Evaluation of Bird-watching Spatial Suitability Under Multi-source Data Fusion: A Case Study of Beijing Ming Tombs Forest Farm

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Abstract Taking the Ming Tombs Forest Farm in Beijing as the research object, this research applied multi-source data fusion and GIS heat-map overlay analysis techniques, systematically collected bird observation point data from the Global Biodiversity Information Facility (GBIF), population distribution data from the Oak Ridge National Laboratory (ORNL) in the United States, as well as information on the composition of tree species in suitable forest areas for birds and the forest geographical information of the Ming Tombs Forest Farm, which is based on literature research and field investigations. By using GIS technology, spatial processing was carried out on bird observation points and population distribution data to identify suitable bird-watching areas in different seasons. Then, according to the suitability value range, these areas were classified into different grades (from unsuitable to highly suitable). The research findings indicated that there was significant spatial heterogeneity in the bird-watching suitability of the Ming Tombs Forest Farm. The north side of the reservoir was generally a core area with high suitability in all seasons. The deep-aged broad-leaved mixed forests supported the overlapping co-existence of the ecological niches of various bird species, such as the *Zosterops simplex* and *Urocissa erythrorhyncha*. In contrast, the shallow forest-edge coniferous pure forests and mixed forests were more suitable for specialized species like *Carduelis sinica*. The southern urban area and the core area of the mausoleums had relatively low suitability due to ecological fragmentation or human interference. Based on these results, this paper proposed a three-level protection framework of "core area conservation—buffer zone management—isolation zone construction" and a spatio-temporal coordinated human-bird co-existence strategy. It was also suggested that the human-bird co-existence space could be optimized through measures such as constructing sound and light buffer interfaces, restoring ecological corridors, and integrating cultural heritage elements. This research provided an operational technical approach and decision-making support for the scientific planning of bird-watching sites and the coordination of ecological protection and tourism development.

Keywords Multi-source data fusion, GIS heat map, Kernel density analysis, bird-watching spot planning, Habitat suitability
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In recent years, with the elevation of people's living standards and the growing focus on the natural ecological environment, bird-watching, as a recreational activity that enables people to get close to nature and understand the ecosystem, has garnered increasing popularity. bird-watching not only enables people to admire the beauty and diversity of avian species but also heightens people's environmental protection awareness, thereby facilitating the harmonious co- existence between humans and nature. As the community of bird-watching enthusiasts continues to expand, the demand for high-quality bird-watching locations has been on the rise. The rational planning of bird-watching sites can not only offer birdwatchers a more rewarding bird-watching experience but also ensure the sustainable utilization of ecological tourism resources while safeguarding bird habitats. Nevertheless, traditional approaches to bird-watching site planning lack in scientific data support and systematic analytical methods. They predominantly rely on empirical judgment and straightforward field surveys, fail to take a full consideration of various factors, including the ecological behaviors of birds, the distribution of their habitats, and the influence of human activities[1].

The Ming Tombs Forest Farm in Beijing is situated in the northern part of Changping District, Beijing. Endowed with abundant natural resources and a distinctive geographical environment, it serves as a crucial habitat and migratory stopover site for numerous avian species. This region encompasses lush forests, extensive water areas, and diverse wetland ecosystems. Coupled with relatively suitable climatic conditions, it offers birds a rich supply of food resources and an optimal living environment. During the spring and autumn seasons each year, a substantial number of migratory birds pause here for foraging, resting, and breeding. The avian species found here are diverse, with numerous rare birds, including those under national key protection, being observable. Moreover, the Ming Tombs area, renowned as a prominent historic and cultural scenic region, is replete with rich cultural landscapes and tourism resources. Annually, it attracts a large influx of tourists for sightseeing, thereby providing a sound foundation and favorable conditions for the implementation of bird-watching activities. Research on the planning of bird-watching locations within the Ming Tombs Forest Farm not only caters to the needs of bird-watching enthusiasts for bird-watching activities in this area but also furnishes a scientific basis for the conservation of local bird resources and the ecological environment. Simultaneously, it promotes the development of local ecological tourism, thus holding significant practical implications and application value.

