Effects of habitat heterogeneity on the elevational distribution of bird diversity in a typical modern montane

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Abstract

The biodiversity in montane ecosystems is high but is threatened by rapid environmental change. Urbanization and other anthropogenic activities in the mountains surrounding cities can affect changes in land use and habitat heterogeneity. Moreover, patterns of habitat heterogeneity are closely related to elevation and have a major effect on montane biodiversity. The aim of this study was to analyze the effects of habitat heterogeneity on the vertical distribution pattern of bird diversity by characterizing the structure of the bird community, biodiversity, and landscape factors at different altitudes. Continuous monitoring of the breeding birds at Mount Tai from 2016 to 2019 revealed that forest reduced the diversity and abundance of birds and favored montane birds. Habitat composition varied at different altitudes. In the high-mountain belt and the middle-mountain belt, the habitat was primarily composed of forest. In contrast, artificial habitat was more common in the low-mountain belt. Bird abundance, species richness, and the Shannon-Wiener index decreased as the altitude increased, and the structure of the bird community significantly differed in the different belts. Some rare species tended to only occupy specific belts. Road density, number of habitat patches, patch density, and the percentage of forest significantly affected bird diversity. The effect of patch density was higher compared with other landscape factors. The “habitat amount hypothesis” was more suitable for explaining the elevational distribution pattern of bird diversity at Mount Tai. Sufficient habitat and more patches in the low-mountain belt supported higher bird diversity. The middle-mountain belt and high-mountain belt showed contrasting patterns. Our results highlight the effects of ongoing urbanization and human activities on montane biodiversity and emphasize the need for artificial habitats in the mountains surrounding cities to be managed.

KEYWORDS

bird diversity, montane, urbanization, elevational distribution

1. INTRODUCTION

Montane ecosystems are some of the most important and vulnerable ecosystems worldwide because of their rich biodiversity (Quintero & Jetz, 2018; McCain, 2009). With the decline in terrestrial biodiversity, understanding population structure and spatial-temporal distribution patterns in montane ecosystems is important for formulating conservation strategies, especially in biodiversity hotspots (Barbier et al., 2018). In mountainous areas, there is a vertical gradient in species composition because of variation in abiotic conditions. Multiple environmental factors, such as climate, hydrology, slope, habitat type, man-made interference, and landform, affect distribution patterns of biodiversity in montane ecosystems (Mccain, 2005; Jetz et al., 2012). The elevational distribution patterns of insects, moss, bats, birds, vascular plants, and other taxa often show unimodal or monotonic change due to environmental factors (Tabarelli et al., 1999; Mccain, 2007b; Song et al., 2015).

As montane birds are highly sensitive to habitat changes (Soh et al., 2006), many studies have explored the structure of bird communities and the distribution patterns of montane birds under different degrees of disturbance (Wu et al., 2010; Fletcher et al., 2018). Landscape and climate conditions often show significant changes over short distances in montane ecosystems, and birds have developed specialized adaptations, behaviors, and diets (Quintero & Jetz, 2018). Functionally similar and closely related montane birds are clustered into groups under the constraints of regional habitats and environmental factors (Fahrig, 2003; Haddad et al., 2015; Gao et al., 2018). Furthermore, rapid changes in landform, vegetation, and climate can lead to changes in the structure, richness, and diversity of bird communities in mountainous areas.

Habitat heterogeneity, especially that resulting from habitat fragmentation and changes in land utilization, plays an important role in population stability and biodiversity (Fahrig, 2017; Fletcher et al., 2018; Fahrig et al., 2019). Natural habitats are continuously being degraded and lost because of anthropogenic activities and climate change, and the ecological mechanisms associated with the loss and degradation of natural habitat have become a major focus of research (Butchart et al., 2010; Pereira et al., 2010; Pimm et al., 2014). Tourism, plantation, land development, and species invasion all affect natural habitats and lead to variation in food production, intensity of disturbance, vegetation, and landform (Peh et al., 2005; Xu et al., 2018; Lele et al., 2020). For montane birds, habitat fragmentation and heterogeneity can restrict the ranges of activity, affect levels of biodiversity, and make birds more vulnerable to climate change (Lele et al., 2020). Continuous observations of birds in New Jiangwan Town in Shanghai have revealed that the mean species abundance (MSA) is strongly correlated with the degree of urbanization and loss of natural habitats (Xu et al., 2018). There is thus a need to analyze the effects of human activities and urbanization on bird diversity in montane ecosystems (Rybicki et al., 2020).

Here, the elevational distribution pattern of birds on Mount Tai is analyzed by integrating data on landscape factors with data on montane biodiversity (Figure 1). This study can be divided into three parts: (1) community structure, diversity, and distribution pattern of birds; (2) interpretation of remote sensing and the acquisition of landscape features, including roads, elevation, and habitat types; and (3) characterization of the relationship between bird diversity and landscape data.

2. METHODS

2.1 Study area

Mount Tai is located in the middle of Shandong Province (36°05′~36°75′N，116°50′~117°24′E) on the edge of North China, a priority region for biodiversity protection. Mount Tai, a UNESCO World Heritage Site, has profound ecological and cultural value. The terrain of Mount Tai is precipitous and open on all sides. The elevation changes sharply, and the height of its peak, the Heavenly Emperor, is 1,545 m.

There are obvious distinctions among the different vertical belts of the climate and vegetation zone, and the habitat types from low to high elevation include deciduous forest, broad-leaf coniferous mingled forest, coniferous forest, and high-mountain scrub-grassland (Wang & Li, 2013). Based on altitude and vegetation, Mount Tai can be separated into three vertical belts: the low-mountain belt (altitude lower than 500 m), middle-mountain belt (altitude from 500 to 1,200 m), and high-mountain belt (altitude above 1,200 m) (Du, 1985). From 1986 to 2001, the biodiversity and natural habitat declined and tourism (and the degree of human interference generally) increased (Xiao & Luo, 2005).

2.2 Field survey

In May or June from 2016 to 2019, variable-distance line transects were used to monitor the breeding bird population at Mount Tai. The average speed of movement along the transect was 1~2 km/h, and the bird species, number of individuals, coordinates, distance to birds, habitat type, threat factors, and altitude were recorded. Ten line transects (each 1.5 km in length) were designed to cover the majority of habitat types at different altitudes (Figure 2).

2.3 Interpretation and environmental variables

A Landsat TM remote sensing image (May 20, 2019) of 30 m × 30 m resolution was downloaded. After field verification, we conducted the supervised interpretation of the remote sensing image to acquire the land use and cover using the software ENVI 5.1 (Figure 3). The land use in Mount Tai was divided into seven types: Forest (FOR), Shrub (SHR), Woodland (WOO), Water (WAT), Tourist area (TOU), Construction land (CON), and Undeveloped land (UND) (Table S1).

We used ArcGIS 10.2 to extract road, altitude, and land use data within a 1000-m buffer around every line transect (Figure 3). The WGS 1984 UTM zone 50 N was used as the uniform projected coordinate system. We conducted the analysis of the class matrix and landscape matrix using the software Fragstates 4.2 and then calculated the number of patches (NP), patch density (PD), and patch percentage of forest (FP) within these buffers. The 8-cell neighborhood rule was used as the operating parameter, and the sampling method was based on user-provided points.

