Bird Conservation International (2021) 31:438–449. © The Author(s), 2021. Published by Cambridge University Press on behalf of BirdLife International.
doi:10.1017/S0959270921000137

Modelling suitable breeding habitat and GAP analysis for the endangered Scaly-sided Merganser *Mergus squamatus*: implications for conservation

WENYU XU[1], DIANA SOLOVYEVA[2], SERGEY VARTANYAN[3], HAIFENG ZHENG[4], VLADIMIR PRONKEVICH[5], YE GONG[1,6*] and HAITAO WANG[1,6*]

[1]*School of Life Sciences, Jilin Engineering Laboratory for Avian Ecology and Conservation Genetics, Northeast Normal University, Changchun 130024, China.*
[2]*Institute of Biological Problems of the North FEB RAS, 685000, Portovaya Str., 18, Magadan, Russia.*
[3]*North-East Interdisciplinary Scientific Research Institute FEB RAS, 685000, Portovaya Str., 16, Magadan, Russia.*
[4]*Northeast Institute of Geography and Agroecology, 130102, China.*
[5]*Institute of Water and Ecological Problems FEB RAS, Khabarovsk, Russia.*
[6]*Jilin Key Laboratory of Animal Resource Conservation and Utilization, Northeast Normal University, Changchun 130024, China.*

**Authors for correspondence; e-mail: gongy798@nenu.edu.cn; wanght402@nenu.edu.cn*

(Received 18 December 2019; revision accepted 08 March 2021)

Summary

The Scaly-sided Merganser *Mergus squamatus* is a globally 'Endangered' species breeding in north-east Asia. Limited by information on the geographic distribution of suitable habitat, the conservation management programme has not been comprehensive or spatially explicit for the breeding population. This study combines potentially important environmental variables with extensive data on species occurrence to create the first species distribution model for the breeding Scaly-sided Merganser, followed by a GAP analysis to highlight the unprotected areas containing suitable habitat. The predictive map showing the most suitable breeding habitat for the Scaly-sided Merganser covered broad-leaved deciduous forest distributed in six provincial regions in south-east Russia, north-east China, and North Korea. The conservation GAP, i.e. 90% (38,813 km^2) of highly suitable habitat, is mainly concentrated in the Sikhote-Alin and Changbai mountain ranges. This study suggests that prioritizing conservation of unprotected broad-leaved deciduous riverine forests within the above two mountainous regions should be included in international conservation planning, and the remaining suitable patches need to be preserved to allow range expansion in future. This predictive map improves the expert global assessment of breeding Scaly-sided Merganser distribution and provides a basic reference for establishing conservation areas or implementing conservation actions for the breeding Scaly-sided Merganser in north-east Asia.

Key words: *Mergus squamatus*, breeding habitat suitability, habitat distribution, GAP analysis

Introduction

The Scaly-sided Merganser is among the most threatened species of Mergini and has been classified as 'Endangered' on the IUCN Red List of Threatened Species since 2002 (BirdLife International 2017). It was listed as a national first-class animal under protection in China, a protected species in the Democratic People's Republic of Korea (DPRK) and the Republic of Korea (RK) and listed as threatened in Russia (BirdLife International 2001). The small population less than 2000 pairs is likely to be stable after rapid declines in the 1940s–1980s (Solovyeva *et al.* 2014, BirdLife International 2017).

As one of the two specialist mergansers of riverine landscapes, its occurrence may be affected by adiabatic effects and geomorphological complexity as found in other river birds (Buckton and Ormerod 2002). The species prefers to breed on undisturbed rivers in mountains and foothills, with clean rapid waters, gravel or rocky substrates, shingle islands, deep stretches, and shoals (Zhao and Piao 1998, BirdLife International 2001). The females often nest in holes of old-growth trees among riverine primary forests that provide potential nest cavities in abundance (BirdLife International 2001, 2017). The breeding population is confined to the temperate conifer-broadleaf forest zone in south-east Russia, north-east China, and North Korea (Solovyeva *et al.* 2014). However, it is absent from many of its previously known habitats, such as those of the Wusili River basin and the Great Khingan Ridge, both in China (Solovyeva *et al.* 2014).

Due to the economic value of timber and farmland reclamation, many riverine primary forests in the breeding habitats of Russia, China and North Korea have been greatly altered during recent decades (Liu *et al.* 2010, Wu 2007, BirdLife International 2017). Currently, large-scale deforestation in river valleys is forbidden in Russia and China (BirdLife International 2001). The Forest Law has been strengthened since 1999 to improve forest conservation in DPRK (Liu *et al.* 2010). However, some other threats in breeding and wintering grounds, such as hydroelectric dam construction (leading to significant changes to river flow and form and thus affecting the suitability of rivers as feeding areas), dredging (causing a change in river morphology, an increase in turbidity downstream of the activity, and disturbance), pollution (affecting prey availability both directly and indirectly as well as having a direct impact on breeding success), and human disturbance are suspected to continue to contribute to the 'Endangered' status of the Scaly-sided Merganser (Shao *et al.* 2012, BirdLife International 2017, Solovyeva et al. 2017, Zeng *et al.* 2018.

The Scaly-sided Merganser's 'Endangered' status, and the potentially increased extinction risk associated with human developments has been demonstrated for other threatened taxa (An *et al.* 2018, Li *et al.* 2019, Khaliq *et al.* 2019). This reflects the necessity for a conservation management programme for this species which to date has not been comprehensive or spatially detailed. Effective and efficient conservation of the breeding Scaly-sided Merganser requires the ability to make decisions over a large range. Though range maps have been delineated for many species, including the Scaly-sided Merganser (Solovyeva *et al.* 2014), the gaps in survey effort have imposed limits on conservation and spatial planning (Merow *et al.* 2016).

