RESEARCH ARTICLE

Gravel Bars Can Be Critical for Biodiversity Conservation: A Case Study on Scaly-Sided Merganser in South China

Qing Zeng¹, Linlu Shi¹, Li Wen², Junzhu Chen¹, Hairui Duo¹, Guangchun Lei^{1*}

1 School of Nature Conservation, Beijing Forestry University, Beijing, 100083, China, **2** Water Wetlands and Coasts Science, NSW Office of Environment and Heritage, Sydney, NSW, 2001, Australia

* guangchun8099@gmail.com

OPEN ACCESS

Citation: Zeng Q, Shi L, Wen L, Chen J, Duo H, Lei G (2015) Gravel Bars Can Be Critical for Biodiversity Conservation: A Case Study on Scaly-Sided Merganser in South China. PLoS ONE 10(5): e0127387. doi:10.1371/journal.pone.0127387

Academic Editor: Cédric Sueur, Institut Pluridisciplinaire Hubert Curien, FRANCE

Received: December 8, 2014

Accepted: April 15, 2015

Published: May 21, 2015

Copyright: © 2015 Zeng et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are available via Figshare (<http://dx.doi.org/10.6084/m9.figshare.1386631>).

Funding: This work was supported by National Basic Research Program of China (973 Program) (No.2009CB421103 & No. 2012CB417005). GL received the funding. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

Abstract

Gravel bars are characteristic components of river landscapes and are increasingly recognized as key sites for many waterbirds, though detailed studies on the ecological function of gravel bars for waterbirds are rare. In this study, we surveyed the endangered Scaly-sided Merganser *Mergus squamatus* along a 40 km river section of Yuan River, in Central China, for three consecutive winters. We derived the landscape metrics of river gravel bars from geo-rectified fine resolution (0.6 m) aerial image data. We then built habitat suitability models (Generalized Linear Models—GLMs) to study the effects of landscape metrics and human disturbance on Scaly-sided Merganser presence probability. We found that 1) the Scaly-sided Merganser tended to congregate at river segments with more gravel patches; 2) the Scaly-sided Merganser preferred areas with larger and more contiguous gravel patches; and 3) the number of houses along the river bank (a proxy for anthropogenic disturbance) had significantly negative impacts on the occurrence of the Scaly-sided Merganser. Our results suggest that gravel bars are vital to the Scaly-sided Merganser as shelters from disturbance, as well as sites for feeding and roosting. Therefore, maintaining the exposure of gravel bars in regulated rivers during the low water period in winter might be the key for the conservation of the endangered species. These findings have important implications for understanding behavioral evolution and distribution of the species and for delineating between habitats of different quality for conservation and management.

Introduction

The river ecosystem plays a fundamental role in global ecosystem services, providing harvestable resources, regulating hydrological regimes and bringing spiritual well-being and recreational opportunities [1]. Rivers are also dispersal corridors and pivotal for biodiversity, therefore often cited as harboring higher abundance of biota [2] or species richness [3]. Composed of a mosaic of aquatic and terrestrial patches, rivers could provide heterogeneous and dynamic habitats for macroinvertebrates, fish and waterbirds. Gravel bars, with braided structure, high relative edge area and connectivity through the landscape, are a characteristic

component of river landscapes [4]. These bars are ephemerally inundated at higher flows and subject to wetting and drying processes with changing water levels, thereby alternately offering terrestrial, wet and aquatic habitats [5], and are increasingly, recognized as key sites for many waterbirds [6]. Although the ecological benefits of greater diversity in physical habitat are well known, the influence of spatial distribution of gravel bar mosaics has been less thoroughly studied [5], and the ecological function of gravel bars for waterbirds is not duly appreciated in academic and practitioner communities, ultimately jeopardizing river management and biodiversity conservation.

In this study, we consider the globally endangered Scaly-sided Merganser *Mergus squamatus*, an endemic species restricted to eastern Asia [7] as a case study. Scaly-sided Mergansers are cryptic in nature, and encountered throughout year mostly in small groups (e.g. less than 10 individuals). They breed in south-east Russia and northeast China, however, the location of majority of the wintering population is still unknown [8, 9]. Small numbers occur on rivers and fresh water bodies in southern and central China [10–12]. Threats at wintering sites includes dam construction, sand and gravel extraction, industrial and domestic pollution, electrical fishing and anthropogenic disturbance [8]. Scaly-sided Mergansers prefer fast-flowing clear water rivers with riffles, shoals or sand banks in mountainous areas with low levels of human disturbance [8]. Empirical observations [8, 13] are in agreement with such qualitative descriptions of habitat preference of the Scaly-sided Merganser. However, there are few studies quantifying the relationships between the occurrence of Scaly-sided Merganser and gravel bars in riverine landscape, thus bars are usually overlooked in river regulation, and targeted conservation of endangered species is hampered.

