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Supplementary Materials

Three-dimensional assessment of movement patterns of Sichuan snub-nosed monkeys affected by habitat structure in temperate forests

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SUPPLEMENTARY MATERIALS AND METHODS

Study area and monkey subjects

This study was conducted in Guanyinshan National Nature Reserve (GNNR) (33°35′–33°45′ N, 107°51′–108°01′ E) on the southern slopes of the Qinling Mountains in Shaanxi, China (Figure 1a). The study area is characterized by a rugged mountainous landscape, ranging from 1 150 m to 2 574 m above sea level (a.s.l.). The major forest types include deciduous broadleaved forest, coniferous and broadleaved mixed forest, and coniferous forest (Wang et al., 2015). Average annual temperature ranges from −8.3 °C to 9.8 °C, and average annual precipitation is 922.8 mm. GNNR is covered with snow from early December until early February (Zhao et al., 2015). Logging activities in GNNR ceased in 1998.

The focal band of free-ranging golden snub-nosed monkeys has been continuously studied since 2010 and is well habituated. During the study period, the band comprised 95 individuals belonging to seven one-male units.

Collection of movement data

Movement data were collected from adult and subadult males and females from 16 November 2018 to 5 January 2019. To track the movements of each focal monkey, GPS coordinates were recorded for each tree that the monkey moved to from the previous night's sleep site until it settled into the current night's sleep site (Davies et al., 2017). Data collection was ceased for a day if the focal monkey could not be located. Monkeys were categorized into five age-sex classes: adult males (>7 years old), adult females (>5 years old), subadult males (5–7 years old), sub females (3–4 years old), and young (0–3 years old) (Zhang et al., 1999; Zhang et al., 2006). The young class was excluded in this study due to the difficulty in identifying sex and their small body size. The final dataset consisted of 51 day follows, involving 3 087 steps (i.e., linear paths between successive trees through which monkeys moved) of 20 individual monkeys, including 748 steps from five adult males, 741 steps from five adult females, 813 steps from six subadult males, and 785 steps from four subadult females.

Airborne LiDAR and structural metrics

We used a RIEGL VUX-1UAV LiDAR scanner (Riegl, Austria) to collect LiDAR data for the study area between 7 and 14 January 2019. Data were collected 300 m above ground using a 30° scanning angle. The laser pulse frequency was set to 380 kHz with a 905 nm wavelength, resulting in a measurement accuracy of 10 mm and an average point density of

50.5 shots per m^2. The airborne LiDAR subsystem provided a 3D structure of the forest canopy and terrain, combining the GPS inertial measurement unit system of position and orientation data to obtain accurate positioning of the LiDAR point cloud. From the LiDAR point cloud data, after denoising and normalizing point clouds, we extracted 3DSF to examine patterns of habitat selection of golden snub-nosed monkeys (Supplementary Table S1). We initially carried out ground-filtering to separate ground and non-ground points, with a digital terrain model (DTM) and digital surface model (DSM) then obtained from the ground point clouds and vegetation point clouds, respectively, which were interpolated into raster grids with a spatial resolution of 0.5 m. A canopy height model (CHM) was then derived from the difference between DSM and DTM (Supplementary Table S1). Mean canopy height was measured from the CHM height within the 0.5 m grid and calculated in each pixel of a 2×2 m area. We calculated the canopy relief ratio, canopy shape, variability in vertical distribution of vegetation, crown thickness, and height of the bottom of the crown using vertical distribution of the LiDAR point cloud data (Supplementary Table S1) with LiDAR360 v5.0 (https://www.lidar360.com/archives/portfolio/lidar360). Tree species classification in the study area was based on individual tree detection from LiDAR-derived CHM segmentation (Zhao et al., 2011). In individual tree-based classification methods, point cloud data were used to derive neighborhood information on structural attributes, such as individual tree height, crown size, and location (Yu et al., 2011), with the random forest then used to discriminate vegetation types in the area.

