Zoological Research

Supplementary Materials

Dynamic foraging strategy adaptation to heterogeneous environments contributes to social aggregation in snub-nosed monkeys

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SUPPLEMENTARY MATERIALS AND METHODS

Supplementary Method S1 Study site and subject

This study was conducted in the Yuhuangmiao area, Zhouzhi National Nature Reserve (107°45.5'–108°18.8' E, 33°45.7'–33°54' N), Shaanxi Province, China (Figure 1A, B). The nature reserve covers 56 393 hectares and mainly protects rare wild animals such as the golden snub-nosed monkey and their habitat on the north slope of the middle Qinling mountains. Located in the temperate zone, this area is a typical mountain climate with significant seasonal differences, with hot summers (June to August, average air temperature: 18.92 °C) and cold winters (December to February, average air temperature: –0.82 °C). The annual ambient temperature was 8.4 °C, ranging from –17.34 °C to 36.11 °C during the study period. Three forest types are found along an elevation gradient: (1) deciduous broadleaf forest (1 400–2 200 m above sea level, asl), (2) mixed coniferous and broad-leaf forest (2 200–2 600 m asl), and (3) coniferous forest (above 2 600 m asl) (Li et al., 2000).

Qinling golden snub-nosed monkeys *Rhinopithecus roxellana qinlingensis* mainly ranged in middle elevations (1 500–2 200 m) in the Qinling mountains. They were separated into fragmented habitats by human interference and steep topography (Huang et al., 2021). Two troops of the golden snub-nosed monkey in the study area were named East ridge troop (ERT) and west ridge troop (WRT). The WRT is divided into two herds which are called the Gongnigou-herd (GNG-herd) and Dujiafen-herd (DJF-herd) (Qi et al., 2014). GNG-herd contained a breeding band (BB) with 11–15 OMUs and an all-male band (AMB) with 24–40 individuals, for a total of 160–190 individuals during 2013–2017. DJF-herd consisted of 70–80 individuals including a BB with 6–7 OMUs and an AMB with 11–12 individuals. We focused on the BB because AMB migrated in and out frequently. Although a few OMUs also migrated, the group size of GNG-BB is larger than that of DJF-BB. GNG herd had been initially habituated by food provisioning since 2001 (Qi et al., 2009), mainly during spring and autumn. Therefore, the GPS data of GNG-herd in summer (June to August) and winter (December to February) could objectively reflect the natural living conditions of wild golden snub-nosed monkeys. DJF-BB is free-ranging in four seasons.

Supplementary Method S2 GPS tracking

From December 2012 to January 2018, seven and eight GPS collars were fitted to adult individuals to track the BBs of the GNG-herd and DJF-herd, respectively (Supplementary Table S1). Physically healthy and well-developed adults were selected for collaring (Qi et al., 2014; Qi et al., 2017). Fourteen of the fifteen individuals have not migrated between herds while wearing collars. Only one adult female Xiaoxue (XX) migrated from DJF-herd to GNG-herd in the Spring of 2016, whose data were not included in the calculation. Staff in the reserve supervised the entire procedure to ensure ethical standards were maintained to the policies of the National Forest Administration.

GPS collars were programmed to record the location every two hours from 5:00 to 19:00 daily. The location data were stored in the collar's memory chip. We used the Biotracter 4M receiver (LOTEK Wireless Inc., Canada) to search for VHF beacon signals from the collars and used the hand-controlled wireless unit (HCU) (LOTEK Wireless Inc., Canada) to download the location data when a GPS collar was within 1 km of the receiver. Data were screened to remove significant positional errors by using the data determined with 3-dimensional fixes, and precision value dilution was no more than ten (BjØrneraas et al., 2010; D'eon & Delparte, 2005). A total of 38 374 GPS location records (33 059 valid data points after filtering) were collected to synthesize the ranging behaviors of GNG-BB and DJF-BB (Supplementary Table S1). To avoid food provisioning interference, we excluded data from the spring and autumn of GNG-BB. In addition, we eliminated repeated locations taken from individuals at the same time to prevent pseudo-replication. Finally, 6 158 loci data were used to calculate the ranging behaviors of GNG-BB in summer and winter and 8 192 loci data to calculate that of DJF-BB in the four seasons.

Supplementary Method S3 Home range, core area, and daily travel distance

Home range and core area were determined using the 'kernel density estimation' method (Worton, 1989) in ArcGIS 10.6 (ESRI., Redlands, CA, USA). Home ranges were constructed as a 95% envelope of the utilization distribution, and the core area was set to 50% (Brockmeyer et al., 2015; Miller et al., 2014). We then calculated the overlap of the core area (Minta, 1992) between summer and winter:

$$\text{Overlap area} = \frac{\text{areaAB}}{\sqrt{\text{areaA} \times \text{areaB}}} \qquad (1)$$

The overlap area is the proportion of overlap between the core area in summer and winter, area A is the core area in summer, area B is the core area in winter, and area AB is the dimension of overlap in the core area between summer and winter. According to the degree of habitat utilization, we classified the area into four categories: core area (50%), moderately-utilized area (non-core area within the home range, 50%–95%), seldom-utilized area (the area outside of the home range but within the scope of activity, 95%–100%), and non-utilized area (the area outside the scope of activity) (Supplementary Figure S1 and Table S2).

In addition, we used the 'Tracking Analyst' module in ArcGIS 10.6 to track the movements of the monkeys and computed the distance between adjacent anchor points based on a time series coordinates (ESRI., Redlands, CA, USA). We used the data located at eight available sites, which are fully tracked in a day to calculate the multipoint cumulative daily ranging distance (Ren et al., 2008). In total 735 days of 1 760 days are available for GNG-BB, and 399 days of 1 202 days are fully tracked for DJF-BB. We calculated the distance parameters including the horizontal distance, altitude distance (vertical distance), and daily travel distance (sum of the Euclidean distance between adjacent points) using the available data.

To distinguish between long-distance migration between habitat patches and short-distance movement within patches, we used K-means clustering in SPSS v26 (SPSS Inc., Chicago, IL) to classify the daily travel distances for a total of 735 days into three categories. The clustering centers of the three categories were 2 178.53 m (*n*=121) for the long-distance category, 1 371.76 m (*n*=317) for the moderate-distance category, and 744.91 m (*n*=297) for the short-distance category. The distances between two OMUs within the GNG breeding band ranged from 14 to 385 m (Huang, 2015). Therefore, the short-distance category, with a clustering center of less than 770 m (385×2), indicated that the band stayed in the same location or moved to a neighboring area that may belong to the same habitat patch as the previous day. Additionally, the category with the largest clustering center, which is more than five times 385 m, could be confirmed as long-distance migration to gain access to another habitat patch.

Supplementary Method S4 Diversity, richness, evenness, and variables of trees

The ecological project for collecting the parameters of plants (both edible and inedible plants for golden snub-nosed monkeys) in the study area since 2014. The parameters included: scientific name, quantity per quadrat, height, diameter at breast height ($DBH \geqslant 15$ cm, 1.37 m above the ground), and crown width of each tree, as well as the species and quantity of liana (wooden vine) attached to trees. The diet of golden snub-nosed monkeys in winter and summer was determined from a dataset reconstructed by Huang (2015) with a total of 1 117.5 h of observation data.

Plant diversity (*PD*), food diversity (*FD*), and main food diversity (*MFD*) were represented by the Shannon-Wiener index (Shannon & Weaver, 1998), the following formula:

$$H = -\sum P_i \times \ln P_i \qquad (2)$$

Plant richness (*PR*), food richness (*FR*), and main food richness (*MFR*) were measured using the Margalef index (Margalef, 1958):

$$D = (S-1)/\ln N \qquad (3)$$

Plant evenness (*PE*), food evenness (*FE*), and main food evenness (*MFE*) were represented by the Pielou index (J_{sw}) (Pielou, 1975):

$$J_{sw} = (-\sum P_i \times \ln P_i)/\ln S \qquad (4)$$

Where Pi is the proportion of food or main food in the quadrat, S is the number of species in the quadrat, and N is the individual number of food or main food species in the quadrat.

In addition, we calculated the average diameter at breast height (*a-DBH*), total tree basal area (*t-TBA*), average tree height (*a-TH*), and total canopy density (*t-CD*) to measure the character of the tree in the quadrat by simplifying the trunk and canopy area to a circle.

The t-TBA was the cross-sectional area determined using *DBH* (Moskal & Zheng, 2012):

$$t\text{ - }TBA(\mathrm{m}^2) = \pi\sum_{i=1}^{n}\left(\frac{DBH_i}{2}\right)^2 \quad (5)$$

The total canopy density was derived by crown width (l) which is the width of branch:

$$t\text{ - }CD(\mathrm{m}^2) = \pi\sum_{i=1}^{n}\left(\frac{l_i}{2}\right)^2 \quad (6)$$

Where n is the number of trees. The higher the *a-TH* value, the greater the degree of trunks. The higher the *t-CD* value, the greater the shade of the plant in the quadrat.

Supplementary Method S5 Interspecific eco-behavioral dataset construction

Ecological data

We downloaded and recompiled the sub-dataset for occurrence records of African colobines from the Global Biodiversity Information Facility (GBIF, https://doi.org/10.15468/dl.6un47t). A total of 2 574 coordinates are available for data extraction of bioclimate and habitat heterogeneity. We obtained 19 bioclimatic variables and elevation data from WorldClim version 2.1 at a spatial resolution of 2.5 arc-minutes (Fick & Hijmans, 2017), and downloaded the metrics (2.5 arc-minutes) quantifying spatial heterogeneity of global habitat at multiple resolutions based on the textural features of Enhanced Vegetation Index (*EVI*) imagery from a published dataset (Tuanmu & Jetz, 2015). Data extraction was conducted in ArcGIS 10.6.1(ArcGIS version 10.6, Environmental Systems Research Institute Inc., Redlands, CA, USA). The ecological data of Asian colobines from a social-ecological dataset soon-to-be published (Qi et al., 2023). Finally, 19 bioclimatic variables, elevation, and latitude of in total of 4 763 coordinates of 79 colobine species (including subspecies) are available in this study (Dataset S1).

Behavioral data

We compiled a dataset covering average home range, group size, and body mass based on the Ecological traits of the world's primates (Galán-Acedo et al., 2019). For missing data, we checked a dataset about home range overlapping in primates (Pearce et al., 2013) and a specific dataset for Asian colobines (Grueter, 2009). Then we search for the available data in the web database of all the world primates (Rowe & Myers, 2017) and other literature. Data and resources are listed in Dataset S1 and Dataset S2.