Combining environmental and/or geographic variables with observations of species occurrence, species distribution modelling (SDM) can predict spatial distributions across landscapes over large spatial extents, including inaccessible areas in remote or transboundary zones, and provide strong ecological insights (Phillips et al. 2006, Elith and Leathwick 2009. To zoom in on the elements that need further protection, GAP analysis can be used to determine the extent to which biodiversity elements are represented in existing protected areas (PAs; Pressey *et al.* 1993). Here, to our knowledge, we created the first SDM for the breeding Scaly-sided Merganser worldwide and carried out a GAP analysis by comparing the results with the pattern of the existing PA network to highlight unprotected or insufficiently protected suitable habitats and put forward suggestions for priority setting in international conservation planning.

Methods

Data preparation

We compiled 112 Scaly-sided Merganser point of occurrence records from our extensive surveys (combining boat and foot surveys to identify the breeders) which were carried out in south-east Russia and north-east China between 2000 and 2020 (Solovyeva *et al.* 2014, Gong *et al.* unpubl. data), and from a literature review, other publicly accessible databases (including websites of local government and news), and personal communication with experts and birdwatchers (Figure 1; Table S1 in the online supplementary material). To minimize spatial autocorrelation, duplicate presence locations falling within the same cell of a 1-km resolution raster were removed before the SDM analysis. A subset of original presence data was arranged in an appropriate manner for inputting into the SDM.

Environmental variables

Variables used in SDMs should be ecologically relevant to ensure models can offer ecological insight (Elith *et al.* 2011). In consideration of the ecological requirements of Scaly-sided Merganser, we collected 26 biotic and abiotic variables, including 19 climatic variables (annual and seasonal temperature/precipitation, etc. from http://www.world clim.org/; Table S2), land cover (including 20 land types, such as broadleaf/coniferous/mixed forest, etc.; http://www.geodata.cn), human influence indicator (as proxies of human settlement, land transformation, accessibility and electrical power infrastructure with values ranging from 0 to 64 which corresponds to no, or maximum,

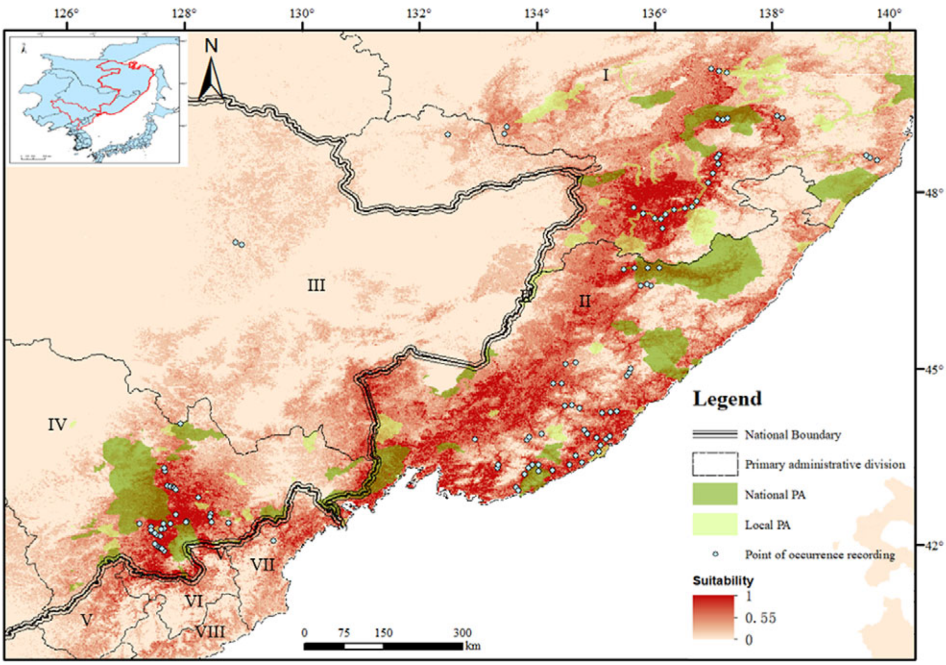

Figure 1. Potential distribution areas and conservation gaps for the breeding Scaly-sided merganser in Northeast Asia. The provincial regions were marked by Roman numbers (I = Khabarovsky Krai; II = Primorsky krai; III = Heilongjiang Province; IV = Jilin Province; V = North Pyongan; VI = Ryanggang; VII = North Hamgyeong; VIII = South Hamgyong).

https://doi.org/10.1017/S0959270921000137 Published online by Cambridge University Press

human influence; http://sedac.ciesin.columbia.edu/data/collection/wildareas-v2/sets/browse), three terrain factors (elevation, aspect and slope; DEM, http://www.gscloud.cn), canopy height (generated from the satellite images of the whole globe from MODIS sensor of Terra; https://globalmaps.github.io/) and river density (http://hydrosheds.cr.usgs.gov). The reason why these variables were chosen, and the original resolution, are shown in Table 1. Although the important spatial scale(s) of the habitat selection remain unexplored, habitat characteristics within a 1 km-section were found to affect the occurrence of Scaly-sided Merganser (Zeng *et al.* 2015a, 2015b) and of closely related species (Gregory *et al.* 2010, Kajtoch *et al.* 2014). Therefore, the scale of 1 km was applied to match the pixel size of environmental variables with the spatial resolution of the species records in this study (Feng *et al.* 2019).