This study aimed to employ multi-source data fusion techniques, in conjunction with GIS heat map overlay analysis methods, to comprehensively analyze multi-source data, including the distribution of bird species, habitat characteristics, and human activities in the Ming Tombs

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Forest Farm. The ultimate goal was to achieve a scientific and rational planning of bird-watching sites. By integrating diverse data sources and uncovering the latent relationships and regularities within the data, it became possible to gain a more thorough understanding of the ecological environment and bird behavior patterns in the Ming Tombs Forest Farm. This, in turn, could provide scientific and accurate decision-making support for the site selection, layout design, and optimization of bird-watching sites.

1 Research status at home and abroad

Abroad, birdwatching activities have an early origin. In European and American countries, public birdwatching has a history spanning over a century, during which a relatively systematic investigation mechanism and data platform have been established. For example, programs such as the "Christmas Bird Count" (CBC) and the "North American Breeding Bird Survey" (BBS) in the United States have been continuously monitoring bird diversity over the long term using standardized methodologies. These efforts have laid a solid foundation for species conservation and ecological research. Additionally, the creation of open platforms like eBird has enabled numerous non-professional birdwatchers to contribute to bird data recording. This not only raises public awareness of the ecosystem but also provides precious data resources across different times and spaces for scientific research. In comparison, bird-watching in China started relatively late; however, it has witnessed rapid development. Since the 1990s, along with the popularization of nature education and the concept of ecological civilization, public bird-watching and bird-watching tourism have gradually emerged as prominent topics. Currently, platforms such as the "Bird Song Network" and the "China Bird-watching Records Center" have been established in China. These initiatives have gradually formed a certain system for public participation in science, offering fundamental support for bird monitoring and conservation. Researches indicated that public bird-watching held distinct advantages in documenting bird diversity. Specifically, it often outperformed traditional transect methods, especially when it came to recording migratory birds and rare species. Nevertheless, due to issues such as inconsistent experience levels among participants and uneven spatial distribution of surveys, the scientific rigor and representativeness of public surveys still required further standardization and enhancement. Moreover, there was a dearth of relevant theoretical and practical guidelines for the selection of optimal bird-watching locations.

2 Related theories and technical foundations

2.1 Theory of multi-source data fusion

Multi-source data fusion, alternatively referred to as multi-sensor data fusion, represents a process that comprehensively leverages data or information from diverse data sources. Through a series of processing and analytical techniques, it aims to acquire information that is more precise, comprehensive, and reliable compared to that obtainable from a single data source. Multi-source data fusion has found extensive and profound applications within the domain of geographical research, offering robust technical support for addressing intricate geographical issues. In the context of urban planning, multi-source data fusion technology assumes a pivotal role. By integrating satellite remote sensing data, Geographic Information System (GIS) data, census data, and traffic flow monitoring data, among others, it becomes possible to gain a comprehensive understanding of a city's spatial structure, land use patterns, population distribution characteristics, and traffic congestion situations. Satellite remote sensing imagery can be employed to obtain information regarding the overall layout of a city, the distribution of buildings, and the extent of green space coverage. GIS data provides detailed information on road networks, infrastructure, and administrative divisions, which are essential geographical elements. Census data unveils the population size, age composition, and distribution across different regions. Traffic flow monitoring data, on the other hand, reflects the volume of vehicular traffic and the traffic conditions on roads. The integration and analysis of these multi-source data enable urban planners to more accurately apprehend the current state and development trends of cities. This, in turn, served as a scientific foundation for the rational planning of urban functional areas, the optimization of traffic network layouts, and the determination of the locations of public facilities[2-4].

2.2 GIS heat map overlay analysis technique

GIS heat maps, also known as kernel density estimation maps, are based on the kernel density estimation method. They conduct spatial analysis on discrete point data and visually represent the distribution density and aggregation degree of the data in space through color changes. In a heat map, areas with darker colors indicate a denser distribution of data points, meaning a higher frequency of events or phenomena in that area; while areas with lighter colors indicate a relatively sparse distribution of data points, with a lower frequency of events or phenomena. This intuitive presentation of data distribution through color enables users to quickly and clearly understand the spatial characteristics and patterns of the data, thereby providing strong support for subsequent analysis and decision-making.

