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Abstract

Background: The Bar-headed Goose ( ) breeds across the high plains and plateau of Central Asia and winters in the Qinghai-Tibet Plateau (QTP), the Yunnan-Guizhou Plateau and the Indian sub-continent. Of the two recognized discrete flyways of the Bar-headed Goose, the Eastern Tibetan Flyway (ETF) is the larger, comprising at least six migration routes. However, we remain ignorant about their migratory connectivity, habitat use and effectiveness of site-safeguard mechanisms set in place for the species.

Methods: We tracked 30 ETF Bar-headed Geese from Chinese and Mongolian breeding areas to their wintering grounds using GPS/GSM transmitters, to determine their migration routes and stopover staging patterns within the QTP, overlaying these upon GIS layers of protected area status and habitat type, to model their habitat selection.

Results: In total, 14 tagged Bar-headed Geese provided information on their entire autumn migration and 4 geese on their entire spring migration. Qinghai Lake marked birds overwintered in the QTP (= 2), geese tagged in Mongolia wintered either in the QTP (= 3) or in India/Bangladesh (= 9), representing three of the migration routes within the ETF. In total, tagged birds staged at 79 different stopover sites within QTP in autumn and 23 in spring, of which 65% (autumn) and 59% (spring) of all fixes fell within the boundaries of either National Nature Reserves (NNRs) or Important Birds Areas (IBAs) in the QTP. Bar-headed Geese predominantly occurred on four land-cover types: grassland (mostly by day), water bodies (at night), wetlands and bare substrates (salt flats, dry lake/river substrates and plough) with little change in proportion. Generalized linear mixed models comparing presence with pseudo-absence data suggested geese strongly selected for wetlands as staging habitat, avoiding bare substrates in spring.

Conclusions: Based on our limited observations of these tagged geese, this study is the first to show that the current designated National Nature Reserves in place in the staging areas within the QTP appear adequate to protect this increasing population. In addition, Hala Lake in Qinghai Province and adjacent areas used as initial QTP staging during

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Background

e Bar-headed Goose (*Anser indicus*) has increased greatly in abundance since the 1990s, reaching an esti-

Here, we attempt to define Bar-headed Goose habitat selection (as distinct from simple habitat use; Jones 2001) to understand how the birds might be showing behavioral responses to changes in habitat conditions, which potentially a ect the survival and adaptability of individuals (Block and Brennan 1993). Only by revealing habitat selection patterns, can we fully understand the spatial and temporal distribution of the Bar-headed Geese we follow. Based on results from a previous study, which used geographical information to model habitat selection in ETF breeding areas (Zheng et al. 2018), we identified six key parameters in modelling habitat selection, including land cover (each class is treated as a separate variable), elevation, slope, aspect, distance to river/lake and road.

In this investigation, we applied further telemetry devices to samples of birds on their key breeding areas in China and Mongolia, to extend earlier studies of this species, with the specific aim of identifying key staging areas throughout the migratory life cycle of these birds. Most importantly, we specifically compare the areas used by tagged Bar-headed Geese to assess the e ectiveness of currently designated areas in the QTP to protect key staging areas during migration for the species and to determine their habitat use and selection at these areas.

Methods

Capture of individuals and transmitter attachment

In June 2016, three Bar-headed Geese (of unknown age and sex) rescued and rehabilitated by the Qinghai Lake National Nature Reserve Rescue Center were fitted with neck collar-mounted GPS/GSM loggers (weight 40 g, Hunan Global Messenger Technology Co., China) and released at Qinghai Lake (37.07 °N, 99.82 °E, China). e signal was lost from one of the birds during autumn migration, but the two other geese completed their autumn migrations in 2016.

In July 2018, 27 individuals (adult, unknown sex) were rounded up during the flightless moult period and captured at Terkhiin Tsagaan Lake (48.15 °N, 99.59 °E, Mongolia) and Bayan Lake (49.94 °N, 93.90 °E, Mongolia), and fitted with backpack-mounted GPS/GSM loggers (weight natural and artificial waterbodies, such as lake, river and reservoir/pond (for detailed definitions of land cover categories, see Gong et al. 2013). We assigned each GPS location within the stopover sites in the QTP to a specific land-use type defined by the land cover data using R 3.6.0 (R Core Team 2019). GPS fixes were assigned to day or night based on local sunrise and sunset times calculated by "solartime" package (v0.0.1; Wutzler 2018).