Data analysis

Many studies on animal movement patterns assume that environmental variables affect movement decisions (Zeller et al., 2012). Consequently, modeling the movements of monkeys requires clarification of the spatial heterogeneity in the forest environment at a scale congruent with detailed field observations (McLean et al., 2016). We used step selection functions (SSFs) to determine how 3DSF and environmental heterogeneity affect monkey movement patterns (Davies et al., 2017; Fortin et al., 2005; Thurfjell et al., 2014). SSFs are case-control functions used in resource selection functional analysis. SSFs are estimated from observed and random steps through conditional logistic regression (Davies et al., 2017; Fortin et al., 2005). The probability of an individual monkey selecting a step was determined by comparing each observed step with a matched sample of 10 randomly drawn available steps (Thurfjell et al., 2014) (Figure 1Aa and b). Available steps for each monkey were determined by randomly selecting step lengths and turning angles from the movement distributions of tracked monkeys in different age and sex groups (Thurfjell et al., 2014). Available steps that projected movements beyond the boundaries of the LiDAR data were clipped. Each predictor variable, including canopy structural metrics and environmental variables (Supplementary Table S1), was extracted for all observed and available steps (Figure 1Ab). SSFs were built using the *mclogit* package in R v3.6.1. A confusion matrix was used to evaluate model accuracy (Stehman, 1997; Zharikov et al., 2005). Models were built by randomly selecting 70% of the strata and then comparing the results with the remaining 30% of the strata. This procedure was

repeated 100 times for monkeys in each age and sex group. The confusion matrix was built using the *caret* package (Kuhn, 2008) in R v3.6.1. Kruskal-Wallis tests were conducted to compare differences in habitat selection among the four age and sex groups in R v3.6.1.

Following Davies et al. (2017), continuous covariates were scaled prior to analysis, and candidate sets of conditional logistic regression models were built for each focal monkey. Multi-collinearity between continuous covariates was assessed using the variance inflation factor (VIF); variables were excluded from the model when VIF was greater than 4. Variables correlated with covariates were also excluded from the model if |r| was greater than 0.7.

Lurking variable plots (Baddeley & Turner, 2005; Liu et al., 2012; Yang et al., 2007) were used to quantify the effects of spatially continuous variables on movement patterns of monkeys in the different age and sex groups. This technique involves plotting cumulative Pearson residuals against continuous spatial covariates within a subregion to identify the systematic pattern that best accounts for specific spatial covariates. If the fitted model explains the continuous variables (null model), the cumulative Pearson residual values should be approximately zero. The null model overestimates or underestimates the effect of a variable on movement patterns when cumulative Pearson residual values exceed two times the standard deviation of this variable, indicating that monkeys either prefer or avoid areas in a particular variable range. All analyses were conducted using the *maptools*, *raster*, *sp*, and *spatstat* packages in R v3.6.1.