2.4 Vertical Distribution Index

Different bird species tended to be associated with different altitudes. We designed the Vertical Distribution Index (VDI) to indicate the selection of altitude for different species on Mount Tai. The numbers 1, 2, and 3 were the weights used for the percentage of the population of birds in the low-altitude zone, middle-altitude zone, and high-altitude zone, respectively.

Vertical Distribution Index (VDI):

$$Y=\frac{n_L}{N}\times 1+\frac{n_M}{N}\times 2+\frac{n_H}{N}\times 3$$

VDI represents the Vertical Distribution Index of specific species; n_L is the observed individual number of special birds in the low-altitude zone; n_M is the observed individual number of special birds in the middle-altitude zone; n_H is the observed individual number of special birds in the high-altitude zone; N is the total observed individual number of special birds on Mount Tai. If the index approaches 1, the species tends to occur in the low-altitude zone. If the index approaches 2, the species tends to occur in the middle-altitude zone. If the index approaches 3, the species tends to occur in the high-altitude zone.

2.5 Data analysis

We calculated the number of species as well as the individual and Shannon-Wiener index (*H'*) to analyze variation in bird diversity at different altitudes using the Permute package, vegan package, and Spaa package. Multivariable regression analysis was used to determine the weight of different landscape factors on bird diversity with altitude. To examine the effect of landscape factors on bird diversity, we considered elevation, road, NP, PD, and FP as independent variables and simulated the linear relationship between landscape factors and bird diversity. All analyses were performed in the program R 3.5.1.

The percentage of bird taxonomic categories and areas in different land use types were determined. Based on the distributional characteristics of each bird, we conducted a principal component analysis (PCA). VDI, elevation, number, and land use type were the variables used in the PCA. The two-way cluster analysis and detrended correspondence analysis were conducted to analyze the relationship among different bird species using the Sorenson (Bray-Curtis) method in software PC-ORD 6.0 (Wild Blueberry Media, LLC, USA).

3. RESULTS

3.1 Changes in land use along the altitudinal gradient

The composition of land use varied significantly with altitude (Table 1). The main type of land use was forest (2.65 km^2) in the high-mountain belt, and there was also a small tourist area (0.89 km^2). Forest (111.93 km^2) was also the main landscape in the middle-mountain belt, accounting for 87.69% of the total area. Forest, construction land, and shrub cover most of the low-mountain belt, accounting for 88.84% of the total area. Compared with the high-mountain belt and the middle-mountain belt, there are more types of land use in the low-mountain belt, and the proportion of different types of land is similar. The area of forest is larger in the middle-mountain belt than in the other belts. The area of construction land is the highest in the low-mountain belt because of human activities and urbanization.

3.2 The composition of birds under different types of land use

From 2016 to 2019, 7,444 birds from 113 species and from 14 orders were detected on Mount Tai (Table S2). Species richness and abundance of birds were highest in forest and lower in tourist area, construction land, and woodland. Values of the Shannon-Wiener index were higher in forest (3.29), water (2.75), and shrub (2.99) and lower in tourist area (0.12) (Table S3). The number of bird orders in water was greater compared with the other habitat types and included *Charadriiformes*, *Anseriformes*, and *Podicipediformes* (Figure 4). In construction, tourist area, and undeveloped land, *Passeriformes* and *Columbiformes* were the most common, and some common species included *Pycnonotus sinensis* and *Passer montanus*. Overall, *Passeriformes* was the main component of the bird community at Mount Tai.

3.3 Distribution pattern of bird diversity along an altitudinal gradient

On Mount Tai, the abundance, richness, and Shannon-Wiener index of birds tended to decrease with altitude (Figure 5). The relationships among different bird species were analyzed using a two-way cluster analysis and detrended correspondence analysis (Figure 6). In the low-mountain belt, construction land, water, and woodland supported some species from *Anseriformes*, *Columbiformes*, and *Passeriformes*, including *Tachybaptus ruficollis*, *Egretta garzetta*, *Streptopelia chinensis*, *Passer montanus*, and *Phasianus colchicus*. These bird species in the low-mountain belt are highly adaptable to human activities and the city environment. In the middle-mountain belt, some species that relied on forest and shrub were frequently observed, such as *Parus palustris*, *Urocissa erythrorhyncha*, and *Accipiter nisus*. These species primarily belonged to *Passeriformes* and *Accipitriformes*. In the high-mountain belt, a large percentage of forest and shrub supported bird species with a preference for high elevation, such as *Luscinia phaenicuroides*, *Apus pacificus*, *Apus pacificus*, and *Prunella montanella*. The 113 bird species were clustered into four groups according to the PCA. Birds in forest formed Group 1, and birds in the other types of land use were closely related and formed Group II, III, and IV.

3.4 Effect of landscape factors on the vertical distribution of birds

Under the background of urbanization, habitat heterogeneity limits the distribution pattern of birds in mountainous areas. The correlation between landscape factors and bird diversity was analyzed to characterize the landscape factors affecting the bird community (Figure 7). Roads have a significant effect on bird abundance ($F = 133.30$, $P < 0.05$), richness ($F = 105.71$, $P < 0.05$), and the Shannon-Wiener index ($F = 1608.00$, $P < 0.05$). Bird richness and the diversity index increased stably as the distance to road increases. The opposite pattern was observed for bird abundance. The number of patches has a significant effect on bird abundance ($F = 270.24$, $P < 0.05$), richness ($F = 173.02$, $P < 0.05$), and the Shannon-Wiener index ($F = 54.15$, $P < 0.05$). Moreover, the increase in bird diversity was accompanied by an increase in the number of patches. As the patch density increased, bird abundance ($F = 466.55$, $P < 0.05$), richness ($F = 181.85$, $P < 0.05$), and the Shannon-Wiener index ($F = 16.51$, $P < 0.05$) significantly increased. In addition, there was a significant decline in abundance ($F = 64.47$, $P < 0.05$), richness ($F = 69.58$, $P < 0.05$), and the Shannon-Wiener index ($F = 183.40$, $P < 0.05$) as the percentage of forest increased.

As the altitude increased, distance to road ($F = 77.77$, $P < 0.05$), number of patches ($F = 87.60$, $P = 0.00 < 0.05$), and patch density ($F = 88.75$, $P = 0.00 < 0.05$) decreased significantly, but the percentage of forest patches ($F = 72.56$, $P = 0.00 < 0.05$) increased (Figure 8). Thus, the number of patches, patch density, and roads became more numerous at lower altitudes, which is where the degree of habitat heterogeneity was higher. We then combined elevation with landscape factors to analyze the relationship between elevational variation and bird diversity under the background of habitat heterogeneity. The regression analysis indicated that patch density has a strong effect on bird richness and abundance with a high weight of coefficient (Table 2). Nevertheless, the coefficient of the elevation is low compared with the other factors.

