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# Ecological Risk Assessment of Forest Landscapes in Lushan National Nature Reserve in Jiangxi Province, China

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**Abstract:** It is highly valuable to analyze and assess the landscape ecological risk of nature reserves to prevent and resolve ecological risks, as well as to effectively protect and maintain the sustainable development of nature reserves. Taking the forest landscape of the Lushan National Nature Reserve as its study object, this study performed grid processing for the nature reserve and classified forest landscape types using the Forest Resource Inventory Database in 2019. A landscape ecological index model was constructed to evaluate the ecological risk. Global and local Moran index values were used to reveal the autocorrelations for ecological risk. The geodetector method was used to comprehensively analyze the effects of natural and human factors on ecological risk. The results showed that, in general, the ecological risk level of the nature reserve was relatively low, as the proportion of the lowest-, lower-, and medium-risk areas to the total forestry land area accounted for 91.03%. The ecological risk ranking of each functional zone, from high to low, was in the order of the experimental zone, the buffer zone, and the core zone. The ecological risk levels of different forest landscape types were closely related to their area, spatial distribution, and succession stage, as well as human factors, such as the proximity to roads and settlements, etc. The forest landscape with the highest ecological risk was the *Cunninghamia lanceolata* (Lamb.) Hook. forest, and the forest landscape with the lowest ecological risk was other forestry land. Ecological risk had a positive spatial correlation and tended to be aggregated in space, demonstrating coupling with the proximity to roads and settlements. The ecological risk was affected by both human and natural factors, among which human factors played a dominant role. The proximity to roads and settlements, the relative humidity, and the temperature were the main driving factors. The interaction of pairwise factors had a stronger influence than that of single factors. Therefore, controlling the intensity of human activities and enhancing the coordination between humans and nature are beneficial for alleviating the ecological risks in the forest landscapes of nature reserves.

**Keywords:** ecological risk assessment; forest landscape; spatial pattern; nature reserve; Lushan Mountain

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## 1. Introduction

Natural ecosystems provide important basic materials and ecological services for the development of human society. As human society continuously expands, natural ecosystems in most of the world are facing pressures that directly or indirectly result from human activities. Therefore, establishing nature reserves plays an important role in maintaining biodiversity, maintaining an ecological balance, and safeguarding ecosystem stability, as well as promoting an eco-environment [1]. However, with the rapid development of society and the economy, the biological resources in nature reserves have been under certain pressures, and the eco-environments in nature reserves are also subject to certain risks [2]. Forest vegetation plays an important role in ecosystem services such as soil and water conservation [3]. As the main bodies of forest vegetation, nature reserves containing forest landscapes account for more than half of the nature reserves in China, and they are regarded as one of the most important types of nature reserves in China [4]. Forest landscapes, which are significant natural landscape resources, have come to form an important basis for ecotourism. However, the impact of human and natural factors has led to the emergence of environmental and ecological problems [5], especially forest and biodiversity loss, forest fragmentation, etc., in forest nature reserves due to natural and human factors [4] that change the structure and spatial pattern of the forest ecosystem. A change in the organization and structure of an ecosystem has regional and accumulative influences on ecology [6]. This results in ecosystem sensitivity and fragility [7], as well as the degradation of ecological services and functions [8], which results in ecological risks. The ecological risks resulting from changes in natural ecosystems are important factors affecting regional ecological security [9]. Indeed, it is of utmost importance to evaluate the ecological risks of the environment in order to sustain its ecological security, improve the quality of ecological services, and harmonize the relationship between conservation and development.

Ecological risk refers to the risk that an ecosystem experiences due to external disturbances such as environmental changes and human activities [10]. It is often considered an important method for evaluating the effectiveness of ecological and environmental protection [11]. The earliest ecological risk assessment mainly concerned the ecological effects of chemical pollution and toxic chemicals [12]. It gradually developed into a regional ecological risk assessment of the likelihood of adverse impacts and the degree of potential hazards caused by various risk factors such as environmental pollution, anthropogenic coercion, or natural disasters in different types of ecosystems within the region [13]. With the combination of landscape ecology theory and ecological risk assessments, landscape ecological risk assessments have become a hot topic in the field of regional ecological risk assessments [14]. The main method used to achieve this includes two aspects: one involves constructing ecological risk models based on risk sources and sinks. For example, Malekmohammadi et al. [15] evaluated the wetland ecological risk based on pressure sources. This method is mainly applicable to assessments with a clear regional ecological security of risk factors [16,17]. The other method involves constructing ecological risk assessment models based on landscape patterns. For example, Jin et al. [18] and Zhang et al. [19] examined the ecological effects of land use changes through landscape ecological indices. This method is mainly aimed at assessing the impact of human activities or natural factor changes on the landscape ecosystems of specific regions [20]. Additionally, it takes the specific situation of ecological risk and its impacts on the regional landscape into account. Furthermore, it pays attention to the spatial heterogeneity of the regional landscape's ecological risks [21]. It is not only used for land use changes, but also for forest ecosystems [6]. Presently, this method is widely used, and it has become the main method used for ecological risk assessments [22].

The Lushan National Nature Reserve is an isolated mountain body located in the center of a vast plain in the middle and lower reaches of the Yangtze River. It has a relatively complete middle and lower mountain forest ecosystem and an orderly ecological gradient distribution. The nature reserve is "an ecological intersection island", as its vegetation is located at the intersection of the mid-subtropical evergreen broad-leaved forest belt and the northern subtropical evergreen deciduous broad-leaved mixed forest belt, which has a typically transitional nature. It delivers a wealth of ecological services to the local people, and it maintains the ecological stability of the local area. However, the landform, steep slope, and other natural conditions have resulted in ecosystem fragility. The forest ecosystem of Lushan Mountain has suffered severe damage throughout history, and it has a long history of being affected by human activities, and then protected and restored by humans [23]. In 1981, it became one of the first provincial-level nature reserves in Jiangxi Province, and in 2013, it was named a national-level nature reserve. In addition, it was listed as a scenic area in 1982, and it was one of the earliest areas to cultivate tourism. Thus, it may be hypothesized that ecological risks exist in the nature reserve, that there are differences in the ecological risks of different forest landscape types, and that the ecological risks are the result of natural and human factors.