We observed the endangered duck persistently preferred some river sections over others within the same river reach in its known wintering distribution [14]. The study is therefore designed to investigate why Scaly-sided Mergansers choose particular habitats, and aims to test the hypotheses that more gravel bars support high occurrence probability of Scaly-sided Merganser, and that occurrence probability is also influenced by human disturbance.

Materials and Methods

This study was authorized by Department of Forestry of Hunan Province and Yuanshui National Wetland Park.

Study area

With a length of 1022 km and watershed area of $8.91 \times 10^4 \text{ km}^2$, the Yuan River is one of the largest tributaries of the Yangtze River in central China. It originates in Guizhou Plateau, flows through the Wuling Mountain region, and hence brings high water quality and abundant stream fishes. Our study was conducted in a 36 km river section ($28^\circ 44' - 28^\circ 52' \text{N}$, $111^\circ 12' - 111^\circ 30'$, Fig 1) in the lower Yuan River. The average water depth is about 6 m and channel width varies from 330 m to 670 m. There are five islands, superior in size and height with most part completely over water surface at high water season, and a range of gravel bars in this river section, with pebbles randomly piled up. Four towns and two villages are distributed along the river banks, which impose different disturbances, including fishing and traffic in river and on riverside roads. This river section supports a population of approximate 40 wintering Scaly-sided Mergansers [14]. The Yuanshui National Wetland Park was established in 2012 specifically for the conservation of this endangered Scaly-sided Merganser population.

Fig 1. The study area in Yuan River and its location within the Yangtze River Basin in China.

doi:10.1371/journal.pone.0127387.g001

Scaly-sided Merganser occurrence

Field data were collected in three winters (2010/2011, 2011/2012, 2012/2013) when Scaly-sided Mergansers arrived for wintering. Winter is the low water season, and the river is very stable in terms of water level fluctuation. Field survey were conducted every second week from November to February (when the bird population was relatively stable), resulting in a total of 24 surveys.

At each survey, we travelled along the 36 km long river course by boat, and used binoculars (8×42) to identify and locate Scaly-sided Merganser, and then mapped the Scaly-sided Mergansers using a GPS (Fig 2). Each survey lasted for four hours (09:00–13:00). During the survey, we kept our boat in the middle of the river to minimize disturbance to birds, and also to ensure that we had a full view of the river section. Distances of less than 10 m between individuals were defined as a flock (i.e. identified as a single occurrence point in mapping). To avoid repeat counting, only birds not flying, e.g. the ducks resting on land or foraging in water were counted. All field surveys were conducted on clear days, avoiding snowy, rainy, or strong windy days, to ensure the quality of the field survey data.

Fig 2. Distribution of Scaly-sided Merganser flocks and gravel bar patches in the 36 km river section of the lower Yuanjiang River. The red dots indicate 127 Scaly-sided Merganser flocks recorded over three winters. Green points represent houses along the river within a 50 m buffer zone. Areas in dark grey are gravel bars in river and area in light grey are islands.

doi:10.1371/journal.pone.0127387.g002

We mapped the presence points from the three winter surveys and summed all points within the 36 predefined 1 km river segments. We termed the ratio of this sum and total points (i.e. 127) as occurrence probability, which is the response variable in our model (Table 1).

Gravel patch data

We used the Bing Maps aerial image (2011–12) to derive the gravel patches within the surveyed river section. The images have a spatial resolution of 0.6 meter. We vectorized all the identifiable habitat patches through visual interpretation, and classified them into three types: water, islands, and gravel bars. Islands are much larger and higher, with human habitation or activity, and seldom used by waterfowl. We drew a central line of the river, and equally divided the studied river section into 36 segments by drawing 35 lines perpendicular to the central line (Fig 2). We converted the vector overlays to raster format with 1 m cell size, and used the three patched types for landscape analysis. Buildings along the river banks within the 50 meters buffer zone were depicted as points, and the total number of building within 1 km river segment

Table 1. Summary of selected candidate predictor variables and their relevance to Scaly-sided Merganser.