4. DISCUSSION

4.1 Vertical distribution pattern of bird diversity

Montane ranges harbor exceptionally high biodiversity, and most studies examining the vertical distribution pattern of birds have focused on regions with natural habitat and with lower levels of disturbance. By contrast, fewer studies have examined the vertical distribution pattern of birds in regions near or inside cities (Ruggiero & Hawkins, 2008). With the development of urbanization, some montane systems might suffer from varying degrees of human disturbance and land development at different altitudes. Land use in montane systems often experiences large changes as natural habitats are continuously converted to other land types, including roads, towns, tourist areas, and parks. Thus, the effect of habitat heterogeneity on flora and fauna in montane systems cannot be neglected, as it is one of the main causes of losses of biodiversity (Saunders et al., 1991; Tabarelli et al., 1999). There is thus a need to identify the effect of habitat heterogeneity on the elevational distribution pattern of birds in montane ecosystems faced with urbanization. As a UNESCO World Heritage Site, Mount Tai features rich ecological and cultural resources. Because of the development of tourism, the percentage of tourist areas increases from the low-mountain belt to the high-mountain belt. Thus, Mount Tai is a suitable region for studying the effect of habitat heterogeneity on biodiversity with urbanization.

Land use and altitude can restrict the distribution of biota and hinder bird activity (Jetz et al., 2007; Harris & Pimm, 2010). Elevation, temperature, humidity, and habitat type can have a significant effect on metabolism. In addition, the environment at different altitudes strongly affects the ecological, evolutionary, physiological, and protective function of biodiversity (Pounds et al., 1999; Pounds et al., 2006). Constraints and niche selection at different altitudes may increase biodiversity and filter functionally similar bird species (Pounds et al., 2006).

Our findings suggest that there are more habitat types supporting higher diversity in the low-mountain belt. Some species associated with urban areas are common in the low-mountain belt, such as *Pycnonotus sinensis* and *Pica serica*. Abundant wetlands in the low-mountain belt provide suitable habitat for waterbirds, such as *Tachybaptus ruficollis* and *Egretta garzetta*. In the middle-mountain or high-mountain belt, the richness and abundance of birds were lower, and the percentage of natural habitat and elevation were higher. Furthermore, a high percentage of forest and higher elevations are more suitable for some specialized species of *Passeriformes* and *Accipitriformes*, such as *Apus apus*, *Aviceda leuphotes*, *Luscinia phoenicuroides*, *Aviceda leuphotes*, *Phylloscopus armandii*, and *Rallina eurizonoides* (a new record for Shandong Province). There were significant distributional differences in the structure of the bird community at different altitudes on Mount Tai.

Movement, ecological niches, and environmental constraints play an important role in determining bird diversity along an altitudinal gradient (McCain, 2009). Although depauperate assemblages at higher elevations are characterized by higher rates of diversification, the small areas of habitat at higher elevations are unable to support high levels of diversity. In addition, unfavorable climates and lower productivity at higher elevations reduce population persistence (Quintero & Jetz, 2018). However, diverse habitat types can lead to divergent selection favoring different characteristics or activities at different altitudes. Based on the features of birds at different altitudes, the composition of the bird community shows fast turnover as bird diversity decreases with altitude.

There are at least four possible patterns of variation in biodiversity along altitudinal gradients: (1) decreasing diversity with increasing elevation; (2) high diversity across a plateau of lower elevations and then decreasing monotonically; (3) a unimodal pattern with maximum diversity at intermediate elevations; and (4) increasing monotonically (Mccain, 2007a; McCain, 2009; Quintero & Jetz, 2018). Abiotic and biotic changes occur within short distances on montane gradients, and the strong elevational shifts in climate, habitat, and topography often lead to strong selective pressures in the high-mountain belt (Loughnan & Gilbert, 2017). Thus, birds have a narrow distribution range in high-mountain belts because of narrow physiological tolerances, life history characteristics, behavioral plasticity, and other factors (Jetz & Rahbek, 2002). The elevational distribution pattern at Mount Tai is consistent with the first model (decreasing diversity with increasing elevation). This finding demonstrates that diversity is constrained in the high-mountain belt and that there are abundant ecological niches in the low-mountain belt. The vertical distribution pattern on Mount Tai is different from the unimodal pattern. The patterns of habitat occupancy and distributional patterns contribute to enhancing biodiversity via the aggregation effect (Kattan & Franco, 2004). In addition, there is tourism activity at various altitudes, and the bird community in middle and high-altitude areas is also disturbed by human activity to a certain extent.

4.2 Mechanism underlying the effects of multiple landscape factors

The vertical distribution of bird diversity along altitudinal gradients is related to multiple factors, such as survey intensity, habitat area, temperature, hydrology, and evolutionary history (Colwell et al., 2004; Zhang et al., 2020). Many hypotheses have been proposed to explain elevational distribution patterns of biodiversity. However, mountains surrounding cities have generally been neglected, and most studies do not carefully consider the effect of landscape factors (Kattan & Franco, 2004; Wu et al., 2010). Mount Tai is a typical montane system that reflects the effect of human disturbance or habitat heterogeneity on the vertical distribution pattern of biodiversity. Although Mount Tai is not as high as Tibet, there are diverse land types and different types of habitats. Habitat heterogeneity caused by fine-scale and diverse habitats play a vital role in biodiversity and ecosystem health (Pimm et al., 2014; Wilson et al., 2016). Because of human activity and urbanization, the connectivity and quality of habitat have been greatly compromised (Haddad et al., 2015). At Mount Tai, the level of development varies with altitude, and habitat heterogeneity in the low-mountain belt is relatively high because of extensive construction activities. The spatial disparity in habitat heterogeneity is the main reason for the vertical variation in the bird community. Some landscape factors have a considerable influence on bird diversity and can be considered key factors, such as roads, real estate development, and tourism development.

The "species-area relationship" describing the regular pattern between species abundance and habitat area is one of the core hypotheses of montane ecology (Losos & Schluter, 2000; Dengler, 2009). The "species-area relationship" embodies the co-existence of species among different communities and links biodiversity in different spatial scales. There is a negative correlation between bird diversity and the patch area of forest, indicating that larger areas of natural habitat correspond to lower bird diversity. This relationship is not consistent with the "species-area relationship." Similarly, the analysis of 150 bird datasets of montane systems revealed that the "species-area relationship" might often not be suitable for explaining the vertical distribution pattern of bird diversity (McCain, 2009).

The number of patches and patch density are important indicators reflecting habitat heterogeneity (Haddad et al., 2015). Compared with previous montane studies, this study found that bird diversity was positively correlated with the number of patches and patch density. However, the number of patches and patch density were negatively correlated with altitude. To make sense of the effects of habitat heterogeneity on species richness, the "habitat amount hypothesis" was recently proposed, which notes that what is important is the total amount of habitat in an appropriate spatial extent of the local landscape independent of its spatial configuration (Fahrig, 2013; Fahrig et al., 2019). When the area of habitat is larger, habitat heterogeneity may increase species diversity. When the area of habitat is smaller, habitat heterogeneity may decrease species diversity (Rybicki et al., 2020). Therefore, various landscape factors in montane systems require consideration, with perhaps the exception of the area of habitat. There is a high percentage of natural habitat, and the total amount of habitat at Mount Tai is sufficient. Thus, the “habitat amount hypothesis” provides a better explanation for the elevational distribution pattern at Mount Tai.

