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# Suitability assessment for forest landscape restoration based on species diversity conservation

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Forest landscape fragmentation poses a significant challenge to the conservation of species diversity. Evaluating the suitability of forest landscape restoration (FLR) becomes essential as it promotes effective management of forest resources and protects species diversity. This study focused on deploying and testing a suitability evaluation framework system for FLR in the Saihanba area of Hebei, China. The framework system incorporated factors such as land cover type, landscape structure, soil quality, and topography. Using the matter-element model, the study evaluated the restoration suitability and identified priority restoration areas. The results revealed that land cover type and landscape structure were the primary factors influencing FLR in the study area. The suitable area for FLR in the study area was about 519.20 km$^2$, accounting for 55.55% of the total area. The area of moderate, marginal, and unsuitable restoration accounted for 17.30%, 23.96%, and 3.18% of the study area, respectively. The suitable restoration areas predominantly consisted of natural secondary forest characterized by large patch areas, short distances between patches, and complex patch shapes. In the study area, the objective of FLR should be protect large and complex shaped patches of natural secondary forests for better conservation of species diversity. The FLR suitability evaluation conducted in this study provide a valuable guidance for promoting species-diversity conservation and restoration of forest ecosystems at the landscape scale in the study area and other similar regions.

## 1 Introduction

Forests play a vital role in terrestrial ecosystems and are responsible for protecting approximately 80% of terrestrial species diversity (Meng, 2006). However, with the progression of industrialization and urbanization, forest landscape fragmentation has intensified, leading to a decline in species diversity (Haila, 2002) and a reduction in ecosystem functioning (Noulèkoun et al., 2021). The alarming rate of forest loss has prompted conservationists to acknowledge that merely protecting or curbing deforestation is insufficient to conserve biodiversity. Restoration of damaged forest landscapes has

become a crucial necessity (Suding et al., 2015). In line with this, global initiatives such as the United Nations Decade of Ecosystem Restoration, the Bonn Challenge, and the New York Declaration on Forests have explicitly stated the global objective of restoring 350 million hectares of forests worldwide by 2030, with a particular focus on restoring forest functions at the landscape scale (Orsi and Geneletti, 2010). The emphasis on forest landscape restoration (FLR) at the landscape scale has garnered considerable global attention (Noulèkoun et al., 2021). A prerequisite and guarantee for these efforts is the suitability assessment of FLR, which carries significant implications for forest management (Chen et al., 2019). Identifying priority areas for restoration through suitability evaluation represents a prominent topic in current research on FLR.

Species diversity is an essential requirement for FLR (Beatty et al., 2018a). It is influenced by various factors, including land cover type (Newbold et al., 2015), landscape structure (Gustafson, 1998; Fahrig, 2003), soil quality (Li et al., 2020), and topography (Chen et al., 2021). Different land cover types offer diverse habitat and environmental conditions, which directly or indirectly affect species diversity (Lambin et al., 2001). Compared to grasslands, natural secondary forests with complex community structures and habitat characteristics provide rich and diverse habitats for wildlife (Chazdon et al., 2009), thus supporting species diversity. Managed plantations, characterized by single-species monocultures, often experience intense human disturbances and exhibit regular patch shapes, resulting in lower species diversity. Conversely, grasslands feature curved patch boundaries and a diverse composition of plant communities (Dong et al., 2014), generally harboring higher species diversity compared to managed plantations. Landscape patterns also have an impact on species diversity (Lindenmayer et al., 2008). Several studies have demonstrated that changes in landscape structure are a significant cause of species diversity loss at the landscape scale (Higgins, 2007). According to island biogeography theory, patch size, and distance are the primary determinants of habitat species diversity (Fahrig, 2013). Unfragmented large forest patches can sustain higher species diversity compared to several small forest fragments that are more susceptible to edge effects (Li L. et al., 2021). Moreover, seed dispersal is critical for maintaining and increasing plant diversity at a landscape scale (Beatty et al., 2018a). Different tree species exhibit varying seed dispersal distances under different conditions. For example, pollen from *Larix principis-rupprechtii* can disperse up to 100 m (Wen and Shen, 1990), while pollen from *Cunninghamia lanceolata* can disperse distances exceeding 600 m (Chen et al., 1996). Different animal species also have varying dispersal distances, with small mammals, reptiles, and amphibians having primary dispersal distances of approximately 750 m (Chen et al., 2012). When the spatial extent exceeds 300 m, landscape patterns undergo noticeable fluctuations, posing a significant threat to the survival of reptiles and birds sensitive to habitat range (Wei et al., 2022). Under fragmented forest conditions, patch shape also impacts species diversity (Cook, 2002). More complex patch shapes facilitate stronger interactions between patches and the surrounding matrix, promoting energy, material, and biological exchange, thus benefiting species diversity conservation. Therefore, when evaluating the suitability of FLR, the influence of landscape indices such as patch area, shape index, patch density, and landscape diversity should be considered. Additionally, soil (Van Der Heijden et al., 2008), topography (Qian and Ricklefs, 2000),

and climate change (Dawson et al., 2011) also impact species diversity. Good soil quality implies better soil and water retention capabilities, providing more suitable habitats for species. Studies have shown that the contribution of topography to species diversity increases with spatial scale (Hu et al., 2014), while climate change influences species distribution, reproduction, and survival (Copenhaver-Parry and Cannon, 2016). Currently, most traditional restoration methods focus on local scales, and there are limited studies at the landscape scale. Therefore, conducting a comprehensive evaluation of FLR suitability based on factors such as land cover type, landscape structure, soil quality, and topography at the landscape scale is necessary.

To scientifically assess the suitability of landscape restoration, extensive research has been conducted by scholars, exploring various evaluation models. These models include multiple logistic regression (Schulz and Schröder, 2017), artificial neural networks (Liu et al., 2015), geographical detector (Wang et al., 2019), suitability models (Darwiche-Criado et al., 2017), and matter-element models (Chen et al., 2021). The matter-element model has emerged as a notable solution to the challenge of compatibility between indicators and methods, making it suitable for multifactor evaluation (Cai, 1999). Compared to other evaluation models, the matter-element model provides more objective and scientific evaluation results. This method assesses the degree of belonging to a certain set based on quantitative values, allowing for precise evaluation and quantification of correlation degree (Wu et al., 2019). It has been applied in various evaluations such as ecological security evaluation (Wu et al., 2019), water safety evaluation (Li et al., 2017; Wang et al., 2019), ecosystem health evaluation (Li and Li, 2014; Su et al., 2019), and land suitability evaluation (Geng et al., 2019; Chen et al., 2021). The assessment of FLR suitability encompasses multiple indicators, often yielding incompatible results when assessing individual indicators. Therefore, the matter-element model can be employed to facilitate comprehensive evaluation. Additionally, the importance of each evaluation index varies depending on the specific evaluation objectives. The analytic hierarchy process (AHP) is a systematic method used in multi-criteria decision making. Its fundamental concept involves decomposing intricate problems into several hierarchical levels and multiple factors (Saaty, 1977). By evaluating the importance of pairwise indicators, establishing judgment matrices, and calculating the maximum eigenvalue of these matrices, the AHP method determines the relative weights of various alternatives based on their significance (Saaty, 1977; Atkinson et al., 2005). This process serves as a foundation for guiding the selection of the optimal solution. By determining weights through the AHP method, it mitigates the limitations of strong human subjective interference in traditional suitability evaluation processes, leading to more accurate evaluation results. As a result, AHP is widely employed in the field of landscape restoration suitability evaluation.