However, what are the ecological risks and the spatial characteristics exposed by the nature reserve? How effective is the conservation of forest vegetation in the nature reserve after a cycle of damage and protection? Moreover, which has a greater impact on the ecological risk of the forest ecosystem, natural or human factors? As a consequence, the main objectives of this study included the following: (1) taking the Lushan National Nature Reserve as the study area to quantitatively evaluate the ecological risk characteristics of different forest landscape types and functional zones, and to reveal the spatial heterogeneity of ecological risks by constructing a landscape ecological risk model; (2) revealing the ecological risks of different forest types in the nature reserve; and (3) exploring and analyzing the driving factors affecting the forest landscape ecological risk in the nature reserve by using geodetector method. This research not only provides a decision-making reference for the protection and optimization of forest ecosystems, and for the formulation of management and control strategies in the nature reserve to promote the harmonization of conservation and utilization, but it also provides a scientific reference for forest-type nature reserves.

## 2. Materials and Methods

### 2.1. Study Area

The Lushan National Nature Reserve (29°25′18″~29°39′57″ N, 115°52′38″~116°05′25″ E) is situated in the southern part of Jiujiang City, Jiangxi Province, China, near Poyang Lake in the east and Yangtze River in the north (Figure 1). It covers an area of 20,120 hm$^2$, of which the forestry land area covers 19,454.30 hm$^2$. The nature reserve stretches across Lushan City, Chaisang District, and Lianxi District, which are all under the jurisdiction of Jiujiang City. The overall landform is characterized as being "flat on the top and steep on the outside", with a maximum elevation of 1474 m. It lies in the subtropical monsoon humid area that forms a transition from the central subtropical zone to the northern subtropical zone, with an average annual temperature of 11.4 °C and an average annual rainfall of 1916 mm. The main soil types include red soil, yellow soil, mountain yellow soil, mountain yellow-brown soil, and so on. The forest coverage is 85.3%, and the tree species mainly include *Pinus massoniana* Lamb., *Pinus taiwanensis* Hayata, *Cunninghamia lanceolata* (Lamb.) Hook., *Cryptomeria japonica* (Linn. f.) D. Don, and other broad-leaved trees, including *Lithocarpus glaber* (Thunb.) Nakai, *Cinnamomum camphora* (L.) Presl, *Castanopsis sclerophylla* (Lindl.) Schottky, *Castanea henryi* (Skan) Rehder & E. H. Wilson, and *Liquidambar formosana* Hance, as well as *Phyllostachys edulis* (Carrière) J. Houz., etc.

### 2.2. Data Source and Processing

The forest landscape status data were derived from the sub-compartment data of the Forest Resource Inventory Database (FRID) in 2019. The inventory factors mainly comprised the tree species, vegetation coverage, community structure, forest naturalness, stand volume, fire and pest levels, and site factors such as the slope, elevation, soil thickness, etc. The data sources for the digital elevation model (DEM), meteorology, and human activities in 2019 are shown in Table 1. Slope and slope aspect data were extracted from ArcGIS Pro 3.0 (Manufacturer: Environmental Systems Research Institute, California, Redlands, CA, USA). The proximity to settlements, roads, and rivers was obtained using a multiple ring buffer analysis in ArcGIS Pro 3.0.