5 CONCLUSION

Montane forest is a important ecosystem to maintain high biodiversity. Due to the rapid development of urbanization and human activity, these patterns of biodiversity in different montane belts is suffering various levels of threat except elevation, slope and other natural factors. This work integrated bird diversity with landscape factors to reveal the effects of habitat heterogeneity on the vertical distribution pattern at different altitudes. Our results demonstrated bird diversity decreased as the altitude increased, and the percentage of different land types and the structure of the bird community significantly differed in the different belts. Special habitats with harsh environment have a constraint on the structure of bird community and some rare species tended to only occupy specific belts. Moreover, our study indicated sufficient habitat and more patches in the low-mountain belt supported higher bird diversity. The “habitat amount hypothesis” was more suitable for explaining the elevational distribution pattern of bird diversity in a typical modern montane. Our results highlight the effects of ongoing urbanization and human activities on montane biodiversity and emphasize the management of artificial habitats.

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CONFLICT OF INTEREST

All authors state that there is no conflict of interest

AUTHOR CONTRIBUTIONS

Conceptualization-WL, HGX; Methodology-MCC, CLL,WL; Software-MCC, WL, DDY; Investigation-XFL, JFY; Writing-Original Draft Preparation, WL, HGX; Writiong-Supervision-MCC, CLL, CHL. All authors read and approved the final manuscript.

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DATA AVAILABILITY STATEMENT

All data have been archived and made available at https://doi.org/10.5061/dryad.866t1g1q2.

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Figure captions

FIGURE 1 Flowchart of the study design

FIGURE 2 Survey line transects of birds at Mount Tai

FIGURE 3 Land use (left) and landscape factors (right) at Mount Tai

FIGURE 4 Bird community composition in different habitats. Habitat abbreviations are defined in

Table 1.

FIGURE 5 Changes in bird abundance, richness, and diversity with elevation at Mount Tai

FIGURE 6 Vertical distribution pattern of the bird community at Mount Tai along the elevational gradient

FIGURE 7 Effect of habitat factors on bird community characteristics

FIGURE 8 Variation in landscape factors with elevation

FIGURE 1

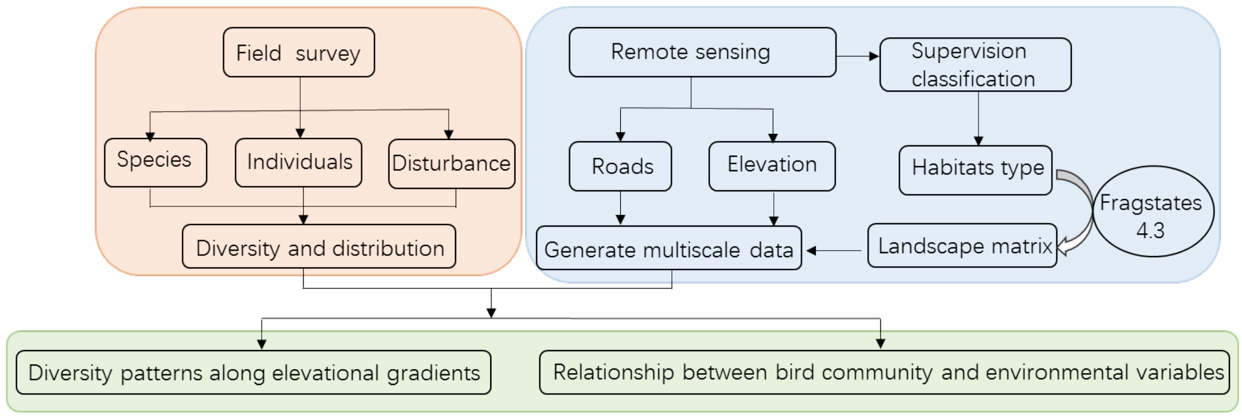


FIGURE 2

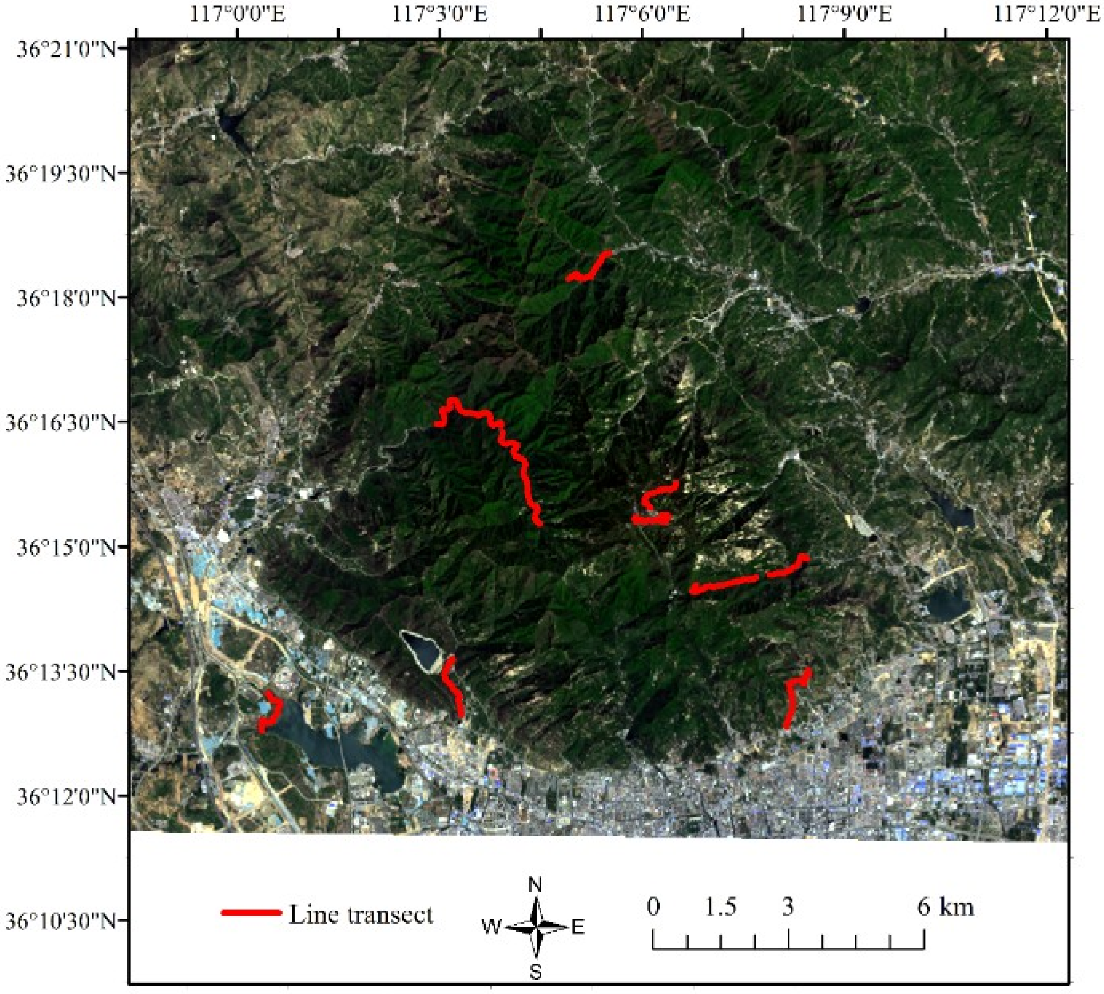

117°0'0"E
117°3'0"E
117°6'0"E
117°9'0"E
117°12'0"E
36°21'0"N
36°19'30"N
36°18'0"N
36°16'30"N
36°15'0"N
36°13'30"N
36°12'0"N
36°10'30"N
Line transect
N
W
E
S
0
1.5
3
6 km