To avoid biasing results, we screened variables for collinearity using the Variance Inflation Factor (VIF) in R with package "raster" and "usdm" (Naimi *et al.* 2014). The remaining variables (13 predictors with vif < 10; Elith *et al.* 2002, Worthington *et al.* 2016; Table 1) were converted to 1-km resolution layers for further analysis. The spatial processes were performed using Spatial Analyst tools and Raster Processing in ArcGIS10.2.

Table 1. Biotic and abiotic predictors in the SDM.

Variable	Original resolution	Biological hypothesis
Isothermality	1 km	The bioclimatic variables provided by Worldclim have been proved to play a key role in the distribution of wildlife and have been widely used in species distribution models. The climate variables may also affect the occurrence of the SSME, as temperature and water level (affected by precipitation) in rivers of the habitats were suggested to influence the breeding (e.g. hatching success; Zhao *et al.* 1995) and foraging (Solovyeva 2002).
Temperature Seasonality	1 km	
Mean Temperature of Wettest Quarter	1 km	
Precipitation of Wettest Month	1 km	
Precipitation Seasonality	1 km	
Precipitation of Coldest Quarter	1 km	
Elevation	30 m	The SSME was reported to breed in mountainous areas and the middle reaches of rivers (BirdLife International 2017), where the featured terrain characteristics may be related to potential food availability (Snyder *et al.* 2003) and predation risk (Heath *et al.* 2006), thus has a potential to affect the occurrence of this species.
Aspect	30 m	
Slope	30 m	
Human influence indicator	1 km	Human activities generally have a negative impact on wildlife (Zhang *et al.* 2019). Consistent with this, deforestation, hydro-electric dam construction, pollution, river excavation, and human disturbance were considered to be factors contributing to the range contraction of the SSME (BirdLife International 2017).
River Density	1 km	As a river specialist, river density may contribute to the occurrence of the SSME, such as that found in the distribution analysis of the overwintering population (Zeng *et al.* 2015a).
Land use classification	1 km	SSME is mainly distributed in the temperate conifer-broadleaf forest zone and is largely confined to forest with abundant potential nest cavities (BirdLife International 2017). Land use type (mainly forest area) may affect the habitat selection of this species.
Canopy Height	50 om	SSME is distributed along clear flowing rivers with tall riverine forest (BirdLife International 2001). In addition, height of trees was found to affect nest selection (Yi *et al.* 2008; Mi 2012).

Species distribution model

The distribution of breeding Scaly-sided Merganser was predicted using MaxEnt version 3.3.3k (Philips *et al*. 2006). The base models were run using the default settings within MaxEnt and model fit was assessed based on the Area Under the Curve (AUC) statistic after 10-fold cross validation (Worthington *et al*. 2016). A value of AUC close to one indicated good model fit (Elith *et al*. 2011). A jackknife analysis was applied to estimate consistency in variable importance for model building. During this process, a series of models were generated to screen the most informative model by in turn excluding each variable and modelling with the remaining variables. Then, a model was also created for each variable to assess which one had the most information that was not present in the others, i.e. the most uncorrelated variable. The relative importance of each environmental variable to the SDM was estimated using the percentage contribution and permutation importance averaged over 10 replicates. Response curves were used to investigate how the predictors effected the SDM prediction.

Gap analysis

To examine the extent of the currently protected breeding habitat and to show gaps in the existing network, we produced a GAP analysis of the suitable habitat contained within each PA and the total percentage of the species' habitat in all PAs by overlaying the international PA-network dataset on top of the SDM in ArcGIS 10.2. To further understand the extent to which the habitats were protected by the existing network, the classification (local vs. national PA; https://panda.maps.arcgis.com) and how much suitable habitat contained by each PA within the target area was determined worldwide and in provincial administrative regions across countries. To calculate the size of highly suitable habitats, the areas of each grid (1 km^2) representing the most suitable habitats with occurrence probability 0.55 (Zeng *et al*. 2015a) in the SDM analysis were summed in ArcGIS 10.2 with Spatial Analyst tools.

Results

The species distribution model

The total area of highly suitable habitat estimated by the model for the Scaly-sided Merganser was 43,125 km^2, located in south-east Russia (31,801 km^2, 74% of the global total, mainly in the Sikhote-Alin Range), north-east China (9,772 km^2, 23%, concentrated in the Changbai Range) and north-east DPR Korea (1,552 km^2, 3%, in the Paektu Massif; Figure 1).

The SDM predicted potential suitable habitat for the Scaly-sided Merganser with high success rates (AUC training = 0.988, AUC test = 0.983; Figure S1). The contribution of environmental predictors was variable, ranging from 0.2 to 32.3%. The percentage contribution of each predictor is shown in Table 2, and the results of the jackknife test of variable importance are shown in Figure S2. Land cover was the most important variable in the occurrence of breeding Scaly-sided Merganser, with a model contribution of 32.3%. Temperature seasonality, precipitation of wettest month and coldest quarter, and human influence were of lesser importance. Terrain factors (aspect, slope, and elevation), canopy height, and isothermality contributed the least to the model. The response curve of the highest influential variable, land cover, is presented in Figure 2. The four variables with lesser importance are shown in Figure S3. It was evident that the non-linear relationships between the occurrence probability of the breeding Scaly-sided Merganser and the environmental variables were strong. The most suitable breeding habitat was broad-leaved deciduous forest, distributed in six provincial areas (Primorsky Krai, Khabarovsky Krai, Jilin province, North Hamgyong, Ryanggang and South Ryanggang).