Phylogeny

The phylogenetic tree is based on the evolutionary relationships constructed by Springer et al. (Springer et al., 2012) and updated according to the latest reports. The phylogeny relationship and divergence time among genera across colobines were updated by referring to (Qi et al., 2023), within *Colobus angolensis* referring to work of McDonald et al. (Mcdonald et al., 2022), and within *Trachypithecus* referring to work of Roos (Roos et al., 2020) and Liu (Liu et al., 2020). As for the *Rhinopithecus* genus, the phylogeny relationship is updated from the work of Qi (Qi et al., 2023) and Yu (Yu et al., 2016).

Supplementary Method S6 Statistical analysis tools and methods

We used Levene's test to examine the homogeneity of variance by using the 'leveneTest' function in the R package 'car' before the test for sample differences. For data with variance homogeneity, we completed analysis of variance (ANOVA), post hoc least significant difference test, independent samples *t*-test, and paired *t*-test using SPSS software v26 (SPSS Inc., Chicago IL). As for data with variance heterogeneity, we used the Mann-Whitney *U*-test to compare differences between two groups, and used the nonparametric Kruskal-Wallis test and post hoc Dunn's all-pairs test with FDR correction for multiple comparisons by the "ggbetweenstats" function in the "ggstatsplot" package (Patil, 2021). Before principal component analysis (PCA) analysis, we used correlation analysis, Kaiser-Meyer-Olkin (KMO), and Bartlett's test to measure the partial correlations between variables. These results were used to make methodological decisions on whether the PCA would be available to reduce the dimensionality. PCA would be accepted if KMO⩾0.5 and a statistical significance testing coefficient for Bartlett (P<0.05) (Hair Jr et al., 2009). A KMO statistic from 0–1 and a value of at least 0.80 are sufficient for PCA to yield distinct and reliable factors (Hair Jr et al., 2009). PCA is acceptable for values 0.5-0.8, and there are isolated variables worth addressing. Therefore, if the KMO value was between 0.5 and 0.8, we considered both principal components extracted by PCA and some important original variables. Correlation analysis was conducted using the "cor" function in the 'corrplot' package in R 4.1.0 (R Core Team, 2022; Wei & Simko, 2021). KMO and Bartlett's tests are performed by "KMO" and "cortest.bartlett" functions in "psych" packages (Revelle, 2022). PCA was conducted with the "principal" function in "psych" packages (Revelle, 2022) or SPSS software v26 (SPSS Inc., Chicago IL). The PCA was rotated using "maximum variance" to promote interpretation. The output was visualized using the ggplot2 package (v3.3.3; Wickham, 2016) and Origin Pro 2018 (Origin Lab Inc., Northampton, Massachusetts, USA.). The eigenvalue (>1) criterion was used to determine the initial set of factors (Hair Jr et al., 2009). Statistically significant differences were identified at the 95% confidence level (P<0.05*) of all two-sided tests. The highly significant results in the analysis are marked P<0.01** and P<0.001***.

Specifically, the ecological constraints hypothesis suggested that the increases in group size will increase intragroup feeding competition, thus forcing individuals to visit more patches and cover a larger home range (Grove, 2012). Group sizes changed little in summer and winter each year because golden snub-nosed monkeys exchange members between bands and give birth in spring. Therefore, differences tests per year were appropriate to control the effect of variation in group size when testing the seasonal difference of ranging behaviors.

Supplementary Method S7 Phylogenetic comparative analysis

As most bioclimatic variables and log transformed correlated with each other

(Supplementary Table S9–S10 and Figure S6), we extracted four principal components (*PCs*), which explained 92.56% of the variances in total using PCA (Supplementary Table S11). *PC1* is positively correlated with isothermality, *PC2* is positively contributed by the mean and max temperature of the warmest quarter, *PC3* includes precipitation of the wettest quarter, and PC4 is mainly related to the diurnal range (Supplementary Table S11). In addition, we calculated the total score (*PCT*) using the variance percentage weighted principal components (Supplementary Table S11). The higher scores of *PCT* indicated a more stable, warm, and humid climate.

Phylogenetic generalized least squares analysis (PGLS) was used to test the correlation between the home range and the 30 candidate variables, including 19 *BCs* (bioclimatic variables), elevation, the absolute value of latitude, and five principal components of bioclimatic variables. First, we examine the effect of each variable on *HR* and *GS* using a single variable as the independent variable. The top five models in terms of goodness-of-fit show that HR is correlated with *bio 11*, *bio 6*, *GS*, *bio 9*, and *bio 1*; *GS* is correlated with *HR*, *elevation*, *PCT*, *bio 6*, *bio 1*; *BM* is associated with the *HR*, *PCT*, *GS* and *bio 6*. Then we performed a complex model which considered *HR* as the dependent variable and the remaining variables were independent variables. The top three models in terms of goodness-of-fit are *HR ~ bio 6·GS·BM*, *HR ~ bio 11·GS·BM*, and *HR ~ bio 4·GS·BM*. As for *GS*, the top three models are *GS ~ bio 2·HR·BM*, *GS ~ PC4·HR·BM*, and *GS ~ bio 10·HR·BM*. These variables are interrelated; for example, *bio 11* is significantly correlated with *bio 9* (r=0.993, P<0.01) and *bio 6* (r=0.988, P<0.01) (Supplementary Table S10 and Figure S6), therefore, bio 11 would be the proxy variable of *bio 6* and *bio 9* to characterize the temperature in cold period. After simplifying the similarly related variables, the following 8 variables are considered in the phylogenetic path analysis: *HR*, *GS*, *BM*, *bio 11*, *bio 4*, *PCT*, *elevation*, and the absolute latitude value. Based on the PGLS and correlation test results, we formed three sets of variables (8 variables, 9 variables and 6 variables) by adding and removing these uncertain variables. For each set of variables, we used phylogenetic path analysis (PPA) to determine the best causal model of these interrelated variables from 16 candidate models. The candidate models were designed by altering indirect links and causal direction between variables to distinguish paths. The first is direct effect versus indirect effect, such as whether elevation affects group size directly (model 5 and model 6) or via other bioclimate variables (other models). The second is the direction of causality, for example, whether home range size affects group size (odd ordinal models) or group size affects home range size (even ordinal models) (Supplementary Figure S7–S8). The third is independent effect versus joint effect, such as whether home range affects group size independently or jointly with other bioclimate variables. The best-supported model was obtained by assessing the goodness of fit of the above candidate models using the R package "phylopath" (Van Der Bijl, 2018).

3D phylomorphospace plots are drawn by using the "phylomorphospace3d" function in the R package "phytools" (Revell, 2012); The PGLS analysis is performed with the "pgls" function in the "caper" package (Orme et al., 2018), and PPA is conducted using the "phylo_path" function in "phylopath" package (Van Der Bijl, 2018).

SUPPLEMENTARY TABLES

Supplementary Table S1 The individual's information and valid loci data tracked by GPS collars

Direct observation and collar data validation showed that 14 individuals stayed in the studied group during the period of collar wearing except for the female XX (XiaoXue). This female dispersed from DJF-herd to GNG-herd in the spring of 2016.

ID	Breeding Band	Gender	Collar ID	Circumference length	Start-up time	Ending time	Total data	Valid data
TB	GNG	Male	33200	30	2012.12.21	2013.04.03	656	522
BB	GNG	Male	33202	32	2012.12.29	2013.12.30	2 959	2 552
FZ	GNG	Male	33199	32	2013.11.16	2014.04.26	661	595
TH	GNG	Female	35025	25	2014.04.04	2016.04.12	5 016	4 529
HX	GNG	Female	35026	23	2014.05.14	2014.07.01	144	130
YT	GNG	Female	39365	27	2015.12.14	2017.05.06	4 075	3 762
ST	GNG	Male	39360	32	2015.12.05	2018.01.31	5 814	3 781
BD	DJF	Male	33203	33	2013.01.08	2013.04.13	538	481
DS	DJF	Male	33203	35	2014.01.09	2014.09.08	1 596	1 408
PL	DJF	Male	33201	33	2014.01.09	2014.09.04	1 895	1 636
XQ	DJF	Female	35028	24	2014.12.10	2015.03.30	857	509
ML	DJF	Female	35027	24	2014.12.11	2015.07.04	4 567	4 171
DX	DJF	Female	39439	26	2015.12.19	2017.04.29	3 989	3 746
XX	DJF/ GNG	Female	39364	26	2015.12.23	2016.06.29	1 578	1 482

LD	DJF	Male	3944 0	33	2015.12.2 2	2017.04.29	4 029	3 755
Total							38 374	33 059

Supplementary Table S2 The coordinate, elevation, and forest type on sample quadrats

N-1, N-2 are small quadrats 50 m×50 m. Others are large quadrats 200 m×200 m, each large quartile comprising 16 small quartiles 50 m×50 m. "○": The reused samples.

BB	Sample No.	Longitude	Latitude	Utilization	Seasons	Habitat types	Elevation
GNG	S-H-1	108.2912	33.8178	High	Summer	Deciduous broadleaf forest	2 048
	S-H-2○	108.2596	33.8240	High			1 772
	S-H-3○	108.2436	33.8254	High			1 624
	S-M-1○	108.2793	33.8153	Moderate			1 563
	S-M-2○	108.2825	33.8078	Moderate			1 602
	S-M-3○	108.2471	33.8251	Moderate			1 712
	S-S-1 ○	108.2907	33.8044	Low			1 608
	S-S-2	108.2462	33.8188	Low			1 838
	S-S-3○	108.2933	33.8187	Low			2 062
	W-H-1○	108.2436	33.8254	High	Winter	Deciduous broadleaf forest	1 624
	W-H-2○	108.2471	33.8251	High			1 712
	W-H-3	108.2564	33.8206	High			2 042
	W-M-1○	108.2793	33.8153	Moderate			1 563
	W-M-2○	108.2907	33.8044	Moderate			1 608
	W-M-3○	108.2596	33.8240	Moderate			1 772
	W-S-1○	108.2825	33.8078	Low			1 602
	W-S-2	108.2453	33.8224	Low			1 728
	W-S-3○	108.2933	33.8187	Low			2 062
DJF	D-S-H-1	108.2496	33.8132	High	Summer	Deciduous broadleaf forest	2 000
	D-S-H-2	108.2228	33.8177	High	Summer		2 176
	D-S-H-3	108.2611	33.8051	High	Summer		2 291
	D-W-H-1	108.2457	33.8215	High	Winter		1 514
	D-W-H-2	108.2453	33.8166	High	Winter		1 667

	D-W-H-3	108.2544	33.8119	High	Winter		2 080
	N-1	108.3141	33.8484	Non	Whole years	Coniferous forest	2 961
	N-1	108.3135	33.8488	Non			2 960
	N-1	108.3131	33.8497	Non			2 973
	N-1	108.3111	33.8563	Non			2 855
	N-1	108.3107	33.8563	Non			2 835
	N-1	108.3011	33.8615	Non			2 728
	N-1	108.3017	33.8622	Non			2 719
	N-1	108.2981	33.8601	Non			2 656
	N-1	108.2975	33.8596	Non			2 646
	N-1	108.2925	33.8572	Non		Coniferous and deciduous broadleaf mixed forest	2 574
	N-1	108.2925	33.8576	Non			2 561
	N-2	108.2997	33.7649	Non	Whole year	Coniferous forest	2 877
	N-2	108.2976	33.7655	Non			2 850
	N-2	108.3009	33.7663	Non			2 773
	N-2	108.3028	33.7662	Non			2 762
	N-2	108.3024	33.7683	Non			2 645
	N-2	108.2995	33.7679	Non			2 655
	N-2	108.3026	33.7704	Non		Coniferous and deciduous broadleaf mixed forest	2 571
	N-2	108.3013	33.7699	Non			2 566
	N-3	108.2109	33.8732	Non	Whole year	Deciduous broadleaf forest	1 155

Supplementary Table S3 Classification of habitats

The classification is based on the degree of home range calculation each year. H: highly utilized; M: moderately utilized; S: seldom utilized; N: non-utilized area.