FIGURE 3

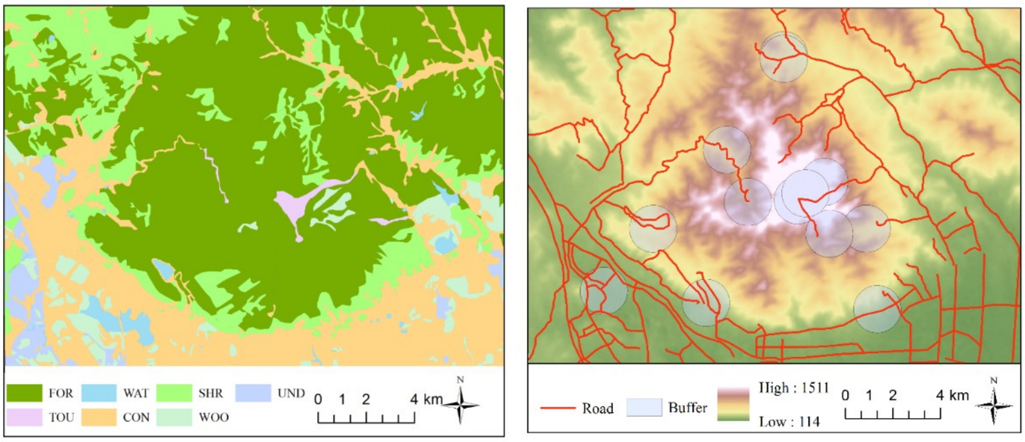
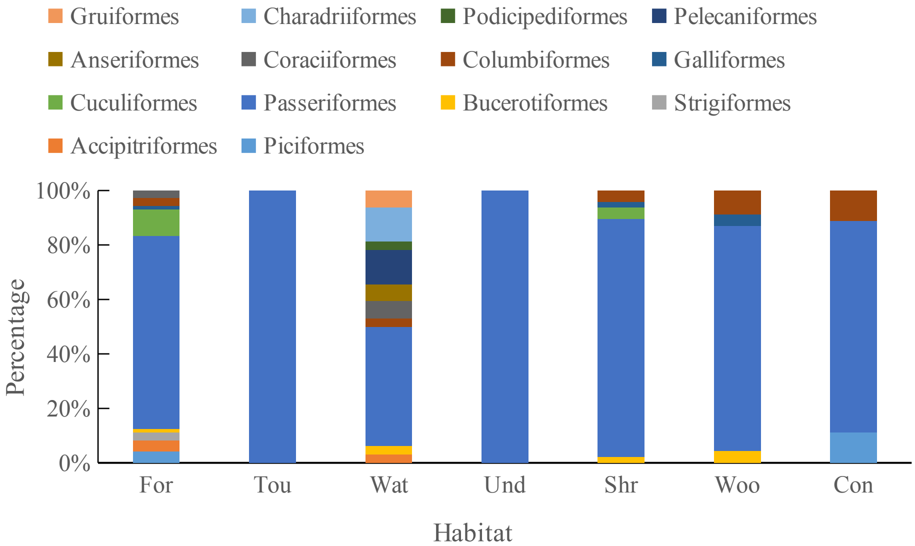
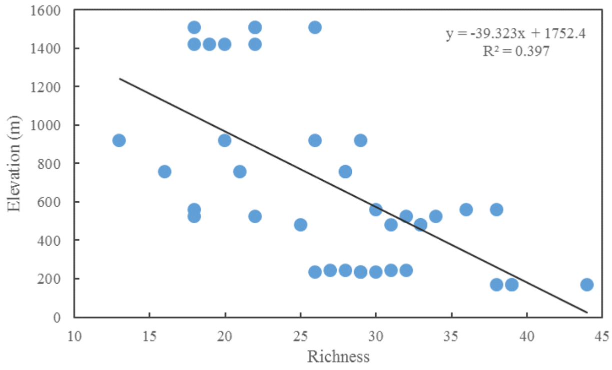

FOR
WAT
SHR
UND
TOU
CON
WOO
0 1 2 4 km
N
Road
Buffer
High : 1511
Low : 114
0 1 2 4 km
N

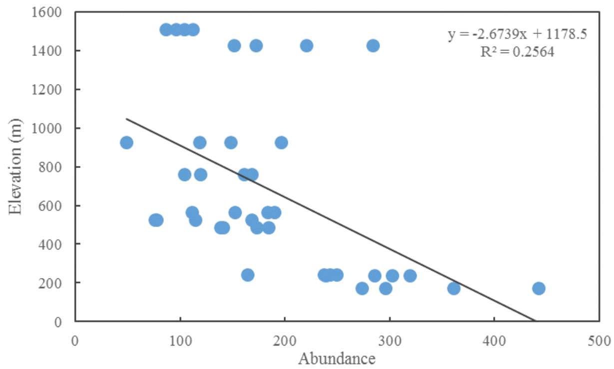
FIGURE 4



Gruiformes
Charadriiformes
Podicipediformes
Pelecaniformes
Anseriformes
Coraciiformes
Columbiformes
Galliformes
Cuculiformes
Passeriformes
Bucerotiformes
Strigiformes
Accipitriformes
Piciformes
Percentage
100%
80%
60%
40%
20%
0%
For
Tou
Wat
Und
Shr
Woo
Con
Habitat