Acronym	Short Description	Median (range)	Relevance
BLD*	Number of buildings per km along the river	0.39 (0.02–1.09)	Human disturbance
NP^	Number of patches within 1 km river length	0.10 (0–0.88)	sites for foraging and roosting
AREA_AM	Area-weighted mean patch area	0.16 (0–4.07)	roosting area
NLSI	Normalized landscape shape Index	3.37 (0–6.98)	Shape of sites
SHAPE_AM	Area-weighted mean Shape Index	1.72 (0–2.89)	Shape of sites
FRAC_SD	Standard deviation of fractal dimension	0.04 (0–0.12)	Complexity of sites
PARA_AM#	Area-weighted mean perimeter area ratio	1.62 (0–6.49)	Complexity of sites
CONTIG_AM	Area-weighted mean Contiguity Index	0.94 (0–0.98)	Shape of sites

* divided by 100

^ divided by 10

#divided by 1000 to reduce the variability of the predictors for fitted coefficients comparison.

doi:10.1371/journal.pone.0127387.t001

was used as proxy for the degree of human disturbance (Fig 2). We used ArcGIS 10.4 (ESRI) to prepare all the maps in the study.

Landscape metrics

All these 36 datasets of the Yuan River were processed in Fragstats 3.3 [15, 16]. According to our aims, we chose patch level metrics to identify gravel bar patches. Many of the landscape metrics are highly correlated [17], especially for metrics in the same class. For the 58 landscape metrics derived from the aerial imagery for our study area, the Pearson's r ranges from -0.249 (weakly negatively correlated, *standard deviation in patch area* versus *area-weighted mean perimeter area ratio*) to 0.999 (highly identical, many pairs such as *Aggregation Index* vs *Clumpiness Index*). Therefore, pre-screening the variables to address the co-linearity in the following regression is necessary. Furthermore, to avoid over fitting, we limited the predictor variables to three due to the relatively small dataset (i.e. 36 samples). We used a two-step approach to select the candidate variables for model fitting:

1. We grouped the 58 metrics into seven clusters using hierarchical cluster analysis based on dissimilarities defined by the Euclidean distance [18];
2. For the clusters that have two or more members, we checked the Pearson product moment correlation coefficient (Pearson's r) for the paired variables in each cluster. Not surprisingly, they are highly or strongly correlated (i.e. $|r| \geq 0.70$). We selected one variable from each of multi-member clusters by fitting a simple regression model with the occurrence probability, and chose the variable in the model with the highest R^2 for further investigation (Table 2).

Table 2. Summary of GLMs (predictor variables restricted to three or less) supported by survey data.

Model term*	AICc	$\Delta AICc$	AICw	psedu R^2 ^
BLD, CONTIG_AM, and BLD: CONTIG_AM#	151.51	0.00	0.33	0.68
BLD, CONTIG_AM, and NP	151.76	0.25	0.29	0.68
CONTIG_AM, NLSI, and PARA_AM	152.35	0.84	0.21	0.67
CONTIG_AM, NP, and PARA_AM	152.79	1.28	0.17	0.67

* See Table 1 for definition of terms

interaction term

^ Maximum likelihood pseudo R^2

doi:10.1371/journal.pone.0127387.t002

The process reduced the candidate variables to seven: NP, NLSI, AREA_AM, PARA_AM, SHAPE_AM, FRAC_SD, and CONTIG_AM (see [Table 1](#) for explanation of the variables). In addition, we calculated the building density along the river banks (buildings per 100 m river length) and used it as a proxy for human disturbance intensity. A summary of the candidate variables was listed in [Table 1](#).

Habitat modeling

Generalized linear models (GLMs) are commonly used for modeling habitat suitability because of their strong statistical foundation and ability to realistically model ecological relationships [19]. To specify an appropriate link function in GLM, we fitted four probability distribution functions (PDF) of the dependent variable (i.e. occurrence probability), namely Poisson, negative binomial, zero-inflated Poisson and Gaussian, and used Akaike's information criterion (AIC) to select the best PDF. As negative binomial describes the distribution best, we used log link and negative binomial error distribution for our habitat model building.