Sample	Summer					Sample	Winter				
	2013	2014	2015	2016	2017		2012-2013	2013-2014	2014-2015	2015-2016	2016-2017
S-H-1	**H**	**H**	**H**	**H**	M	W-H-1○	M	S	**H**	S	S
S-H-2○	**H**	S	**H**	M	**H**	W-H-2○	M	S	**H**	S	S
S-H-3○	M	M	M	**H**	M	W-H-3	S	**H**	M	M	S
S-M-1○	S	M	M	M	M	W-M-1○	M	M	S	/	/
S-M-2○	M	M	M	S	S	W-M-2○	M	M	N	N	M
S-M-3○	M	M	M	S	N	W-M-3○	M	S	S	M	S
S-S-1○	N	M	N	S	N	W-S-1○	M	S	S	N	S
S-S-2	M	S	S	N	N	W-S-2	M	N	N	S	N
S-S-3○	M	S	S	S	S	W-S-3○	N	M	S	S	S
N-1	N	N	N	N	N	N-1	N	N	N	N	N
N-2	N	N	N	N	N	N-2	N	N	N	N	N
N-3	N	N	N	N	N	N-3	N	N	N	N	N

Supplementary Table S4 The estimation of home range, core area and overlap of GNG-breeding band in summer and winter

The locate data of December 2012 are incomplete due to food provisioning or recorder-wearing problems. A large amount of data failed in location as the collar ran out of power in the summer of 2017. Summer: June-August; Winter: from December to February of next year. *CA* to *HR* (%) : the proportion of core area to home range (%).

Item	Summer					Winter					Seasonal overlap of the core area (%)
	Year	Value	*CA* to *HR* (%)	Data points	Individ-uals	Year	Value	*CA* to *HR* (%)	Data points	Indivi-duals	
Core area (50%)/km²						2012–2013	*0.26*	*3.19*	644	TB, BB	
	2013	0.88	5.93	613	TB, BB	2013–2014	0.72	8.83	640	FZ	0.09
	2014	0.21	1.58	659	BB	2014–2015	1.30	12.70	671	TH	0.00
	2015	1.08	7.02	670	TH	2015–2016	0.73	11.70	606	TH	0.1
	2016	0.52	4.38	654	YT	2016–2017	0.18	5.19	677	YT	0.15
	2017	0.56	4.01	324	YT, ST						
Home range (95%)/km²						2012–2013	*8.16*		644	TB, BB	
	2013	14.85		613	TB, BB	2013–2014	8.15		640	FZ	
	2014	13.27		659	BB	2014–2015	10.24		671	TH	
	2015	15.39		670	TH	2015–2016	6.24		606	TH	
	2016	11.88		654	YT	2016–2017	3.47		677	YT	
	2017	*13.98*		324	YT, ST						

Supplementary Table S5 The estimation of daily travel distances of GNG-breeding band

Group sizes are approximately the same in summer and winter each year because golden monkeys exchange members between herds and give birth in spring. Therefore, to remove the effect of variation in group size, a paired *t*-test was conducted using the data from each summer and winter as a pair. Spring: March to May; Summer: June to August; Autumn: September to November; Winter: December to February in the next year.

Item	Year	Daily travel distance / m		Independent samples *t*-test		
		Summer	Winter	*t*	*df*	*P*
GNG-BB	2013	1 531.27±498.05 (24 d)	1 005.24±485.39 (42 d)	4.20	64	<0.001***
	2014	1 416.2±707.19 (42 d)	936.39±427.32 (53 d)	3.87	63.94	<0.001***
	2015	1 708.35±470.30 (42 d)	890.38±423.49 (53 d)	8.90	93	<0.001***
	2016	1 461.96±607.25 (36 d)	924.69±458.53 (58 d)	4.56	59.58	<0.001***
Paired *t*-test				7.68	3	0.005**

Supplementary Table S6 The estimation of daily travel distances of DJF-breeding band

BB	Seasons	Daily travel distance (m)	
		2015	2016
DJF-BB	Spring	1 104.99±380.85 (22 d)	1 144.34±578.22 (35 d)
	Summer	1 309.77±383.78 (25 d)	1 105.90±415.17 (44 d)
	Autumn	1 242.51±333.64 (28 d)	1 139.37±464.78 (33 d)
	Winter	1 038.34±589.27 (34 d)	786.77±399.37 (64 d)
ANOVA test	*df*	3	3
	F	2.17	7.803
	P	0.096	**<0.001*** **

Supplementary Table S7 Multiple comparisons of daily travel distance among seasons of DJF-BB

Year	Seasons I	Seasons J	Mean Difference (I-J)	Standard error	*P*	95% Confidence interval Lower limit	95% Confidence interval Upper limit
2015	Spring	Summer	–204.772	131.452	0.122	–465.417	55.873
		Autumn	–137.517	128.113	0.286	–391.542	116.508
		Winter	66.862	123.039	0.588	–177.101	310.826
	Summer	Spring	204.772	131.452	0.122	–55.873	465.417
		Autumn	67.255	123.734	0.588	–178.086	312.597
		Winter	271.635	118.472	**0.024***	36.726	506.543
	Autumn	Spring	137.517	128.113	0.286	–116.508	391.542
		Summer	–67.255	123.734	0.588	–312.597	178.086
		Winter	204.379	114.756	0.078	–23.161	431.920
	Winter	Spring	–66.862	123.039	0.588	–310.826	177.101
		Summer	–271.635	118.472	**0.024***	–506.543	–36.726
		Autumn	–204.379	114.756	0.078	–431.920	23.161
2016	Spring	Summer	28.440	103.242	0.783	–175.344	232.224
		Autumn	4.972	110.603	0.964	–213.342	223.285
		Winter	357.564	95.829	**<0.001*****	168.413	546.716
	Summer	Spring	–28.440	103.242	0.783	–232.224	175.344
		Autumn	–23.468	104.970	0.823	–230.663	183.727
		Winter	329.125	89.268	**<0.001*****	152.922	505.327
	Autumn	Spring	–4.972	110.603	0.964	–223.285	213.342
		Summer	23.468	104.970	0.823	–183.727	230.663
		Winter	352.593	97.688	**<0.001*****	159.771	545.414
	Winter	**Spring**	–357.564	95.829	**<0.001*****	–546.716	–168.413

	Summer	–329.125	89.268	**<0.001*****	–505.327	–152.922
	Autumn	–352.593	97.688	**<0.001*****	–545.414	–159.771

Supplementary Table S8 The differences in range parameters between breeding bands

The range parameters of GNG in spring and autumn have yet to be calculated because the food provision will affect the range behaviors. The data of DJF-BB are not as sufficient as GNG-BB's, which may cause errors due to sampling size differences. Therefore, we eliminate the extra data of GNG-BB so that the amount of data is approximately equal. As a result, there are data from 2014 to 2016 (9 months) in summer, and Jan. 10, 2013 - Feb. 28, 2013; Jan. 10, 2014 - Feb. 28; 2014, Dec. 2014–Feb. 2017 (~ 12 months) in winter included in the calculation of core area and home range. The full-day data of DJF-BB's DTD in 2014 are not sufficient for analysis purposes, therefore, we only merged the *DTD* data in 2015 and 2016 to compare the differences. Nonparametric data are shown as median (first quartile (Q1) and third quartile (Q3)).

Range parameters	Breeding band	Spring	Summer	Autumn	Winter	Winter and summer
Core area	GNG	/	0.36	/	0.22	1.48
	DJF	0.10	0.93	0.74	0.41	1.57
Home range	GNG	/	16.83	/	11.27	20.11
	DJF	33.76	21.93	8.09	14.82	24.51
Daily travel distance (DTD)	GNG	/	1 495.15 (1 109.03 – 2 095.49) (78 d)	/	885.78 (621.49–1 123.08) (111 d)	
	DJF	1 064.19 (1 741.81–1 458.63) (57 d)	1 150.18 (881.49–1 515.02) (69 d)	1 158.99 (968.68–1 486.03) (61 d)	749.32 (532.36–1 055.36) (98 d)	
Mann-Whitney *U*-test for DTD between breeding	*U*		1 524		4 786	
	Z		-4.53		–1.50	
	P		**<0.001*****		0.135	

bands

Supplementary Table S15 Seasonal daily travel distance (m) of *Rhinopithecus*

Species	Locality	Group size	Daily travel distance(m)						Methods	Reference
			Average	Annual	Winter	Spring	Summer	Autumn		
Rhinopithecus roxellana	Zhouzhi	160–190 60–80			926 ⬇ [212d] 749⬇ [98d]	1 318 [147d] 1 159 [61d]	1 532 [120d] 1 150 [69d]	1 309 [156d] 1 064 [57d]	Auto-released GPS; Tracking analyst in ArcGIS	This study
	Zhouzhi	112		2 100 [126]	1 600 ⬇ [33d]	2 200 [40d]	2 600 [25d]	1 900 [28d]	Visual tracking	(Tan et al., 2016)
Rhinopithecus biet	Gehuaqing (Baimaxueshan Nature Reserve)	410		1 514 (212–4 216) [40 d]	985 ⬇ [10 d]	1 721 [10 d]	1 516 [10 d]	1 877 [10 d]	Following group	(Grueter et al., 2013)
	Jinsichang	291		909±472 [29]	814 ⬇ [75d]	870 [88d]	1 023 [81d]	940 [47d]	Auto-released GPS	(Ren et al., 2009a)
	Xiaochang-du	207	765 (350–3 500)		Lowest⬇		Highest		The map grid cell method	(Xiang et al., 2013)
Rhinopithecus brelichi	Fanjingshan National Nature Reserve				3 500–6 200 ⬆	5 200–7 000	550–2 000	1 100–4 000	GPS (Garmin Etrex 20)	(Guo et al., 2018)