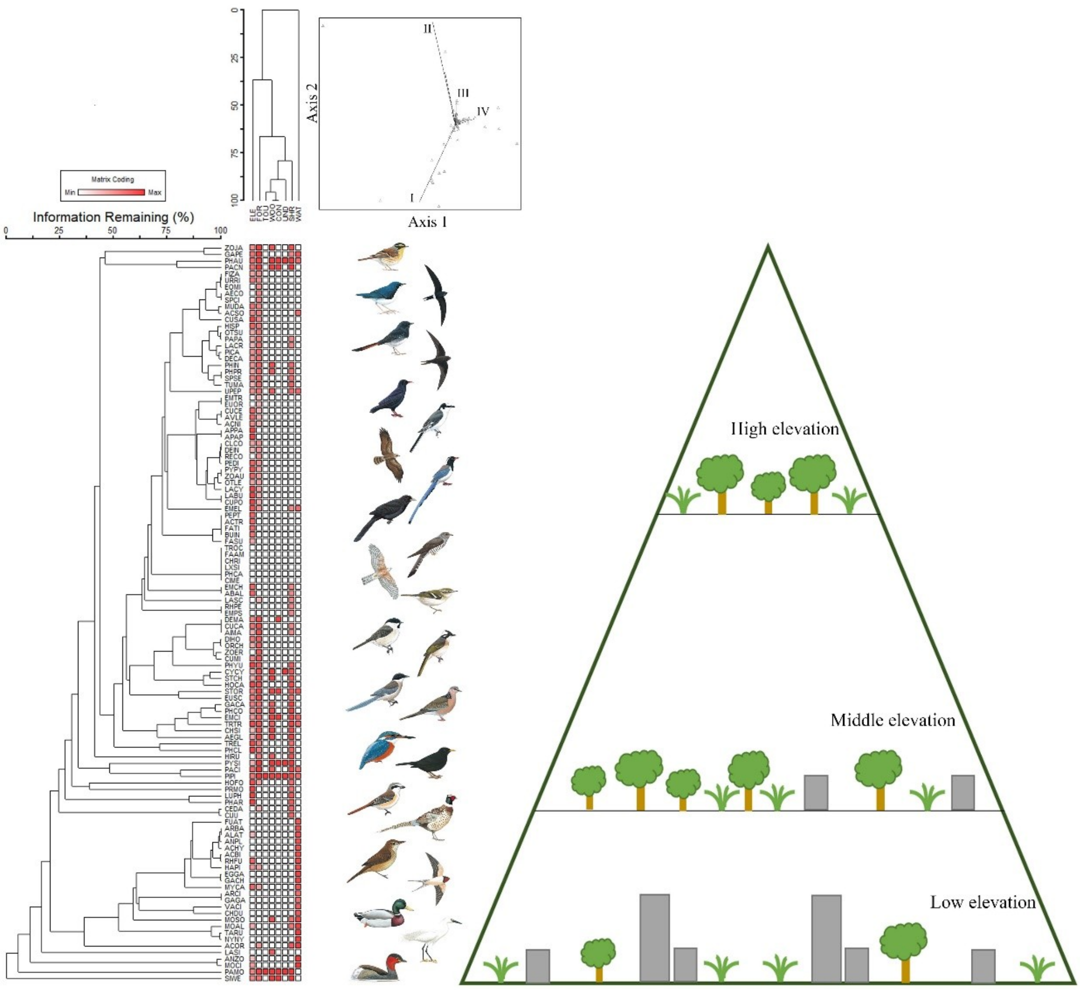
FIGURE 5


y = -39.323x + 1752.4
R² = 0.397
Elevation (m)
Richness
1600
1400
1200
1000
800
600
400
200
0
10
15
20
25
30
35
40
45


y = -2.6739x + 1178.5
R² = 0.2564
Elevation (m)
Abundance
1600
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500

1600
1400
1200
1000
800
600
400
200
0
Elevation (m)
1.5
2
2.5
3
3.5
Shannon-Wiener Index
y = -767.54x + 2733.8
R² = 0.3

FIGURE 6



Matrix Coding
Min
Max
Information Remaining (%)
0
25
50
75
100
Axis 1
Axis 2
I
II
III
IV
High elevation
Middle elevation
Low elevation

FIGURE 7

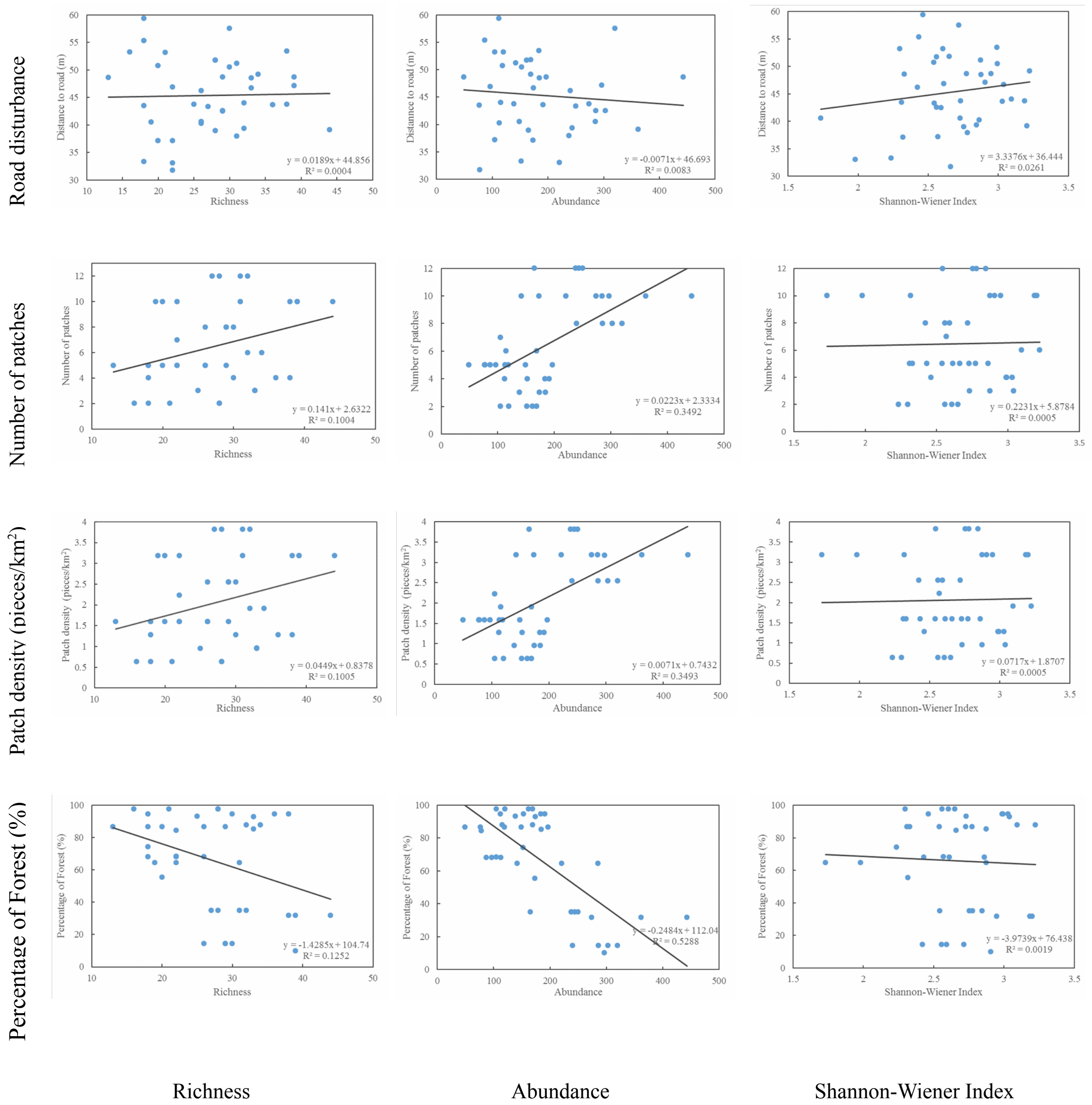

Road disturbance
Number of patches
Patch density (pieces/km²)
Percentage of Forest (%)
y = 0.0189x + 44.856
R² = 0.0004
y = -0.0071x + 46.693
R² = 0.0083
y = 3.3376x + 36.444
R² = 0.0261
y = 0.141x + 2.6322
R² = 0.1004
y = 0.0223x + 2.3334
R² = 0.3492
y = 0.2231x + 5.8784
R² = 0.0005
y = 0.0449x + 0.8378
R² = 0.1005
y = 0.0071x + 0.7432
R² = 0.3493
y = 0.0717x + 1.8707
R² = 0.0005
y = -1.4285x + 104.74
R² = 0.1252
y = -0.2484x + 112.04
R² = 0.5288
y = -3.9739x + 76.438
R² = 0.0019
Richness
Abundance
Shannon-Wiener Index