The Saihanba Nature Reserve, situated in the forest-steppe ecotone, is a diverse ecosystem integrating forest, grassland, meadow, and marsh (Tian et al., 2016). This area holds significant conservation value due to its rich species diversity. However, the area has been negatively affected by long-term anthropogenic disturbances and extensive plantation management practices (Sa and Fan, 2023). Historically, the area experienced extensive deforestation, leading to the disappearance of the original forests by the early 1950s. This situation resulted in desertification,

soil erosion, and ecological degradation (Liu et al., 2023). To address these issues, the Chinese government initiated a large-scale afforestation program in 1952. Saihanba was designated as one of the first pilot areas under this program. Since the establishment of the Saihanba Mechanical Forest Farm in 1962, continuous afforestation efforts have transformed it into the largest plantation base in the north of China (Sa and Fan, 2023). However, the plantations still face the challenge of single-species dominance (Fan and Li, 2008), with a higher proportion of pure stands and a lower proportion of mixed forests (Zhang et al., 2022). The predominant plantation species include *L. principis-rupprechtii*, *Pinus sylvestris* var. *mongolica*, *Picea asperata*, and *Quercus mongolica* (Li et al., 2021b). The prevalence of pure forests can lead to unstable forest ecosystems, which may result in the ineffective performance of ecosystem services (Wang et al., 2009). Especially, the lack of information on suitable areas for FLR hinders species diversity conservation in the study area. There is an urgent need for FLR in this region, making the identification of suitable restoration area a crucial and challenging task. In this study, the suitability of FLR in the area was evaluated by using a matter-element model. The study aimed to explicitly identify the suitable areas for FLR to effectively conserve species diversity in the area.

# 2 Materials and methods

## 2.1 Study area

The Saihanba Nature Reserve (42°04′-42°39′N, 116°56′-117°42′E) is located in Weichang County, Hebei Province, China. It covers a total area of 929.97 km$^2$ and is located on the border between the Inner Mongolia and Hebei Province. The elevation is low in the southwest and high in the northeast. The slopes range from 0° to 53°, and the elevations range from 1,014 to 1,952 m (Qin et al., 2016; **Figure 1**). The climate is characterized as a cold-temperate semi-arid and semi-humid continental monsoon climate. The average annual temperature is −1.3°C, with extreme maximum and minimum temperatures recorded at 33.4°C and −43.3°C, respectively (Dong et al., 2021). The annual precipitation amounts to approximately 460 mm (Zhao et al., 2023). The unique topography and climate conditions have contributed to the formation of various soil types in the area, including Arenosols, Cambisols, and Luvisols (Li et al., 2021b).

Saihanba is the largest plantation forest base in China (Sa and Fan, 2023). Statistics reveal that the plantations in the Saihanba area cover an area of approximately 561.76 km$^2$, but only 33.67% of this area consists of mixed forests. Additionally, the distribution of forest patches across different development stages is imbalanced, with middle and young-aged forests constituting over 50% of the total forest landscape, while the proportion of mature forests is low in study area. Moreover, plantation patches are generally small in size and exhibit simple shapes (Xu et al., 2021). These factors have led to landscape fragmentation (Wei et al., 2022) and a decrease in biodiversity (Ge et al., 2020), thereby impeding the ecological environment's improvement and the area's sustainable development. Consequently, there is an urgent need for FLR to harness the multifunctional benefits of the forest in a sustainable and efficient manner.

## 2.2 Data acquisition and processing

Land use status plays a decisive role in the suitability of FLR (Lambin et al., 2001). The land cover types were classified into natural secondary forest, shrub meadow, plantation, and others (wetland, agricultural landscape, sandy, and construction) by employing the ENVI 5.1 software (Exelis Visual Information Solutions, Broomfield, CO, USA). Prior to classification, several pre-processing steps were conducted on the Landsat 8 image data, including multiband blending, geometric correction, image mosaic, and image cropping. The Landsat remote sensing data, obtained in July 2020, were sourced from the U.S. Geological Survey.[1] The supervised classification approach yielded an overall classification accuracy of 98.62%, and a KAPPA coefficient of 0.98. To better verify the accuracy of the land cover type classification results, we conducted ground truthing in the study area in August 2022. A stratified random sampling approach was adopted, and the sample size was determined based on the proportional area of various land cover types in the study area (Pu et al., 2020). A total of 60 testing plots were surveyed. Through ground truth verification, necessary corrections (e.g., some plantations were incorrectly classified as shrub meadow by the algorithm and needed to be corrected to plantation) were applied to the classification results.

Soil nutrients play a crucial role in determining soil fertility and influencing species diversity (Ge et al., 2017). This study focuses on assessing soil fertility using the soil quality index (SQI), a widely used method that combines various biochemical indicators into a single index, particularly in the evaluation of forest soil quality. Soil data were obtained from the National Earth System Science Data Center.[2] Seven soil factors were selected: total nitrogen, total phosphorus, total potassium, available potassium, alkali-hydrolysis nitrogen, available phosphorus, and pH. These factors were spatially interpolated and masked using the ArcGIS 10.2 software (Environmental Systems Research Institute, Redlands, CA, USA). The final raster soil factor dataset for the study area was generated. Subsequently, the SQI was calculated by performing principal component analysis (PCA) to construct a minimum data set (MDS) and selecting the principal component with eigenvalues greater than 1. The MDS index scores were then computed, and the weights were determined. Ultimately, a weighted sum model was used to compute the SQI. The formulas for calculating the index scores and SQI (Askari and Holden, 2014) were calculated based on **Equations 1**, **2**.

$$S = a/(1 + (x/x_0)^b) \quad (1)$$

where $S$ is the index score, $a$ is the highest score ($a = 1$), $x$ is the soil variable value, $x_0$ is the mean value of the variable, and $b$ is the slope assumed to be −2.5 for "more is better" and 2.5 for "less is better."

$$SQI = \sum_1^n W_i S_i \quad (2)$$

where $W_i$ is the weight of the indicator $i$; $S_i$ is the score of the indicator $i$; $n$ is the indicator number of the MDS.

Changes in landscape structure can influence the flow and exchange of energy and materials within the landscape, ultimately resulting in a decline or increase in species diversity (Muneepeerakul et al., 2019). Considering the objectives of this study, we focused on three landscape structure factors, namely patch area, patch distance, and patch shape, to assess the suitability of FLR. The patch distance was centered on natural secondary forest patches, and a buffer zone of four magnitudes, 300, 750, 1,000, and 2,000 m, was set (Chen et al., 2012; Wei et al., 2022). The landscape shape index (LSI) was calculated according to **Equation 3** (Wu, 2000):

$$LSI = \frac{0.25L}{\sqrt{A}} \tag{3}$$

where $L$ is the perimeter of the patch; $A$ is the patch area. $LSI \geq 1$, no upper limit. When there is only one square patch in the landscape, $LSI = 1$; when the patch shape in the landscape is irregular or deviates from square, the $LSI$ value increases.

Topography controls the spatial pattern of basic ecological factors, such as light, temperature, moisture, and soil nutrients (Swanson et al., 1988). Among the various attributes of topography, slope is particularly important as it influences soil thickness, soil erosion, and soil conservation (Li et al., 2013; Méndez-Toribio et al., 2016). The digital elevation model (DEM) data was acquired from the geospatial data cloud.[3] We extracted the slope data from the DEM using the spatial analyst tool in the ArcGIS10.2 software.

Raster data were generated for each evaluation factor mentioned above, and all of them used CGCS2000_GK_Zone_20 projection coordinate system. The details of the data used in this study are presented in **Table 1**.