Table 2. Percentage contribution of each predictor in the SDM of the breeding Scaly-sided Merganser

Variable	Percentage Contribution
Land Cover	32.3
Temperature Seasonality	13.5
Precipitation of Wettest Month	10.5
Human Influence Indicator	10
Precipitation of Coldest Quarter	9.5
Precipitation Seasonality	6.4
Mean Temperature of Wettest Quarter	6
River Density	3.1
Elevation	2.8
Slope	2.6
Canopy Height	1.9
Aspect	0.6
Isothermality	0.2

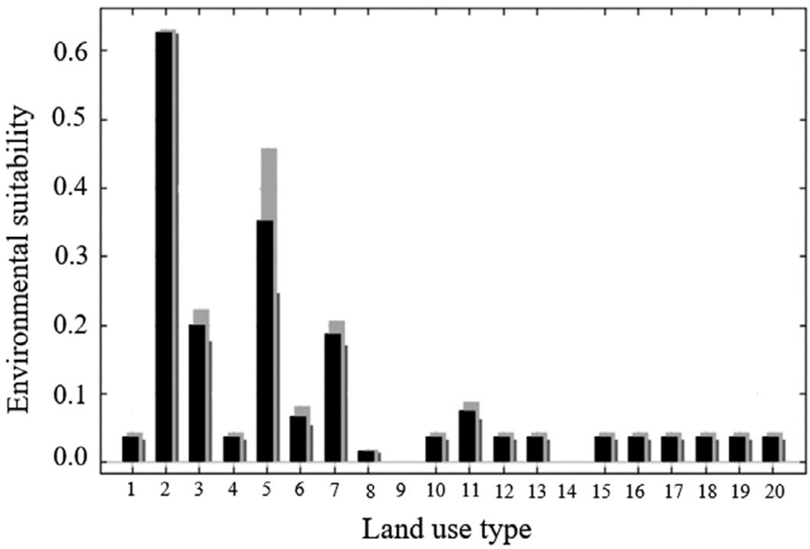

Figure 2. Response of Scaly-sided Merganser to land use type (demonstrating the mean response of 10 replicate MaxEnt runs and +/- one standard deviation). 1 = Broadleaf Evergreen Forest; 2 = Broadleaf Deciduous Forest; 3 = Needleleaf Evergreen Forest; 4 = Needleleaf Deciduous Forest; 5 = Mixed Forest; 6 = Tree Open; 7 = Shrub; 8 = Herbaceous; 9 = Herbaceous with Sparse Tree/Shrub; 10 = Sparse vegetation; 11 = Cropland; 12 = Paddyfield; 13 = Cropland/Other Vegetation Mosaic; 14 = Mangrove; 15 = Wetland; 16 = Bare area, consolidated (gravel, rock); 17 = Bare area, unconsolidated (sand); 18 = Urban; 19 = Snow/Ice; 20 = Water bodies.

Gap analysis

There are 28 protected areas containing highly suitable habitats (Table S3), 19 in Russia (nine local and 10 national PAs) and nine in China (five local and four national). No PA was found in the DPRK. The gap analysis revealed that 18% (7,755 km^2) of the global highly suitable breeding habitats lay within the existing PAs, leaving 82% (34,569 km^2) unprotected. The gaps were distributed among six provincial administrative regions in East Asia, the largest in Russia (17,908 km^2 in Primorsky

https://doi.org/10.1017/S0959270921000137 Published online by Cambridge University Press

Krai; 8,116 km² in Khabarovsky Krai), less in China (7,794 km² in Jilin province), and smallest in DPR Korea (750 km² in North Hamgyong; 684 km² in Ryanggang; 80 km² in North Pyongan; 38 km² in South Ryanggang; Figure 1). The last reflected the small area of highly suitable habitats in this range state.

Discussion

Potential highly suitable habitat

Our dataset, based on 112 occurrence records for native populations, updates the distribution maps of breeding Scaly-sided Merganser and improves the IUCN assessment (Figure S4). The predictive map shared a 56.38% overlap with the range delineated from surveys and added some potential new distribution areas in part of Jilin province (some areas around Dunhua-city and Baishan-city) which were confirmed with evidence of occurrence of the Scaly-sided Merganser in the field survey in 2018–2020; Gong *et al.* unpubl. data). However, the suitability was intermediate in the northern part of the eastern slope of Sikhote-Alin Range (predicted by experts as the area most densely populated by the Scaly-sided Merganser; Solovyeva *et al.* 2014). As this site is highly localized, it only results in few occurrence points, which may lead to underestimation of highly suitable areas (Kramer-Schadt *et al.* 2013). Despite this limitation, the SDM could be used as a reference point for conservation planning.

Environmental predictors

Response curves represent the quantitative relationship between environmental predictors and the logistic probability of occurrence, and they help to understand the ecological niche of the species (Yi *et al.* 2016). Forest-cover (broad-leaved deciduous forest in particular) exerted the strongest influence on the probability of presence; the variable was different from the SDM predicting potential habitat in winter, mainly influenced by the minimum temperature of the coldest month and the mean temperature of the coldest quarter (Zeng *et al.* 2015a). The Scaly-sided Merganser is not capable of excavating its own nesting cavities and relies on those already created in trees (Sánchez *et al.* 2007). This explains the preference for broad-leaved deciduous forest, due to the higher of cavities than in coniferous forest (Newton 1998, van Balen *et al.* 1982). Canopy height contributed little to the landscape-scale model, though the suitable canopy height (15–20m) is similar to that recorded in field investigations (Yi *et al.* 2008). As old-growth broad-leaved trees, especially those preferred by the Scaly-sided Merganser, often had a broken top, canopy height may not always be a reliable indicator of potential nest site. Alternatively, canopy height may be a preferred element at a smaller scale, which could potentially be affected by a trade-off between concealment and view of the surroundings (Gotmark *et al.* 1995).