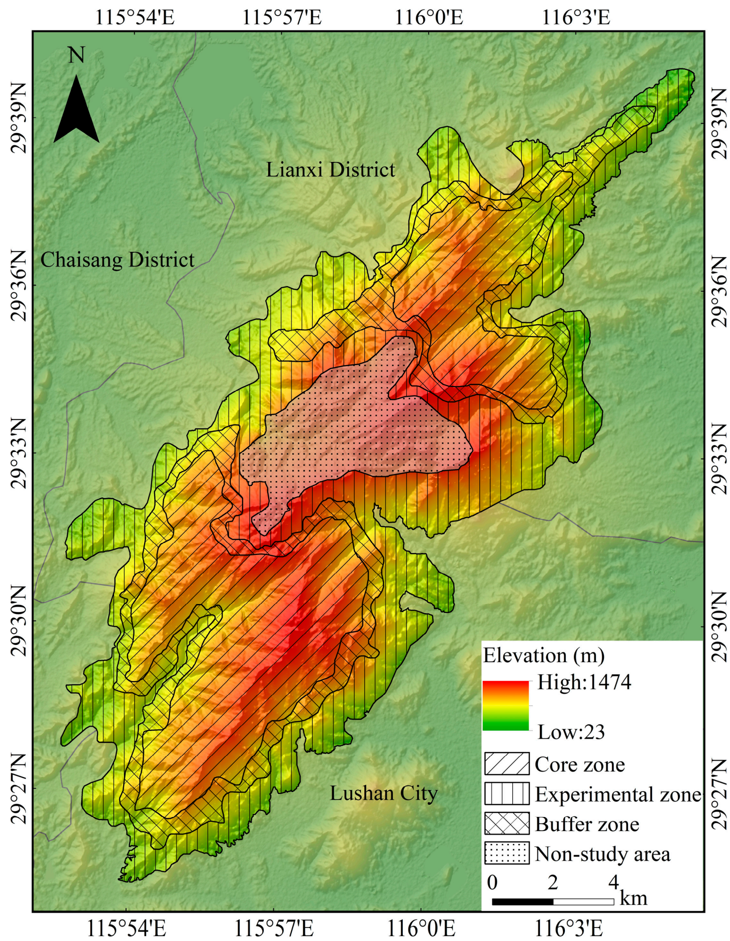


**Figure 1.** The location and functional zones in the Lushan National Nature Reserve.

**Table 1.** Data sources.

| Name of Data | Data Production Unit | Data Source Website | Resolution |
|---|---|---|---|
| DEM | Geospatial Data Cloud | https://www.gscloud.cn/ (accessed on 7 March 2023) | 30 m |
| Meteorological data | National Earth System Science Data Center | http://www.geodata.cn/ (accessed on 21 March 2023) | 1 km |
| Proximity to settlements | National Catalogue Service for Geographic Information | https://www.webmap.cn/ (accessed on 31 August 2023) | 1:250,000 |
| Proximity to roads | National Catalogue Service for Geographic Information | https://www.webmap.cn/ (accessed on 31 August 2023) | 1:250,000 |
| Proximity to rivers | National Catalogue Service for Geographic Information | https://www.webmap.cn/ (accessed on 31 August 2023) | 1:250,000 |
| Nighttime light | The Harvard Dataverse | https://dataverse.harvard.edu/ (accessed on 9 March 2023) | 1 km |
| Population density | WorldPop Dataset | http://www.worldpop.org/ (accessed on 13 March 2023) | 1 km |

The nature reserve was classified into grids using, and the grid size followed the principle that the landscape patch size should be two to five times the size of the average patch area [21]. Moreover, by comprehensively considering the size of the study area, an average patch area of 6.4146 hm$^2$, and the spatial heterogeneity, the study area was divided into a grid cell size of 500 m $\times$ 500 m, with a total of 954 grid cells, and each of the grid cells was defined as an ecological risk cell.

*2.3. Classification of Forest Landscape*

Based on the results of the Forest Resource Inventory Database and by taking the characteristics of the dominant tree species of forest vegetation in the nature reserve, the size of their area, and other factors into account, the forest landscape types were classified into 13 types, including 6 landscape types of pure forests, as follows: *Pinus massoniana* forest, *Cunninghamia lanceolata* forest, *Pinus taiwanensis* forest, *Cryptomeria japonica* plantation, other coniferous pure forests, and broad-leaved pure forests (i.e., an arbor forest landscape in which the volume or number of trees of a given tree species accounted for more than 65% of the total volume or number of trees). In addition, there were 3 types of mixed-forest landscapes, as follows: coniferous mixed forests, coniferous and broad-leaved mixed forests, and broad-leaved mixed forests (i.e., an arbor forest landscape in which the volume or number of any tree species was less than 65% of the total volume or number of trees). Moreover, the landscape of the *Phyllostachys edulis* forest, the landscape of the shrub economic forest (which mainly produces oil, fresh and dried fruits, industrial raw materials, medicinal materials, and other by-products), other shrub forest landscapes (except for the shrub economic forest), and other forestry land landscapes (which are used for forestry development, other than those mentioned above) were also present. The forest landscape distribution is shown in Figure 2.

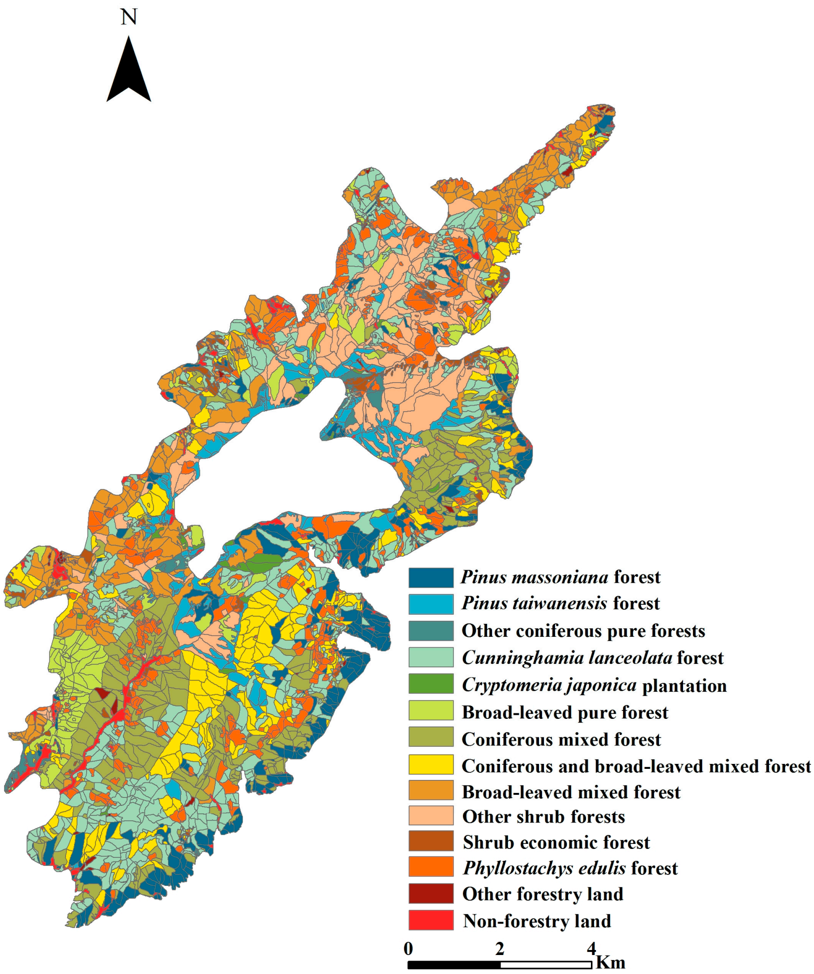


**Figure 2.** Forest landscape distribution.

*2.4. Construction of the Landscape Ecological Risk Index*

According to previous studies, the landscape ecological risk index is usually constructed by the landscape disturbance index and the landscape vulnerability index [24].