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3   http://www.gscloud.cn/
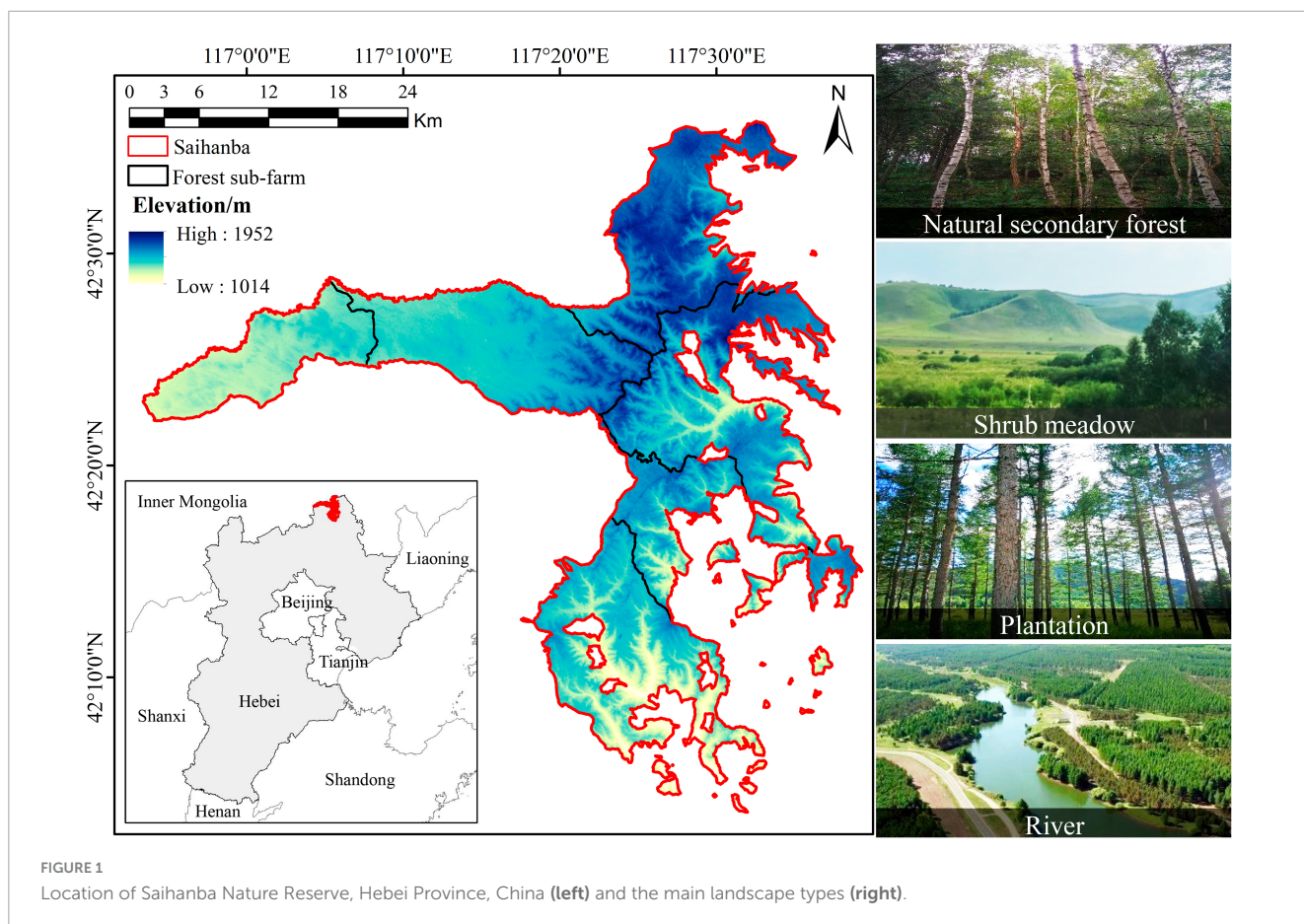


FIGURE 1
Location of Saihanba Nature Reserve, Hebei Province, China **(left)** and the main landscape types **(right)**.

TABLE 1   Description of the data used in this study.

| Data type | Data source | Acquired time | Resolution |
|---|---|---|---|
| Land cover type | The U.S. Geological Survey (http://glovis.usgs.gov/) | 2020 | 30 m |
| Soil | The National Earth System Science Data Center (http://www.geodata.cn) | 2018 | |
| DEM | The geospatial data cloud (http://www.gscloud.cn/) | 2020 | |
| Patch area | The national forest inventory data | 2021 | |
| Patch distance | | | |
| Patch shape | | | |

## 2.3 Determination of indicator weights

In this study, the AHP method was employed to determine the weights of the evaluation factors. The AHP method involves two main steps. Firstly, the relative importance of the evaluation factors was determined using the expert scoring method. We invited a total of 30 forestry experts to participate in the scoring process. To ensure the objectivity and accuracy of the assessment, the selection of these experts was based on their extensive experience and deep knowledge in the field of FLR. A pairwise judgment matrix ($C$) was constructed for the criterion layer, and the maximum eigenvalue of the judgment matrix ($\lambda_{max}$) and the corresponding eigenvector ($W$) were calculated. The components of the $W$ represent the weights of the indicators in the criterion layer (Saaty, 1977). Secondly, a consistency test was conducted. The consistency index ($CI$), average randomness index ($RI$), and random consistency ratio ($CR$) were calculated using **Equations 4**, **5** (Saaty, 1977). If the $CR \leq 0.10$, the consistency of matrix $C$ is deemed acceptable, indicating the reliability of the calculated weight values. However, If the $CR > 0.10$, it signifies the need for readjusting the judgment matrix (Atkinson et al., 2005). Following multiple iterations of adjusting the judgment matrix, the final consistency test value is obtained as $CR = 0.0355$ ($CR \leq 0.10$), confirming the reasonableness of the derived weights (**Table 2**).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

$$CR = \frac{CI}{RI} < 0.10 \tag{5}$$

## 2.4 Matter-element analysis

A mathematician first introduced the matter-element analysis theory in the 1980s to tackle incompatibility issues (Cai, 1999). Ecosystems were traditionally viewed as a collection of matter-elements, each comprising objects and characteristics that participate in various processes and transformations (Tang et al., 2009; Gong et al., 2012). Building upon this concept, matter-element analysis now encompasses a set of fundamental steps: firstly, the system undergoes a division into matter-elements. Subsequently, defining the class intervals for each evaluation indicator. Thirdly, calculating the single-index correlation degree to determine the suitability of FLR under each individual indicator. Finally, obtaining comprehensive scores for all indicators through model integration (Gong et al., 2012). Consequently, the evaluation results from matter-element analysis are demonstrated to be more rational and precise in comparison to results obtained through alternative methods (Tang et al., 2009).

### 2.4.1 Construction of FLR suitability matter-element model

The FLR suitability matter-element model ($R$) is comprised of three components: the FLR suitability ($N$), the characteristic of this suitability ($C$), and the magnitude of the character ($V$). The $N$ is represented by a vector $C$ ($c_1$, $c_2$,..., $c_n$) with n dimensions, indicating its various characteristics. The corresponding quantity $C$ is represented by the n-dimensional vector $V$ ($v_1$, $v_2$,..., $v_n$). R

model (Gong et al., 2012; Geng et al., 2019) is expressed according to **Equation 6**.

$$R = (N, C, V) = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \tag{6}$$

### 2.4.2 Determination of the classical and segment field of matter-element

If the evaluation object has $m$ levels with $N_{01}$, $N_{02}$, . . . and $N_{0m}$, the matter-element ($R_{oj}$) (Gong et al., 2012; Geng et al., 2019) is expressed according to **Equation 7**.

$$R_{oj} = (N_{oj}, c_i, V_{oji}) = \begin{bmatrix} N_{oj} & c_1 & < a_{oj1}, b_{oj1} > \\ & c_2 & < a_{oj2}, b_{oj2} > \\ & \vdots & \vdots \\ & c_n & < a_{ojn}, b_{ojn} > \end{bmatrix} \tag{7}$$

where $R_{oj}$ denotes the classical field of matter-element; $N_{oj}$ is the $j$-th evaluation level ($j = 1, 2, \ldots, m$); $c_i$ is the $i$-th evaluation indicator; $V_{oji}$ is the $j$-th-level value range of $c_i$, that is the classical domain. The range of $V_{oji}$ is interval $< a_{oji}, b_{oji} >$, which can be recorded as $V_{oji = <a_{oji}, b_{oji}>}$, $i = 1, 2, \ldots, n$.