We first developed a full GLM model that includes all eight selected predictor variables ([Table 1](#)) and the interactions between BLD and other landscape metrics using the "MASS" package [20] within the R Language and Environment for Statistical Computing, version 3.0.1 [21]. We included the interaction terms in the modelling to explore the "shielding" effect of gravel bars on the Scaly-sided Merganser from human disturbances. We then used the backward stepwise technique to select the best fitted GLM which resulted in six predictor variables. Due to the relative small sample size, it is necessary to restrict the number of terms to three to avoid over-fitting [20, 22]. We also diagnosed the models for multicollinearity by calculating the condition indexes [23] using the package "perturb" [24]. We used the automated model selection function "dredge" in the "MuMIn" package [25] to limit the maximum term to three and reported the model with lowest AIC_c (small sample corrected AIC) as the final model. We also assessed the relative likelihood of each candidate model by AIC weight (AIC_w). In order to evaluate the relative importance of the predictive variables for the occurrence of the Scaly-sided Merganser, we followed Burnham and Anderson [22] to sum the AIC_w over all models with ΔAIC_c less than 4. To address the uncertainty in the estimated coefficients of predictor variables caused by small sample size, we re-fitted the final model using the Markov Chain Monte Carlo (MCMC) approach implemented in the MCMC package [26]. We simulated a sample of 55,000 iterations from the posterior distribution using standard Gibbs sampling method, and calculated the 95% intervals of the coefficients after 50,000 burn-in and a thinning interval of 1000.

Results

During the whole 24 surveys (2011–2013), we counted 514 Scaly-sided Mergansers, belonging to 127 flocks in total ([Fig 2](#)). The number of individual in a flock varied from 1 to 20.

There are four feasible GLMs for the Scaly-sided distribution data based on model AIC_c ($\Delta AIC_c < 2$, [Table 2](#)). All these models had considerable prediction power: based on the pseudo- R^2 the models explained 67%–78% of the variations in the duck occurrence data ([Table 2](#)). In addition, the largest condition number was 4.35 for Model 3 in [Table 3](#), suggesting there is no multicollinearity problem [23]. Collectively, these models involved five variables: BLD, CONTIG_AM, PARA_AM, NLSI, NP, and the interaction between BLD and CONTIG_AM. Among these predictor variables, CONTIG_AM was the top variable with the highest importance to predict the occurrences of the Scaly-sided Merganser based on model AIC_w . PARA_AM and BLD were comparably important, and NLSI and NP were the two least

Table 3. Coefficients of the top three GLM and the credible interval based on Markov Chain Monte Carlo sampling.

Models		GLM			Bayesian Inference		
		Estimate	Std. Error	p value	Lower 2.5%	Medium	Upper 97.5%
Model 1	BLD	-5.35	1.99	**	-5.41	-1.75	2.11
	CONTIG_AM	1.09	1.19	NS	1.11	4.11	7.01
	BLD:CONTIG_AM	5.21	1.67	**	-5.83	-1.44	3.23
Model 2	BLD	-2.02	0.72	**	-5.95	-2.88	0.75
	CONTIG_AM	4.11	0.90	***	2.35	5.58	8.52
	PARA_AM	-0.57	0.19	**	-2.01	-1.08	-0.03
Model 3	CONTIG_AM	3.55	0.96	***	1.34	4.66	8.34
	NLSI	0.87	0.39	*	-0.94	0.42	1.72
	PARA_AM	-2.12	0.81	*	-3.05	-1.40	0.35
Model 4	CONTIG_AM	3.26	0.97	*	1.41	4.21	7.49
	NP	1.85	0.70	*	0.71	4.83	9.10
	PARA_AM	-0.50	0.22	*	-1.81	-0.88	0.04

Significant: $p > 0.1$, NS* $p < 0.1$ ** $p < 0.05$ *** $p < 0.01$

doi:10.1371/journal.pone.0127387.t003

important variables (Fig 3). Furthermore, the BLD/CONTIG_AM interaction term also had considerable importance (Fig 3).

Model-averaged Importance

Fig 3. The importance of predictor variables to Scaly-sided Merganser occurrence based on the sum of AIC_w over all models listed in Table 2.

doi:10.1371/journal.pone.0127387.g003

Fig 4. The density of estimated coefficients for A) Model 1, B) Model 2 C) Model 3, and D) Model 4 through 50,000 iterations of Gibbs sampling.

doi:10.1371/journal.pone.0127387.g004

The model with BLD, CONTIG_AM and their interaction term as predictor variables had the lowest AIC_c, and was ranked as the best model supported by data. However, the Δ AIC_c of four possible models were less than 2, we considered them were equally supported. Therefore, we performed Bayesian inference via MCMC for the four models and calculated the credible intervals of the coefficients (Table 3).

The occurrence of the Scaly-sided Merganser was significantly negatively affected by BLD, and this was consistent for both the GLM estimates (Table 3) and the Bayesian inferred posterior density distribution (Table 3 and Fig 4B). In addition, the GLM estimation of -2.02 was close the medium of -2.88 from MCMC posterior sampling for the model which included BLD as main factor only (i.e. model 2).