We used elevation data measured from SRTM3-DEM dataset (resolution 30 m × 30 m) created by NASA and NIMA, and calculated slope and aspect (defined as a parameter value running from 0 to 360, starting from the West and increasing clockwise) for each GPS fix using ArcMap 10.6. Finally, we calculated the shortest distance of each GPS fixes in stopovers to roads (downloaded from https://www.worldclim.org/) and rivers (downloaded from https://download.csdn.net/download/weixin_38779546/10613773), respectively.

Resource selection modeling

We used generalized linear mixed models (GLMMs) with a binomial error structure to evaluate stopover resource selection during autumn and spring migration respectively, with use/availability as response variable and environment variables as explanatory variables (Meng et al. 2020). We diluted GPS fixes to hourly intervals to reduce the potential for autocorrelation (Signer et al. 2019).

Availability data (i.e., pseudo-absence data) at each stopover site were generated by creating 100% minimum convex polygons (MCPs) based on each set of positions for tagged individuals. We extended these outwards by 11.3 km (the average maximum hourly displacement for all individuals at all stopover sites) in all directions around the MCPs to represent the area potentially available to each of the staging birds. We then randomly selected locations from the extended MCP for each stopover site as pseudo-absence data, generating 20 pseudo-absence points for each positional fix to gain stable and unbiased parameter estimates (Northrup et al. 2013).

Rare land cover types (<5% of total land use by either use or availability data points) were excluded (namely artificial surfaces, cropland, forest, shrubland, tundra and snow/ice), to escape model convergence problems likely below such levels (Altman et al. 2004). We rescaled variables using the "scale" function in "base" package in R, following the method of Becker and Chambers (1984) to estimate the effect size of explanatory variables.

We used the "dredge" function in "MuMIn" package (v1.43.10; Bartoń 2019) in R to develop our resource selection model using model weights derived from AICc criteria. The cross-prediction accuracy of our resource selection model was tested by estimating the area under the receiver operating characteristic (ROC) curve (AUC). AUC values can range between 0 and 1, where 0.5 indicates predictions no better than chance, 1 indicates perfect discrimination, with values above 0.7 being generally accepted as indicating reasonable predictions (Hosmer et al. 2013). Finally, we applied odds ratios to evaluate effect size of the variables (Szumilas 2010).

Results

Tracking results

A total of 17 geese in autumn, and 8 geese in spring began migration with functioning transmitters, however, due to mortalities and transmitter malfunction, we were only able to obtain information on the full migration for 14 and 4 geese during autumn and spring migration, respectively. Based on the complete migration data from 2016 and 2018 combined, the tagged birds followed three different migration routes. Birds marked at Qinghai Lake overwintered in the Shigatse Prefecture of Tibet Autonomous Region (TAR) ($n=2$), whereas geese marked in Mongolia either wintered in the Shigatse Prefecture ($n=3$) or continued down into India ($n=7$) or Bangladesh ($n=2$) to winter (Fig. 1). In addition, tracked geese (another three geese in autumn and another four in spring that started but did not complete migration) staged at 79 different stopover sites in autumn and 23 in spring within the QTP (Fig. 1; Additional file 2: Tables S2, S3). The cumulative time that all birds spent at stopover sites within the QTP totaled 1445 h, which constituted 86.7% of the entire stopover duration (1667 h).

Tagged Bar-headed Geese that summered in Mongolia and wintered in India/Bangladesh, arrived in the QTP during autumn migration on average on September 8 (±7 days standard deviation; $n=9$ individuals) and left the QTP on November 19 (±13 days). In spring, they arrived in the QTP from India or Bangladesh on average on March 15 (±6 days; $n=6$) and left on April 25 (±6 days; $n=3$; another three geese started but did not complete migration). Bar-headed Geese spent an average of 72.3 ± 17.3 days ($n=9$) and 44.3 ± 7.1 days ($n=3$) in the QTP during autumn and spring migration respectively.

Conservation status of stopover sites

Data from the goose-borne loggers generated 123,539 non-moving GPS fixes in autumn and 51,282 in spring at stopover sites within the QTP. Of these, 59% and 53% of GPS fixes in autumn and spring respectively fell within NNRs, while 27% and 23% of GPS fixes were

Fig. 1 Autumn and spring individual migration routes (black lines) and stopover sites (green circles) of Bar-headed Geese ( ) derived from GPS/GSM telemetry devices deployed on birds tracked in 2016 and 2018/2019. The shaded red region shows the Qinghai-Tibet Plateau. TtoT: Qinghai Lake – Shigatse Prefecture routes; MtoT, Mongolia – Shigatse Prefecture routes; MtoA, Mongolia-India/Bangladesh routes. Sample sizes are indicated by (number of individuals finishing migration)

these, there were three areas containing at least three stopovers, which fell outside existing NNRs/IBAs designation (Fig. 2). ese were: (1) Shule River, Qinghai Province, $N_s = 6$ (N_s in each case represents the number of stopovers; No. 2 in Table 1; close to Hala Lake); (2) Dangqu River, TAR, $N_s = 3$ (No. 11; outside of the Se Lin Cuo NNR and near downtown Dangxiong county); (3) Duoqingcuo Lake, TAR, $N_s = 11$ (No. 12; a national wetland park and close to the highway).