According to the classical domain, the section domain ($R_p$) (Gong et al., 2012; Geng et al., 2019) is expressed according to **Equation 8**.

$$R_p = (N_p, c_i, V_{pi}) = \begin{bmatrix} N_p & c_1 & < a_{p1}, b_{p1} > \\ & c_2 & < a_{p2}, b_{p2} > \\ & \vdots & \vdots \\ & c_n & < a_{pn}, b_{pn} > \end{bmatrix} \tag{8}$$

where $N_p$ is the whole evaluation levels, and the $V_{pi}$ is the value range of $c_i$. All that is the $N_p$ section domain, which can be recorded as $V_{pi = <a_{pi}, b_{pi}>}$, $i = 1, 2, \ldots, n$. Obviously, here are $V_{oji}$ belongs to $V_{pi}$. Determining the classical field is a crucial step in the analysis of matter-element. The evaluation factors were categorized into different suitability levels and assigned scores ranging from 0 to 100. These scores represent the degree to which each evaluation factor contributes to the conservation of species diversity. A higher score indicates a greater benefit to species diversity conservation. **Table 2** presents the scores of the suitability evaluation factors for FLR in the study area. The classical and segment domain were calculated as follows **Equations 9–13**.

$$R_{01} = \begin{bmatrix} S1 & c_1 & < 99 - 101 > \\ & c_2 & < 0.60 - 0.76 > \\ & c_3 & < 10 - 95.95 \ km^2 > \\ & c_4 & < 99 - 101 > \\ & c_5 & < 2.20 - 3.19 > \\ & c_6 & < 1 - 15° > \end{bmatrix} \tag{9}$$

$$R_{02} = \begin{bmatrix} S2 & c_1 & < 49 - 51 > \\ & c_2 & < 0.40 - 0.60 > \\ & c_3 & < 5 - 10 \ km^2 > \\ & c_4 & < 49 - 51 > \\ & c_5 & < 1.90 - 2.20 > \\ & c_6 & < 15 - 25° > \end{bmatrix} \tag{10}$$

TABLE 2 Evaluation system of forest landscape restoration suitability in Saihanba Nature Reserve, Hebei Province, China.

| Target layer | Criterion layer | Index layer | Degree of suitability | Score | Weight |
|---|---|---|---|---|---|
| Forest landscape restoration suitability | $C_1$ Land cover type | $C_{11}$ Natural secondary forest | S1 Suitable | 100 | 0.354 |
| | | $C_{12}$ Shrub meadow | S2 Moderately suitable | 50 | |
| | | $C_{13}$ Plantation | S3 Marginally suitable | 30 | |
| | | $C_{14}$ Others | S4 Unsuitable | 10 | |
| | $C_2$ SQI | $C_{21}$ >0.6 | S1 Suitable | 100 | 0.100 |
| | | $C_{22}$ 0.4–0.6 | S2 Moderately suitable | 50 | |
| | | $C_{23}$ 0.25–0.4 | S3 Marginally suitable | 30 | |
| | | $C_{24}$ <0.25 | S4 Unsuitable | 10 | |
| | $C_3$ Patch area ($km^2$) | $C_{31}$ >10 | S1 Suitable | 100 | 0.153 |
| | | $C_{32}$ 5–10 | S2 Moderately suitable | 50 | |
| | | $C_{33}$ 1–5 | S3 Marginally suitable | 30 | |
| | | $C_{34}$ <1 | S4 Unsuitable | 10 | |
| | $C_4$ Patch distance (m) | $C_{41}$ <300 | S1 Suitable | 100 | 0.153 |
| | | $C_{42}$ 300–750 | S2 Moderately suitable | 50 | |
| | | $C_{43}$ 750–1,000 | S3 Marginally suitable | 30 | |
| | | $C_{44}$ >1,000 | S4 Unsuitable | 10 | |
| | $C_5$ LSI | $C_{51}$ >2.2 | S1 Suitable | 100 | 0.153 |
| | | $C_{52}$ 1.9–2.2 | S2 Moderately suitable | 50 | |
| | | $C_{53}$ 1.6–1.9 | S3 Marginally suitable | 30 | |
| | | $C_{54}$ <1.6 | S4 Unsuitable | 10 | |
| | $C_6$ Slope (°) | $C_{61}$ <15 | S1 Suitable | 100 | 0.087 |
| | | $C_{62}$ 15–25 | S2 Moderately suitable | 50 | |
| | | $C_{63}$ 25–35 | S3 Marginally suitable | 30 | |
| | | $C_{64}$ >35 | S4 Unsuitable | 10 | |

$$R_{03} = \begin{bmatrix} S3 & c_1 & <29-31> \\ & c_2 & <0.25-0.40> \\ & c_3 & <1-5\,km^2> \\ & c_4 & <29-31> \\ & c_5 & <1.60-1.90> \\ & c_6 & <25-35°> \end{bmatrix} \quad (11)$$

$$R_{04} = \begin{bmatrix} S4 & c_1 & <9-11> \\ & c_2 & <0.10-0.25> \\ & c_3 & <0.06-1\,km^2> \\ & c_4 & <9-11> \\ & c_5 & <1.07-1.60> \\ & c_6 & <35-53°> \end{bmatrix} \quad (12)$$

$$R_p = \begin{bmatrix} N_p & c_1 & <0-100> \\ & c_2 & <0.10-0.76> \\ & c_3 & <0.06-95.95\,km^2> \\ & c_4 & <0-100> \\ & c_5 & <1.07-3.19> \\ & c_6 & <0-53°> \end{bmatrix} \quad (13)$$

The land cover type ($C_1$) was a discrete variable, and its score was assigned within a range of 0–100 for ease of calculations,

as shown in Equation 13 and summarized in Table 2. Among the four land cover types, natural secondary forests exhibited the highest species diversity. Shrub meadows typically had lower species diversity compared to natural secondary forests but higher diversity compared to plantation. The other land cover types predominantly consisted of urban construction, which exhibited the lowest species diversity due to the greater impact of human activities. Based on these considerations, the classification criteria for different levels of suitable restoration were as follows: natural secondary forests were considered suitable for restoration, shrub meadows were moderately suitable, plantations were marginally suitable, and the other land cover types were deemed unsuitable for restoration. Specific details of the segment field, suitability classification criteria, and score for other factors (SQI, patch area, patch distance, LSI, and slope) are shown in Table 2.

### 2.4.3 Calculation of correlation degree

Based on the classical domain and the segmented domain, the degree of correlation between each characteristic and each class (Gong et al., 2012; Su et al., 2019) was calculated using the following functions:

$$K_j(v_i) \begin{cases} \dfrac{-\rho(v_i, V_{oji})}{|V_{oji}|} & v_i \in V_{oji} \\ \dfrac{\rho(v_i, V_{oji})}{\rho(v_i, V_{pi}) - \rho(v_i, V_{oji})} & v_i \notin V_{oji} \end{cases} \quad (14)$$

where

$$\rho(v_i, V_{oji}) = \left| v_i - \frac{1}{2}(a_{oji} + b_{oji}) \right| - \frac{1}{2}(b_{oji} - a_{oji}) \quad (15)$$

$$\rho(v_i, V_{pi}) = \left| v_i - \frac{1}{2}(a_{pi} + b_{pi}) \right| - \frac{1}{2}(b_{pi} - a_{pi}) \quad (16)$$

where $|V_{oji}| = |a_{oji} - b_{oji}|$; $\rho(v_i, V_{oji})$, $\rho(v_i, V_{pi})$ are respectively the distances between $v_i$ and classical domain $V_{oji}$ and section domain $V_{pi}$.