3 Collection and extraction of multi-source data in the Ming Tombs Forest Farm

3.1 Main data collection

3.1.1 Collection of bird data. In accordance with the species abundance ranking presented in the *Biodiversity Survey Report of the Beijing Ming Tombs Forest Farm Management Office*, 10 bird species with the highest observation frequencies within the study area were designated as target species. These species include *Zosterops simplex*, *Phoenicurus auroreus*, *Corvus macrorhynchos*, *Urocissa erythrorhyncha*, *Carduelis sinica*, *Passer montanus*, *Rhopophilus pekinensis*, *Garrulax davidi*, *Pica pica* and *Parus minor*. Considering the spatio-temporal constraints associated with large-scale field observations, the bird distribution data were primarily sourced from the Global Biodiversity Information Facility (GBIF). This platform consolidates global citizen- science observation records and offers standardized and traceable data regarding the occurrence locations of species[5-6]. By sifting through the spatio-temporal distribution records of relevant bird species in the Ming Tombs region, the fundamental dataset for this research was established (Fig.1).

3.1.2 Population data collection. Regarding the collection of population data, the population distribution dataset furnished by the Oak Ridge National Laboratory (ORNL) of the United States was employed. This dataset, accessible on the relevant website, presented detailed information regarding population size and density. Leveraging advanced spatial modeling techniques and geospatial data sources, it enabled a precise comprehension of global population settlement patterns.

3.1.3 Data collection on suitable forest land for birds. Given the significant differences in habitat preferences among the target bird species, it is necessary to establish a suitable forest land evaluation system for each of the 10 target bird species. Since a single species often utilizes multiple types of forest land, this study systematically reviewed authoritative literature such as *The Avifauna of China* to quantify the habitat preference index of each species for different forest land compositions. Based on the ecological niche theory, the forest land types within the medium to high preference range were defined as the suitable habitat for the species.

At the same time, based on a comprehensive forest stand survey of the Ming Tombs Forest Farm, high-precision spatial vector data was obtained. This dataset comprehensively recorded the key habitat parameters such as the dominant tree species composition, forest layer structure, and canopy density of each patch within the forest farm, providing a foundation for subsequent spatial matching analysis.

3.2 Data Processing and Integration

3.2.1 Processing and integration of bird data. Utilizing the bird distribution data provided by the GBIF platform as the foundation, a comprehensive regional avian distribution map layer was assembled (Fig.2). In accordance with the observation dates, and following the phenological criteria of the North Temperate Zone, the data were classified into 4 temporal subsets: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). This classification established the basis for analysis at the seasonal scale.

3.2.2 Processing and integration of population data. The population distribution dataset of the ORNL was stored in a raster format. Its attribute table documented the total population of each pixel. To accommodate the requirements of kernel density analysis, it was necessary to convert the areal data into point data. In the resultant population point dataset, each point represented a population of 1,000 individuals (Fig.3).

4 Analysis of data on suitable forest lands for birds

Based on the tree species composition of forest lands suitable for birds and the basic information data of forest lands in the Ming Tombs Forest Farm, an analysis was conducted on the distribution of suitable forest land types for 10 common bird species (Fig.4–5). Among these 10 major bird species, *P. montanus* is a typical synanthropic bird. Its habitat selection shows minimal association with the structure of natural forests. Instead, it predominantly relies on the semi-open environments created by human activities. As a result, the enclosed forest areas within the Ming Tombs Forest Farm were not conducive to the survival of sparrows. Conversely, the marginal areas of the forest land, in close proximity to human settlements, provided suitable habitats for sparrow survival and roosting[7-8].