The occurrence of the Scaly-sided Merganser had significantly positive relationship with CONTIG_AM. The significantly positive relationship was consistent across all the plausible GLMs although their estimation varied (i.e. the coefficients are 1.09, 4.11, 3.55, and 3.26 for models 1, 2, 3 and 4 respectively, Table 3). The significant level of positive relationship between Scaly-sided Merganser presence and CONTIG_AM was verified by Bayesian inference (i.e. the 95% intervals were all positive and 0 was not included, Table 3 and Fig 4). The MCMC estimates were consistently higher across the models (Table 3).

Based on the fitted GLMs, PARA_AM negatively affects the occurrence of the Scaly-sided Merganser although the coefficient in model 2 and model 4 was considerably higher than in model 3. Furthermore, the Bayesian estimates were higher for models 2 and 4, but lower for

model 3. In addition, the 95% intervals included 0 for model 3 and 4 ([Table 3](#)) although the distribution density was heavily skewed to the left (negative) ([Fig 4](#)).

The posterior MCMC showed a strong positive relationship between NP and the occurrence of the Scaly-sided Merganser ([Fig 4D](#) and [Table 3](#)). The coefficient was 1.85 and 4.83 based on GLM and Bayesian estimation, respectively. For NLSI, although the GLM indicated a significantly positive effect, the Bayesian posterior inference was not conclusive ([Table 3](#)): the 95% internals were -0.94 and 1.72, and the distribution density was slightly skewed to the positive range ([Fig 4C](#)).

Discussion

Landscape metrics

Our results indicated that the occurrence of the Scaly-sided Merganser had significantly negative relationship with the perimeter-area ratio and positive with the contiguity index. Perimeter-area ratio reflects both the area and shape of a patch. Large patches tend to have more irregular shapes, thus landscapes with larger patches could represent higher values for area-weighting patch shape indexes [27]. This may lead them to be more related to patch size than to patch shape [28]. In agreement with our findings, Schlossberg and King [29] also concluded that small and irregularly-shaped and clearcut patches were less likely to provide quality habitat for shrubland species. Similarly, Helzer and Jelinski [30] found that the probability of occurrence for six common grassland avian species was significantly inversely correlated with perimeter-area ratio. Aligning with these findings, Embling et al. [31] proposed a methodology combining spatial modelling with perimeter-to-area ratio for selecting protected areas of harbor porpoises, as well as other animal species. The contiguity index is a metric that assesses the spatial connectedness of cells within a grid-cell patch to provide an index of patch boundary configuration and thus patch shape [15]. Therefore, patches that are large and contiguous have larger Contiguity Index values [15]. The positive relationship between the occurrence of the Scaly-sided Merganser and Contiguity Index suggested that the species preferred areas with larger and more contiguous gravel patches that may serve as shelters from disturbance, as well as sites for foraging and roosting.

Gravel bar's function

Larger gravel bars could improve the function of river section as possible roosting sites. The incessant, strongly turbulent flow requires strong rooting to resist, or significant expenditure of energy to withstand [32]. Scaly-sided Merganser uses gravel bars to roost and preen, which could minimize the necessary expenditure of energy to maintain position for other activities such as feeding and social interaction. These resting and maintenance behaviors could account for 39% and 24% of time budget in male and female during days [13].

The composition and configuration of the river landscape determines the fish assemblage diversity and abundance [33, 34]. As in-stream refugia for feeding and spawning, larger gravel bars also harbor a diversity of organisms, and increase the abundance and diversity of fish and macroinvertebrates, providing rich food sources for waterfowls. Many species (e.g. darter, salmon) favor riffles and runs with substrates of gravel and sand. For lithophilous species, the bar edges offers both shelter and proximity to spatially segregated food resources [35]. Indeed, compared with the nearby unvegetated sediment areas, the abundance of predatory fishes associated with cobble and boulder patches was significantly higher, and within cobble and boulder patches, abundances were significantly higher along the edge than in the interior [36]. Furthermore, proximity to cobble patch edges also influences crustacean distribution [37]. The Scaly-sided Mergansers have a wide range of diets, mainly stream fish, supplemented with benthic

invertebrates, aquatic larvae, frogs, etc [38, 39]. They search for prey with their eyes below the water surface or dive into the water column. Synchronous diving and drifting the fish assemblage to the bar is a strategy in group foraging of Scaly-sided Merganser. Although several studies indicated that mean food intake rate (MFIR) increased in groups [40], group hunting and foraging were generally assumed to be a strategy to decrease predation risk and led to increased food competition [41, 42]. Gravel bars are therefore especially important for such “group effects”.

