta (Catalonia, northeast Spain) with a multi-temporal set of Landsat images from October to March. We applied a similar method, but extended it to cover the whole crop season, and also focused on the different paddy field stages, which are directly related to their use by different groups of waterbirds. As shown in the results of the 'jacknife method', the accuracy of our method in the classification of 'mudflat with water' paddy fields is low in comparison with 'flooded' paddy fields. However, we think that this error does not compromise the conservation value of our method: as a 'flooded' paddy field always becomes a 'mudflat with water' after some days, the high accuracy of our method in the classification of 'flooded' paddy field allowed us to predict with precision the actual habitat availability for waterbirds with preference for flooded habitats, and at the same time the potential habitat availability for waders (with preference for 'mudflats with water' paddy fields). Landsat images from a wide span of dates are now freely available (http://landsat.usgs.gov/) and are an excellent tool when applying this method to the study of habitat availability for waterbirds.

The density of the waterbird species groups with habitat preferences linked to particular types of rice management increased when the corresponding paddy field stage became available. This pattern was clearest in the case of the group of species that prefer the 'mudflats with water' stage. The greater density of these species in rice fields compared with natural marshlands between October and February supports the idea that rice fields are an important alternative habitat for these species.

The seasonal flooding of the natural marshland in Doñana National Park has been found to have a direct effect on the distribution of wintering ducks and waders. Migrants arrive after autumn migration, when most of the natural marshland is usually dry, and concentrate in the nearby artificial ponds of Veta la Palma. This area, formed by around 40 brackish fish ponds (3000 ha) with a semi-permanent flooding regime, is included in the Natural Park (Fig. 1) (see Rendón *et al.* 2008, Kloskowski *et al.* 2009 for more details). As soon as winter rains begin, many waterbirds leave the artificial ponds and move to the flooded marshes. Our results suggest that rice fields are used to a greater extent by waders, as the areas of 'mudflat with water' are available from October through to March, whereas the availability of 'flooded' paddy fields is limited to just a couple of months a year. However, the use of rice fields by ducks and some species of waders and herons could be underestimated, as they could be present in Veta la Palma by day but could also be feeding in rice fields by night. Given that different species have different preferences, the ideal situation would seem to be a mosaic of different paddy field stages, as suggested by Lourenço and Piersma (2009).

The artificial fish ponds of Veta la Palma help the Doñana wetland complex to support a larger and more diverse community of wintering waterbirds than it otherwise might (Kloskowski *et al.* 2009). The data presented here suggest that rice fields are also of paramount importance for the conservation of waterbirds that visit the area during autumn and winter. After examining the temporal phenology of the availability of habitat and comparing it with dates of arrival and departure of migrant waterbirds, best crop practices could be defined to favour waterbirds (i.e. adjusting harvest, ploughing and flooding dates), and the impact of agricultural schemes based on different water flooding regimes could be evaluated.

Changes in the EU Common Agricultural Policy, such as the actual scenario of reductions in the subventions to rice farmers, may in the future reduce the area of rice fields in southern Europe, which would lead to a net loss of habitat for many waterbirds. In addition to rice fields of Doñana, the near rice field areas in the Portuguese west coast and Extremadura (southwest Spain) are important stopover habitats for migratory waterbirds, supporting 38–44% (Portugal) and 14% (Extremadura) of the declining Western European population of Black-tailed Godwit during their migration (Lourenço *et al.* 2010, Masero *et al.* 2011). Efforts should thus be made to ensure that rice cultivation is maintained under environmentally friendly agricultural practices, and/or that the functionality of former wetland area is restored.

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REFERENCES

Acosta, M., Mugica, L., Mancina, C. & Ruiz, X. 1996. Resource partitioning between Glossy and White Ibises in a rice field system in southcentral Cuba. *Colon. Waterbirds* **19**: 65–72.

Alonso, M.J.C., Barbero, R.E. & Henar, T.V. 2005. *Seguimiento por teledetección de la superficie inundada en otoño - invierno en la zona de cultivo de arroz en la Albufera de Valencia*. XI Congreso Nacional de Teledetección, 21–23 September. Puerto de la Cruz, Tenerife.

Aragonés, D., Díaz-Delgado, R. & Bustamante, J. 2005. *Tratamiento de una serie temporal larga de imágenes Landsat para la cartografía de la inundación histórica de las marismas de Doñana*. XI Congreso Nacional de Teledetección, 21–23 September. Puerto de la Cruz, Tenerife.