The majority of the 10 bird species exhibited a preference for the forest tree species in the deeper regions of the Ming Tombs. Their distributions were relatively scattered. For 5 bird species, namely the *Zosterops simplex*, *Urocissa erythrorhyncha*, *Parus minor*, *Garrulax davidi* and *Rhopophilus pekinensis*, the forest tree species suitable for them were remarkably similar. Conversely, *Carduelis sinica* showed a stronger inclination towards pure coniferous forests and coniferous-broadleaved mixed forests, which were typically located in the shallower areas of the Ming Tombs forestlands. This phenomenon suggested that within the Ming Tombs forest region, the deep-aged broadleaved mixed forests supported the ecological niche overlap and stable coexistence of the aforementioned 5 bird species through three-dimensional structural heterogeneity. This included features such as a highly closed canopy layer, microhabitats provided by standing deadwood, and a continuous shrub matrix[9-10]. The composition of this community validated the biodiversity-bearing function of complex forest ecosystems. In contrast, the pure coniferous forests and pine-oak mixed forests in the shallow transitional zone, characterized by high seed production and moderate canopy light transmittance, have become the core areas for *Carduelis sinica* to specialize in resource utilization. This spatial differentiation pattern of "generalist guilds in the core area - aggregation of specialist species in the marginal zone" unveiled the dual functions of the historic mausoleum area as an ecological sanctuary. The deep mixed forests buffered interspecific competition through structural redundancy, while the shallow forest edge zones supported specialist species through resource pulses. Based on the theories of niche differentiation and spatial gradients, a three-tier protection framework was proposed for the Ming Tombs Forest Farm. The core concept of this framework was coordinated longitudinal management and complementary functional gradients[11-12].

In the core area, the structural integrity of the deep aged mixed forests was stringently preserved. By maintaining the quantity of standing deadwood and the continuity of the shrub matrix, this area provided support for the ecological niche overlap and stable co-existence of 5 bird species, including *Zosterops simplex*, *Urocissa erythrorhyncha*, *Parus minor*, *Garrulax davidi* and *Rhopophilus pekinensis*. The buffer zone placed emphasis on the dynamic management of the shallow forest edge areas. Here, pine-oak mixed vegetation corridors were established, and human disturbances were regulated to ensure the exclusive utilization of coniferous seed resources by *Carduelis sinica*. The isolation zone constructed a three-dimensional barrier composed of arbors and shrubs along the agro-forestry interface. This barrier served to block the infiltration of agricultural pollutants and maintain the forest nutrient cycle. Through the spatial hierarchical decoupling mechanism, this

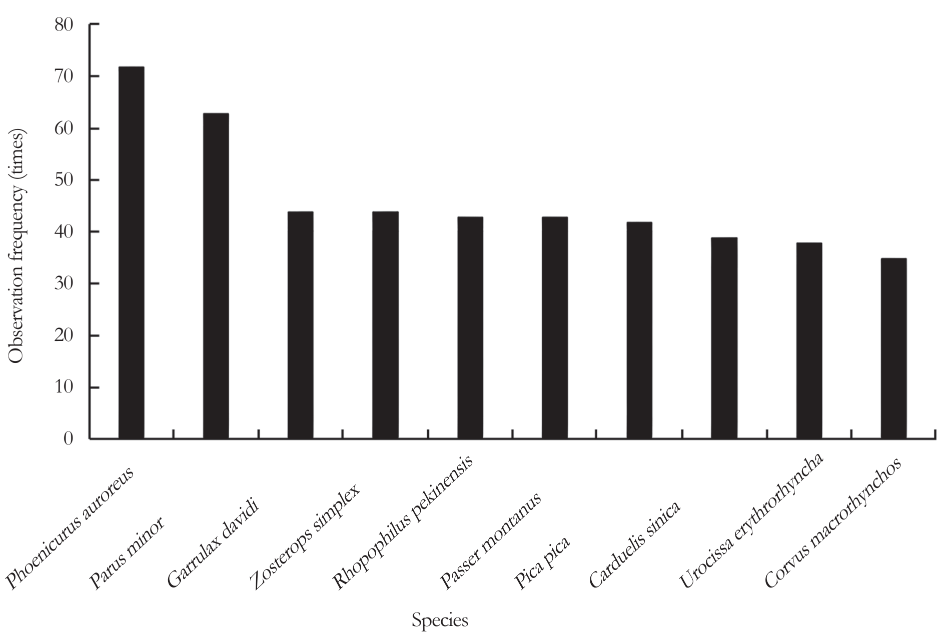

Fig.1 The top 10 bird species with the highest observation frequencies using the line transect method in the Beijing Ming Tombs Forest Farm Management Office

framework enabled the functional coupling between the "ecological foundation" of the deep mixed forests and the "resource pulse belt" of the marginal coniferous forests. Ultimately, it aimed to strike a balance among maintaining the co-existing bird community, ensuring the survival of specialized species, and enhancing the resilience of the ecosystem.