Rhinopithecus avunculus	851.3 673.5	(Hoang & Covert, 2012)

Supplementary Table S16 Seasonal home range sizes (km²) of *Rhinopithecus*

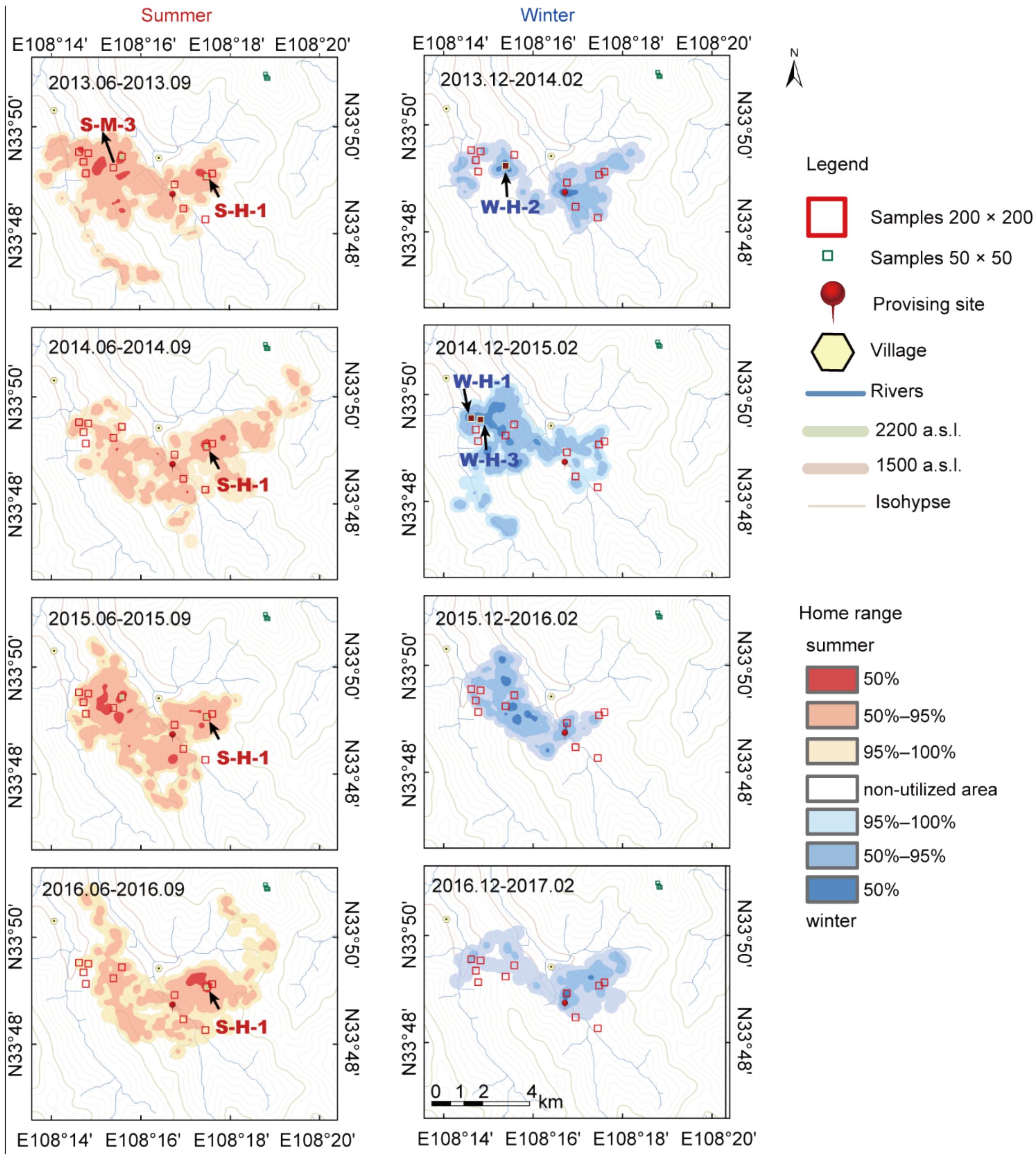
"⬇": The home range is smaller in winter than that in summer; "⬆": larger, "≈": approximately equal. In terms of the investigation of seasonal changes in the home range, the MCP method might not be the most appropriate technique when compared to the grid-cell (GC) method (Ren et al., 2009b).

Species	Locality	Group size	Home range size (km²) [*n*]					Methods	Reference
			Annual	Winter	Spring	Summer	Autumn		
Rhinopithecus roxellana	Zhouzhi	180–220		11.27 ⬇		16.83		GPS auto tracking, Kernel Density Estimation (KDE), multi-year	This study
	Zhouzhi	60–80		14.82⬇	33.76	21.93	8.09		
	Zhouzhi	65–131	22.5	12.3 ⬆ [81]	14.1 [59]	9.5 [51]	12.1 [71]	Radio telemetry; 500× 500 m; minimum convex polygon (MCP) method	(Li et al., 2000)
	Zhouzhi	112	18.3	7.1 ⬆	11.9	5	2.9	Visual tracking, an hour interval, 250 m×250 m grid-cell (GC) method	(Tan et al., 2007)
	Shennongjia	236	22.5	12.3 ⬇	18.6	14.5	19.4	Visual tracking; Handheld GPS; 30 min intervals; KDE	(Fan et al., 2019)
	Shennongjia	62	12.4 (Nov.–Jun.)	6.0 ⬇	12.0	11.7			
	Qingmuchuan	100–120	20.35	7.43⬇		8.09		Visual tracking; Handheld GPS; Kernel density	(Li et al., 2010)
	Tangjiahe	138	18.64	13.04⬆	12.24	11.56	13.68	Visual tracking; Handheld GPS; 200 m×200 m grid-cell (GC) method	(Fan, 2017)

	Baihe	280	22.13	8.13↓ [29]	8.94 [30]	10.25 [27]	6 [32]	Visual tracking; Handheld GPS; 30-min intervals; 250m×250 m grid-cell (GC) method	(Li, 2016)
	Baihe	250		4.94↓	14.19	15.16	25.17	Visual tracking; Handheld GPS; 30 min interval, Kernel Density Estimation (KDE)	(Dong et al., 2021)
Rhinopithecus biet	Xiaochangdu	207	21.25 (2 years)	10.50 ↓		16.75		Visual or auditory clue with the aid of GPS points and landmarks; every 2 h via GPS receiver; 500 m × 500 m GC	(Xiang et al., 2013)
	Jinsichang		17.30	10.5 ↑	8.5	9.2	23	Global positioning system collar; 100% MCP [2]	(Grueter, 2009; Ren et al., 2009b)
				5.1 ↓ [81]	7.0 [112]	7.3 [117]	6.0 [96]	250 m × 250 m grid-cell (GC) method; GPS	
	Tacheng			18.2 ≈ [172]	17.8 [333]	18.6 [239]	9.3 [954]	30-min intervals; Visual or auditory contact; trailing the group; GPS receiver; 250 m × 250 m GC; MCP	(Grueter et al., 2008)
Rhinopithecus brelichi	Yangaoping (Fanjingshan National Nature Reserve)	450 (Spring, summer, and early autumn) 50–200 (Late autumn and winter)	34.50	5 ↑ (Cold season)		3.875 (Warm season)		250 m×250 m GC	(Grueter, 2009; Xiang et al., 2010)
Rhinopithecus avunculus	(1) 1.7 to 3.14 km^2. (2) 4.55 km^2 (3) 10 km^2 for the TSNMs in the Tat Ke sector, Na Hang Nature Reserve (Tuyen Quang province).								(Hoang & Covert, 2012)

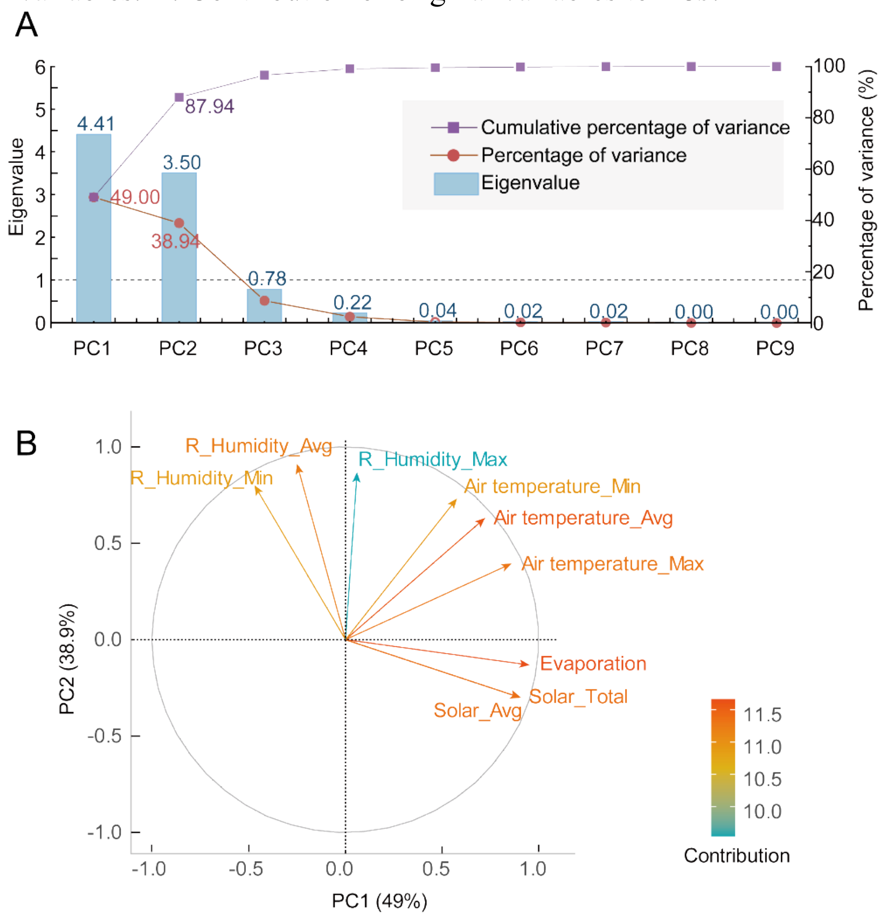
SUPPLEMENTARY FIGURES

Supplementary Figure S1 Seasonal home range of the GNG breeding band from 2013 to 2017