### 2.4.1. Landscape Disturbance Index

The landscape disturbance index refers to the intensity of the ecological system affected by natural and human factors, which comprehensively reflects the degree of landscape fragmentation, landscape splitting, and landscape dominance [25]. The specific calculation method is shown in Table 2.

**Table 2.** The calculation formulas for landscape metrics.

| Landscape Index | Formula | Description |
|---|---|---|
| Landscape fragmentation index | $C_i = \frac{n_i}{A_i}$ | $C_i$ represents the degree of patch fragmentation in a certain landscape type, $n_i$ represents the number of patches in landscape type *i*, and $A_i$ is the total area of landscape type *i* [26]. |
| Landscape splitting index | $S_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A}}$ | $S_i$ indicates the degree of patch separation in a certain landscape type; *A* represents the total area of the study area; and $n_i$ and $A_i$ are the same as above [27]. |
| Landscape dominance index | $D_i = \frac{(Q_i+M_i)+2L_i}{4}$ | $D_i$ indicates the importance of patches in a certain landscape type; $Q_i$ is the ratio of the number of patches in landscape type *i* to the total number of patches; $M_i$ is the ratio of the number of samples that appeared in landscape type *i* to the total number of samples; and $L_i$ is the ratio of the area of landscape type *i* to the total study area [27]. |
| Landscape disturbance index | $LDI_i = aC_i + bS_i + cD_i$ | $LDI_i$ represents the intensity of the interference to landscape type *i*. $a + b + c = 1$, *a* is 0.5, *b* is 0.3, and *c* is 0.2 [26]. |

### 2.4.2. Landscape Vulnerability Index

The landscape vulnerability index represents the fragility of an ecosystem to external disturbances [25].

(1) Selection of vulnerability indicators

The indicators were selected by thoroughly considering the FAO (Food and Agriculture Organization of the United Nations) guidelines and international indicators for forest decline, forest health, and stability [28,29], as well as performing an analysis of previous studies in the literature concerning forest vulnerability evaluations [30,31]. Based on the actual conditions of the forest ecosystem in the nature reserve and the feasibility of the FRID, this study selected nine indicators, including the elevation, slope, soil thickness, intensity of soil erosion, community structure, vegetation coverage, forest naturalness, fire level, and pest level, from the aspects of topography, soil, vegetation, and disasters. Specific descriptions of each indicator are given in Table 3.

(2) Calculation of vulnerability index

Firstly, the entropy weight method, which is an objective and accurate quantitative weight allocation method, was used to determine the weight of each indicator [32]. Then, we classified the selected indicators into positive indicators and negative indicators. Positive indicators indicated that the vulnerability increased with an increase in the indicator value, whereas negative indicators indicated that the vulnerability decreased with an increase in the indicator value. After normalizing the indicators, the weight of each indicator was calculated (Table 3) and multiplied by its normalized value, and the results of each indicator were totaled to obtain the vulnerability index of each patch. The specific calculation formulas are shown in references [30,33].

**Table 3.** The selection of vulnerability indicators and weight value.

| Primary Indicators | Secondary Indicators | Description | Type of Relationship | Weight |
|---|---|---|---|---|
| Topography factors | Elevation | Given the climate characteristics of the study area, the higher the elevation, the more susceptible it is to ice and snow hazards, and the greater the fragility of the vegetation. | Positive | 0.0454 |
| | Slope | The larger the slope, the more likely it is to cause soil erosion and landslides, and the greater the vulnerability. | Positive | 0.0696 |
| Soil factors | Soil thickness | The thicker the soil, the better the water and fertilizer availability and resistance to erosion, and the less fragile the vegetation. | Negative | 0.0572 |
| | Intensity of soil erosion | The greater the intensity of soil erosion, the greater the degree of damage and the greater the fragility of the vegetation. | Positive | 0.0119 |
| Vegetation factors | Community structure | A complete community structure with three levels, including a tree layer, understory layer, and ground cover layer, has a stronger ability to resist interference; a community with only a single vegetation layer has poor stability. The simpler the community structure, the greater the vulnerability. | Negative | 0.5321 |
| | Vegetation coverage | The greater the vegetation coverage, the less vulnerable it is. | Negative | 0.0648 |
| | Forest naturalness | Forest naturalness refers to the degree of difference between the current status of the forest community types and zonal climax communities (or native plant communities). Primitive forests with a high naturalness or vegetation that is relatively primitive due to minimal human influence have a low vulnerability. Therefore, the lower the naturalness of forests, the greater their vulnerability. | Negative | 0.0983 |
| Disaster factors | Fire level | The more severe the fire damage to vegetation, the higher the fire level, and the greater the vulnerability. | Positive | 0.0534 |
| | Pest level | The more severe the harm caused by pests and diseases to vegetation, the higher the level of pests and diseases and the greater the vulnerability. | Positive | 0.0673 |

The first step involved the normalization of indicators.

Positive indicators:

$$X'_{ij} = \frac{X_{ij} - X_{j\min}}{X_{j\max} - X_{j\min}} \tag{1}$$

Negative indicators:

$$X'_{ij} = \frac{X_{j\max} - X_{ij}}{X_{j\max} - X_{j\min}} \tag{2}$$

where $X_{ij}$ represents the $j$th value in the $i$th indicator and $X'_{ij} \notin [0, 1]$ represents its normalized value. $X_{j\max}$ and $X_{j\min}$ represent the maximum and minimum value of $j$.

The above normalized value is dimensionless, so the second step requires the calculation of the normalized value ($P_{ij}$) for each indicator.

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}} \tag{3}$$

The third step requires calculating the entropy ($e_j$) of each indicator.