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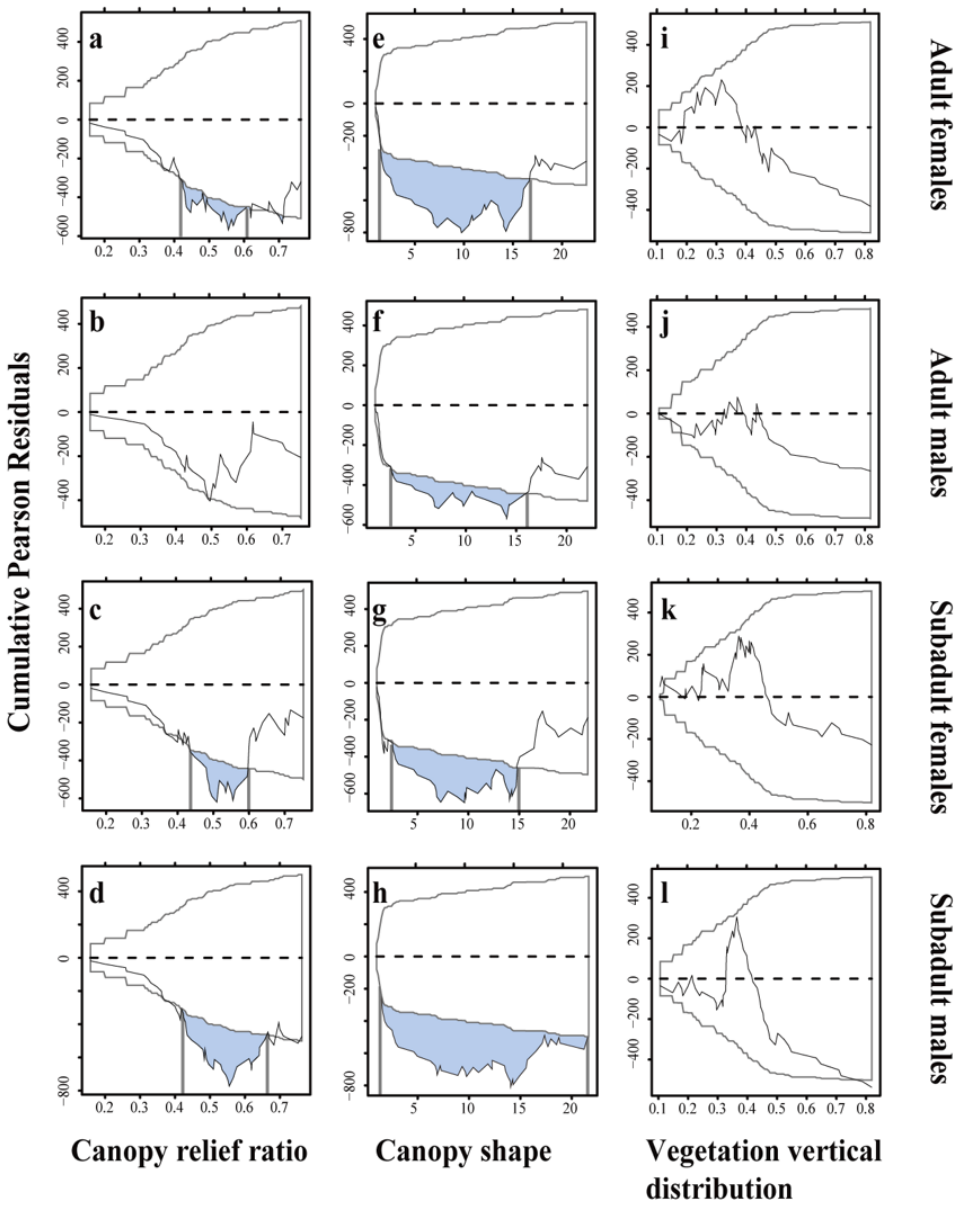
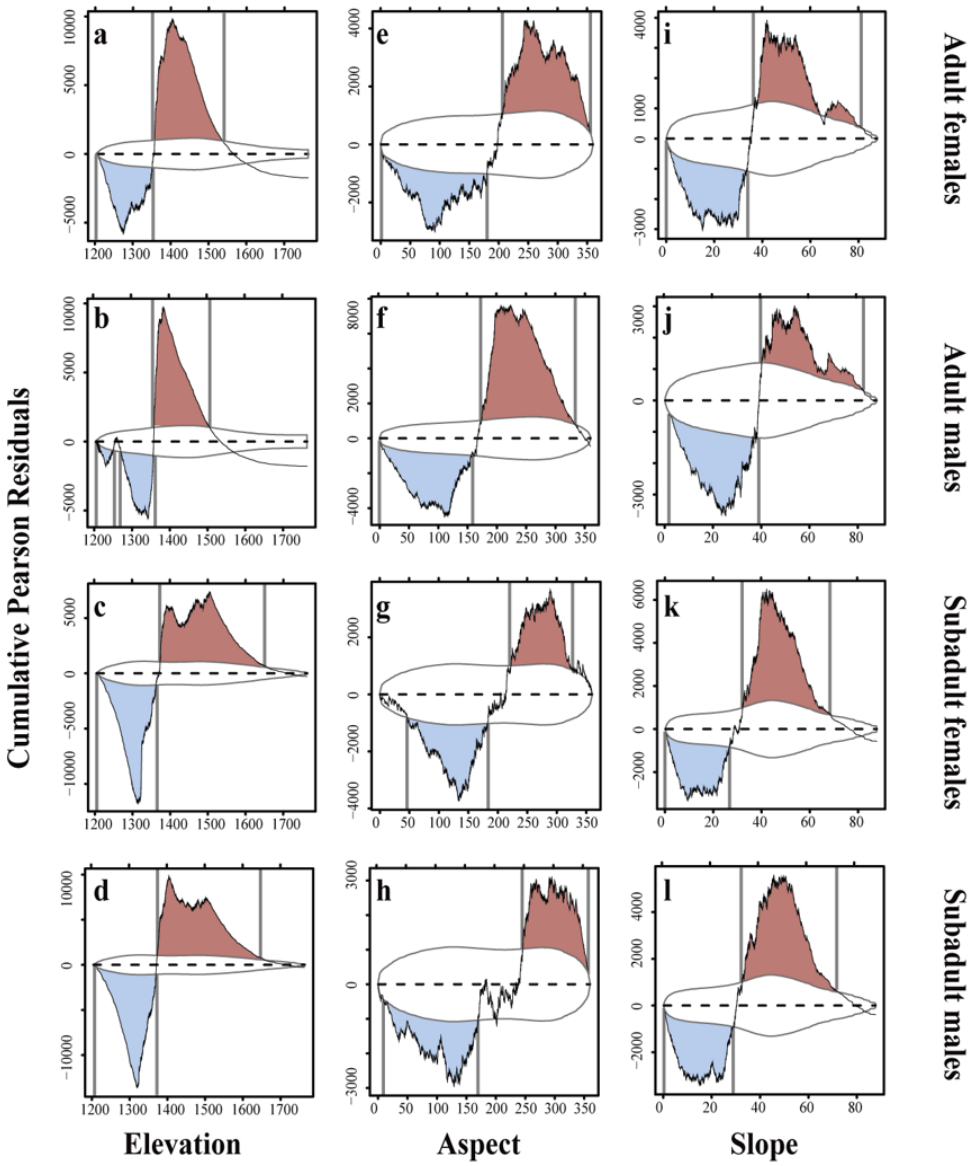