Temperature seasonality, precipitation of wettest month and coldest quarter, and human disturbance made a lesser contribution. Temperature seasonality is a measure of temperature change over the course of the year (Ma and Sun 2018), reflecting the difference between maximum and minimum temperatures. Temperatures well below freezing were observed during the early breeding season (late March to early April) but were unlikely to affect waterfowl or their eggs, as egg-laying begins in the second half of April and most clutches are laid by early May (BirdLife International 2001). Summer heat can be compensated for by using the cold water of fast-flowing rivers and by resting in the shade of trees. Breeding range of the Scaly-sided Merganser significantly overlaps the northern range limits of Korean pine *Pinus koraiensis*, Amur linden *Tilia amurensis*, Mongolian oak *Quercus mongolica*, Manchurian fir *Abies holophylla*, Manchurian ash *Fraxinus mandshurica* and other representatives of Manchurian fauna such as Amur tiger *Panthera tigris altaica* and yellow-throated marten *Martes flavigula*, indicating the overall influence of climate (Krestov 2003, Miquelle and Pikunov 2003, Chutipong *et al.* 2016).

Rainfall is the predominant and ultimate source of the land surface water budget (Fekete *et al.* 2004). The high-altitude mountain rivers are mainly derived from atmospheric water replenishment and mountain snowmelt (Woo *et al.* 2019). Precipitation of the wettest month and coldest quarter may be among the most important climate variables in maintaining water levels, which could be essential for effective foraging of fish-hunting duck and providing refuge against predators (Cerón and Ferreiro 2017) and could additionally support growth of the forest with potential nest sites (Lu *et al.* 2016). However, the nesting and incubation success of the Scaly-sided Merganser may be less influenced by the variation in water level than other ground-nesting waterbirds (e.g. Hake *et al.* 2005, Carneiro *et al.* 2016). Human disturbance is often negatively related to species occurrence (Zhang *et al.* 2019), and the Scaly-sided Merganser is not an exception. In proximity to human developments, it could be at risk of threats such as deforestation, reclamation, and hydro-electric dam construction (Li *et al.* 2019, Khaliq *et al.* 2019), which could result in changing more habitats from suitable to unsuitable.

Highly suitable habitats, proposed by the SDM for south-west Primorsky Krai (such as Anuchinsky, Yakovlevskiy and Shkotovsky Districts), are actually areas destroyed by intensive agriculture and industry, which lack old-grown trees and fish resources in the rivers, supporting a single pair of the Scaly-sided Merganser according to our field surveys (Solovyeva *et al.* unpubl. data), though these districts support human densities of only 100–500 people/km^2. Similar to the ecological parameters, human populations often differ among geographic scales and populated areas in Russia are not comparable to those in China (Johnson 1979). However, many Scaly-sided Mergansers live close to human developments (roads and/or residential houses) in the Changbai Mountains of Jilin province, China. Those birds may colonize suboptimal habitats because of low availability of highly suitable habitats or be lured to less suitable patches as cues used by individuals to assess site quality not affected by human influence (Doligez and Boulinier 2009). Therefore, potentially suitable habitats close to or overlapping with human influence (Figure S5), should be given a priority in protection and restoration planning.

Conservation GAP

As a cornerstone of conservation, designation of PAs plays an important role in safeguarding species and ecosystems globally (Watson *et al.* 2014). The GAP analysis showed that about 1/6 of the highly suitable breeding habitats were covered by PAs. However, it is also important to prevent downgrading, downsizing, and degazettement of protected areas (PADDD; Mascia and Pailler 2011) events in national PAs and strengthen management in local PAs which may be less effective than national PAs, through the absence of active management of human activities and the demand for local resources. For example, local PAs in Russia are usually designated only "on paper" which means they do not have any equipment and most of the highly suitable habitat is unprotected by any PA. To further protect this species， the PA-network coverage needs to be increased, but local reserves should also be effectively evaluated and managed (Kleijn *et al.* 2014, Amano *et al.* 2018).