FIGURE 8

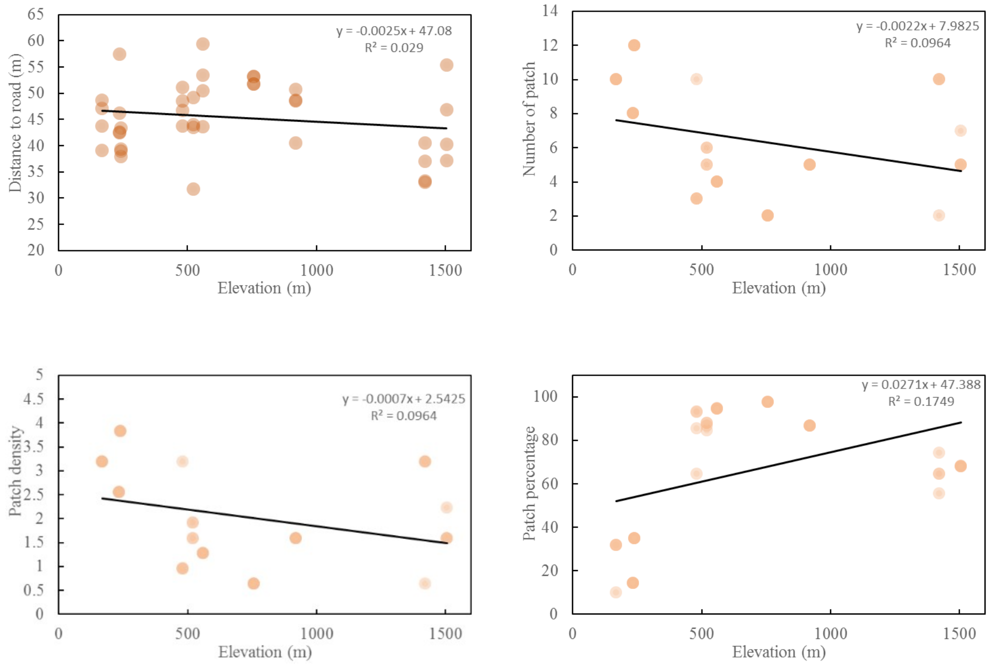


TABLE 1 Changes in land use types along an altitudinal gradient

No	Habitat types	Abbreviation	Area (km²) in mountain belt		
			High	Middle	Low
1	Forest	FOR	2.65	111.93	80.64
2	Tourist area	TOU	0.89	0.97	0.26
3	Water	WAT	0.00	0.12	4.46
4	Construction land	CON	0.00	1.70	84.02
5	Shrub	SHR	0.07	11.68	53.33
6	Woodland	WOO	0.00	1.25	13.82
7	Undeveloped land	UND	0.00	0.00	8.84

TABLE 2 Regression analysis of the effect of landscape factors on bird abundance and richness

Dependent variable	Independent variable	Coefficient	T-test	Significance
Richness	Elevation	-0.01	-3.983	0.001

	Distance to road	-0.038	-0.237	0.814
	Patch density	**0.801**	0.503	0.618
	Patch percentage	-0.001	-0.02	0.984
Abundance	Elevation	-0.044	-1.822	0.077
	Distance to road	0.594	0.366	0.717
	Patch density	**6.402**	0.403	0.69
	Patch percentage	-1.701	-3.092	0.004

Note: Bold letters represented the major dependent variable with higher weight.

TABLE S1 Land use and land cover (LULC) types

LULC type	Abbreviation	Description
Forest	FOR	Forest area with tree canopy density ≥0.2
Shrubland	SHR	Forest area with shrub coverage ≥40%

Woodland	WOO	Including open forest land (forest area with tree canopy density ≥0.1 and < 0.2), young afforested land, slash, nursery garden
Water	WAT	Continental water areas, ditches, hydraulic structures
Tourist area	TOU	Land for commerce and service industry
Construction land	CON	Housing estate, towns, including land for residence, industry, warehouse, governmental organ, school, park
Undeveloped land	UND	Other types of land, including all lands unused in towns, villages, industrial and mining sites

TABLE S2 Bird list of Mount Tai

No	English name	Latin	Abbreviation	Number	IUCN Red List
1	Japanese White-eye	*Zosterops japonicus*	ZOJA	45	LC
2	White-bellied Redstart	*Luscinia phaenicuroides*	LUPH	10	LC
3	Eurasian Coot	*Fulica atra*	FUAT	1	LC
4	White Wagtail	*Motacilla alba*	MOAL	17	LC

5	Little Egret	*Egretta garzetta*	EGGA	11	LC
6	Yellow-rumped Flycatcher	*Ficedula zanthopygia*	FIZA	4	LC
7	Tristram's Bunting	*Emberiza tristrami*	EMTR	1	LC
8	Light-vented Bulbul	*Pycnonotus sinensis*	PYSI	111	LC
9	Green Sandpiper	*Tringa ochropus*	TROC	1	LC
10	Pacific Swift	*Apus pacificus*	APPA	2	LC
11	Chinese Spot-billed Duck	*Anas zonorhyncha*	ANZO	26	LC
12	Daurian Redstart	*Phoenicurus auroreus*	PHAU	104	LC
13	Asian Brown Flycatcher	*Muscicapa dauurica*	MUDA	5	LC
14	Grey Heron	*Ardea cinerea*	ARCI	1	LC
15	Elliot's Laughingthrush	*Trochalopteron elliotii*	TREL	9	LC
16	Chinese Pond Heron	*Ardeola bacchus*	ARBA	10	LC
17	Chinese Sparrowhawk	*Accipiter soloensis*	ACSO	19	LC
18	Great Spotted Woodpecker	*Dendrocopos major*	DEMA	52	LC
19	Common Cuckoo	*Cuculus canorus*	CUCA	50	LC
20	Cinereous Tit	*Parus cinereus*	PACN	118	NR
21	Large Hawk-Cuckoo	*Hierococcyx sparverioides*	HISP	10	LC
22	Common Hoopoe	*Upupa epops*	UPEP	21	LC
23	Oriental Reed Warbler	*Acrocephalus orientalis*	ACOR	13	LC
24	Hair-crested Drongo	*Dicrurus hottentottus*	DIHO	24	LC
25	Grey-headed Canary Flycatcher	*Culicicapa ceylonensis*	CUCE	1	LC
26	Crested Honey-buzzard	*Pernis ptilorhynchus*	PEPT	1	LC
27	Crested Goshawk	*Accipiter trivirgatus*	ACTR	2	LC
28	Claudia's Leaf Warbler	*Phylloscopus claudiae*	PHCL	9	LC
29	Black Baza	*Aviceda leuphotes*	AVLE	3	LC