Supplementary Figure S1 Lurking variable results of forest-canopy relief ratio, canopy shape, and vegetation vertical distribution

Lurking variable plots against vertical features of forest-canopy relief ratio (a-d), canopy shape (e-h), and vegetation vertical distribution (i-l) for influence on movement patterns of monkeys in different age and sex classes. Areas around the line at zero denote two standard-deviation error bounds. Black solid line represents empirical curve of cumulative Pearson residuals. Residuals between solid lines with brown or blue indicate selection for or against a given scope of variables (above areas around the line at zero indicate significantly positive selection (brown); below areas around the line at zero indicate significantly negative selection (blue)).



Supplementary Figure S2 Lurking variable results of environmental variables
Lurking variable plots against terrain features of environment-elevation (a-d), aspect (e-h), and slope (i-l) for influence on movement patterns of monkeys in different age and sex classes. Areas around the line at zero denote two standard-deviation error bounds. Black solid line represents empirical curve of cumulative Pearson residuals. Residuals between solid lines with brown or blue indicate selection for or against a given scope of variables (above areas around the line at zero indicate significantly positive selection (brown); below areas around the line at zero indicate significantly negative selection (blue)).

Supplementary Table S1 LiDAR-derived measurements of forest structure modeled as variables in step selection functions and lurking variable plots to describe golden snub-nosed monkey movement in Qinling Mountains, China

Structural metrics	Variables	Resolution	Description
Upper canopy features	Canopy cover (Cc)	2m	Proportion of 2×2 m pixels containing vegetation above 3 m in height
	Canopy height (Ch)	2m	Mean vegetation height in each pixel
Vertical complexity features	Canopy relief ratio (Crr)	5m	Crr = $\frac{mean-min}{max-min}$, *mean* is the average vegetation height in each pixel, *min* is the minimum height in each pixel, and *max* is the maximum height of all points in each pixel
	Canopy shape (Cs)	5m	the height above ground where maximum canopy volume occurs
	Vegetation vertical distribution (Vvd)	5m	Coefficient of variation of the height value of all points in each pixel, CV=$\frac{Z_{std}}{Z_{mean}} \times 100\%$, Z_{std} is the standard deviation of the height value of all points in each pixel, and Z_{mean} is the average height of all points in each pixel
Substrate features	Crown thickness (Ct)	5m	The height between top and bottom of crown
	Bottom of crown (Bc)	5m	Height of lower boundary of canopy crown
	Understory cover (UC)	2m	Proportion of 2×2 m pixels containing vegetation below 3 m in height
Terrain features	Distance to gap (3×3 m) (Dg9)	1m	Euclidean distance to the nearest canopy gap (no LiDAR – detected vegetation), defined as an area ⩾9 m^2
	Distance to gap (2×2 m) (Dg4)	1m	Euclidean distance to the nearest canopy gap (no LiDAR – detected vegetation), defined as an area ⩾4 m^2, but ⩽9 m^2
	Aspect (As)	0.5m	Terrain orientation
	Slope (Sl)	0.5m	Relief of the terrain in each grid
	Elevation (El)	0.5m	Topographical height that removed surface vegetation
Vegetation types	Tree species classification (Tsc)	5m	Tree species segmentation and classification, namely coniferous and broadleaf trees