Decisions should be made on which elements, such as the conservation GAP area, need attention first, because resources available for conservation efforts are always scarce and need to be invested in strategic ways to ensure that conservation efforts make the greatest contribution to preserving endangered species (Pressey *et al.* 1993). The conservation GAP for on-ground implementation within the Sikhote-Alin mountain range (in Primorsky Krai and Khabarovsky Krai) should be prioritized, as this unique mountain area contains most of the highly suitable breeding habitat supporting 85% of the global breeding population (Solovyeva *et al.* 2014). Most of the remaining highly suitable breeding habitat and breeding population (14%) is found in the Changbai Mountains, straddling China (Jilin province) and the DPR Korea (Ryanggang). Philopatry and site fidelity in waterfowl are often female-biased (Rohwer and Anderson 1988). Smaller breeding enclaves such as Changbai could more likely be threatened and therefore need attention, because when these populations decline, only males— due to strong philopatry of females—can be efficiently supplemented by immigration from larger populations (Hefti-Gautschi *et al.* 2009). Under the rapid pace of development in China (e.g. Songjianghe, a town within the Changbai Mountain area, is projected to increase from 10-20,000 to 100,000 people with plans for a highway and rail link), the risk of dam construction, dredging and disturbance are likely to increase. The vulnerable status of irreplaceable breeding habitat in the Changbai Mountains should be considered another conservation priority. As small and subdivided populations have often greatly decreased in size in the recent past, some potentially suitable patches, such as those in Kur-Urmi rivers in Khabarovsky Krai, Hamgyong and Ryanggang in the DPRK, may be scarcely occupied, but nevertheless need to be preserved (e.g. by managing habitat in terms of meta-reserves) to allow individuals to move in the future (Doligez and Boulinier 2009). Setting a goal of 40% of highly suitable habitats to be protected, we suggest an additional 10,414 km^2 of PA in Russia and 6,836 km^2 in China. Among the priority areas to be protected in Russia we suggest Pavlovka and Zhuravlevka river catchments in Chuguevsky District of Primorsky Krai (c.3,600 km^2) and enlarging the existing Udygeiskaya Legenda NP by adding the upper reaches of the Iman River. In China, to minimize the impacts of human activities on the Scaly-sided Merganser, prioritizing conservation action and land management or small PA establishment along the Fuer, Songjianghe, and Manjiang rivers (i.e. key habitats overlaid with human developments) may be essential. The presence of breeding Scaly-sided Merganser along the modelled highly suitable habitats in DPRK was not confirmed; we suggest that surveys for the Scaly-sided Merganser along the rivers Tumen, Yalu, and Puktae Chion should be the first step in this country.

This study has attempted to model habitat suitability and identify the conservation GAP area, providing insights on conservation priority-setting for the Scaly-sided Merganser. The distribution of highly suitable habitats and the extent to which they are protected should be viewed as a reference point for establishment of conservation areas or implementing conservation actions for the breeding Scaly-sided Merganser in north-east Asia. The map of habitat suitability and the conservation GAP should be subject to continual evaluation and implementation under the International Single Species Action Plan (Solovyeva *et al.* 2017). The map should be refined when up-to-date data become available. In addition, it is remarkable that the current network of protected areas may become unsuitable in future as a result of poleward shifts in temperature (Leroy *et al.* 2014). Future studies should account for ICCP climatic scenarios to assess ongoing gaps between current and future protected areas.

Supplementary Materials

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0959270921000137.

Acknowledgements

We thank the reviewers for suggestions that greatly improved this manuscript. Sincere thanks for great support by the Wildlife Conservation Society of Jilin province, World Wide Fund for Nature (Northeast Region of China), Fundamental Research Funds for the Central Universities, China (2412018QD015), the "13th Five-Year" Science and Technology Research and Planning Project of Jilin Provincial Department of Education (JJKH20201176KJ), and the Wildfowl and Wetlands Trust, UK as well as data support from National Earth System Science Data Center and National Science and Technology Infrastructure of China (http://www.geodata.cn). We thank Peiqi Liu, Longguo Piao, Qing Zeng for support in data collection.

References

Amano, T., Szekely, T., Sandel, B., Nagy, S., Mundkur, T., Langendoen, T., Blanco, D., Soykan, C. U. and Sutherland, W. J. (2018) Successful conservation of global waterbird

populations depends on effective governance. *Nature* 553: 199.
An, A., Zhang, Y., Cao, L., Jia, Q. and Wang, X. (2018) A potential distribution map of wintering Swan Goose (*Anser cygnoides*) in the middle and lower Yangtze River floodplain, China. *Avian Res.* 9: 43.
BirdLife International. (2001) *Threatened birds of Asia: International Red Data Book*. Cambridge, UK: BirdLife International.
BirdLife International. (2017) *Mergus squamatus. The IUCN Red List of Threatened Species 2017*: e.T22680488A118860238. http://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T22680488A118860238.en
Buckton, S. T. and Ormerod, S. J. (2002) Global patters of diversity among the specialist birds of riverine landscapes. *Freshw. Biol.* 47: 695–709.
Carneiro, C., Correia, E., Goncalves, D., Brito, R., Luis, A. and Alves, J. A. (2016) Weather mediated impacts on the breeding output of an Afro-Palearctic migratory waterbird. *Avian Biol. Res.* 9: 167–173.
Cerón, G. and Ferreiro, N. (2017) Environmental factors influencing habitat use of solitary and paired Torrent Ducks (*Merganetta armata*) in Northwestern Patagonia, Argentina. *Wilson J. Ornithol.* 129: 545–553.
Chutipong, W., Duckworth, J. W., Timmins, R. J., Choudhury, A., Abramov, A. V., Roberton, S., Long, B., Rahman, H., Hearn, A., Dinets, V. and Willcox, D. H. A. (2016) *Martes flavigula. The IUCN Red List of Threatened Species* 2016: e. T41649A45212973. Downloaded on 26 November 2019.
Doligez, B. and Boulinier, T. (2009) Habitat selection and habitat suitability preferences. Pp. 1810–1830 in S. E. Jorgensen and B. Fath, eds. *Encyclopedia of ecology*. Amsterdam, Thew Netherlands: Elsevier.
Elith, J., Burgman, M. A., Regan, H. M. (2002) Mapping epistemic uncertainties and vague concepts in predictions of species distribution. *Ecol. Model.* 157: 313–329.
Elith, J. and Leathwick, J. R. (2009) Species distribution models: ecological explanation and prediction across space and time. *Annu. Rev. Ecol. Evol. S.* 40: 677–697.
Elith, J., Phillips, S. J., Hastie, T., Dudik, M., Chee, Y. E. and Yates, C. J. (2011) A statistical explanation of MaxEnt for ecologists. *Divers. Distrib.* 17: 43–57.
Fekete, B. M., Vorosmarty, C. J., Roads, J. O. and Willmott, C. J. (2004) Uncertainties in precipitation and their impacts on runoff estimates. *J. Clim.* 17: 294–304.
Feng, X., Park, D. S., Walker, C., Peterson, A. T., Merow, C. and Papeş, M. (2019) A checklist for maximizing reproducibility of ecological niche models. *Nat. Ecol. Evol.* 3: 1382–1395.
Gotmark, F., Blomqvist, D., Johansson, O. C. and Bergkvist, J. (1995) Nest Site Selection: A Trade-Off between Concealment and View of the Surroundings? *J. Avian Biol.* 26: 305. http://doi:10.2307/367704.
Gregory, R. D., Carter, S. P. and Baillie, S. R. (2010) Abundance, distribution and habitat use of breeding Goosanders *Mergus merganser* and Red-breasted Mergansers *Mergus serrator* on British rivers. *Bird Study* 44: 1–12.
Hake, M., Dahlgren, T., Ahlund, M., Lindberg, P. and Eriksson, M. O. G. (2005) The impact of water level fluctuation on the breeding success of the Black-throated Diver *Gavia arctica* in South-west Sweden. *Ornis Fenn.* 82: 1–12.
Heath, J. P., Robertson, G. J. and Montevecchi, W. A. (2006) Population structure of breeding Harlequin Ducks and the influence of predation risk. *Can. J. Zool.* 84: 855–864.
Hefti-Gautschi, B., Pfunder, M., Jenni, L., Keller, V. and Ellegren, H. (2009) Identification of conservation units in the European *Mergus merganser* based on nuclear and mitochondrial DNA markers. *Conserv. Genet.* 10: 87–99.
Johnson, D. (1979) The comparison of usage and availability measurements for evaluating resource preference. *Ecology* 61: 65–71.
Kajtoch, L., Zmihorski, M. and Piestrzynska-Kajtoch, A. (2014) The Goosander as potential indicator of naturalness and biodiversity in submontane river valleys of northern Carpathians. *Ecol. Indic.* 45: 83–92.
Khaliq, I., Aashard, M. I., Gill, A. H., Chaudhry, A. A., Maan, M. A., Iqbal, M. A., Akbar, M. and Bowler, D. E. (2019) Long-term changes of a waterbird community over 26 years at a Pakistani Ramsar Site. *Wetlands Ecol. Manage.* 27: 363–376.