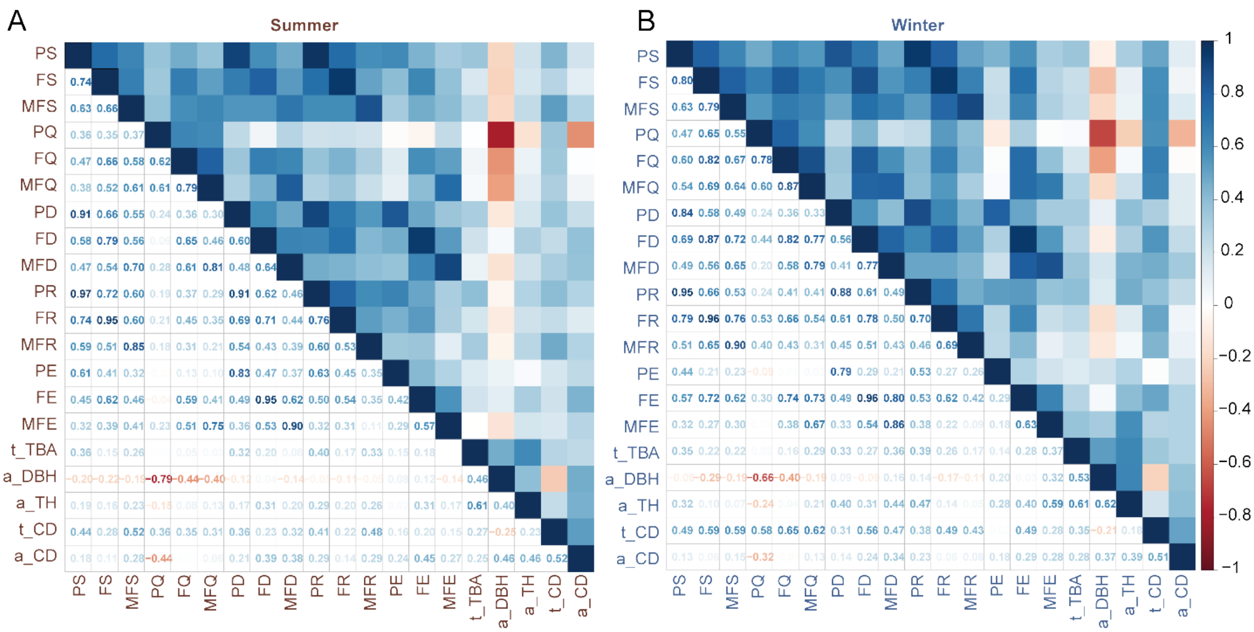
Supplementary Figure S2 Principal component analysis (PCA) of meteorological variables

A: Eigenvalue and percentage of the variance of principal components (*PCs*) in the PCA of meteorological variables. B: Contribution of original variables to *PCs*.



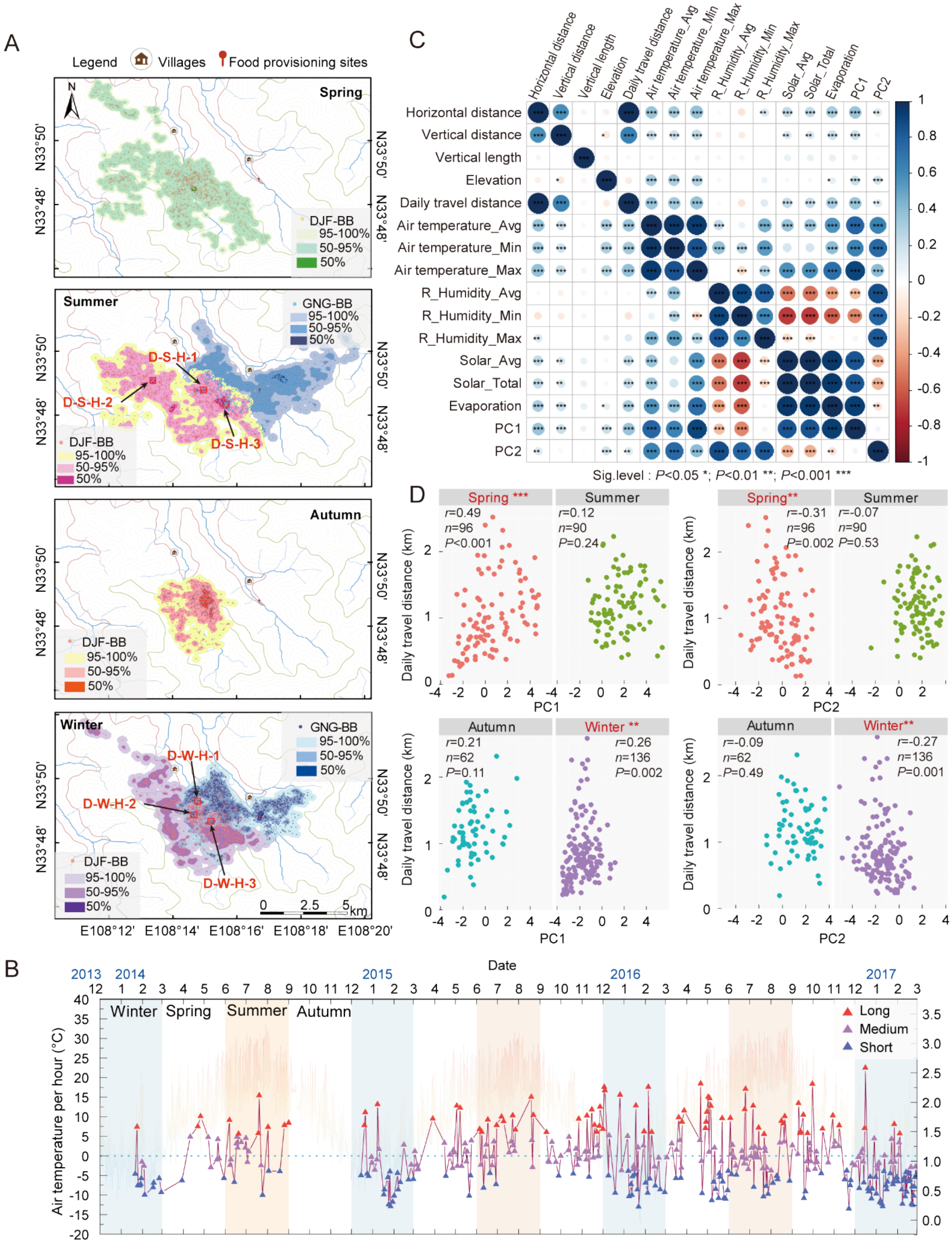
Supplementary Figure S3 Correlation matrix of 20 original vegetation variables of GNG-BB

PS: number of plant species; FS: number of food species; *MFD*: number of main food species; *PQ*/ *FQ*/ *MFQ*: quantity of all plants/food species/main-food species; *PD*/ *FD*/ *MFD*: diversity of plants/food/main-food species; *PR*/ *FR*/ *MFR*: the richness of plants/food/main-food species; *PE*/ *FE*/ *MFE*: evenness of richness of plants/food/main-food species; *t-TBA*: total tree basal area; *a-DBH*: average diameter at breast height; a-TH: average tree height; *t-CD*: total canopy density; *a-CD*: average canopy density.



Supplementary Figure S4 Seasonal ranging behaviors of DJF breeding band (DJF-BB)

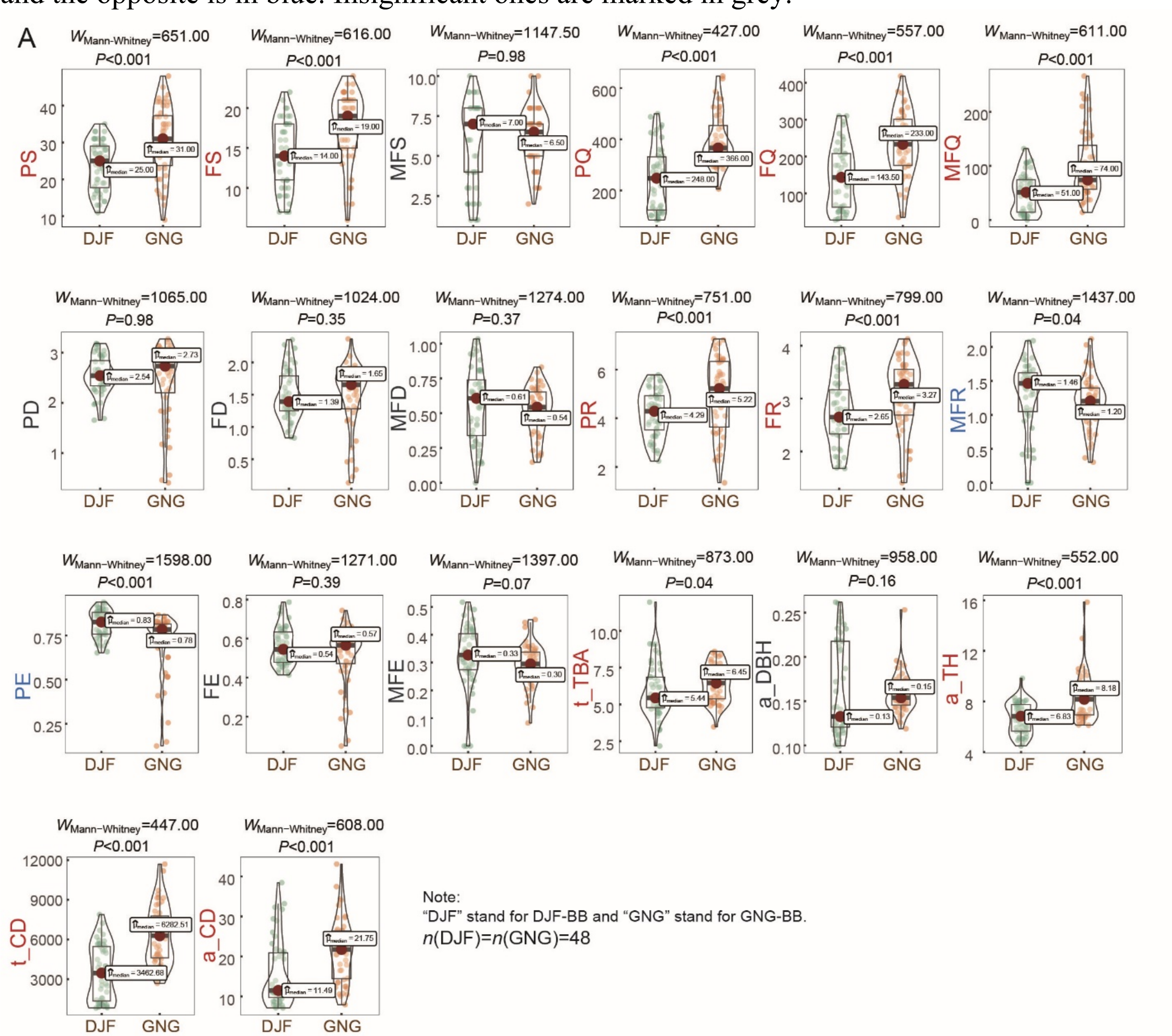
A: Seasonal home range of DJF breeding band (DJF-BB) and the comparison with GNG-BB.
B: Dynamic change in daily travel distance (*DTD*) and temperature from December 2013 to February 2017.
C: Correlation matrix of meteorological variables and ranging parameters of DJF-BB.
D: Scatterplots showing the correlation between the *DTD* of DJF-BB and *PC* scores in four seasons.