Habitat use and selection in stopover sites

Habitat types used by the Bar-headed Geese were predominantly natural ecosystems: 31% grassland, 29% bare substrate (including dry salt flats, bare herbaceous croplands and dry lake/river bottoms; Gong et al. 2013), 26% water bodies and 11% wetlands. Habitat types used by

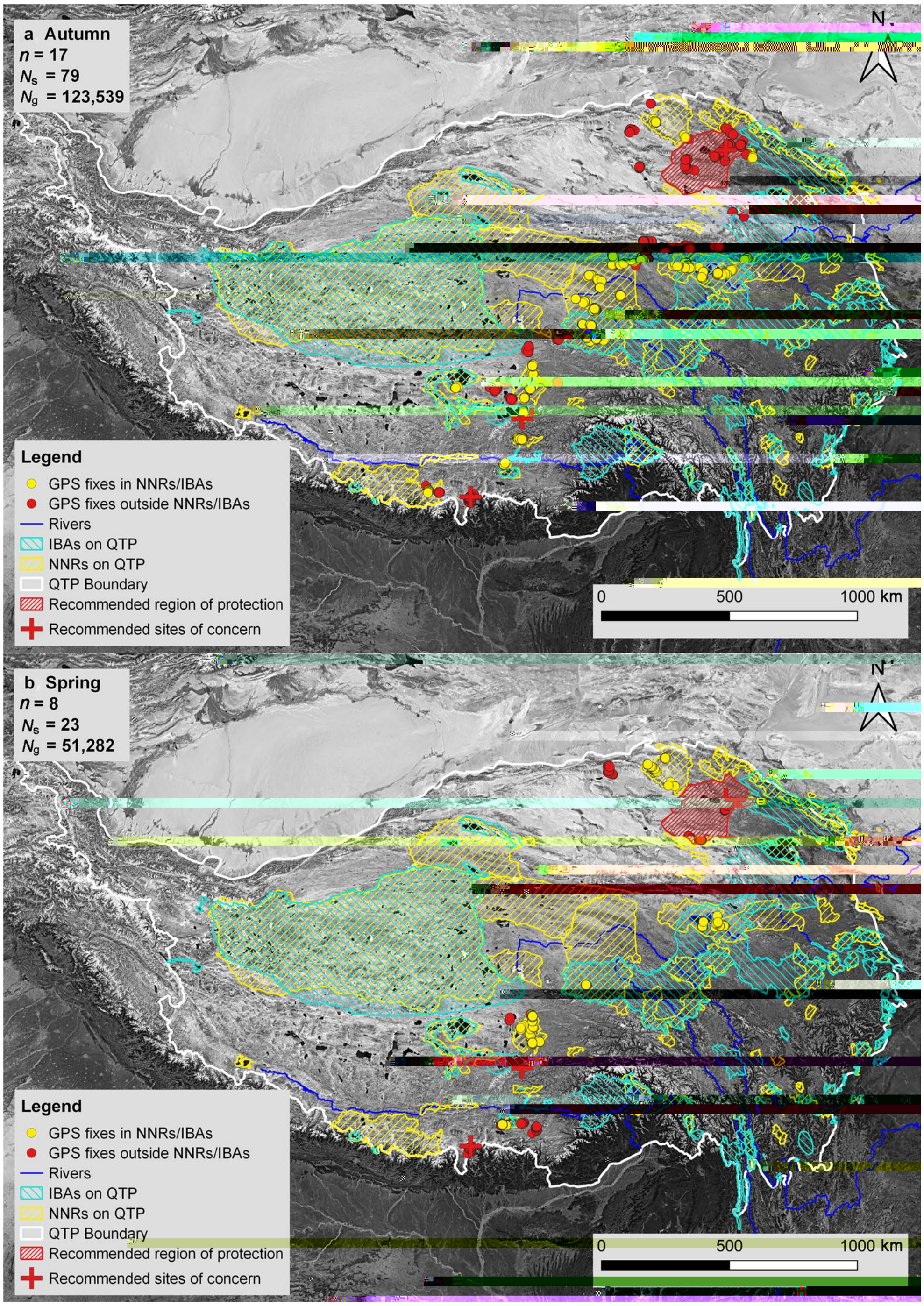

Fig. 2 GPS fixes of stopover sites within the QTP for tagged Bar-headed Geese during autumn and spring migration in 2016 and 2018/2019. **a** stopovers during autumn migration; **b** stopovers during spring migration. NNRs: National Nature Reserves of China; IBAs: Important Bird and Biodiversity Areas; QTP, the Qinghai-Tibet Plateau. Sample sizes are indicated by n (number of instrumented individuals generating the data), N_s (number of stopovers within QTP) and N_g (total number of GPS fixes per category). The explanations apply also to Figs. 3, 4

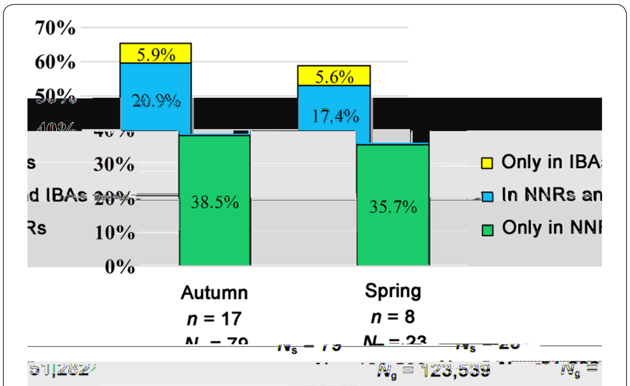

Fig. 3 Conservation status of Bar-headed Geese stopovers within the Qinghai-Tibet Plateau during autumn (totally 63.3%) and spring (58.7%) migration in 2016 and 2018/2019

geese di ered between day (the majority on grassland, 47% in autumn and 33% in spring) and night (when the majority were using waterbodies, 33% in autumn and 41% in spring), but were similar during autumn and spring migration (Fig. 4).