## 2.4.4 Determination of comprehensive correlation degree and suitability level

The formula (Tang et al., 2009; Gong et al., 2012) for calculating the comprehensive degree of correlation of each evaluation unit is:

$$K_j(P_0) = \sum_{i=1}^{n} a_i K_j(v_i) \quad (17)$$

where $K_j(P_0)$ expresses the integrated correlation degree between evaluation object $P_0$ and its corresponding grade $j$. $K_j(v_i)$ is the correlation function of the $i$-th characteristic belonging to $j$ level. $a_i$ is the weight of each evaluation indicator, and $\sum a_i = 1$. If:

$$K_j(P_0) = \max K_j(P_0) \ (j = 1, 2, \ldots, m) \quad (18)$$

then the evaluated matter $P_0$ belongs to rank $j$.

The numerical value of the associated function $K_j(P_0)$ represents the extent to which the subject under evaluation conforms to a certain standard (Su and Chen, 2005). If $K_j(P_0) \geq 0$, it signifies that the evaluation object aligns with the requirements of a specific grade standard, and the degree of compliance increases with its value. When $-1 < K_j(P_0) < 0$, the evaluation object does not meet the criteria of a particular grade standard, yet it possesses the potential for transformation to that standard, with a higher value making this transformation more attainable. However, if $K_j(P_0) < -1$, the evaluation object not only fails to meet the requirements of the grade standard but also lacks the capacity for advancement to that standard. A lower value in this case indicates a more significant disparity between the evaluated object and the evaluation criteria (Su and Chen, 2005; Gong et al., 2012). Using the ArcGIS raster calculator, the distances of the four classical fields and one segment field for the six indicator raster values were calculated based on Equations 14–16, respectively. The correlation degrees corresponding to each suitability level were also calculated, resulting in a total of 24 correlation degree layers for each indicator. The weights for each indicator were determined using the AHP method. These weights were used to calculate the comprehensive correlation degrees for each raster in the four suitability classes: suitable, moderately suitable, marginally suitable, and unsuitable. This was done using Equation 17, which determined the degree of belonging to each class. To obtain the final result of the FLR suitability evaluation, the grade corresponding to the maximum value of the comprehensive correlation degree for each grid was selected as its suitability grade. This selection process was performed using Equation 18.
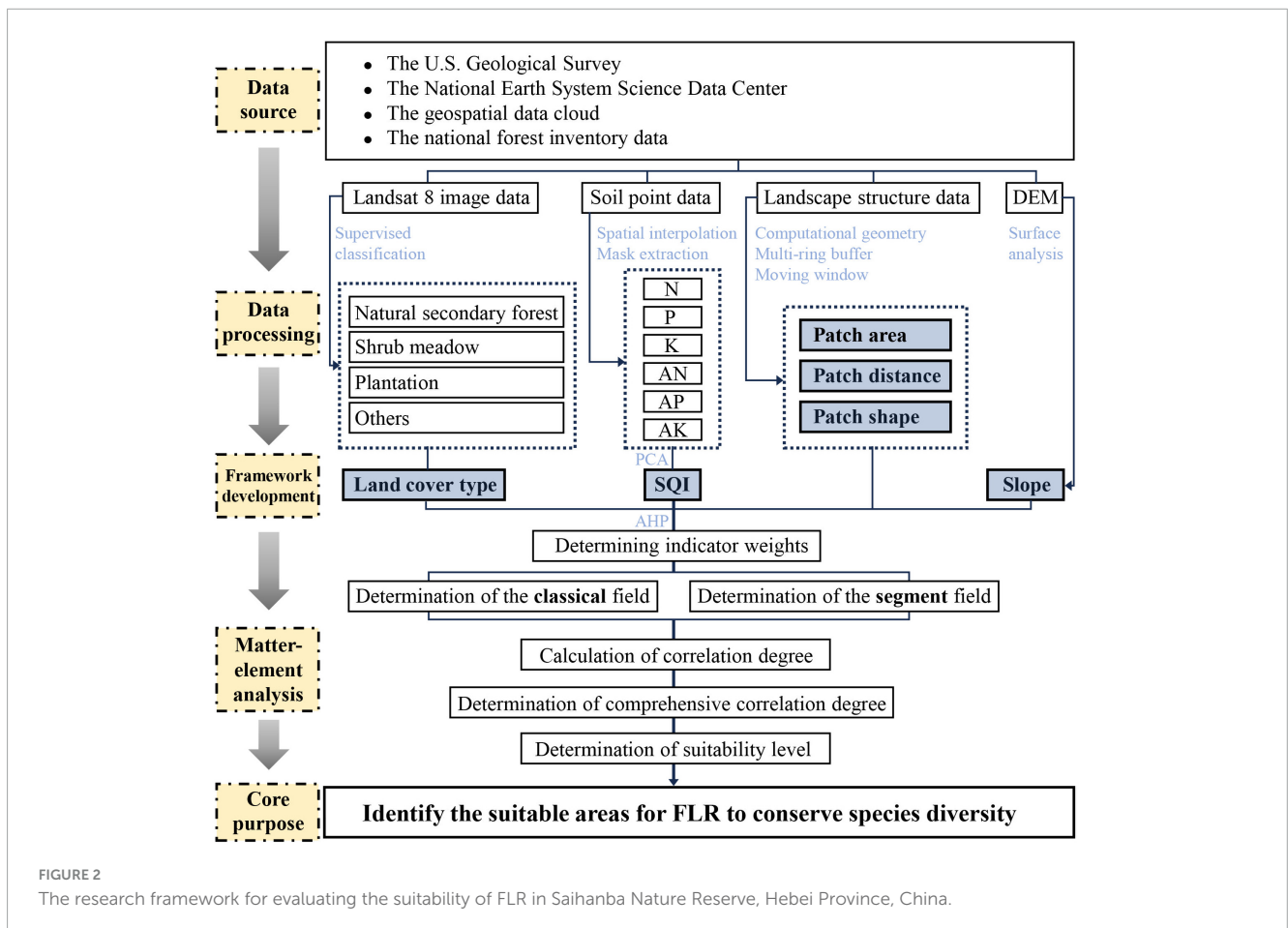


FIGURE 2
The research framework for evaluating the suitability of FLR in Saihanba Nature Reserve, Hebei Province, China.

## 2.5 Statistical analysis

For each sub-farm (a management unit delineated within the Forest Farm for the purpose of conducting forest management activities in a rational manner) as the unit of analysis, a one-way ANOVA and Tukey's difference significance test ($p < 0.05$) were conducted to determine if there were significant variations in the percentage of area among different suitability classes for each index. All analyses were performed using the R4.1.0 software (R Core Team, 2021).

For a framework of the research methods, see **Figure 2**.

# 3 Results

## 3.1 Land cover type, soil quality, landscape structure, and slope analysis

Among the four land cover types, plantation covered approximately 54.40% of the total area in the study area, which was significantly higher than the area occupied by natural secondary forest, shrub meadow, and other types ($p < 0.05$). The area of natural secondary forest accounted for the second highest percentage at 24.25%, but there was no significant difference compared to the area of other types ($p > 0.05$) (**Figures 3, 4**).

The suitability distribution of land cover type, soil quality, landscape metrics, and slope in Saihanba Nature Reserve, Hebei Province, China.

There was no significant difference in the area proportions among soil quality class ($p > 0.05$). The area with SQI lower than 0.25 was the largest, accounting for 39.19% of the total study area, while the second largest proportion, 36.24%, had an SQI greater than 0.6 (**Figures 3, 4**).