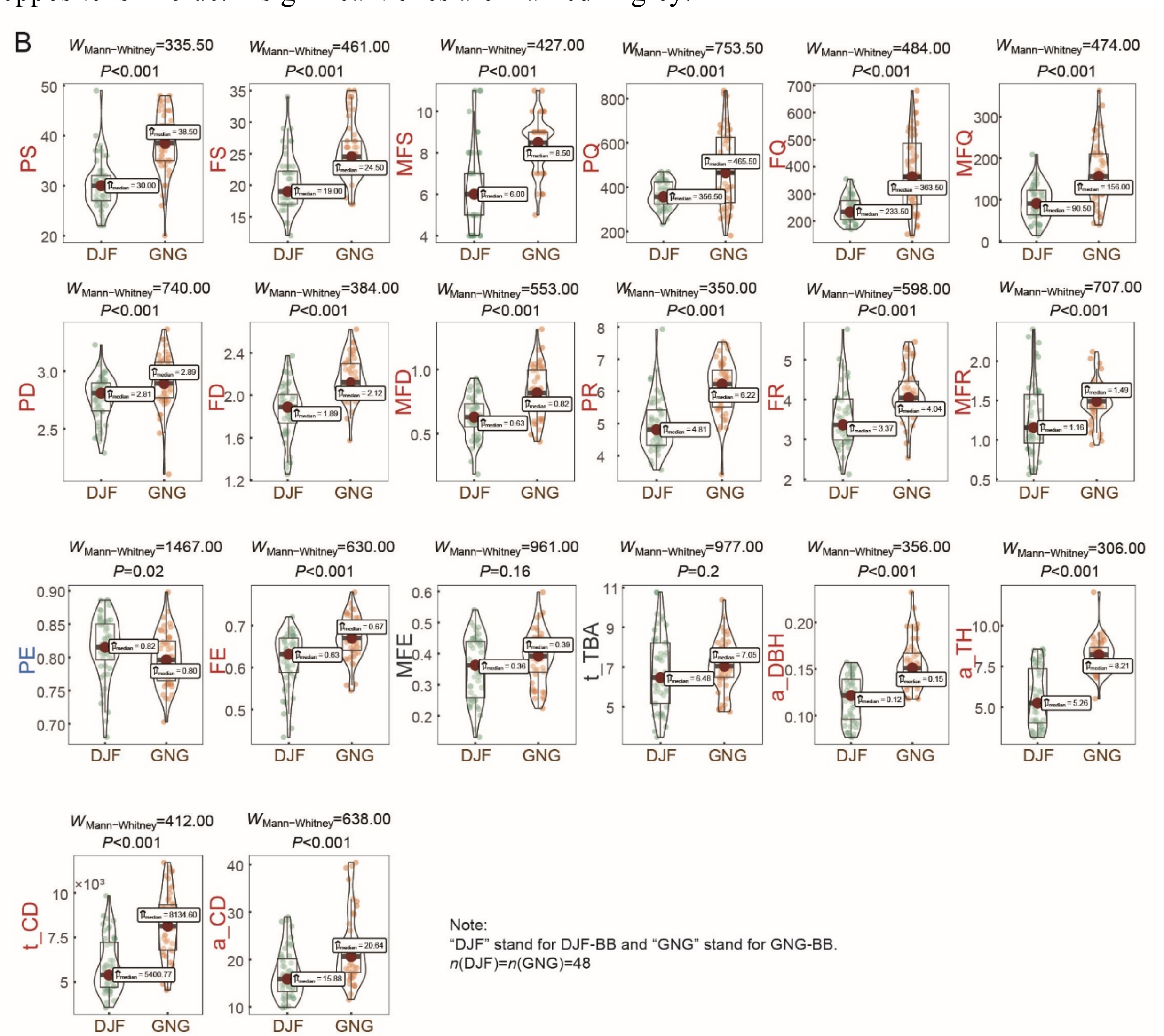
A
Legend
Villages
Food provisioning sites
Spring
Summer
Autumn
Winter
DJF-BB
GNG-BB
95-100%
50-95%
50%
D-S-H-1
D-S-H-2
D-S-H-3
D-W-H-1
D-W-H-2
D-W-H-3
N33°50'
N33°48'
E108°12'
E108°14'
E108°16'
E108°18'
E108°20'
0
2.5
5
km
B
Date
2013
2014
2015
2016
2017
Winter
Spring
Summer
Autumn
Long
Medium
Short
Air temperature per hour (°C)
Daily travel distance (km)
C
Horizontal distance
Vertical distance
Vertical length
Elevation
Daily travel distance
Air temperature_Avg
Air temperature_Min
Air temperature_Max
R_Humidity_Avg
R_Humidity_Min
R_Humidity_Max
Solar_Avg
Solar_Total
Evaporation
PC1
PC2
Sig.level : P<0.05 *; P<0.01 **; P<0.001 ***
D
Spring ***
r=0.49
n=96
P<0.001
Summer
r=0.12
n=90
P=0.24
Spring**
r=-0.31
n=96
P=0.002
Summer
r=-0.07
n=90
P=0.53
Autumn
r=0.21
n=62
P=0.11
Winter **
r=0.26
n=136
P=0.002
Autumn
r=-0.09
n=62
P=0.49
Winter**
r=-0.27
n=136
P=0.001
Daily travel distance (km)
PC1
PC2

Supplementary Figure S5 Comparison of the habitat variables in the core area between bands

A: Habitat differences between GNG-BB and DJF-BB in summer. Variables that are significantly higher in GNG-BB (large group) than in DJF-BB (small group) are marked in red, and the opposite is in blue. Insignificant ones are marked in grey.

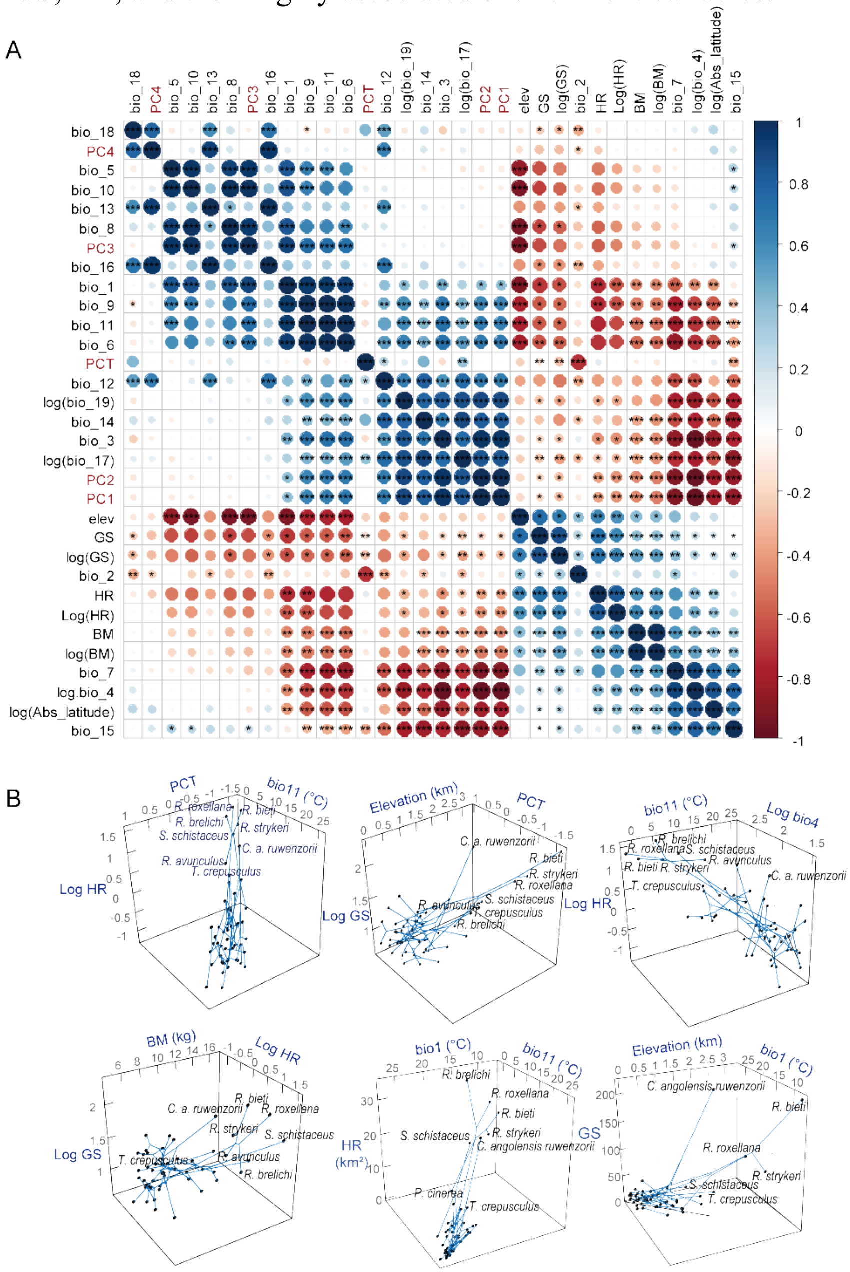


B: Habitat differences between GNG-BB and DJF-BB in winter. Variables that are significantly higher in GNG-BB (large group) than in DJF-BB (small group) are marked in red, and the opposite is in blue. Insignificant ones are marked in grey.