Supplementary Table S2 Step selection functions for different age-sex classes of golden snub-nosed monkeys in Qinling Mountains, China

Groups	All monkey			Adult Female			Adult Male			Subadult Female			Subadult Male		
	β	SE	95% CI	*β*	SE	95% CI	*β*	SE	95% CI	*β*	SE	95% CI	*β*	SE	95% CI
Cc	0.034	0.039	-0.047-0.114	0.109	0.062	-0.004-0.223	0.116	0.068	-0.019-0.244	-0.064	0.041	-0.156-0.012	0.030	0.060	-0.093-0.133
Ch	**0.215**	**0.048**	**0.126-0.314**	**0.155**	**0.070**	**0.024-0.298**	0.121	0.094	-0.014-0.340	0.010	0.028	-0.042-0.062	0.019	0.047	-0.077-0.103
Crr	0.022	0.051	-0.071-0.131	-	-	-	**0.178**	**0.079**	**0.021-0.335**	-0.050	0.104	-0.199-0.200	-0.061	0.091	-0.243-0.093
Cs	-0.039	0.045	-0.130-0.046	0.070	0.053	-0.042-0.161	0.013	0.145	-0.270-0.297	0.026	0.123	-0.218-0.200	0.033	0.067	-0.088-0.168
Vvd	0.014	0.040	-0.063-0.093	0.124	0.094	-0.058-0.293	0.107	0.078	-0.065-0.232	-0.173	0.080	-0.300-0.002	-0.113	0.082	-0.256-0.036
Ct	**-0.179**	**0.060**	**-0.287- -0.058**	-0.124	0.074	-0.259-0.042	-0.209	0.180	-0.602-0.064	-0.021	0.022	-0.058-0.024	-0.103	0.051	-0.200-0.001
Bc	**-0.144**	**0.070**	**-0.287- -0.021**	0.038	0.079	-0.134-0.170	-0.003	0.114	-0.211-0.206	**-0.437**	**0.324**	**-1.182- -0.009**	**-0.197**	**0.079**	**-0.347- -0.051**
Dg9	-0.125	0.134	-0.395-0.136	**0.158**	**0.099**	**0.032-0.379**	**0.578**	**0.189**	**0.199-0.968**	-0.299	0.507	-1.301-0.702	-0.384	0.222	-0.828-0.046
Dg4	0.189	0.090	0.025-0.370	0.134	0.079	-0.040-0.262	**0.424**	**0.145**	**0.137-0.665**	**0.374**	**0.105**	**0.174-0.601**	**-0.288**	**0.096**	**-0.488- -0.117**
As	0.002	0.041	-0.080-0.082	0.010	0.040	-0.081-0.067	-0.020	0.051	-0.103-0.095	-0.024	0.108	-0.218-0.200	0.031	0.084	-0.127-0.205
Sl	-0.054	0.030	-0.114-0.004	**-0.117**	**0.047**	**-0.216- -0.040**	**0.082**	**0.037**	**0.009-0.154**	-0.020	0.031	-0.067-0.049	**-0.127**	**0.026**	**-0.183- -0.081**

El	**-0.922**	**0.241**	**-1.439- -0.498**	**-0.558**	**0.133**	**-0.805- -0.290**	**-2.004**	**0.666**	**-3.371- -0.777**	-1.518	0.924	-3.182-0.208	-0.367	0.395	-0.939-0.178
Tsc	-0.001	0.143	-0.265-0.289	0.073	0.265	-0.425-0.610	-0.077	0.226	-0.548-0.360	**-0.212**	**0.069**	**-0.349- -0.077**	-0.136	0.293	-0.753-0.386