5 Modeling of suitable bird-watching areas and establishment of a grading system

5.1 Model establishment

This research utilized the Kernel Density Estimation (KDE) method to quantify the distribution intensity of spatial point patterns. Mathematically, its essence was to reconstruct the probability density of discrete events through kernel functions. Based on the Rosenblatt-Parzen non-parametric estimation framework, the density value at a two-dimensional spatial location (x, y) was calculated as follows:

$$\hat{f}(x,y)=\frac{1}{n\cdot h^2}\sum_{i=1}^{n}K\left(\frac{d_i}{h}\right)$$

Here, n is the number of observation points, h is the bandwidth parameter (which controls the smoothness intensity), and d_i represents the Euclidean distance from the i^{th} point to (x, y). The Epanechnikov quadratic kernel function was chosen as follows:

$$K(u)=\begin{cases}0.75\,(1-u^2) & |u|\leqslant 1\\ 0 & |u|>1\end{cases}\quad (u=d_i/h)$$

This function exhibited asymptotic optimality under the criterion of minimizing the mean squared error (Silverman, 1986). The bandwidth h was dynamically optimized according to Scott's rule: h=3.5n−1/6σ^ (where σ^ represents the standard deviation of the point set). The calculation of h was automatically performed using the Silverman's Rule of Thumb tool within the Geographic Information System (GIS). To mitigate the area distortion associated with geographic coordinates, all data were uniformly converted to the WGS 1984 projected coordinate system. This ensured that the units of density values were spatially comparable.

The original KDE output values exhibited substantial magnitude disparities attributable to the dimension of n/h^2. Specifically, the typical values of bird density were on the order of 10^2–10^3 points per square kilometer (owing to the sparse distribution of observation points), whereas the population density could reach as high as 10^5–10^6 points per square kilometer (owing to the fine granularity of ORNL data).