Comparing GLMMs results, the best fit models for predicting spring and autumn Bar-headed Goose stopover sites within the QTP were based on the same nine parameters. ese included the four habitat types, as well as slope, aspect, elevation, distance to roads and rivers (autumn: weight = 1.000, AUC = 0.80; spring: weight = 1.000, AUC = 0.83; Table 2). All these parameters are significant ($p < 0.001$; Fig. 5). Among habitat types, Bar-headed Geese tended to strongly select wetlands ($\beta_{autumn} = 1.94$, $\beta_{spring} = 2.03$), slightly select water bodies ($\beta_{autumn} = 0.62$, $\beta_{spring} = 0.80$), slightly avoided to select grassland ($\beta_{autumn} = -0.95$, $\beta_{spring} = -1.05$), and were least likely to select bare substrates in spring ($\beta_{spring} = -2.01$). Among terrain variables, geese tended to select stopovers facing south ($\beta_{autumn} = 0.30$,

Table 1 Important staging areas used by tagged Bar-headed Geese (*Anser indicus*) migrating in the Eastern Tibetan Flyway in 2016 and 2018/2019

No	Stopover sites & coordinates	Season	No. of stopovers	Date range	Length of stay (range in days)	Protection status	IBA sites (Y/N)
1	River of Subei Mongolian Autonomous County, Gansu Province, China (95.829 °N, 39.105 °E)	884105 °E)7d [(S)4162 cm 0 0 e9n526 cm 0 0 m 35.159 0 l S Q q -topoNo. .6917Q q 1 0 f 8 0 0 8 56.692901611ation in					

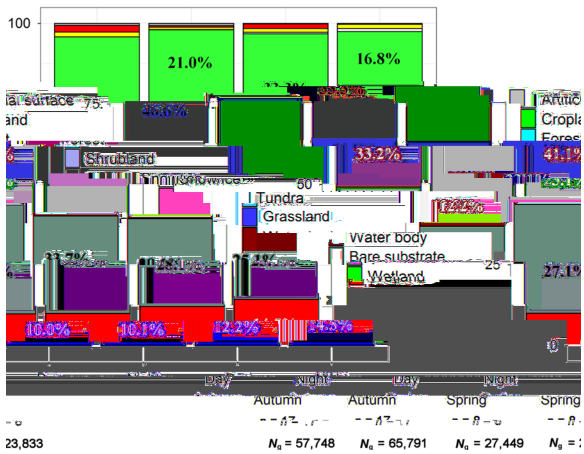

Fig. 4 Percentage habitat use of Bar-headed Geese during stopovers within the Qinghai-Tibet Plateau during autumn and spring migration in 2016 and 2018/2019 respectively, based on positional fixes from deployed GPS loggers overlaid on land-cover maps of the world (see Methods)