30	Black Drongo	*Dicrurus macrocercus*	AIMA	45	LC
31	Greater Necklaced Laughingthrush	*Pterorhinus pectoralis*	GAPE	37	LC
32	Black-browed Reed Warbler	*Acrocephalus bistrigiceps*	ACBI	5	LC
33	Common Moorhen	*Gallinula chloropus*	GACH	7	LC
34	Chinese Grosbeak	*Eophona migratoria*	EOMI	2	LC
35	Black-naped Oriole	*Oriolus chinensis*	ORCH	31	LC
36	Chestnut-winged Cuckoo	*Clamator coromandus*	CLCO	2	LC
37	Oriental Scops Owl	*Otus sunia*	OTSU	8	LC
38	Amur Falcon	*Falco amurensis*	FAAM	1	LC
39	Common Kestrel	*Falco tinnunculus*	FATI	11	LC
40	Black-throated Bushtit	*Aegithalos concinnus*	AECO	2	LC
41	Brown Shrike	*Lanius cristatus*	LACR	12	LC
42	Rufous-tailed Robin	*Larvivora sibilans*	LASI	1	LC
43	Plumbeous Water Redstart	*Phoenicurus fuliginosus*	RHFU	4	LC
44	Chestnut-flanked White-eye	*Zosterops erythropleurus*	ZOER	3	LC
45	Red-billed Blue Magpie	*Urocissa erythroryncha*	URRI	8	LC
46	Black-headed Gull	*Chroicocephalus ridibundus*	CHRI	1	LC
47	Red-billed Chough	*Pyrrhocorax pyrrhocorax*	PYPY	5	LC
48	White's Thrush	*Zoothera aurea*	ZOAU	2	LC
49	Hwamei	*Garrulax canorus*	GACA	51	LC
50	Common Pheasant	*Phasianus colchicus*	PHCO	75	LC
51	Yellow Bittern	*Ixobrychus sinensis*	LXSI	1	LC
52	Yellow-throated Bunting	*Emberiza elegans*	EMEL	5	LC

53	Yellow-browed Warbler	*Phylloscopus inornatus*	PHIN	13	LC
54	Yellow-browed Bunting	*Emberiza chrysophrys*	EMCH	1	LC
55	Pallas's Leaf Warbler	*Phylloscopus proregulus*	PHPR	9	LC
56	Grey Wagtail	*Motacilla cinerea*	MOCI	35	LC
57	Grey-faced Buzzard	*Butastur indicus*	BUIN	5	LC
58	White-cheeked Starling	*Spodiopsar cineraceus*	SPCI	6	LC
59	Ashy Minivet	*Pericrocotus divaricatus*	PEDI	1	LC
60	Grey-headed Woodpecker	*Picus canus*	PICA	18	LC
61	Grey-headed Lapwing	*Vanellus cinereus*	VACI	1	LC
62	Azure-winged Magpie	*Cyanopica cyanus*	CYCY	47	LC
63	Common Sandpiper	*Actitis hypoleucos*	ACHY	1	LC
64	Barn Swallow	*Hirundo rustica*	HIRU	20	LC
65	Eurasian Wren	*Troglodytes troglodytes*	TRTR	48	LC
66	Grey-capped Greenfinch	*Chloris sinica*	CHSI	40	LC
67	Little Ringed Plover	*Charadrius dubius*	CHDU	1	LC
68	Red-rumped Swallow	*Cecropis daurica*	CEDA	5	LC
69	Black-capped Kingfisher	*Halcyon pileata*	HAPI	11	LC
70	Siberian Blue Robin	*Larvivora cyane*	LACY	1	LC
71	Blue Rock Thrush	*Monticola solitarius*	MOSO	7	LC
72	Collared Scops Owl	*Otus lettia*	OTLE	2	LC
73	Collared Finchbill	*Spizixos semitorques*	SPSE	16	LC
74	Mallard	*Anas platyrhynchos*	ANPL	4	LC
75	Eurasian Tree Sparrow	*Passer montanus*	PAMO	96	LC
76	Bull-headed Shrike	*Lanius bucephalus*	LABU	1	LC

77	Common Kingfisher	*Alcedo atthis*	ALAT	9	LC
78	Great Cormorant	*Phalacrocorax carbo*	PHCA	1	LC
79	Common Swift	*Apus apus*	APAP	16	LC
80	Brownish-flanked Bush Warbler	*Horornis fortipes*	HOFO	4	LC
81	Eurasian Sparrowhawk	*Accipiter nisus*	ACNI	10	LC
82	Pied Harrier	*Circus melanoleucos*	CIME	1	LC
83	Oriental Dollarbird	*Eurystomus orientalis*	EUOR	1	LC
84	Meadow Bunting	*Emberiza cioides*	EMCI	49	LC
85	Oriental Turtle Dove	*Streptopelia orientalis*	STOR	98	LC
86	Forest Wagtail	*Dendronanthus indicus*	DEIN	3	LC
87	Russet Sparrow	*Passer cinnamomeus*	PACI	90	LC
88	Beijing Hill Babbler	*Rhopophilus pekinensis*	RHPE	1	LC
89	Common Snipe	*Gallinago gallinago*	GAGA	1	LC
90	Indian Cuckoo	*Cuculus micropterus*	CUMI	36	LC
91	Chinese Blackbird	*Turdus mandarinus*	TUMA	17	LC
92	Eurasian Magpie	*Pica pica*	PIPI	169	LC
93	Asian Lesser Cuckoo	*Cuculus poliocephalus*	CUPO	1	LC
94	Little Grebe	*Tachybaptus ruficollis*	TARU	7	LC
95	Little Bunting	*Emberiza pusilla*	EMPS	1	LC
96	Grey-capped Pygmy Woodpecker	*Yungipicus canicapillus*	DECA	16	LC
97	Eurasian Hobby	*Falco subbuteo*	FASU	2	LC
98	Black-crowned Night Heron	*Nycticorax nycticorax*	NYNY	14	LC
99	Silver-throated Bushtit	*Aegithalos glaucogularis*	AEGL	26	LC
100	Manchurian Bush Warbler	*Horornis canturians*	HOCA	43	LC

101	Chinese Leaf Warbler	*Phylloscopus yunnanensis*	PHYU	23	LC
102	Asian Koel	*Eudynamys scolopaceus*	EUSC	59	LC
103	Marsh Tit	*Poecile palustris*	PAPA	7	LC
104	Himalayan Cuckoo	*Cuculus saturatus*	CUSA	4	LC
105	Chinese Penduline Tit	*Remiz consobrinus*	RECO	1	LC
106	Spotted Dove	*Spilopelia chinensis*	STCH	57	LC
107	Blue Whistling Thrush	*Myophonus caeruleus*	MYCA	8	LC
108	Long-tailed Shrike	*Lanius schach*	LASC	2	LC
109	Rufous-faced Warbler	*Abroscopus albogularis*	ABAL	1	LC
110	Yellow-streaked Warbler	*Phylloscopus armandii*	PHAR	6	LC
111	Siberian Accentor	*Prunella montanella*	PRMO	1	LC
112	Zitting Cisticola	*Cisticola juncidis*	CIJU	3	LC
113	Vinous-throated Parrotbill	*Sinosuthora webbiana*	SIWE	39	LC

TABLE S3 The bird community at different altitudes

Habitat types	Abbreviation	Species	Individuals	Shannon-Wiener index
Forest	For	72	3117	3.29
Tourist area	Tou	2	113	0.12
Water	Wat	32	406	2.73
Undeveloped land	Und	5	24	1.53
Shrub	Shr	48	1485	2.99
Woodland	Woo	23	500	1.93
Construction land	Con	9	66	1.6