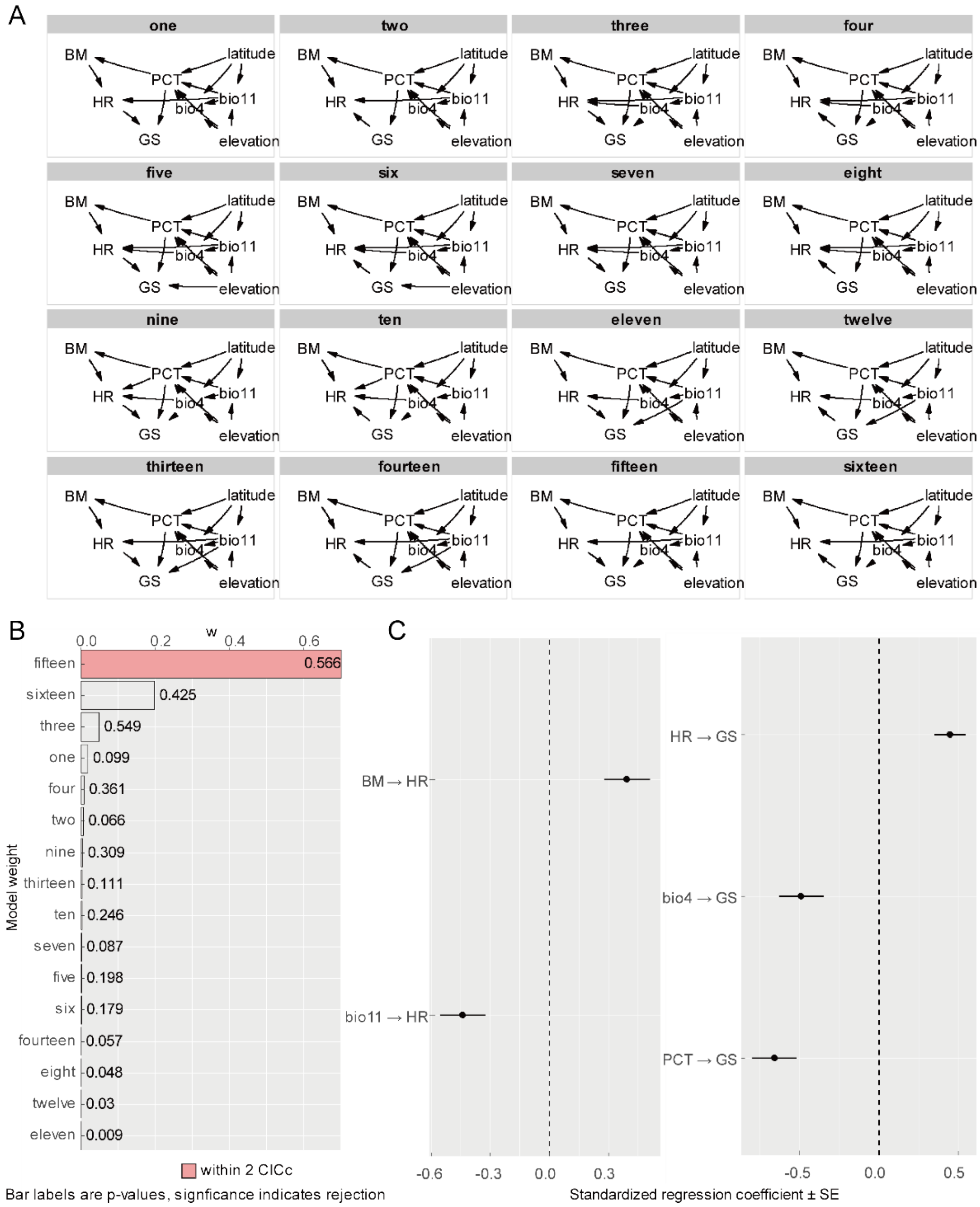
Supplementary Figure S6 Correlations among interspecific ecological-behavioral variables

A: Correlation matrix of 32 eco-behavioral variables. B: The 3D phylomorphospace plots show the correlation of GS, HR, and their highly associated environment variables.



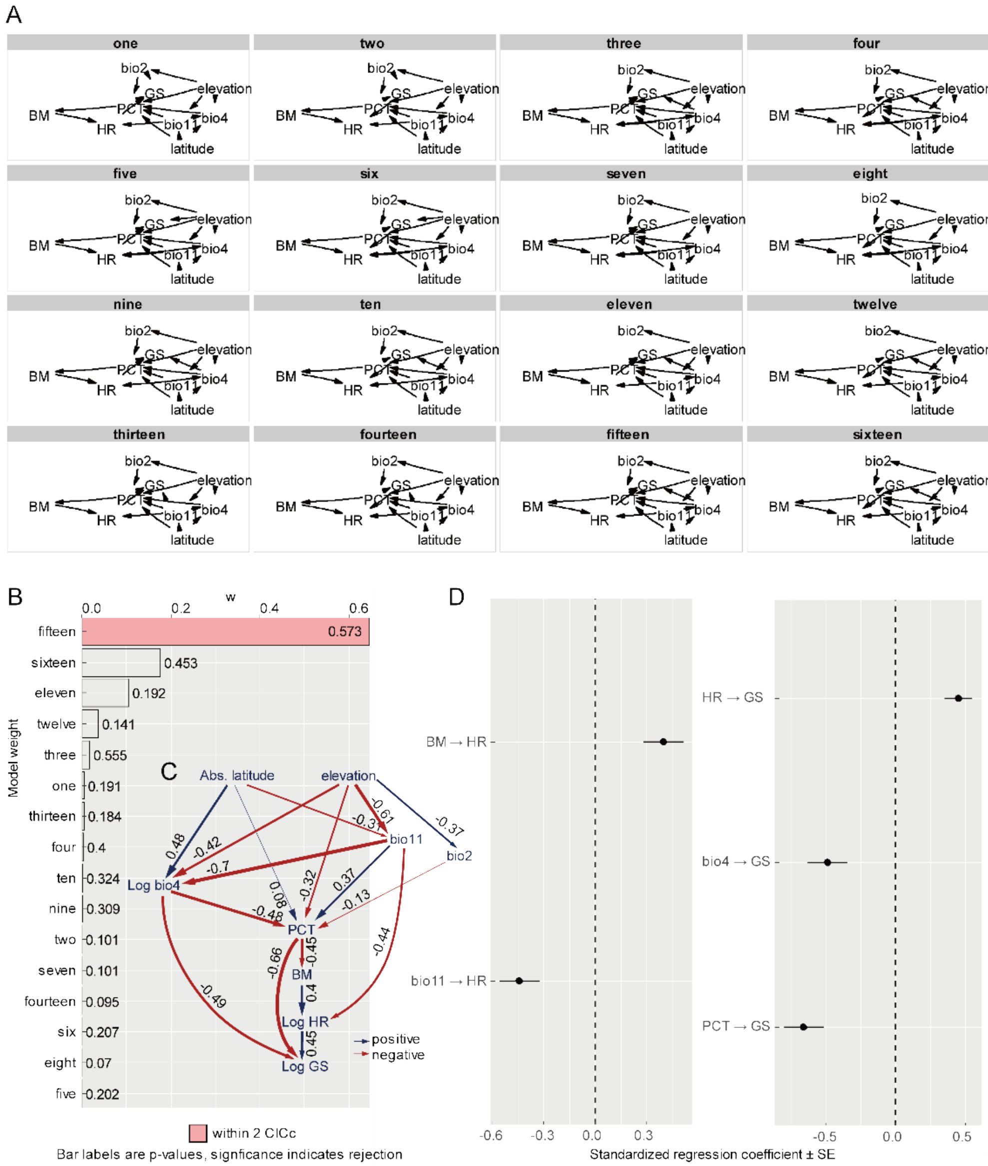
Supplementary Figure S7 Results of phylogenetic path analysis (8 variables)

A: The model set of 8 variables (*BM*, *HR*, *GS*, *bio 4*, *bio 11*, *PCT*, *elevation*, and *absolute altitude*). B: The relative importance of the 16 candidate models. D: The standardized path coefficients and their standard errors.



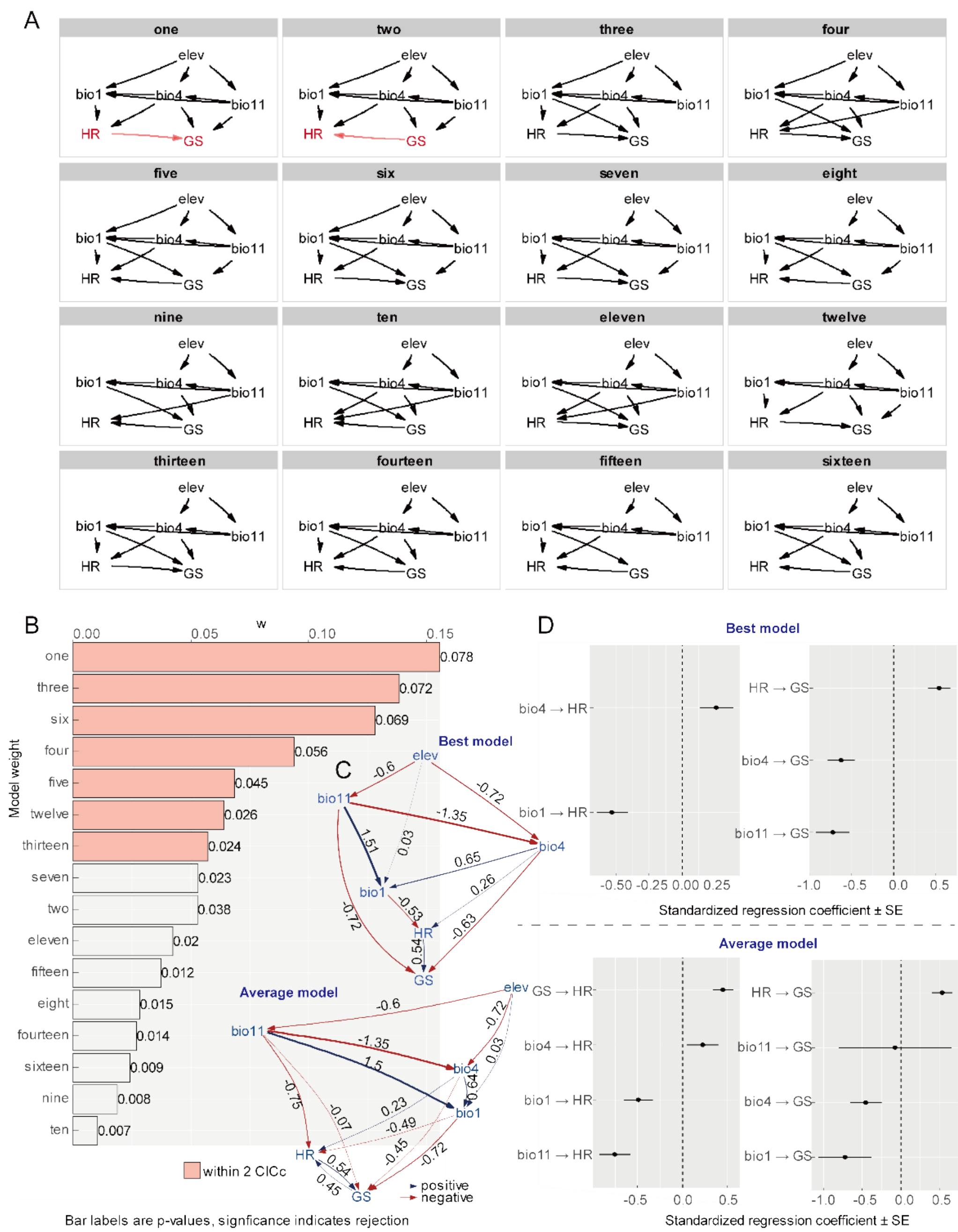
Supplementary Figure S8 Results of phylogenetic path analysis (9 variables)

A: The model set of 9 variables (*BM*, *HR*, *GS*, *bio 4*, *bio 2*, *bio 11*, *PCT*, *elevation*, and *absolute altitude*). B: The relative importance of the 16 candidate models. C: The best supported causal model and the standardized path coefficients. D: The standardized path coefficients and their standard errors.