In addition, large bars might promote visual isolation, which is thought to affect the territory size of visually oriented animals. Some scholars [43] suggested that visual isolation reduced intraspecific competition and increased breeding waterfowl pair density in Manitoba, Canada. Furthermore, large gravel bars interspersing with currents may not only reduce the inter- and intra-specific confrontations, but also minimize human disturbances both in stream and from river banks. Anthropogenic disturbance, represented as the number of houses along the river bank in our study, had significantly negative impacts on the occurrence of the Scaly-sided Merganser. This is in agreement with anecdotal records that most wintering sites for Scaly-sided Merganser were away from major centers of human habitation [8]. It is well documented that disturbance from human activities can be energetically costly due to decreased foraging efficiency and increased escape activities [44], which could cause not only temporary changes in behavior but also locally affect the temporal and spatial distribution of migratory and wintering waterfowl [45]. For example, fishing and boat traffic may increase alertness and even escape activities in pelicans and coots [46]. The “best” fitted model (Model 1 in Table 3) exhibited an interaction effect of human disturbance and gravel bars on the occurrences of Scaly-sided Merganser. The opposite effect of the BLD and the interaction (BLD: PARA_AM) clearly revealed the bar’s function as shelter or fence from outer disturbance. With the presence of human activities, birds on the protected side of the fence or barrier responded similarly to birds at the low visitation control site [47]. In the highly populated south and central China, rivers with low human activities are extremely rare. Scaly-sided mergansers could use large gravel bars to keep themselves safe behind the “cordon”, which acts a buffer before their flight initiation.

Conservation implications

One of the most serious threat associated with wintering Scaly-sided Merganser is dam construction [8]. Released clear water from dams scours downstream bars, reducing bar number and area [48, 49] and reducing the embeddedness of the river bottom substrate that benefit macroinvertebrate and fish production [50]. Maintaining the exposure of gravel bars in regulated rivers during winter is critical for this endangered species, and should be taken into consideration at the very beginning in municipal planning and dam construction. Moreover, the electricity hydropower plants could adjust the operational schedule, e.g. to run in the night or early morning, and keep low water level during day as long as possible. Equally important, within-channel alluvial gravel extraction is one of the important forms of anthropogenically induced morphological change in river channels [51], and is causing gravel-size sediment starvation [52], which leads to lowering of riverbed and decrease of gravel bars, therefore sand mining and gravel extraction should be restricted and regulated.

Conclusion

In the research, we found that 1) the Scaly-sided Merganser tended to congregate at river reaches with more gravel patches; 2) the Scaly-sided Merganser preferred areas with larger and more contiguous gravel patches; and 3) the number of houses along the river bank (a proxy for

anthropogenic disturbance) had significantly negative impacts on the occurrence of the Scaly-sided Merganser. Our results suggested that gravel bars are vital to the Scaly-sided Merganser as shelters from disturbance, as well as sites for feeding and roosting. Therefore, maintaining the exposure of gravel bars in regulated rivers during the low water period in winter might be the key for the conservation of the endangered species. The findings provide a quantitative association between wintering habitat of Scaly-sided Merganser and geomorphic features, as well as human disturbance, an association that previous research has documented in only qualitative terms, therefore have important implications for understanding behavioral evolution and distribution of the species and for delineating between habitats of different quality for conservation and management.

Acknowledgments

We appreciate the valuable comments by Neil Saintilan, and technical support from Zhang Han, Liu Yunzhu and Sun Gongqi. We thank three anonymous reviewers for insightful comments on the manuscript.

Author Contributions

Conceived and designed the experiments: QZ GL. Performed the experiments: QZ JC. Analyzed the data: QZ LW. Contributed reagents/materials/analysis tools: QZ LS HD LW. Wrote the paper: QZ LW GL.