Kleijn, D., Cherkaoui, I., Goedhart, P. W., Jasper, V. D. H., Lammertsma, D. and Fuller, R. (2014) Waterbirds increase more rapidly in Ramsar-designated wetlands than in unprotected wetlands. *J. Appl. Ecol.* 51: 289–298.

Kramer-Schadt, S., Niedballa, J., Pilgrim, J. D., Schröder, B., Lindenborn, J., Reinfelder, V., Stillfried, M., Heckmann, I., Scharf, A. K. and Augeri, D. M. (2013) The importance of correcting for sampling bias in MaxEnt species distribution models. *Divers. Distrib.* 19: 1366–1379.

Krestov, P. (2003) Forest vegetation of easternmost Russia (Russian Far East). Pp: 93–180 in J. Kolbek and M. Srutek ed. *Forest vegetation of Northeast Asia.* Dordrecht, The Netherlands: Springer.

Leroy, B., Ballard, C., Dubos, N., Colliot, A., Vasseur, M., Courtial, C., Bakkenes, M., Canard, A. and Ysnel, F. (2014) Forecasted climate and land use changes, and protected areas: the contrasting case of spiders. *Divers. Distrib.* 20: 686–697.

Li, C. L., Yang, S., Zha, D. D., Zhang, Y. and de Boer, W. F. (2019) Waterbird communities in subsidence wetlands created by underground coal mining in China: effects of multi-scale environmental and anthropogenic variables. *Environ. Conserv.* 46: 67–75.

Liu, P., Li, F., Song, H., Wang, Q., Song, Y., Liu, Y. and Piao, Z. (2010) A survey to the distribution of the Scaly-sided Merganser (*Mergus squamatus*) in Changbai Mountain range (China side). *Chinese Birds. 1: 148–155*. http://doi:10.5122/cbirds.2010.000.

Lu, J., Zhang, S. X., Fang, J. P. and Zheng, W. L. (2016) Nutrient characteristics of throughfall and stemflow in the natural forest of Pinus densata in the Tibetan plateau. *Phyton-Int. J. Exp. Bot.* 85: 142–148.

Ma, B. B. and Sun, J. (2018) Predicting the distribution of *Stipa purpurea* across the Tibetan Plateau via the MaxEnt model. *BMC Ecol.* 18: 12.

Mascia, M. B. and Pailler, S. (2011) Protected area downgrading, downsizing, and degazettement (PADDD) and its conservation implications. *Conserv. Lett.* 4: 9–20.

Merow, C., Wilson, A. and Jetz, W. (2016) Integrating occurrence data and expert maps for improved species range predictions. *Glob. Ecol. Biogeogr.* 26: 243–258.

Mi, H. X. (2012) *Nest site selection of Scaly-sided Merganser in Changbai Mountain during breeding season.* Master dissertation, Northeast Forestry University, Haerbin, China. (In Chinese).

Miquelle, D. G. and Pikunov, D. G. (2003) Status of the Amur tiger and Far Eastern leopards. Pp. 106–109 in J. P. Newwell, ed. *The Russian Far East: A reference guide for conservation and development.* California, USA: Daniel&Daniel Publishers, Inc.