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} P_{ij} \ln P_{ij} \tag{4}$$

The fourth step requires calculating the redundancy ($d_j$) of information entropy.

$$d_j = 1 - e_j \tag{5}$$

The fifth step requires calculating the weight ($W_j$) of each indicator.

$$W_j = d_j / \sum_{j=1}^{n} d_j \tag{6}$$

The vulnerability index of each patch is as follows:

$$LFI_i = \sum_{i}^{j} W_j * X'_{ij} \tag{7}$$

2.4.3. Landscape Ecological Risk Index

The landscape ecological risk index was primarily obtained via calculating the landscape disturbance index and landscape vulnerability index [24]. The formula is as follows:

$$ERI = \sum_{i=1}^{n} \frac{S_{ki}}{S_k} R_i \tag{8}$$

$$R_i = \sqrt{LDI_i * LFI_i} \tag{9}$$

where *ERI* is the landscape ecological index and $n$ is the number of landscape types. $S_{ki}$ is the area of landscape type $i$ in the $k$-th cell, whereas $S_k$ is the total area of the $k$-th cell. $R_i$ is the loss index of landscape type $i$, and $LDI_i$ is the disturbance index of landscape type $i$. $LFI_i$ is the vulnerability index of landscape type $i$. The landscape ecological risk index of each risk cell was calculated, and the Kriging interpolation was implemented in this study. The Jenks natural breaks classification method was used to divide the landscape ecological risk index of the nature reserve into five levels: lowest risk ($ERI \leq 0.48$), lower risk ($0.48 < ERI \leq 0.55$), medium risk ($0.55 < ERI \leq 0.62$), higher risk ($0.62 < ERI \leq 0.72$), and highest risk ($ERI > 0.72$).

### *2.5. Spatial Autocorrelation*

A spatial autocorrelation analysis can quantitatively describe the interdependent relationships between spatial attribute values [22]. The indicators were divided into global spatial autocorrelation and local spatial autocorrelation. Global spatial autocorrelation was used to verify the spatial correlation relationship of a certain element of the entire study area. The local spatial autocorrelation was used to reflect the degree of correlation between a certain geographical phenomenon or attribute in the unit of a small local area of the large entire area and the same phenomenon or attribute in the unit of the adjacent small local area [34]. By using GeoDa 1.20.0.8 (Luc Anselin, Chicago, IL, USA), this study selected and calculated Moran's $I$ for global spatial autocorrelation to reflect the overall spatial correlation and different statuses of landscape ecological risks in the nature reserve.

Furthermore, Moran's $I$ for local spatial autocorrelation was used to reflect the degree of spatial correlation between the region and its surrounding regions in the nature reserve [20].

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{10}$$

Here, $n$ represents the total number of ecological risk cells; $x_i$ and $x_j$ denote the ecological risk index for ecological risk cell $i$ and its adjacent ecological risk cell $j$, respectively; $\overline{x}$ is the average ecological risk index for all ecological risk cells in the study area; and $w_{ij}$ is the spatial weight matrix. The value range of $I$ was from $-1$ to 1. If $I < 0$, it indicated the presence of a negative spatial correlation. If $I = 0$, it indicated the absence of a spatial correlation and that the space was random. If $I > 0$, it denoted the presence of a positive spatial correlation.

The local Moran's $I$ ($I_i$) formula is as follows:

$$I_i = z_i \sum_{j=1}^{n} w_{ij} z_j (i \neq j) \tag{11}$$

where $z_i$ represents the standardized value of the ecological risk index in ecological risk cell $i$ and $z_j$ represents the standardized value of the ecological risk index in ecological risk cell $j$. If $I_i > 0$, it exhibits a high–high cluster (high value in a high-value neighborhood) or a low–low cluster (low value in a low-value neighborhood). If $I_i < 0$, it reveals a negative correlation cluster in local adjacent spaces with low–high outliers (low values in high-value neighborhoods) or high–low outliers (high values in low-value neighborhoods).

### *2.6. Geodetector*

Geodetector is a statistical method used to detect spatial differentiation and reveal the factors that affect it [35], including factor detection, interaction detection, risk zone detection, and ecological detection. Based on the results of previous studies [36], and combined with the actual circumstances of the nature reserve, this study selected 11 impact factors from both natural and human perspectives. The natural factors included the elevation, slope, slope aspect, average annual temperature, annual precipitation, and relative humidity. The human factors included the proximity to settlements, proximity to roads, proximity to rivers, nighttime light, and population density. This study uses the R 4.2.3 (an open software, developped at Bell Laboratories (formerly AT&T, now Lucent Technologies) by John Chambers and colleagues of the University of Auckland, New Zealand) to carry out the geodetector method. Using ArcGIS, the data for all the impact factors were converted to grids, and the projection coordinate system was unified. Moreover, all the factors were resampled to the same resolution. In this study, the factor detection and interactive detection were used to analyze the relationship between the landscape ecological risks and the various impact factors of the nature reserve. The calculation model is shown in reference [37].

Factor detection: This is used to detect the spatial differentiation of the landscape ecological risk (Y), and to what extent the impact factor (X) explains the spatial differentiation of the landscape ecological risk (Y). It is measured by $q$, and the larger the $q$ value, the stronger the explanatory power is.

Interactive detection: This is used to identify the interaction force of two different factors, which quantitatively represents the degree of impact of the two factors on landscape ecological risk after interaction. The interaction types of two factors can be classified into five types, as shown in Table 4.