In terms of patch size, patches larger than 10 km$^2$ covered 38.17% of the total area, which was significantly higher than patches equal to or smaller than 10 km$^2$ ($p < 0.05$). Conversely, patches smaller than 1 km$^2$ made up 16.88% of the total area, and their area was significantly lower than patches equal to or larger than 1 km$^2$ ($p < 0.05$). However, there was no significant difference between patches of 1–5 and 5–10 km$^2$ ($p > 0.05$). The majority of patches, 75.92% of the total area, had distances less than 300 m, which was significantly higher than patches with distances greater than or equal to 300 m ($p < 0.05$). Patches with distances between 300 and 750 m accounted for 15.66% of the total area, and their area was significantly larger than patches with distances greater than 750 m ($p < 0.05$). Regarding the LSI, patches with LSI values between 1.6 and 1.9 had the highest occurrence, and accounted for 42.91% of the total study area. The area of patches with LSI values less than 1.6 or greater than 2.2 was significantly low ($p < 0.05$) (**Figures 3, 4**).

The area of patches with slope less than 15° accounted for 71.38% of the total area, which was significantly higher than that of patches with slope equal to or greater than 15° ($p < 0.05$). However, the area of patches with slope between 15° and 25° was significantly lower than that of patches with slope less than 15°. The area of patches with slope greater than or equal to 25° was significantly lower than that of patches with slope less than 25° ($p < 0.05$) (**Figures 3, 4**).

## 3.2 Forest landscape restoration suitability evaluation

**Figure 5** shows that the overall suitability of FLR was good, presenting a tendency of gradually decreasing suitability from west to east. The suitable restoration area covered 519.20 km$^2$, accounting for 55.55% of the study area, which was significantly higher than the moderately suitable, marginally suitable, and unsuitable areas ($p < 0.05$). The suitable restoration areas were mainly concentrated in the western part of the study area and scattered distribution in the eastern region. The dominant land cover type in these areas was natural secondary forest, characterized by high soil fertility, large patch sizes, close patch distances, complex patch shapes, and gentle slopes.

The moderately and marginally suitable restoration areas covered 161.72 and 223.96 km$^2$, accounting for 17.30% and 23.96% of the total study area, respectively. These areas were primarily scattered in the eastern part of the study area, and the main land cover type was plantation. In these areas, the patches were characterized by close distances, low soil fertility, small patch sizes, and steep slopes.

The unsuitable restoration area covered 29.74 km$^2$, accounting for 3.18% of the total study area, which was significantly lower than the other types ($p < 0.05$). It was primarily located in the northeastern edge of the study area. Among these areas, other land cover types occupied 85.94% of the area. Plantation patches in this region were limited by the combined effects of low soil fertility,
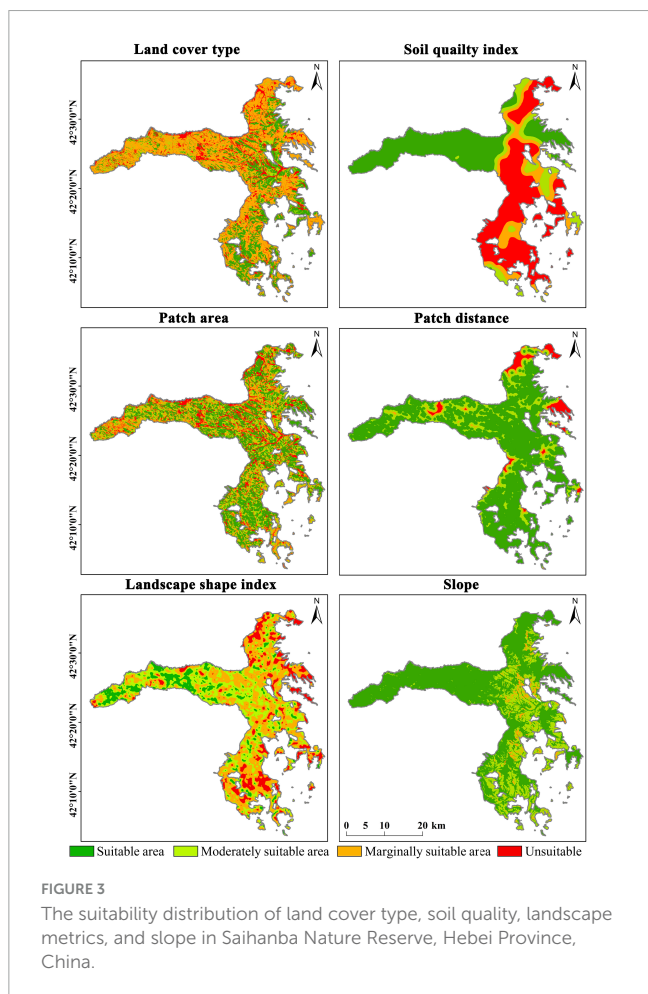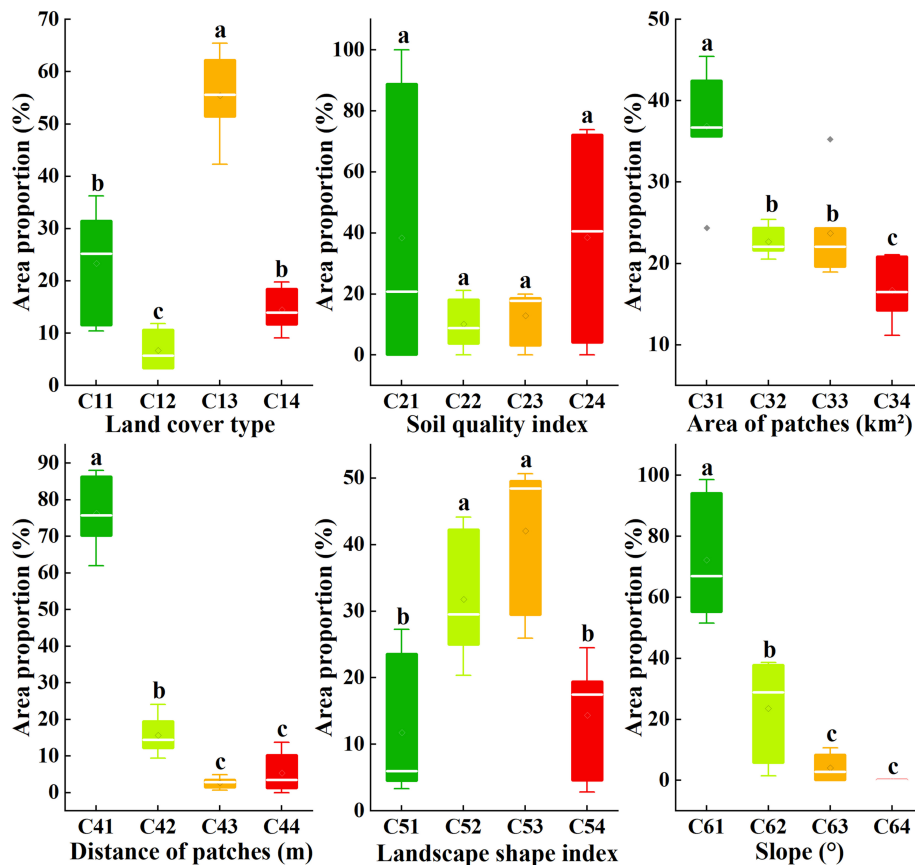
**FIGURE 4**
The differences in area proportions among the suitable classes of land cover type, soil quality, landscape metrics, and slope in Saihanba Nature Reserve, Hebei Province, China. The different letters show significant difference at $p < 0.05$ level; C11−C64 represent the indicators at the index layer. Refer to **Table 2** for their specific meanings. The same applies below.

small patch sizes, long patch distances, regular patch shapes, and steeper slopes, making FLR more challenging.

## 3.3 Suitability characteristics of important factors

Natural secondary forests had the largest area suitable for restoration (226 km$^2$), accounting for 43.53% of the suitable restoration area, followed by plantations, shrub meadows, and others, accounting for 42%, 8.7%, and 5.76% of the suitable restoration area, respectively. The area of plantations in the moderately and marginally suitable restoration areas reached 91.40% and 62.07%, respectively. However, only 0.39% of natural secondary forests were classified as moderately suitable for restoration (**Figure 6**).