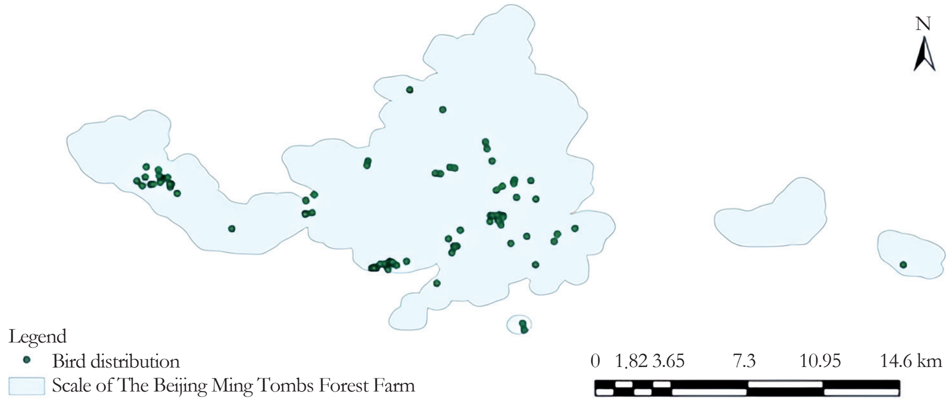

Fig.2 Bird distribution data

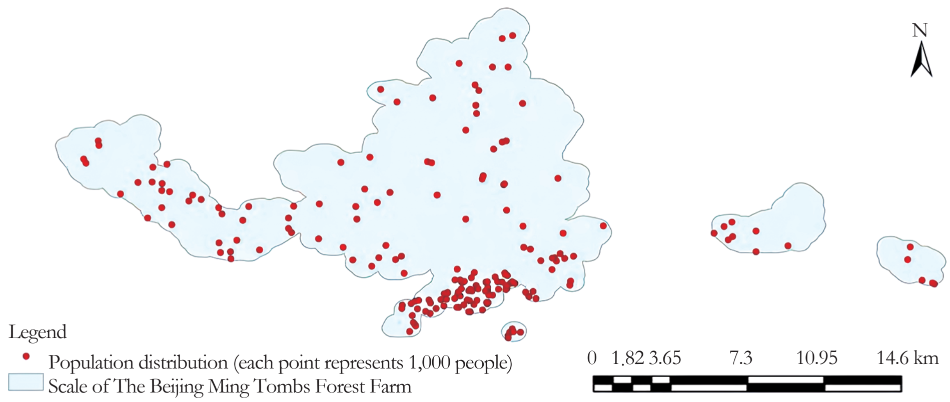

Fig.3 Population distribution data

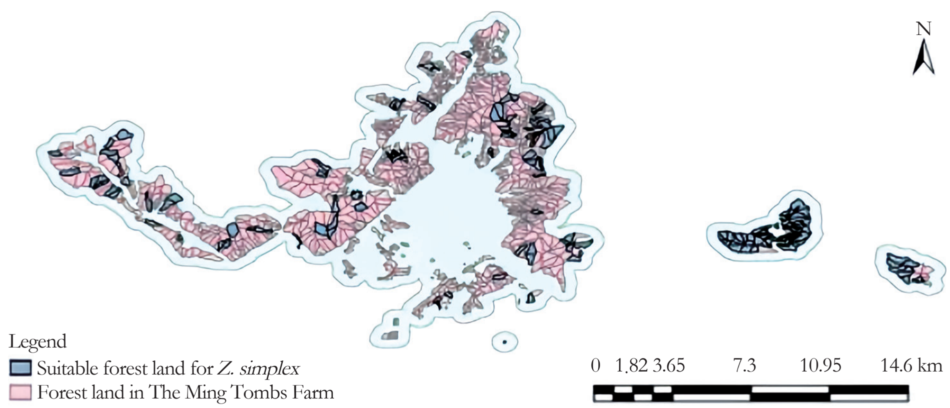

Fig.4 The distribution of *Z. simplex* in suitable forest land

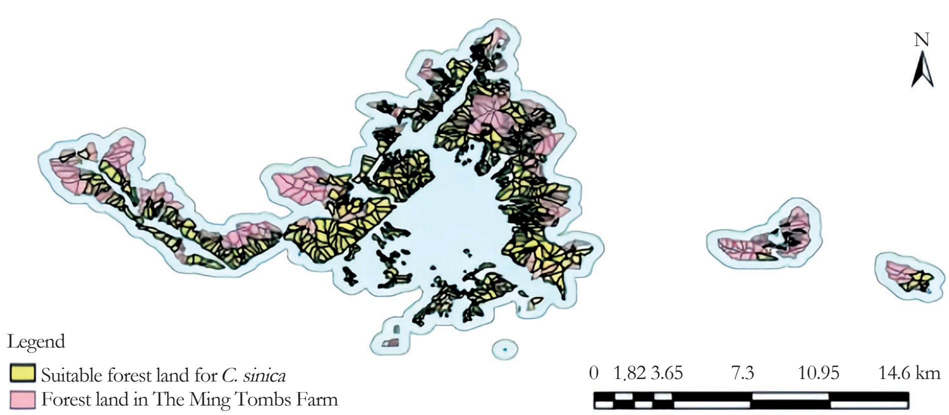

Fig.5 The distribution of *Carduelis sinica* in suitable forest land

To nullify the influence of dimensions, range normalization was employed for dimensionless transformation, as follows:

$$Z_{norm}(x,y)=\frac{\hat{f}(x,y)-\min(\hat{f})}{\max(\hat{f})-\min(\hat{f})}$$

A spatially explicit model of bird-watching suitability was developed based on the niche competition theory. The central hypothesis posited that suitability was dictated by the spatial trade-off between the density of bird distribution and the intensity of human activities. The model was quantitatively implemented through GIS raster algebra operations. On the ArcGIS platform, pixel-by-pixel subtraction was performed between the normalized bird density (denoted as bird_norm, which represents the abundance of habitat resources) and the normalized human population density (denoted as human_norm, reflecting the intensity of anthropogenic disturbances) using the formula: suitability="bird_norm" – "human_norm". The output range of the model spans from [−1, 1]. Areas with positive values (suitability > 0) signified ecological advantageous zones for birds, representing the core spaces that were highly suitable for bird-watching. Conversely, areas with negative values (suitability < 0) denoted regions where human disturbances predominated, and in these areas, the human-bird relationship needed to be optimized through the establishment of buffer zones[13-14].