Bolduc, F. & Afton, A.D. 2004. Relationships between wintering waterbirds and invertebrates, sediments and hydrology of coastal marsh ponds. *Waterbirds* **27**: 333–341.

Boyle, T.P., Caziani, S.M. & Waltermire, R.G. 2004. Landsat TM inventory and assessment of waterbird habitat in the southern altiplano of South America. *Wetl. Ecol. Manage*. **12**: 563–573.

Czech, H.A. & Parsons, K.C. 2002. Agricultural wetlands and waterbirds: a review. *Waterbirds* **25**(Special Publication 2): 56–65.

Elphick, C.S. 2000. Functional equivalency between rice fields and seminatural wetlands habitats. *Conserv. Biol.* **14**: 181–191.

Elphick, C.S. 2010. Why study birds in rice fields? *Waterbirds* **33**(Special publication 1): 1–7.

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

Elphick, C.S. & Oring, L.W. 2003. Conservation implications of flooding rice fields on winter waterbird communities. *Agric. Ecosyst. Environ.* **94**: 17–29.

Fasola, M. & Ruiz, X. 1996. The value of rice fields as substitutes for natural wetlands for waterbirds in the Mediterranean region. *Colon. Waterbirds* **19**: 122–128.

Figuerola, J. 2007. Climate and dispersal: Black-winged Stilts disperse further in dry springs. *PLoS ONE* **2**: e539.

Finlayson, C., Hollis, G.E. & Davis, T.J. 1992. *Managing Mediterranean Wetlands and their Birds*. Slimbridge, UK:

International Waterfowl and Wetlands Research Bureau and Istituto Nazionale di Biologia della Selvaggina. Special Publication no. 20.

Fleskes, J.P., Perry, W.M., Petrik, K.L., Spell, R. & Reid, F. 2005. Change in area of winter-flooded and dry rice in the northern Central Valley of California determined by satellite imagery. *Calif. Fish. Game* **91**: 207–215.

Froneman, A., Mangnall, M.J., Little, R.M. & Crowe, T.M. 2001. Waterbird assemblages and associated habitat characteristics of farm ponds in the Western Cape, South Africa. *Biodivers. Conserv.* **10**: 251–270.

García-Novo, F. & Martín-Cabrera, C. 2005. *Doñana: Agua y Biosfera*. Madrid: UNESCO/Ministerio de Medio Ambiente.

González-Solís, J., Bernadi, X. & Ruiz, X. 1996. Seasonal variation of waterbird prey in the Ebro Delta rice fields. *Colon. Waterbirds* **19**: 135–142.

Goss-Custard, J.D., Burton, N.H.K., Clark, N.A., Ferns, P.N., McGrorty, S., Reading, C.J., Rehfisch, M.M., Stillman, R.A., Townend, I., West, A.D. & Worrall, D.H. 2006. Test of a behavior-based individual-based model: response of shorebird mortality to habitat loss. *Ecol. Appl.* **16**: 2215–2222.

Gottschalk, T.K., Huettmann, F. & Ehlers, M. 2005. Thirty years of analysing and modelling avian habitat relationships using satellite imagery data: a review. *Int. J. Remote Sens.* **26**: 2631–2656.

King, S., Elphick, C.S., Guadagnin, D., Taft, O. & Amano, T. 2010. Effects of landscape features on waterbird use of rice fields. *Waterbirds* **33**(Special Publication 1): 151–159.

Kloskowski, J., Green, A.J., Polak, M., Bustamante, J. & Krogulec, J. 2009. Complementary use of natural and artificial wetlands by waterbirds wintering in Doñana, South-West Spain. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **19**: 815–826.

Lepš, J. & Šmilauer, P. 2003. *Multivariate Analysis of Ecological Data Using CANOCO*. New York: Cambridge University Press.

Lombardini, K., Bennetts, R.E. & Tourenq, C. 2001. Foraging success and foraging habitat use by Cattle Egrets and Little Egrets in the Camargue, France. *Condor* **103**: 38–44.

Lourenço, P. & Piersma, T. 2009. Waterbird densities in South European rice fields as a function of rice management. *Ibis* **151**: 196–199.