**Table 4.** Interaction type classification of the detection factors.

| Criterion | Interaction Type |
|---|---|
| $q$ ($X_1 \cap X_2$) < min ($q$ ($X_1$), $q$ ($X_2$)) | Non-linear weakening |
| min ($q$ ($X_1$), $q$ ($X_2$)) < $q$ ($X_1 \cap X_2$) < max ($q$ ($X_1$), $q$ ($X_2$)) | Single-factor non-linear attenuation |
| $q$ ($X_1 \cap X_2$) > max ($q$ ($X_1$), ($X_2$)) | Two-factor enhancement |
| $q$ ($X_1 \cap X_2$) = $q$ ($X_1$) + $q$ ($X_2$) | Independent |
| $q$ ($X_1 \cap X_2$) > $q$ ($X_1$) + $q$ ($X_2$) | Non-linear enhancement |

## 3. Results

### *3.1. Ecological Risk Characteristics of the Whole Area and Functional Zones in the Nature Reserve*

The spatial distribution of ecological risk in the forest landscape of the nature reserve is shown in Figure 3. The areas of different ecological risk levels and the proportion of different ecological risk levels in relation to the forestry land area are shown in Table 5. The lowest and lower risk accounted for 57.47% of the total area in the nature reserve, and these risk levels were mainly distributed in central-southern and northern areas, far away from the settlements and roads where anthropogenic activities are concentrated. The medium-risk area accounted for 33.56%, and was distributed in a transitional area between the low- and high-risk areas of the nature reserve. The area comprising the higher and the highest risk levels was the lowest, at 8.97%, and these levels were mainly concentrated in the area nearest the settlements and roads in the northern part of the nature reserve that are prone to human interference. The proportion of the total area that comprised the lowest-risk, lower-risk, and medium-risk levels was 91.03%; thus, the overall ecological risk of the nature reserve was relatively low. In addition, the distribution of ecological risk in the nature reserve showed a strong coupling with the proximity to settlements and roads. The closer to settlements and roads, the higher the risk, and vice versa.

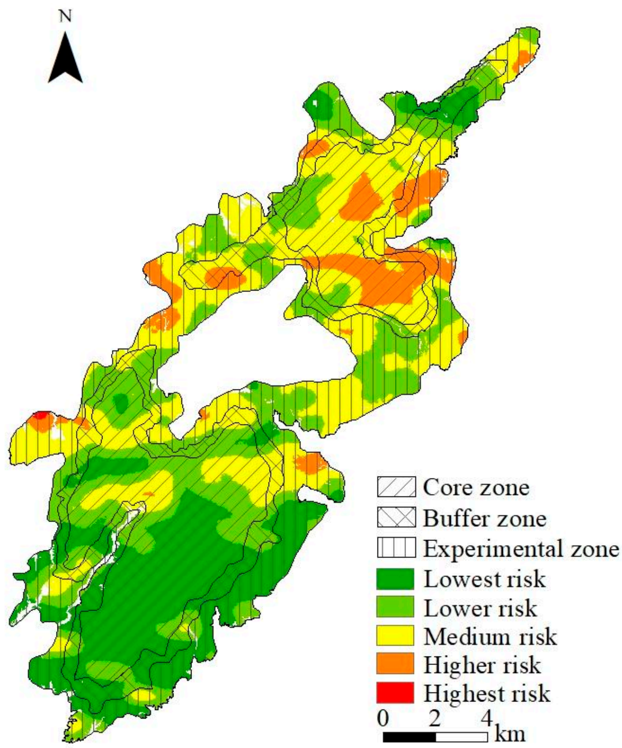


**Figure 3.** The spatial distribution of the ecological risk index and the classification of the Lushan National Nature Reserve.

**Table 5.** The area and percentage of ecological risk levels.

| Ecological Risk Level | Area (hm$^2$) | Percentage (%) | Core Zone | | Buffer Zone | | Experimental Zone | |
|---|---|---|---|---|---|---|---|---|
| | | | Area (hm$^2$) | Percentage (%) | Area (hm$^2$) | Percentage (%) | Area (hm$^2$) | Percentage (%) |
| Lowest risk | 5115.98 | 26.30 | 2391.75 | 33.34 | 947.90 | 24.43 | 1776.33 | 21.15 |
| Lower risk | 6063.50 | 31.17 | 2007.75 | 27.98 | 1308.64 | 33.72 | 2747.11 | 32.71 |
| Medium risk | 6528.19 | 33.56 | 2078.56 | 28.97 | 1324.87 | 34.14 | 3124.76 | 37.20 |
| Higher risk | 1730.65 | 8.89 | 696.53 | 9.71 | 298.28 | 7.69 | 735.84 | 8.76 |
| Highest risk | 15.98 | 0.08 | 0 | 0 | 0.63 | 0.02 | 15.35 | 0.18 |
| Total | 19,454.30 | 100.00 | 7174.59 | 100.00 | 3880.32 | 100.00 | 15.35 | 100.00 |

As is evident from Table 5, in terms of different functional zones, the core zone had the highest proportion of the lowest-risk and lower-risk areas to the area of the functional zones, accounting for 61.32%, followed by the buffer zone at 58.15% and the experimental zone at 53.86%. The area with the highest proportion of medium-, higher-, and highest-risk levels was the experimental zone, with a proportion of 46.14%, followed by the buffer zone at 41.88% and the core zone at 38.68%. Consequently, the order of different functional zones of the nature reserve according to their ecological risk level, from high to low, was the experimental zone, the buffer zone, and the core zone.

### *3.2. Ecological Risk Characteristics of Different Forest Landscape Types*

The ecological risk structure indicators for each forest landscape type are shown in Table 6. For the disturbance index, the other forestry land presented with the highest value, at 2.8347, while the other shrub forests presented with the lowest value, at 0.4489. As for the vulnerability index, the shrub economic forest presented with the highest value, at 0.7489, while the *Pinus massoniana* forest presented with the lowest value, at 0.3905. The loss index was obtained through the disturbance index and the vulnerability index, and the loss indices for other forestry land, the shrub economic forest, and other coniferous pure forests were all greater than 1, whereas the loss index of the coniferous mixed forest presented with the lowest value, at 0.4318. The ecological risk index for forest landscape types was calculated using the loss index and the area proportion of each forest landscape type. The ecological risk index for forest landscape types, from highest to lowest, was as follows: *Cunninghamia lanceolata* forest, other shrub forests, *Phyllostachys edulis* forest, coniferous mixed forest, coniferous and broad-leaved mixed forest, broad-leaved mixed forest, *Pinus massoniana* forest, broad-leaved pure forest, *Pinus taiwanensis* forest, shrub economic forest, other coniferous pure forests, *Cryptomeria japonica* plantation, and other forestry land. In conclusion, the total ecological index was 0.5439, and as a result, the ecological risk level was relatively low.