Naimi, B., Hamm, N. A. S., Groen, T. A., Skidmore, A. K. and Toxopeus, A. G. (2014) Where is positional uncertainty a problem for species distribution modelling? *Ecography* 37: 191–203.

Newton, I. (1998) *Population limitation in birds.* London, UK: Academic Press.

Phillips, S. J., Anderson, R. P. and Schapire, R. E. (2006) Maximum entropy modeling of species geographic distributions. *Ecol. Modell.* 190: 231–259.

Pressey, R. L., Humphries, C. J., Margules, C. R., Vane-Wright, R. I. and Williams, P. H. (1993) Beyond opportunism: key principles for systematic reserve selection. *Trends. Ecol. Evol.* 8: 124–128.

Rohwer, F. C. and Anderson, M. G. (1988) Female-biased philopatry, monogamy, and the timing of pair formation in migratory waterfowl. Pp. 187–221 in R. F. Johnston, ed. *Current ornithology.* Boston, US: Springer.

Sánchez, S., Cuervo, J. and Moreno, E. (2007) Suitable cavities as a scarce resource for both cavity and non-cavity nesting birds in managed temperate forests. A case study in the Iberian Peninsula. *Ardeola* 54: 261–274.

Shao, M. Q., Zheng, B. B., Tim, H., Chen, L. X., You, C. Y., Wang, H. B. and Dai, N. H. (2012) Winter ecology and conservation threats of Scaly-sided Merganser *Mergus squamatus* in Poyang Lake Watershed, China. *Pak. J. Zool.* 44: 503–510.

Snyder, C. D., Young, J. A., Villella, R. and Lemarie, D. P. (2003) Influences of upland

and riparian land use patterns on stream biotic integrity. *Landsc. Ecol.* 18, 647–664.

Solovyeva D. V. (2002) Foraging behaviour and daily time budget of Scaly-sided Merganser *Mergus squamatus* breeding on Iman River, Russia. *Wildfowl* 53: 205–213.

Solovyeva, D. V., Liu, P. Q., Antonov, A. I., Averin, A. A., Pronkevich, V. V., Shokhrin, V. P. and Cranswick, P. A. (2014) The population size and breeding range of the Scaly-sided Merganser *Mergus squamatus*. *Bird Conserv. Internatn.* 24: 393–405.

Solovyeva, D. V., Hughes B. and Cranswick, P. A. (2017) *Scaly-sided Merganser international single species action plan*. Bonn, Germany: CMS and East-Asian-Australasian Flyway Partnership.

van Balen, J. H., Booy, C. J. H., Franeker, J. A. V. and Osieck, E. R. (1982) Studies on hole-nesting birds in natural nest sites. *Ardea* 70: 1–24.

Watson, J. E. M., Dudley, N., Segan, D. B. and Hockings, M. (2014) The performance and potential of protected areas. *Nature* 515: 67–73.

Woo, M. K., Thorne, L. and Brown, L. (2019) Comparison of runoff and river flow in two large northern basins. *Hydrol. Res.* 50: 1609–1622.

Worthington, T. A., Zhang, T. J., Logue, D. R., Mittelstet, A. R. and Brewer, S. K. (2016) Landscape and flow metrics affecting the distribution of a federally-threatened fish: Improving management, model fit, and model transferability. *Ecol. Modell.* 342: 1–18.

Wu, X. (2007) The problems of logging in Heilongjiang province and the suggestions of reform deepening. *Annual meeting of China association for science and technology*. (In Chinese).

Yi, G. D., Yang, Z. J., Chen, G., Li, C. Q., Hao, X. L. and Zhao, J. (2008) Reports on reproductive biology in the Scaly-sided merganser. *Chi. J. Zool.* 43: 57–61.

Yi, Y. J., Cheng, X., Yang, Z. F. and Zhang, S. H. (2016) Maxent modeling for predicting the potential distribution of endangered medicinal plant (*H. riparia* Lour) in Yunnan, China. *Ecol. Eng.* 92: 260–269.

Zeng, Q., Lu, C., Li, G., Guo, Z. B., Wen, L. and Lei, G. C. (2018) Impact of a dam on wintering waterbirds' habitat use. *Environ. Conserv.* 45: 307–314.

Zeng Q., Zhang, Y., Sun, G., Duo, H., Wen, L. and Lei, G. (2015a) Using species distribution model to estimate the wintering population size of the endangered Scaly-Sided Merganser in China. *PLoS ONE* 10(2): e0117307. https://doi.org/10.1371/journal.pone.0117307.

Zeng, Q., Shi, L. L., When, L., Chen, J. Z., Duo, H. R. and Lei, G. C. (2015b) Gravel bars can be critical for biodiversity conservation: a case study on Scaly-sided Merganser in south China. *PLoS ONE* 10(5): e0127387. https://doi.org/10.1371/journal.pone.0127387.

Zhang, Y., Fox, A. D., Cao, L., Jia Q., Lu, C. H., Prins, H. H. T. and de Boer, W. F. (2019) Effects of ecological and anthropogenic factors on waterbird abundance at a Ramsar Site in the Yangtze River Floodplain. *AMBIO* 48: 293–303.

Zhao Z. J. and Piao Z. J. (1998) The foraging behaviour of the Scaly-sided Merganser (*Mergus squamatus*) in the Changbai Mountains and Xiao Xingangling Mountains of China. *Forktail* 14: 76–77.

Zhao Z. J., Han X. D., Wu J. C., Zhang S. H. and Piao Z. J. (1995) The behavior of Scaly-sided Merganser in breeding season (In Chinese). *Chi. J. Wildl.* 16: 19–21.