Table 2 Model selection results for the top five stopover habitat selection analysis models for the Bar-headed Geese during autumn and spring migration in 2016 and 2018/2019 respectively

Season	ID	Model structure[a]	df	ΔAIC[b]	Weight
Autumn	1	LC + ROA + RIV + ELV + SLP + ASP	12	0.0	1
	2	LC + ROA + RIV + SLP + ASP	11	206.6	0
	3	LC + RIV + ELV + SLP + ASP	11	397.4	0
	4	LC + ROA + ELV + SLP + ASP	11	567.8	0
	5	LC + RIV + SLP + ASP	10	607.4	0
Spring	1	LC + ROA + RIV + ELV + SLP + ASP	12	0.0	1
	2	LC + RIV + ELV + SLP + ASP	11	110.9	0
	3	LC + ROA + RIV + SLP + ASP	11	342.6	0
	4	LC + ROA + ELV + SLP + ASP	11	437.8	0
	5	LC + ELV + SLP + ASP	10	446.4	0

LC, ; OA, i ; I , i i ; EL , i ; LP, ; A P,

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$\beta_{spring}=0.32$), with low elevation ($\beta_{autumn}=-0.12$, $\beta_{spring}=-0.31$) and slope ($\beta_{autumn}=-2.00$, $\beta_{spring}=-1.17$) both during autumn and spring migration. Among other variables, geese tended to select stopover sites, which were away from roads ($\beta_{autumn}=0.16$, $\beta_{spring}=0.29$) and close to rivers ($\beta_{autumn}=-0.22$, $\beta_{spring}=-0.43$) both during autumn and spring migration (see Additional file 2: Tables S5, S6 for full model details).

Discussion

e results of this tracking study clearly show that three NRRs: Yan Chi Wan (Gansu Province), San Jiang Yuan (Qinghai Province), and Se Li Cuo (TAR) are of critical importance to Bar-headed Geese in the ETF during both autumn and spring migration. In particular, the importance of rivers in Yan Chi Wan (No. 1 in Table 1) and San Jiang Yuan NNRs (No. 5, 6) were not previously known. Overall, 65% of autumn GPS fixes were from within NNRs/IBAs and 59% in spring. Our studies confirmed the importance of Hala Lake (close to Shule River, No. 2), San Jiang Yuan NNR (No. 3, 4) and Se Lin Cuo NNR (No. 7–10) indentified by tagged Bar-headed Geese in previous studies (Hao et al. 2010; Zhang et al. 2011b; Prosser et al. 2011). Nevertheless, our tracking data found additional areas frequently used by tracked geese, which are not currently designated as NNRs/IBAs. Of these, the most important appear to be the Shule River, Qinghai Province, the Dangqu River, TAR and Duoqingcuo Lake, TAR, all of which are recommended for ground survey during the migration season based on their prolonged use (3–26 days) by tagged birds from this study.

We would also recommend surveying the suitability of adding Hala Lake and adjacent areas (97.60 °N, 38.30 °E; Fig. 2) to the protected area network for this species, as part of the ecological redline for the region. is is part of the NE edge of the QTP which represents the first staging area encountered and used by geese during autumn migration, yet very few of our tracked birds used areas inside the current protected area boundaries, despite the importance of the position of this area in the overall migration network (Xu et al. 2020).

e ETF represents the larger of the two flyways of the Bar-headed Goose, supporting more than 80,000 individuals. Within this flyway, it is thought that there at least six migration routes (Additional file 1). ese are: (1) Mongolia–Yarlung Zangbo River, China; (2) Mongolia–East Indian sub-continent; (3) Qinghai Lake–Yarlung Zangbo River, China; (4) Qinghai Lake–Yunnan-Guizhou Plateau, China (Zhang et al. 2011b); (5) Xinjiang–Yarlung Zangbo River, China (Liu et al. 2010); (6) Yarlung Zangbo River, China–Central Indian sub-continent (Newman et al. 2012). Our study only covered the first three of these migration routes, so there remains three other migration routes that are poorly studied, not to mention those used by geese from the Western Tibetan Flyway (Köppen et al. 2010).