5.2 Grading of bird-watching suitable areas

Based on the model developed, the value range of bird-watching suitable areas was determined to be (−1, 1). It was herein stipulated that areas within the range of (−1, −0.5) were considered unsuitable for bird-watching during this season; areas in the range of (−0.5, 0) were relatively unsuitable; those within (0, 0.25) were moderately suitable; areas between (0.25, 0.5) were relatively more suitable; regions within (0.5, 0.75) were suitable; and areas in the range of (0.75, 1) were highly suitable for bird-watching during this season (see Fig.6−9).

6 Conclusions

Research findings indicated that although the suitable areas for bird-watching varied across different seasons, they were predominantly concentrated in the vicinity of the Ming Tombs Reservoir, particularly in the northern part of the reservoir. Moreover, the bird-watching suitability within the study area exhibited remarkable spatial heterogeneity. In the southern urban area, due to the squeezing effect of the artificial

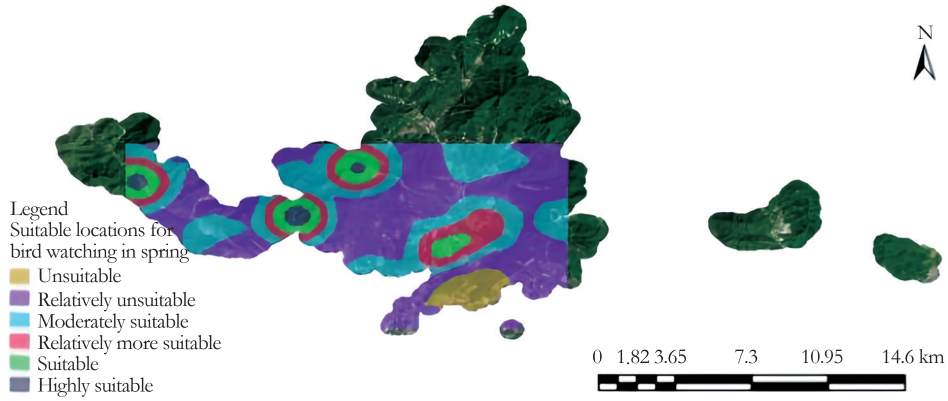

Fig.6 Suitable locations for bird watching in spring

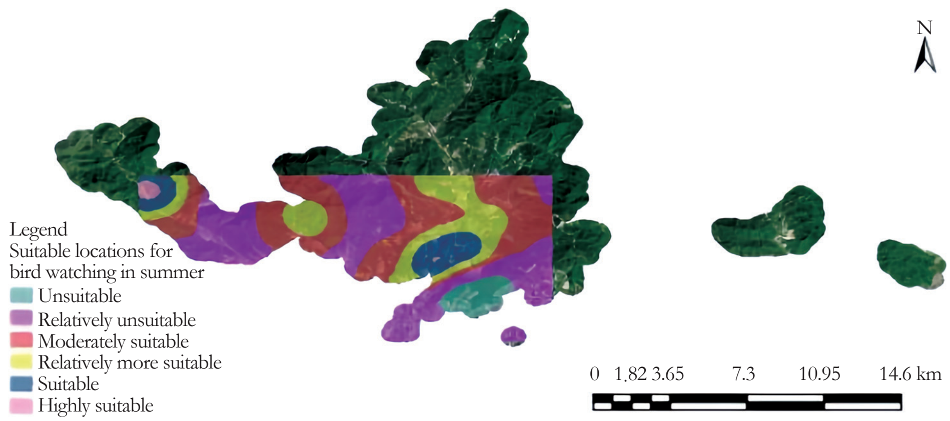

Fig.7 Suitable locations for bird watching in summer

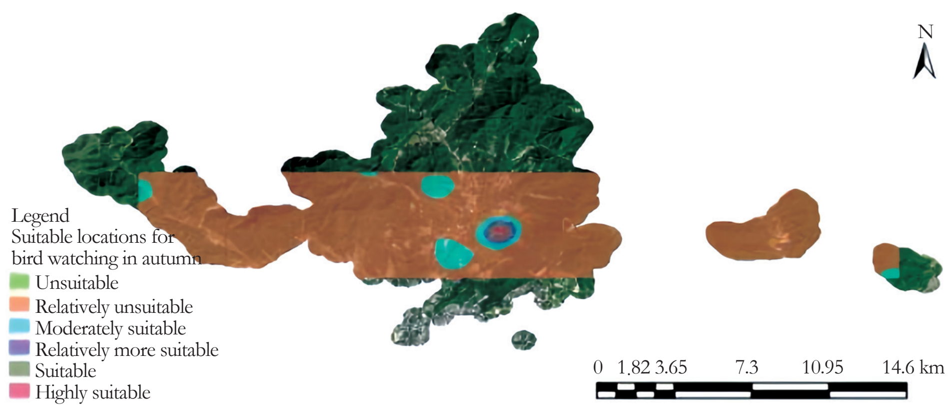

Fig.8 Suitable locations for bird watching in autumn

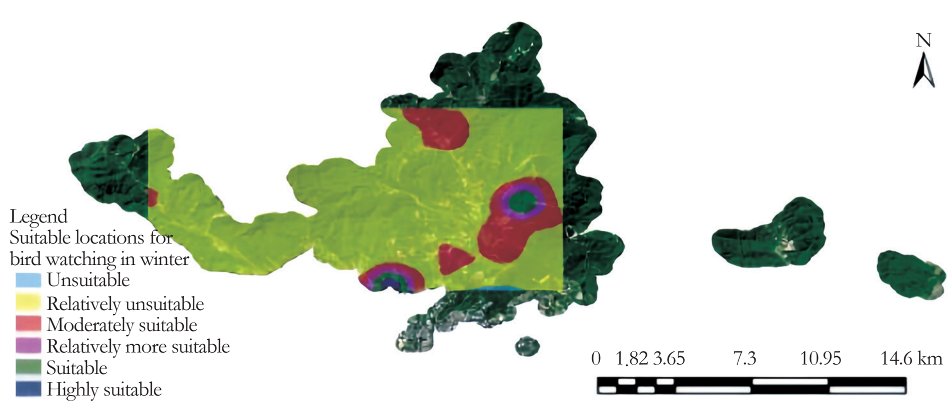

Fig.9 Suitable locations for bird watching in winter

built environment, a break in the biological migration corridor has formed, resulting in an almost complete loss of its bird-inhabiting function. Although the core mausoleum area had a favorable vegetation foundation, the dense commemorative building complexes and tourist routes generated continuous sources of acoustic and light interference. It was recommended that a buffer zone could be established to re-configure the interface between human and bird activities.