### *3.3. The Spatial Correlation of Landscape Ecological Risk*

As previously calculated, the global Moran's $I$ of the landscape ecological risk index in the nature reserve was 0.211 ($p < 0.01$), thus indicating that the landscape ecological risk index of the nature reserve exhibited a positive spatial autocorrelation (to some extent) and that there was a clustered distribution. The local Moran's $I$ result for the landscape ecological risk index in the nature reserve is shown in Figure 4. As is evident from the figure, the high–high clusters of the landscape ecological risk index in the nature reserve were mainly concentrated in the northeast, and they scattered into the middle of the nature reserve. These areas are located in areas with many settlements, and they are close to roads, where the intensity of human interference is relatively high. The low–low clusters were mainly concentrated in the southern part of the nature reserve, where there was little human interference. The low–high outliers were mainly scattered around high-risk areas, whereas the number of high–low outliers was relatively small and they were sporadically distributed around the low-risk areas in the south.

**Table 6.** Ecological risk structure indicators for forest landscape types.

| Landscape Type | Area ($hm^2$) | Percentage (%) | Disturbance Index | Vulnerability Index | Loss Index | Ecological Risk Index |
|---|---|---|---|---|---|---|
| *Pinus massoniana* forest | 1609.82 | 8.27 | 0.6527 | 0.3905 | 0.5048 | 0.0414 |
| *Cunninghamia lanceolata* forest | 3728.84 | 19.17 | 0.5314 | 0.4652 | 0.4972 | 0.0908 |
| *Pinus taiwanensis* forest | 1111.35 | 5.71 | 0.6823 | 0.5267 | 0.5995 | 0.0326 |
| *Cryptomeria japonica* plantation | 155.92 | 0.80 | 1.5661 | 0.5833 | 0.9558 | 0.0068 |
| Other coniferous pure forests | 200.01 | 1.03 | 1.4650 | 0.7108 | 1.0205 | 0.0102 |
| Broad-leaved pure forest | 1050.76 | 5.40 | 0.7499 | 0.6015 | 0.6843 | 0.0330 |
| Coniferous mixed forest | 2698.77 | 13.87 | 0.4827 | 0.3806 | 0.4318 | 0.0599 |
| Coniferous and broad-leaved mixed forest | 2133.31 | 10.97 | 0.5200 | 0.4522 | 0.4849 | 0.0572 |
| Broad-leaved mixed forest | 2122.38 | 10.91 | 0.5301 | 0.5075 | 0.5187 | 0.0556 |
| *Phyllostachys edulis* forest | 1816.89 | 9.34 | 0.7533 | 0.6057 | 0.6755 | 0.0621 |
| Shrub economic forest | 339.13 | 1.74 | 1.9147 | 0.7489 | 1.1974 | 0.0208 |
| Other shrub forests | 2378.30 | 12.23 | 0.4489 | 0.6459 | 0.5385 | 0.0662 |
| Other forestry land | 108.82 | 0.56 | 2.8347 | 0.5650 | 1.2656 | 0.0063 |
| Total | 19,454.30 | 100.00 | - | - | - | 0.5429 |

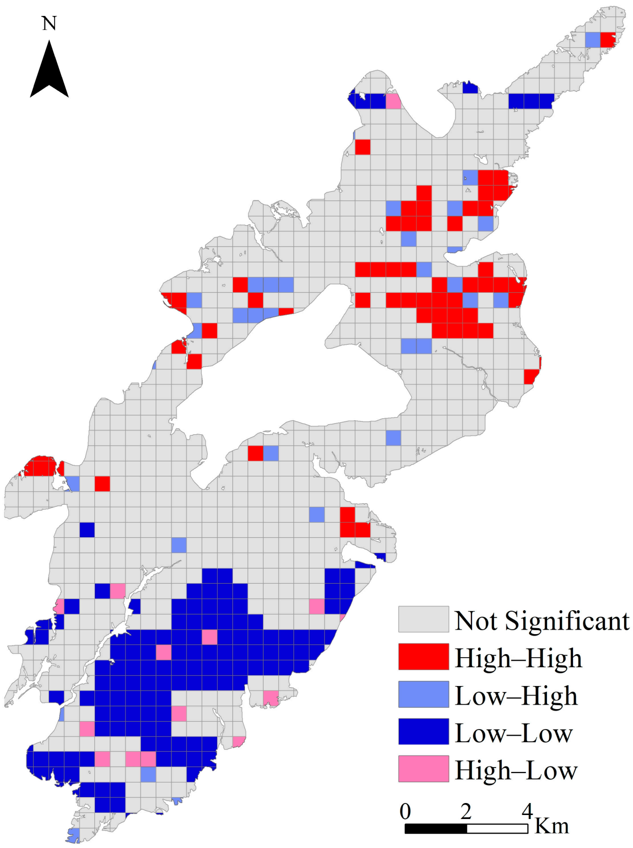


**Figure 4.** The local spatial autocorrelation for forest landscape ecological risk.

### *3.4. Analysis of Driving Factors of Landscape Ecological Risk*

The explanatory power ($q$ value) of each impact factor on the landscape ecological risk was calculated through factor detection in geodetector method, as shown in Figure 5. The descending order of factors, in terms of the $q$ value, was as follows: proximity to roads, proximity to settlements, nighttime light, population density, relative humidity, proximity to rivers, annual precipitation, average annual temperature, slope aspect, elevation, and slope. The explanatory power values of two factors, the proximity to roads and the proximity to settlements, were the highest of all the factors, with values of 0.2377 and

0.2260, respectively. Nevertheless, the explanatory power values of elevation and slope were the weakest of all the factors, with values of only 0.0126 and 0.0019, respectively. On the whole, the explanatory power values of human factors were almost greater than those of natural factors, except for the proximity to rivers of human factors, which was less than the relative humidity of natural factors. Therefore, it was found that human factors are the dominant factors affecting the landscape ecological risk in the nature reserve.