After pooling the data from tracked Bar-headed Geese (both from this and other studies) which completed autumn migration and were captured in Mongolia ($n=24$) and Qinghai Lake, China ($n=40$), 38 of these individuals wintered in the QTP, 25 in Indian sub-continent, and only one on the Yunnan-Guizhou Plateau (Tian

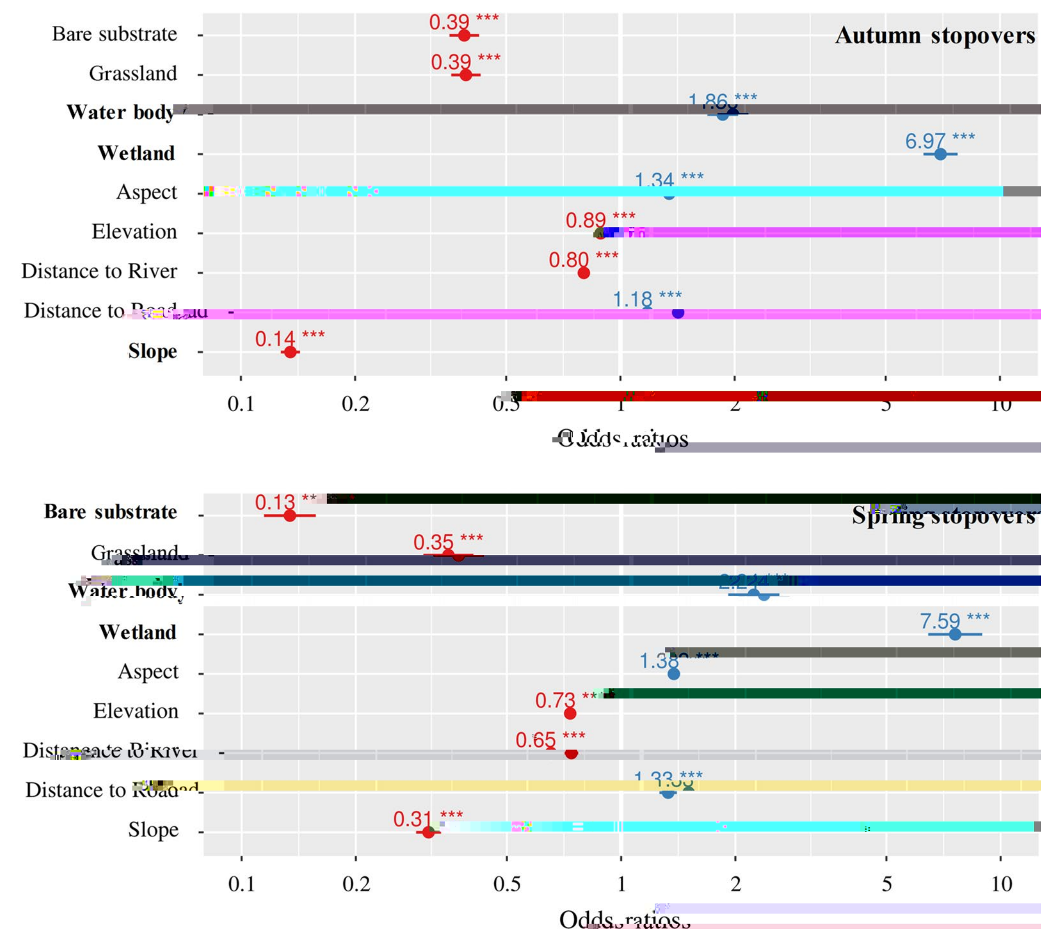

Fig. 5 Odds ratios of fixed e ects in highest-ranked generalized mixed-e ect model for autumn and spring stopovers in 2016 and 2018/2019. Red symbols depict negative e ects, and blue symbols depict positive e ects. Significant results are marked with asterisks (*** indicates -value < 0.001)

et al. 2015; Takekawa et al. 2017). is diversity of migration patterns underlines the need to apply telemetry studies to more Bar-headed Geese marked throughout their breeding distribution to enable us to better delineate the flyway structure of this species, which remains poorly known, and to ensure adequate site safeguard for geese of di erent breeding provenance. Such an understanding is essential if we are to be able to appraise the e ectiveness of the cohesive site-safeguard network to protect all the elements of this complex population throughout its annual cycle. is is especially important because the species exploits arid and high altitude ecosystems at different times of its annual cycle, all of which are known to be particularly susceptible to the e ects of current on-going climate change. For example, e ects of climate change at one of the Bar-headed Goose's major breeding sites in west Mongolia, which has experienced the most rapid rise in temperatures in the past decade outside of the Arctic regions (Batbayar et al. 2014), may have serious impacts on their breeding success. In the QTP, the extent of wetlands have increased in the eastern part and decreased in the western-central sectors (Xu et al. 2019), factors which may explain increases in breeding Bar-headed Geese in this area relative to numbers in Mongolia. On the other hand, in TAR, the species is considered to be more vulnerable to power line strikes (Li et al. 2011) and avian influenza (Liu et al. 2010).