When conducting bird-watching activities in the Ming Tombs area, it was essential to understand the dynamic pattern characterized by "core radiation from the northern side of the reservoir and gradient responses of seasonal habitats", and establish a spatio-temporal coordinated observation system. In the spring mornings, the focus should be on the mixed coniferous and broad-leaved forests in the shallow mountain areas. This allowed for the capture of the reproductive rhythms of forest birds as they shuttled and built nests on the sunny slopes. During summer, by venturing deep into the dense forests of the back mountains, the humid period after rainfall could be utilized to analyze the foraging cooperation and acoustic-landscape positioning of co-occurring species groups within the three-dimensional vegetation structure of the mixed forests. In autumn, the focus was shifted to the southern fracture-restoration areas. In the newly-established shrubbery, the corridor-stepping-stone effect formed by migratory species that rely on the reconstruction of native vegetation was traced. In winter, the clear sky after snowfall was utilized to observe the adaptive behaviors of birds towards cultural-heritage elements such as glazed eaves and stone-carved pedestals within the buffer zones of ancient buildings. This approach aimed to uncover the symbiotic potential between artificial structures and natural survival.

In the future, the planning of bird-watching sites should be more comprehensively integrated with fields such as ecotourism and biodiversity conservation. It is crucial not only to concentrate on the scientific layout and infrastructure construction of bird-watching sites but also to emphasize the development of diverse ecotourism products and services. By integrating bird-watching activities with science education and cultural experiences, the overall value of bird-watching can be enhanced. Furthermore, strengthening collaboration with relevant government agencies and social organizations is essential. This cooperation can facilitate the practical implementation and dissemination of the planning outcomes of bird-watching sites. Simultaneously, it is necessary to establish and refine a sound management mechanism and regulatory framework for bird-watching activities, thereby promoting the sustainable development of bird-watching initiatives[15].

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