Lourenço, P.M., Kentie, R., Schroeder, J., Alves, J.A., Groen, N.M., Hooijmeijer, J. & Piersma, T. 2010. Phenology, stopover dynamics and population size of migrating Black-tailed Godwits *Limosa limosa limosa* in Portuguese rice plantations. *Ardea* **98**: 35–42.

Ma, Z., Li, B., Zhao, B., Jing, K., Tang, S. & Chen, J. 2004. Are artificial wetlands good alternatives to natural wetlands for waterbirds? – a case study on Chongming Island, China. *Biodivers. Conserv.* **13**: 333–350.

Maeda, T. 2001. Patterns of bird abundance and habitat use in rice fields of the Kanto Plain, central Japan. *Ecol. Res.* **16**: 569–585.

Marques, P. & Vicente, L. 1999. Seasonal variation of waterbird prey abundance in the Sado estuary rice fields. *Ardeola* **46**: 231–234.

Masero, J.A., Santiago-Quesada, F., Sánchez-Guzmán, J.M., Villegas, A., Abad-Gómez, J.M., Lopes, R.J., Encarnaçao, V., Corbacho, C. & Morán, R. 2011. Long lengths of stay, large numbers, and trends of the Black-tailed Godwit *Limosa limosa* in rice fields during spring migration. *Bird Conserv. Int.* **21**: 12–24.

Ozesmi, S.L. & Bauer, M.E. 2002. Satellite remote sensing of wetlands. *Wetl. Ecol. Manage*. **10**: 381–402.

Rendón, M.A., Green, A.J., Aquilera, E. & Almaraz, P. 2008. Status, distribution and long-term changes in the waterbird community wintering in Doñana, South-West Spain. *Biol. Conserv.* **141**: 1371–1388.

Sánchez-Guzmán, J.M., Moran, R., Masero, J.A., Corbacho, C., Costillo, E., Villegas, A. & Santiago-Quesada, F. 2007. Identifying new buffer areas for conserving waterbirds in the Mediterranean basin: the importance of the rice fields in Extremadura, Spain. *Biodivers. Conserv.* **16**: 3333–3344.

Serra, P., More, G. & Pons, X. 2007. *Monitoring winter flooding of rice fields on the coastal wetland of Ebro delta with multitemporal remote sensing images*. IGARSS: 2007 IEEE International Geoscience and Remote Sensing Symposium, Vols. 1–12 Sensing and Understanding Our Planet: 2495–2498.

Spell, R., Lewis, A., Kempka, R. & Reid, F. 1995. Evaluation of winter flooding of ricelands in the Central Valley of California using satellite imagery. In Campbell, K.L. (ed.). *Versatility of Wetlands in the Agricultural Landscape*: 357–366. St. Joseph, MI: American Society of Agricultural Engineers.

Ter Braak, C.J.F. & Šmilauer, P. 2002 *CANOCO Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination (version 4.5)*. Ithaca, NY: Microcomputer Power.

Titus, K., Mosher, J.A. & Byron, K.W. 1984. Chance-corrected classification for use in discriminant analysis: ecological applications. *Am. Midl. Nat.* **111**: 1–7.

Toral, G.M. & Figuerola, J. 2010. Unraveling the importance of rice fields for waterbird populations in Europe. *Biodivers. Conserv.* **19**: 3459–3469.

Tourenq, C., Bennets, R.E., Kowalski, H., Vialet, E., Licchesi, J.-L., Kayser, Y. & Isenmann, P. 2001. Are rice-fields a good alternative to natural marshes for waterbird communities in the Camargue, Southern France? *Biol. Conserv.* **100**: 335–343.

Treitz, P. & Howarth, P. 2000. Integrating spectral, spatial and terrain variables for forest ecosystem classification. *Eng. Remote Sens.* **66**: 305–317.

Wade, S. & Hickey, R. 2008. Mapping migratory wading bird feeding habitats using satellite imagery and field data, Eighty-Mile Beach, Western Australia. *J. Coastal Res.* **24**: 759–770.

Xiao, X., Boles, S., Frolking, S., Salas, W., Moore, B.M. & Li, C. 2002. Observation of flooding and rice transplanting of paddy rice fields at the site to landscape scales in China using VEGETATION sensor data. *Int. J. Remote Sens.* **23**: 3009–3022.

Zuur, A.F., Ieno, E.N. & Smith, G.M. 2007. *Analysing Ecological Data*. New York: Springer.

Zuur, A.F., Ieno, E.N. & Elphick, C.S. 2010. A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* **1**: 3–14.

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