References

1. MA. Millennium Assessment Reports 2005 [cited 2010 20 April]. Available: <http://www.maweb.org/en/index.aspx>.
2. Naiman RJ, Bilby RE, Bisson PA. Riparian ecology and management in the Pacific coastal rain forest. *BioScience*. 2000; 50(11):996–1011.
3. Sabo JL, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, et al. Riparian zones increase regional species richness by harboring different, not more, species. *Ecology* 2005; 86(1):56–62.
4. Gilvear D, Francis R, Willby N, Gurnell A. Gravel bars: a key habitat of gravel-bed rivers for vegetation. *Developments in Earth Surface Processes*. 2007; 11:677–700.
5. Garcia X-F, Schnauder I, Pusch M. Complex hydromorphology of meanders can support benthic invertebrate diversity in rivers. *Hydrobiologia*. 2012; 685(1):49–68.
6. Li Z, Wang Z, Pan B, Zhu H, Li W. The development mechanism of gravel bars in rivers. *Quaternary International*. 2014; 336:73–9.
7. BirdLife International (2012) *Mergus squamatus*. [updated 2013.1; cited 2014 12 September]. Available from: www.iucnredlist.org.
8. Barter M, Zhuang X, Wang X, Cao L, Lei J, Solovyeva D, et al. Abundance and distribution of wintering Scaly-sided Mergansers *Mergus squamatus* in China: where are the missing birds? *Bird Conservation International*. 2014; 24(04):406–15. doi: [10.1017/S0959270913000622](https://doi.org/10.1017/S0959270913000622)
9. Solovyeva DV, Liu P, Antonov AI, Averin AA, Pronkevich VV, Shokhrin VP, et al. The population size and breeding range of the Scaly-sided Merganser *Mergus squamatus*. *Bird Conservation International*. 2014; 24(04):393–405.
10. BirdLife International. *Threatened birds of Asia: the BirdLife International Red Data Book*. U.K.: Cambridge; 2001.
11. He F, Melville D, Gui X, Hong Y, Liu Z. Status of the Scaly-Sided Merganser Wintering in Mainland China in the 1990s. *Waterbirds*. 2002; 25(4):462–64.
12. Fenqi H, Jiansheng L, Bin Y, Hangdong J, Haohui Z. Current Distribution and Status of the Wintering Scaly-sided Merganser *Mergus squamatus* in China. *Chinese Journal of Zoology*. 2006; 41:52–6.
13. Shao M, Zeng B, Tim H, Chen L, You C, Wang H, et al. Winter Ecology and Conservation Threats of Scaly-sided Merganser *Mergus squamatus* in Poyang Lake Watershed, China. *Pakistan Journal of Zoology*. 2012; 44:503–10.

14. Zeng Q, Zhang Y, Sun G, Duo H, Wen L, Lei G. Using Species Distribution Model to Estimate the Wintering Population Size of the Endangered Scaly-Sided Merganser in China. PLoS ONE 2015; 10(2): e0117307. doi: [10.1371/journal.pone.0117307](https://doi.org/10.1371/journal.pone.0117307) PMID: [25646969](https://pubmed.ncbi.nlm.nih.gov/25646969/)
15. McGarigal K, Cushman S, Neel M, Ene E. FRAGSTATS: spatial pattern analysis program for categorical maps 2002 [cited 2012 20 April]. Available: <http://www.umass.edu/landeco/research/fragstats/fragstats.html>.
16. McGarigal K, Marks BJ. Spatial pattern analysis program for quantifying landscape structure 1995 [cited 2010 20 April]. Available: <http://www.umass.edu/landeco/pubs/mcgarigal.marks.1995.pdf>.
17. Riitters KH, O'Neill R, Hunsaker C, Wickham JD, Yankee D, Timmins S, et al. A factor analysis of landscape pattern and structure metrics. Landscape ecology. 1995; 10(1):23–39.
18. Legendre P, Legendre LF. Numerical ecology, 3rd English ed. Amsterdam: Elsevier; 2012.
19. Austin M. Spatial prediction of species distribution: an interface between ecological theory and statistical modelling. Ecological modelling. 2002; 157(2):101–18.
20. Venables WN, Ripley BD. Modern applied statistics with S. Berlin: Springer Science & Business Media; 2002.
21. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, 2012. ISBN 3-900051-07-0; 2012.
22. Burnham KP, Anderson DR. Model selection and multimodel inference: a practical information-theoretic approach. Berlin: Springer Science & Business Media; 2002.
23. Belsley DA, Kuh E, Welsch RE. Regression diagnostics: Identifying influential data and sources of collinearity. Hoboken: John Wiley & Sons; 2005.
24. Hendrickx J. perturb: Tools for evaluating collinearity, R package version 2.03; 2008.
25. Barton K. (2012) MuMIn: multi-model inference. R package version 1.7.2. 2012 [cited 2014 25 October]. Available: <http://r-forge.r-project.org/projects/mumin/>.
26. Martin AD, Quinn KM, Park JH. Mcmcpack: Markov chain monte carlo in r. Journal of Statistical Software. 2011; 42(9):1–21.
27. Saura S. Effects of minimum mapping unit on land cover data spatial configuration and composition. International Journal of Remote Sensing 2002; 23(22):4853–80.
28. Torras O, Gil-Tena A, Saura S. How does forest landscape structure explain tree species richness in a Mediterranean context? Biodiversity and Conservation. 2008; 17:1227–40.
29. Schlossberg S, King DI. Are shrubland birds edge specialists. Ecological Applications. 2008; 18(6):1325–30. PMID: [18767611](https://pubmed.ncbi.nlm.nih.gov/18767611/)
30. Helzer CJ, Jelinski DE. The relative importance of patch area and perimeter-area ratio to grassland breeding birds. Ecological applications. 1999; 9(4):1448–58.
31. Embling CB, Gillibrand PA, Gordon J, Shrimpton J, Stevick PT, Hammond PS. () Using habitat models to identify suitable sites for marine protected areas for harbour porpoises (*Phocoena phocoena*). Biological Conservation. 2010; 143(2):267–79.
32. Church M. 1 Multiple scales in rivers. Developments in Earth Surface Processes. 2007; 11:3–28.
33. Tockner K, Stanford JA. Riverine flood plains: present state and future trends. Environmental conservation. 2002; 29(3):308–30.
34. Ward J. Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. Biological Conservation. 1998; 83(3):269–78.
35. Ries L, Fletcher Jr RJ, Battin J, Sisk TD. Ecological responses to habitat edges: mechanisms, models, and variability explained. Annual Review of Ecology, Evolution, and Systematics. 2004:491–522.
36. Robbins SH. The Biology and Behavior of Black Sea Bass, *Centropristis Striata*, on Rhode Island Artificial Reefs. M.Sc. Thesis, University of Rhode Island; 2004.
37. Selgrath JC, Hovel KA, Wahle RA. Effects of habitat edges on American lobster abundance and survival. Journal of Experimental Marine Biology and Ecology. 2007; 353(2):253–64.
38. Solovyeva D. Foraging behaviour and daily time budget of Scaly-sided Merganser *Mergus squamatus* breeding on Iman River, Russia. Wildfowl. 2002; 53:205–14.
39. Zhengjie Z, Zhengjie P. The foraging behaviour of the Scaly-sided Merganser *Mergus squamatus* in the Changbai Mountains and Xiao Xingangling Mountains of China. Forktail. 1998; 14:76–7.
40. Beauchamp G. The effect of group size on mean food intake rate in birds. Biological Reviews 1998; 73(4):449–72.
41. Elgar MA. Predator vigilance and group size in mammals and birds: a critical review of the empirical evidence. Biological Reviews. 1989; 64(1):13–33. PMID: [2655726](https://pubmed.ncbi.nlm.nih.gov/2655726/)