Note: Coefficients (β) are presented with standard errors (SE) and 95% confidence interval (95% CI). Bold font indicates significant variables (95% CI was not overlap with 0). Cc, Canopy cover; Ch, Canopy height; Crr, Canopy relief ratio; Cs, Canopy shape; Vvd, Vegetation vertical distribution; Ct, Crown thickness; Bc, Bottom of crown; Dg9, Distance to gap (3×3 m); Dg4, Distance to gap (2×2 m); As, Aspect; Sl, Slope; El, Elevation; Tsc, Tree species classification. Model accuracy was evaluated using the confusion matrix.

Supplementary Table S3 Model-averaged coefficients, Standard errors (SEs), and variable importance values of LiDAR-derived metrics from conditional logistic regression models applied to different age-sex classes of golden snub-nosed monkeys in Qinling Mountains, China

Sichuan snub-nosed monkey	Adult female			Adult male			Subadult female			Subadult male		
age and sex class	$\hat{\beta}$	SE	Imp	$\hat{\beta}$	SE	Imp	$\hat{\beta}$	SE	Imp	$\hat{\beta}$	SE	Imp
Canopy cover	0.053	0.065	0.235	0.115	0.066	0.800	-0.042	0.058	0.100	0.012	0.051	0.077
Canopy height	**0.163**	**0.057**	**1.000**	0.035	0.077	0.067	-0.009	0.047	0.048	-0.012	0.045	0.077
Canopy relief ratio	-	-	-	0.120	0.067	0.867	-0.004	0.062	0.100	0.029	0.049	0.077
Canopy shape	-	-	-	-0.060	0.091	0.067	-0.044	0.054	0.048	-	-	-
Vegetation vertical distribution	0.067	0.054	0.412	0.030	0.092	0.067	-0.073	0.050	0.524	-0.058	0.055	0.154
Crown thickness	-0.023	0.070	0.059	-0.036	0.078	0.067	-0.058	0.060	0.143	-0.058	0.066	0.154
Bottom of crown	0.028	0.053	0.118	0.041	0.062	0.067	0.043	0.048	0.048	-0.068	0.058	0.231
Distance to gap (3×3 m)	0.225	0.175	0.294	**0.644**	**0.247**	**1.000**	-0.222	0.249	0.100	**-0.425**	**0.135**	**0.923**
Distance to gap (2×2 m)	0.177	0.121	0.647	0.253	0.160	0.733	0.352	0.191	0.905	-0.121	0.121	0.154
Aspect	0.034	0.073	0.059	-0.031	0.076	0.067	-0.116	0.065	0.810	-0.030	0.066	0.077
Slope	**-0.123**	**0.053**	**1.000**	0.061	0.091	0.200	-0.047	0.056	0.100	-0.113	0.053	1.000
Elevation	**-0.559**	**0.222**	**1.000**	**-1.678**	**0.394**	**1.000**	**-1.618**	**0.552**	**1.000**	-0.443	0.247	0.846
Tree species classification	-	-	-	-	-	-	-0.066	0.160	0.048	-	-	-
Accuracy of model	0.90(0.004)			0.91(0.007)			0.91(0.005)			0.90(0.005)		

Note: Bold font indicates significant ($P < 0.05$) variables. Model coefficients indicate the strength of selection for or against a given covariate, with positive coefficients indicating selection for and negative coefficients indicating selection against. Variable importance (Imp) is a measure of the relative importance of each covariate, calculated as the sum of the Akaike weight (w_i) over all models (used in the model averaging) in which the covariate appears.

Supplementary Table S4 Kruskal-Wallis test of structural metrics used in SSFs for modeling movement patterns of golden snub-nosed monkeys in Qinling Mountains, China

Structural metrics	*P* value
Canopy cover	0.267
Canopy height	0.577
Canopy relief ratio	0.316
Canopy shape	0.985
Vegetation vertical distribution	0.054
Crown thickness	0.662
Bottom of crown	0.225
Aspect	0.870
Elevation	0.308
Slope	0.009
Distance to gap (2×2 m)	0.009
Distance to gap (3×3 m)	0.149
Tree species classification	0.757

Note: Structural metric descriptions are provided in Table S1