e results from this analysis of habitat use by Bar-headed Geese reflect those of many northern hemisphere goose species, which typically feed out in wetlands and grassland by day but resort to open water bodies by night as protection from potential predators (Zhao 2017). Bar-headed Geese mainly used natural ecosystems during migration and on the summering areas, but cropland during winter. In summer, 35% of positional fixes from tagged geese captured at Qinghai Lake were from grassland and 54% from wetlands during the breeding and post-breeding period (Prosser et al. 2011). Zheng et al. (2018) reported 53% of positional fixes from their telemetry tracked Bar-headed Geese were from wetland, 21%

forest and 18% bare substrate in Qinghai Lake ($n=8$). We found very low forest cover when overlaying the home ranges from Zheng et al. (2018) on the ESA Global Cover 2009 maps and goose use of forest habitats seems extremely unlikely.

During migration, geese mainly used grassland, water bodies, wetlands and bare substrates at their stopover sites in our study. Prosser et al. (2011) reported 75% of positions of tagged Bar-headed Geese came from grassland and > 12% from wetlands during autumn and spring migration. Both studies therefore confirmed tagged geese mainly used natural ecosystems during migration. Small di erences between our and Prosser et al.'s (2011) results may be the consequence of land-cover changes that have a ected goose habitat availability in the last two decades and improvements in accuracy of the land cover dataset. Prosser et al. (2011) used the 2003 dataset based on 1 km resolution, whereas our study used the 2019 dataset with 10 m accuracy.

During winter, geese mainly used winter wheat fields, or fallow croplands, rivers, lakes and marshes along the Yarlung Zangbo River. Ground counts of feeding geese ($n=44,657$ in January 2009) found 72.1% on fallow cropland (Liu et al. 2010). Prosser et al. (2011) also reported tagged geese used 39% cropland near Lhasa city. In addition, Bar-headed Geese also used grassland and cropland as their main diurnal feeding areas at Caohai, China (Yang et al. 2013), Lashihai Lakes, China (Yan et al. 2014) and Keoladeo National Park, India (Middleton and Van der Valk 1987). Hence, like many northern hemisphere goose species, the Bar-headed Goose has shown a plasticity that has enabled it to take advantage of the new farmland feeding opportunities on the wintering areas (Fox and Abraham 2017). We speculate that restricted use of croplands in summer and on migration simply reflects the general remoteness of the areas that they use at these stages of the life cycle, in regions where the area of cropland available for foraging is extremely restricted.

In our original GLMM modelling to compare the habitat types used by geese with pseudo-absence measures in the immediate vicinity, we also entered water recurrence (Pekel et al. 2016) as a potential explanatory parameter, but it was highly correlated with "water body". Deletion of water recurrence from the model resulted in an AUC of more than 0.7, indicating reasonable predictions from this simplified model. In our final model, geese tended to select wetland and water bodies as habitat, because the seasonal growth of aquatic plants provides accessible digestible biomass which can be exploited to accumulate fat stores by day (Cong et al. 2012; Wang et al. 2013), and open water o ers a night time roosting refuge to avoid predators. Geese also appeared to prefer south facing stopover sites, probably because these areas gain maximum solar insolation to stimulate the growth of food plants to support fat accumulation during the spring migration and shelter from the north wind during the autumn migration. Geese avoided bare substrates strongly in spring, probably because of the low surface temperatures and frost during spring migration in these areas. Summering Bar-headed Geese at Qinghai Lake preferred wetland, open land with sparse vegetation, sites close to rivers/lakes and away from roads, croplands and higher elevations (Zheng et al. 2018) and we contest that they also avoided forest. Wintering Bar-headed Geese at Caohai Lake showed a preference for sites with high vegetation cover, low vegetation height, far from human disturbance, close to the water, open habitats and lower elevation as their foraging sites (Yang et al. 2013). Our results closely followed theirs, confirming that all stages of the life cycle, Bar-headed Geese tend to select wetland areas, close to rivers/lakes, away from roads and at lower elevations than would be expected by chance.

e habitat selection patterns of Bar-headed Geese also reflect patterns shown by Greylag Geese in their breeding and wintering areas in East China (Li 2019). Both species tend to select water bodies and wetland as habitat, although Greylag Geese occur in sites nearer to roads and tend to show greater selection for cropland, suggesting they are more tolerant of human disturbance than Bar-headed Geese. Cropland was not used as a parameter in our model, because it contributed only 1% to habitat use among tagged Bar-headed Geese. In conclusion, these results, together with the results of previous studies of the species, continue to indicate that Bar-headed Geese rely predominantly on wetland and water bodies during migration staging in the QTP in the absence of major human impacts on the landscape in these areas.