Supplementary Figure S9 Results of phylogenetic path analysis (6 variables)

A: The model set of 6 variables (*HR*, *GS*, *bio 4*, *bio 1*, *bio 11*, *elevation*). B: The relative importance of the 16 candidate models. C: The best-supported causal model and the average model. D: The standardized path coefficients and their standard errors of the best supported model (upper) and average model (bottom).



REFERENCES

BjØrneraas K, Van Moorter B, Rolandsen CM, et al. 2010. Screening Global Positioning System Location Data for Errors Using Animal Movement Characteristics. *The Journal of Wildlife Management*, **74**(6): 1361–1366.

Brockmeyer T, Kappeler PM, Willaume E, et al. 2015. Social organization and space use of a wild mandrill (*Mandrillus sphinx*) group. *American Journal of Primatology*, **77**(10): 1036–1048.

D'eon RG & Delparte D. 2005. Effects of radio–collar position and orientation on GPS radio–collar performance, and the implications of PDOP in data screening. *Journal of Applied Ecology*, **42**(2): 383–388.

Dong X, Lang JY, Chuyuan MR, et al. 2021. The seasonal characteristics of home range and habitat utilization of sichuan golden monkeys (*Rhinopithecus roxellana*). *Ecology and environmental sciences*, **30**(7): 1342–1352. (in Chinese)

Fan PL, Li YM, Stanford CB, et al. 2019. Home range variation of two different–sized groups of golden snub-nosed monkeys (*Rhinopithecus roxellana*) in Shennongjia, China: implications for feeding competition. *Zoological Research*, **40**(2): 121–128.

Fan YY. 2017.Home range use and habitat selection of Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) in Tangjiahe National Nature Reserve. China west normal university. (in Chinese)

Fick SE & Hijmans RJ. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, **37**(12): 4302–4315.

Galán-Acedo C, Arroyo-Rodríguez V, Andresen E, et al. 2019. Ecological traits of the world's primates. *Scientific Data*, **6**(1): 55.

Grove M. 2012. Space, time, and group size: a model of constraints on primate social foraging. *Animal Behaviour*, **83**(2): 411–419.

Grueter CC. 2009.Determinants of modular societies in snub–nosed monkeys (*Rhinopithecus bieti*) and other Asian colobines. University of Zurich.

Grueter CC, Li D, Van Schaik CP, et al. 2008. Ranging of *Rhinopithecus bieti* in the Samage Forest, China. I. Characteristics of Range Use. *International Journal of Primatology*, **29**(5): 1121–1145.

Grueter CC, Li DY, Ren BP, et al. 2013. Overwintering strategy of Yunnan snub–nosed monkeys: adjustments in activity scheduling and foraging patterns. *Primates*, **54**(2): 125–135.

Guo YQ, Zhou J, Xie JH, et al. 2018. Altitudinal ranging of the Guizhou golden monkey (*Rhinopithecus brelichi*): Patterns of habitat selection and habitat use. *Global Ecology and Conservation*, **16**: e00473.

Hair Jr JF, Black WC, Babin BJ, et al. 2009. Multivariate data analysis. 7th Ed.

London: Pearson Education.
Hoang TM & Covert HH. 2012. New records of home range of Tonkin snub–nosed monkey (*Rhinopithecus avunculus* Dollman, 1912) in Khau Ca forest, Ha Giang province.
Huang PZ, Bian K, Huang ZP, et al. 2021. Human activities and elevational constraints restrict ranging patterns of snub-nosed monkeys in a mountainous refuge. *Integrative Zoology*, **16**(2): 202–213.
Huang ZP. 2015.Ecological mechanism of fission-fusion of golden snub–nosed monkey (*Rhinopithecus roxellana*) in Qingling mountains. Northwest university. (in Chinese)
Li BG, Chen C, Ji WH, et al. 2000. Seasonal home range changes of the Sichuan snub-nosed monkey (*Rhinopithecus roxellana*) in the Qinling Mountains of China. *Folia Primatologica*, **71**(6): 375–386.
Li YK, Jiang ZG, Li CW, et al. 2010. Effects of seasonal folivory and frugivory on ranging patterns in *Rhinopithecus roxellana*. *International Journal of Primatology*, **31**(4): 609–626.
Li YW. 2016.Research on home range and diet of Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) in Baihe Nature Reserve. China West Normal University. (in Chinese)
Liu ZJ, Zhang LY, Yan ZZ, et al. 2020. Genomic Mechanisms of Physiological and Morphological Adaptations of Limestone Langurs to Karst Habitats. *Molecular Biology and Evolution*, **37**(4): 952–968.
Margalef DR. 1958. Information theory in ecology. *General Systems*, **3**: 36–71.
Mcdonald MM, Cunneyworth PMK, Anderson AG, et al. 2022. Mitochondrial genetic diversity and divergence dating of Angolan colobus monkeys (*Colobus angolensis*) in the eastern forests of Kenya and Tanzania: Implications for subspeciation and reconstructing historical biogeography. *American Journal of Primatology*, **84**(7): e23384.
Miller JA, Pusey AE, Gilby IC, et al. 2014. Competing for space: female chimpanzees are more aggressive inside than outside their core areas. *Animal Behaviour*, **87**: 147–152.
Minta SC. 1992. Tests of Spatial and Temporal Interaction Among Animals. *Ecological Applications*, **2**(2): 178–188.
Moskal LM & Zheng G. 2012. Retrieving Forest Inventory Variables with Terrestrial Laser Scanning (TLS) in Urban Heterogeneous Forest. Remote Sensing.
Orme D, Freckleton R, Thomas G, et al. 2018. Caper: comparative analyses of phylogenetics and evolution in R. 1.0.1 ed.
Patil I. 2021. Visualizations with statistical details: The 'ggstatsplot' approach. *Journal of Open Source Software*, **6**: 3167.
Pearce F, Carbone C, Cowlishaw G, et al. 2013. Space-use scaling and home range

overlap in primates. *Proceedings of the Royal Society B: Biological Sciences*, **280**(1751): 20122122.
Pielou EC. 1975. Ecological diversity. New York: John Wiley & Sons.
Qi XG, Garber PA, Ji WH, et al. 2014. Satellite telemetry and social modeling offer new insights into the origin of primate multilevel societies. *Nature Communications*, **5**(1): 5296.
Qi XG, Huang K, Fang G, et al. 2017. Male cooperation for breeding opportunities contributes to the evolution of multilevel societies. *Proceedings of the Royal Society B: Biological Sciences*, **284**(1863): 20171480.
Qi XG, Li BG, Garber PA, et al. 2009. Social dynamics of the golden snub-nosed monkey (*Rhinopithecus roxellana*): female transfer and one-male unit succession. *American Journal of Primatology*, **71**(8): 670–679.
Qi XG, Wu JW, Zhao L, et al. 2023. Adaptations to a cold climate promoted social evolution in Asian colobine primates. *Science*, **380**(6648): eabl8621.
R Core Team. 2022. R: A language and environment for statistical computing. 4.1.1 ed. R Foundation for Statistical Computing, Vienna, Austria.
Ren B, Li M, Long Y, et al. 2009a. Influence of day length, ambient temperature, and seasonality on daily travel distance in the Yunnan snub-nosed monkey at Jinsichang, Yunnan, China. *American Journal of Primatology*, **71**(3): 233–241.
Ren B, Li M, Long Y, et al. 2009b. Home range and seasonality of Yunnan snub-nosed monkeys. *Integrative Zoology*, **4**(2): 162–171.
Ren BP, Li M, Long YC, et al. 2008. Measuring daily ranging distances of *Rhinopithecus bieti* via a global positioning system collar at Jinsichang, China: a methodological consideration. *International Journal of Primatology*, **29**(3): 783–794.
Revell LJ. 2012. phytools: an R package for phylogenetic comparative biology (and other things). *Methods in Ecology and Evolution*, **3**(2): 217–223.
Revelle WR. 2022. psych: Procedures for psychological, psychometric, and personality research. 2.2.9 ed. Northwestern University, Illinois.
Roos C, Helgen KM, Miguez RP, et al. 2020. Mitogenomic phylogeny of the Asian colobine genus *Trachypithecus* with special focus on *Trachypithecus phayrei* (Blyth, 1847) and description of a new species. *Zoological Research*, **41**(6): 656-669.
Rowe N & Myers M. 2017. All the World's Primates. Primate Conservation Inc., Charlestown RI.
Shannon CE & Weaver W. 1998. The mathematical theory of communication. Illinois: University of Illinois Press.
Springer MS, Meredith RW, Gatesy J, et al. 2012. Macroevolutionary dynamics and historical biogeography of primate diversification inferred from a species supermatrix. *PLOS ONE*, **7**(11): e49521.

Tan CL, Guo S, Li B. 2007. Population structure and ranging patterns of *Rhinopithecus roxellana* in Zhouzhi national nature reserve, Shaanxi, China. *International Journal of Primatology*, **28**(3): 577–591.
Tan CL, Li YM, Li BG. 2016. *Rhinopithecus roxellana*. *In*: Rowe N and Myers M. All the World's Primates. Charlestown, Rhode Island: Pogonias press, 625–626.
Tuanmu M-N & Jetz W. 2015. A global, remote sensing-based characterization of terrestrial habitat heterogeneity for biodiversity and ecosystem modelling. *Global Ecology and Biogeography*, **24**(11): 1329–1339.
Van Der Bijl W. 2018. phylopath: Easy phylogenetic path analysis in R. *PeerJ*, **6**: e4718.
Wei TY & Simko V. 2021. R package 'corrplot': visualization of a correlation matrix. 0.92 ed.
Worton BJ. 1989. Kernel methods for estimating the utilization distribution in home range studies. *Ecology*, **70**(1): 164–168.
Xiang ZF, Huo S, Xiao W. 2010. Activity budget of *Rhinopithecus bieti* at Tibet: Effects of day length, temperature and food availability. *Current Zoology*, **56**: 650 – 659.
Xiang ZF, Xiao W, Huo S, et al. 2013. Ranging pattern and population composition of *Rhinopithecus bieti* at Xiaochangdu, Tibet: Implications for conservation. *Chinese Science Bulletin*, **58**(18): 2212–2219.
Yu L, Wang GD, Ruan J, et al. 2016. Genomic analysis of snub-nosed monkeys (*Rhinopithecus*) identifies genes and processes related to high-altitude adaptation. *Nature Genetics*, **48**(8): 947–952.