In terms of patch sizes in the suitable restoration area, about half of the patches were larger than 10 km$^2$, followed by patches with an area of 1–5 and 5–10 km$^2$, accounting for 22.19% and 21.40% of the suitable restoration area, respectively. Patches smaller than 1 km$^2$ accounted for only 9.35% of the suitable restoration area. In the moderately suitable restoration area, the majority of patches (45%) fell within the 5–10 km$^2$ range. For the marginally and unsuitable restoration areas, there was a gradual increase in the

proportion of patches smaller than 1 km$^2$, accounting for 34.65% and 79.76%, respectively (**Figure 6**).

When examining patch distances, the suitable restoration area had the largest number of patches with a distance of less than 300 m, accounting for 90.62% of the suitable restoration area. In the moderately suitable restoration area, patches with distances of 300–750 m were the most prevalent, accounting for 48.64% of this area. As for the marginally and unsuitable restoration areas, the proportion of patches with distances greater than 750 m gradually increased (**Figure 6**).

Regarding the LSI, patches with an LSI of 1.9–2.2 were more common in the suitable and moderately suitable restoration areas, accounting for 31.61% and 42.95% of these areas, respectively. The proportion of patches with an LSI greater than 2.2 gradually decreased in these areas. In the marginally suitable and unsuitable areas, there were more patches with LSIs of 1.6–1.9 or less than 1.6, comprising 58.47% and 33.67% of these areas, respectively (**Figure 6**).

## 4 Discussion

Identifying priority areas for FLR is a crucial task (Mansourian et al., 2006). At the landscape scale, factors such as land cover
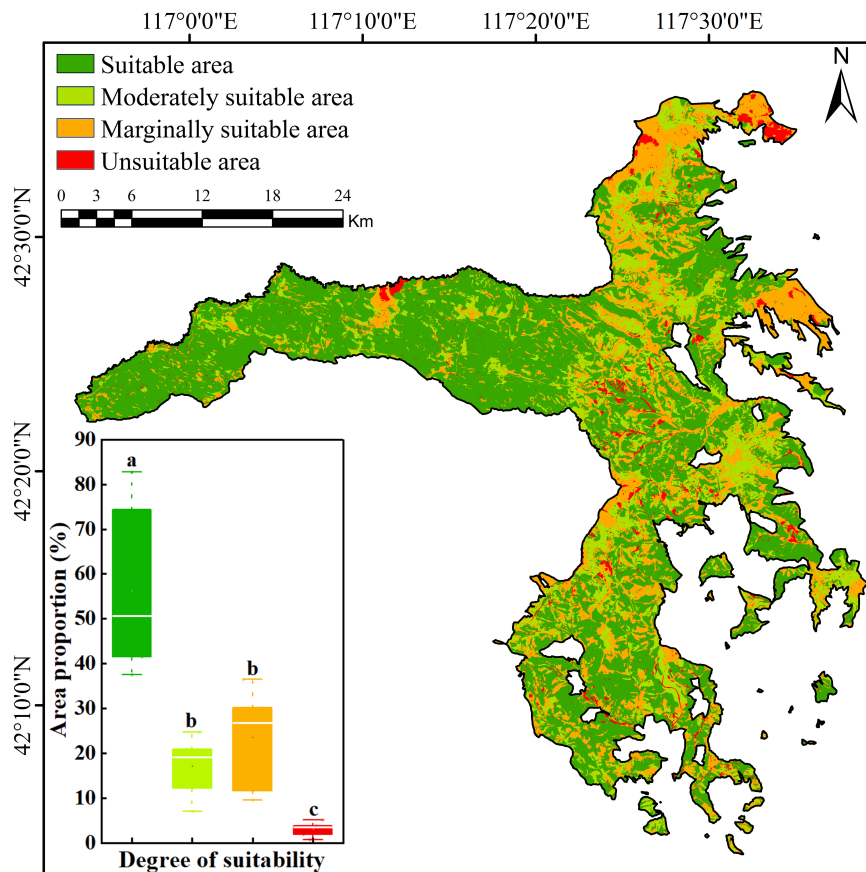
**FIGURE 5**
Suitability for forest landscape restoration in Saihanba Nature Reserve, Hebei Province, China. The different letters show significant differences among the suitable classes at a significance level of $p < 0.05$ in boxplot.

type, landscape structure, soil quality, and topography significantly influence the suitability of FLR. The evaluation results indicated that suitable restoration areas were predominantly concentrated in the western part of the study area and scattered distribution in the eastern part. The land cover types in these areas are mainly natural secondary forests, followed by plantation, with no significant difference in their proportions (**Figures 3**, **6**). This may be because both land cover types play a crucial role in the conservation of species diversity. Natural secondary forests exhibit strong adaptability and a relatively stable stand structure. There is substantial evidence that plantations can provide habitats for certain endangered species and contribute to the conservation of species diversity through various mechanisms (Brockerhoff et al., 2008). In our study area, endangered species such as *Paris verticillata* M.-Bieb, *Rhodiola rosea* L., *Aquila clanga* Pallas, and *Cervus elaphus* Linnaeus have been identified as beneficiaries of these plantation (Du et al., 2020). However, plantations often exhibit extensive fragmentation, which restricts species migration and hinders the conservation of species-diversity (Mensah et al., 2020). Therefore, establishing artificial mixed forests and adjusting their landscape patterns has recently been a key focus of landscape restoration (Löf et al., 2019; Stanturf and Mansourian, 2020). The specific characteristics of the suitable restoration areas, including large patch area, proximity to natural secondary forests, and complex patch shape (**Figures 3**, **6**), align with the principles of