42. Caraco T. Time budgeting and group size: a theory. *Ecology*. 1979;611–617.
43. Murkin HR, Kaminski RM, Titman RD. Responses by dabbling ducks and aquatic invertebrates to an experimentally manipulated cattail marsh. *Canadian Journal of Zoology*. 1982; 60(10):2324–32.
44. Hunt Jr GL. Influence of food distribution and human disturbance on the reproductive success of Herring Gulls. *Ecology*. 1972:1051–61.
45. Madsen J. Impacts of disturbance on migratory waterfowl. *Ibis*. 1995; 137:S67–S74.
46. Schummer ML, Eddleman WR. Effects of disturbance on activity and energy budgets of migrating waterbirds in south-central Oklahoma. *The Journal of wildlife management*. 2003:789–95.
47. Ikuta LA, Blumstein DT. Do fences protect birds from human disturbance? *Biological Conservation*. 2003; 112:447–52.
48. Tracy-Smith EK. Relation of Missouri River Flows to Sandbar Morphology with Implications for Selected Biota. Doctoral Dissertation, University of Missouri—Columbia; 2006.
49. Sanford JP. Dam Regulation Effects on Sand Bar Migration on the Missouri River: Southeastern South Dakota. Doctoral Dissertation, University of Montana; 2007.
50. Osmundson D, Ryel RJ, Lamarra V, Pitlick J. Flow-sediment-biota relations: implications for river regulation effects on native fish abundance. *Ecological Applications*. 2002; 12:1719–39.
51. Wishart D, Warburton J, Bracken L. Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. *Geomorphology*. 2008; 94:131–52.
52. Nakamura F, Kawaguchi Y, Nakano D, Yamada H. Ecological responses to anthropogenic alterations of gravel-bed rivers in Japan, from floodplain river segments to the microhabitat scale: a review. Gravel-bed rivers VI: from process understanding to river restoration. Edited by Habersack H, Piégay H, and Rinaldi M Elsevier, Oxford, UK. 2008:501–23.