In contrast, increasing numbers of Bar-headed Geese are shifting to croplands during the winter. is is especially evident along the Yarlung Zangbo River (where the area of cropland increased by 15.5% between 1990 and 2015; Wu et al. 2017). Numbers of Bar-headed Geese wintering along the Yarlung Zangbo River rose from 15,000 in the 1990s (Bishop et al. 1997) to 30,000 in 2007 (Bishop and Tsamchu 2007) to 67,000 in 2014 (Liu et al. 2017) as increasing numbers resorted to farmland to feed.

e Qinghai-Tibet Plateau is a vast territory with high biodiversity interest and a sparse human population, which has benefitted from the positive e ects of nature conservation designation, particularly evident through the current large extent of protected areas. Relatively high levels of site protection for the Greylag Geese in East China have resulted in that species spending more than 65% of their stopover duration within IBA/protected areas during migration, and their population size is increasing (Li et al. 2020), suggesting that site protection can contribute to supporting increasing numbers of geese over time. It would therefore appear that Bar-headed Geese have benefitted from improved conservation action (especially protected areas designation) at migration stopovers en route to and from their breeding areas, as well as from the increasing use of energy rich agriculture areas as winter quarters. Nevertheless, as we identify above, with climate change imposing spatially explicit patterns of change in di erent parts of the annual range of the Bar-headed Goose, it remains essential we improve our understanding of their migration routes and flyways through extended telemetry studies and monitor their population dynamics and abundance to ensure the future of this unique Asian goose species.

Conclusions

is study is the first to identify the paramount importance of stopover sites within the QTP to Bar-headed Geese in their annual cycle, but also to confirm the satisfactory level of current site protection given the patterns revealed by our telemetry data, which is consistent with the upward trend in abundance of the ETF Bar-headed Goose. We recommend Hala Lake and adjacent areas for protection because of their disproportionate importance to the geese during the initial stages of their autumn migration, which are currently outside the present network of NNRs/IBAs. Bar-headed Geese mainly used natural ecosystems during migratory stopovers (the majority feeding on grasslands by daytime and roosting on water body at night). Habitat modelling confirmed geese tend to select wetland areas, close to rivers/lakes, away from roads and at lower elevations.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40657-020-00230-9.

Additional le 1: Figure S1. Map showing the nature and extent of the two distinctive flyways of the Bar-headed Goose ( ) in Central Asia.

Additional le 2: Table S1. Summary table of Bar-headed Geese ( ) fitted with solar-powered GPS/GSM telemetry devices in the current analysis. **Table S2.** The location and duration of stopover sites in the Qinghai-Tibet Plateau used by tracked Bar-headed Geese (=17) during autumn migration in 2016 and 2018. **Table S3.** The location and duration of stopover sites in the Qinghai-Tibet Plateau used by tracked Bar-headed Geese (=8) during spring migration in 2019. **Table S4.** Conservation status of Bar-headed Geese stopovers in the Qinghai-Tibet Plateau during autumn and spring migration. **Table S5.** Parameter estimates ( ), standard errors, values, and 95% confidence limits from the highest-ranked model (Table 2) estimating habitat selection of Bar-headed Geese in stopovers within the Qinghai-Tibet Plateau during autumn migration. **Table S6.** Parameter estimates ( ), standard errors, values, and 95% confidence limits from the highest-ranked model (Table 2) estimating habitat selection of Bar-headed Geese in stopovers within the Qinghai-Tibet Plateau during spring migration.

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Authors' contributions

LC, JZ, YX and ADF conceived the ideas and designed methodology; LL, NB, ID and FM collected the data; JZ and XD analyzed the data. JZ led the writing of the manuscript, with contributions from LC, YX and ADF. All authors contributed critically to the drafts and gave final approval for publication. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used in the present study are available from the corresponding author on reasonable request.

Ethical approval and consent to participate

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers): The Animal Ethics Committee, Research for Eco-Environmental Sciences, Chinese Academy of Sciences fully approved this study. Approval for bird capture and transmitter deployment in Mongolia was obtained from the Ministry of Nature, Environmental and Tourism of Mongolia (permission number: No 06/2862). Approval for transmitter deployment at Qinghai Lake, China was obtained from the Qinghai Lake National Nature Reserve authorities.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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