island biogeography theory and are consistent with the findings of Diniz et al. (2023), indicating that closely connected patches are potential candidates for FLR. The relatively low slope of the suitable restoration areas (**Figure 3**) may be due to the fact that gentle sloping areas can offer diverse ecological niches for various species, thereby facilitating species dispersion and promoting higher species biodiversity (Wang et al., 2018). As slope steepness increases, water and nutrient loss escalate, leading to a gradual decrease in species numbers (Li et al., 2013). In FLR projects, priority should be given to these patches, focusing on identifying and establishing ecological corridors among suitable restoration areas. This approach aims to create continuous habitat areas, establishes pathways for plant and animal migration and dispersal, and enhances species diversity conservation with relative lower effort (Fahrig et al., 2022). This is similar to the viewpoint of Volis (2018) who suggests that priority should be given to changing the minimum, in other words, focusing on habitats that are currently in the best condition. Moderate and marginally suitable restoration areas were scattered in the eastern and northern parts of the study area, mainly comprising plantations. These patches were in close proximity to natural secondary forest but possessed limitations such as low soil fertility, small patch sizes, regular patch shapes, and steep slopes (**Figures 3**, **6**). These factors imposed challenges for conserving species diversity. There were limited areas unsuitable for restoration, mainly concentrated in the northeastern edge of the
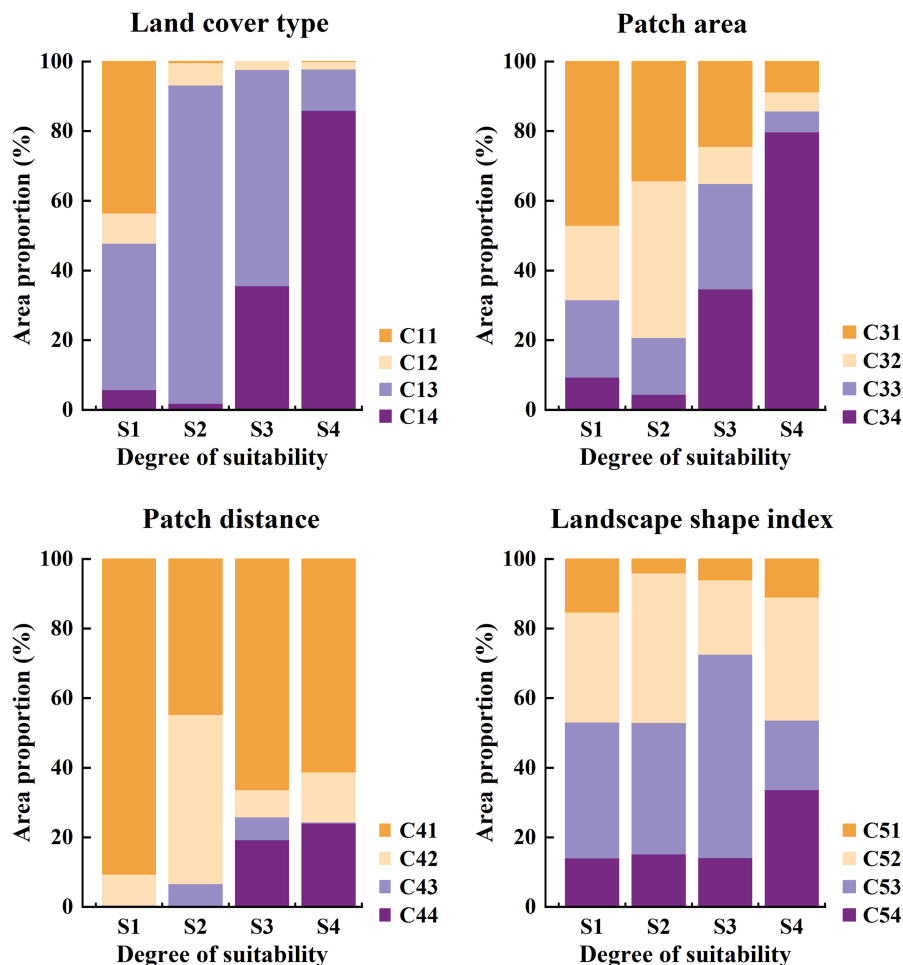
**FIGURE 6**
The area proportions of the sub-classes of land cover type, patch area, patch distance, and landscape shape index at corresponding suitable level.

study area, where the main land cover type was classified as "other" (**Figures 3**, **6**). These areas mainly consisted of patches influenced by human activities, such as construction land, characterized by regular patch shapes, small patch areas, and frequently human disturbances. These factors hinder the migration and dispersal of some species and do not contribute to landscape functionality or species diversity conservation (O'Neill et al., 1997), classifying them as unsuitable for restoration.

In this study, the FLR evaluation was mainly performed by using the matter-element model. Compared with the traditional overlay analysis, the calculation of the correlation function by the matter-element model is dimensionless, which can avoid the inaccurate evaluation results caused by the inappropriate method of standardizing the data. Additionally, the computation of the comprehensive correlation degree is based on the calculation of the correlation degree for each level of suitability of the evaluation index. The level corresponding to the highest value of the comprehensive correlation degree is then chosen as the suitable level of the evaluation unit. This approach effectively minimizes the impact of subjectivity in the suitable level classification, enhancing the scientific accuracy of FLR suitability evaluations. Additionally, this method is characterized by its ease of computation (Su and Chen, 2005). Compared to other methods, the matter-element

model not only facilitates a comprehensive assessment of the target, but also enables separate evaluations of each indicator, thereby offering more information (Gong et al., 2012). This approach has found extensive use in urban planning (Gong et al., 2012), the assessment of farmland quality, the evaluation of ecological vulnerable areas (Qi et al., 2020), and reclamation efforts in mining areas (Liu et al., 2022), as well as various other contexts. Furthermore, there is significant potential for its extended application and exploration in areas such as the selection of evaluation criteria, the establishment of thresholds, the universality of correlation functions in the matter-element analysis method, and its integration with advanced geographic information technology and big data analysis methods. The AHP method is a well-established technique for determining weights of multiple factors and assessing their consistency in the presence of conflicting criteria (Valente and Vettorazzi, 2008). However, it is important to limit the number of factors used in the evaluation to avoid difficulties in determining weight values and solving complex judgment matrix eigenvalues and eigenvectors. In future research, this issue can potentially be addressed by employing fuzzy hierarchical analysis to optimize the evaluation process.

The dominant factors influencing FLR vary at different scales. At a large scale, factors such as climate and altitude directly

affect the distribution patterns of species diversity (Kreft and Jetz, 2007), consequently impacting FLR. In our study, we did not incorporate the elevation factor into the assessment framework. In future research, it is advisable to consider relevant environmental factors for a more comprehensive analysis. At the landscape scale, the prioritization of FLR presents a multi-objective planning challenge that involves nature conservation and other problems, particularly socio-economic issues (Höhl et al., 2020). Socio-economic factors and stakeholder involvement can considerably influence FLR in the long term (Kremen and Merenlender, 2018). Since the Saihanba Nature Reserve is primarily a natural landscape and socio-economic factors are more closely related to the choice of restoration measures (Beatty et al., 2018b), natural factors were more frequently considered than socio-economic factors in the evaluation process. Different stakeholders hold distinct perspectives on FLR. Implementers of landscape restoration are primarily concerned about the regional scope and technical implementation methods, while policy makers prioritize factors such as budgetary requirements, funding sources, benefits of landscape restoration, social benefits, and cost-effectiveness (Maginnis et al., 2014). Therefore, future efforts can collect various socio-economic information, including statistics and census data of government department (Wang D. et al., 2015), commercial data sources (Zhang and Zhou, 2018), as well as independent research initiatives data such as surveys or interviews with local scientists and farmers (Chen and Huang, 2020). Furthermore, integrating 3S (GIS, GPS, and RS) technologies (Wang et al., 2015b) can facilitate the acquisition of socio-economic data, which can then be incorporated into the assessment framework. It is essential to consider the interests of different stakeholder groups to conduct forest landscape suitability assessments from a more scientific and comprehensive perspective. In this study, species diversity was substituted indirectly with vegetation types due to data limitations. To enhance the precision of assessment results in future research, it is essential to conduct field surveys on species diversity to improve the accuracy in FLR evaluations.

## 5 Conclusion

Determining priority restoration areas is a crucial topic in FLR, and the conservation of species diversity is an inherent requirement in this endeavor. In this study, we focus on the Saihanba Nature Reserve and develop a suitability evaluation framework system for FLR. By integrating factors such as land cover type, landscape structure, soil quality, and topography, our aim is to analyze the distribution pattern of suitability for FLR, with a specific emphasis on conserving species diversity. The findings of this study reveal that the suitable restoration area in the Saihanba Nature Reserve encompasses approximately 519.20 km$^2$, which accounts for 55.55% of the total region. The areas classified as moderate, marginally suitable, and unsuitable for FLR occupy 17.30%, 23.96%, and 3.18% of the study area, respectively. In the suitable restoration area, the predominant land cover type is natural secondary forest, characterized by large patch areas, close patch distances, and complex patch shapes. In conclusion, these findings suggest that the potential for FLR in this area is enormous. Meanwhile, land cover type and landscape metrics (patch area, patch distance, and patch shape) are the key factors influencing FLR in the Saihanba region.

The quantitative and visual results of this FLR suitability evaluation provide valuable insights into identifying patches with the highest conservation value in terms of species diversity in the study area. Simultaneously, these findings serve as a scientific foundation for evaluating FLR suitability in other regions. Future FLR should focus on protect large and complex shaped patches of natural secondary forests for better conservation of species diversity.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

ZZ, NF, and YW designed the study and performed the formal analysis. NF performed the software analysis and wrote the first draft of the manuscript. XY, JL, QL, and JK contributed the data curation. ZZ contributed to the writing, review, and editing. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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