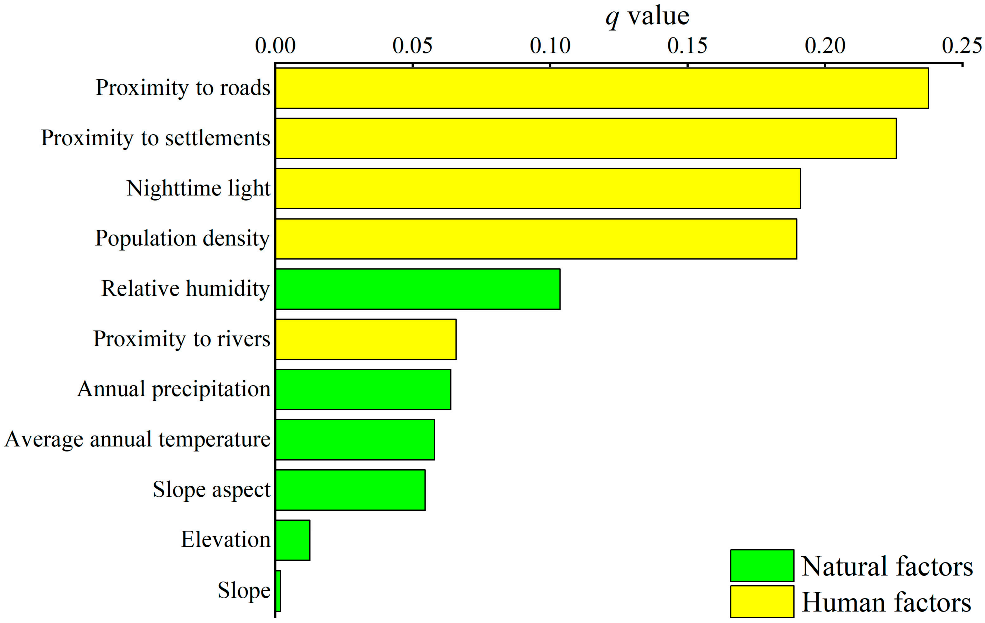


**Figure 5.** The explanatory power of landscape ecological risk.

The interaction detection results for the driving factors of the forest landscape ecological risk are shown in Figure 6. The interaction between any two factors was greater than the impact of a single factor, and the interaction types were mainly two-factor enhancements and non-linear enhancements. This indicates that landscape ecological risks in the nature reserve are caused not by a single driving factor, but by a combination of multiple driving factors. Among them, the interaction between the proximity to roads and the relative humidity was the strongest, with the highest $q$ value of 0.483. The second strongest interaction was that between the average annual temperature and the proximity to settlements, with a $q$ value of 0.455. The explanatory power of the proximity to roads and the proximity to settlements was 0.442. Although the interaction values between other factors were less than 0.4, this also shows that interactions between two driving factors have a greater impact on the landscape ecological risk than do single factors.

Regarding the interaction factors, the $q$ values of the interaction between natural factors all fell below 0.3. When natural factors and human factors interacted together, the explanatory power was greater than that of the interaction between the natural factors, indicating that the interactions between natural and human factors are stronger than the interactions between natural factors. The separate interactions between the proximity to roads, the proximity to settlements, and other factors were stronger than the interactions with other pairwise factors. This further indicates that the explanatory power of the proximity to roads and the proximity to settlements was stronger than that of other factors.

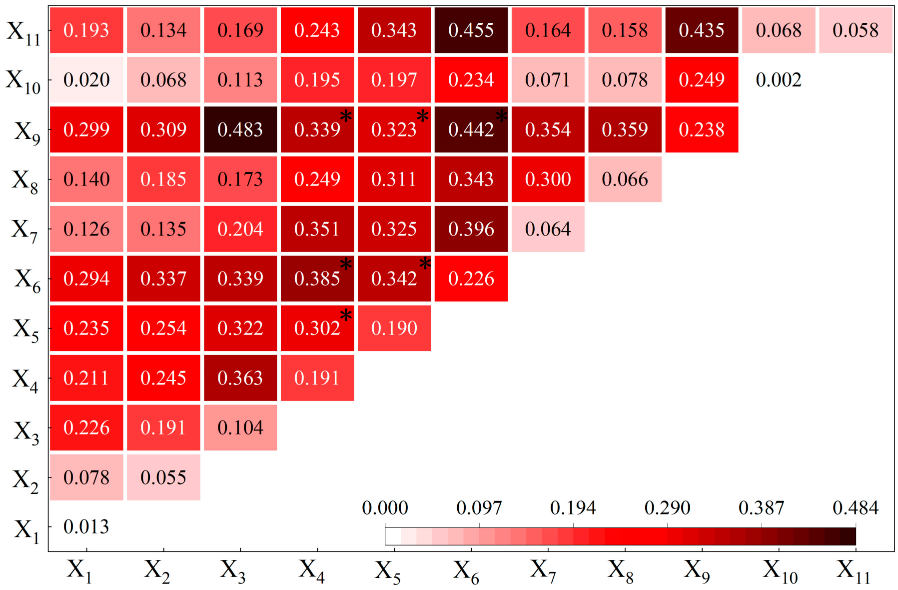


**Figure 6.** Results from the interactive detection of the driving factors of landscape ecological risk. * represents two-factor enhancement; the absence of * represents non-linear enhancement. $X_1$ is the elevation, $X_2$ is the slope aspect, $X_3$ is the relative humidity, $X_4$ is the nighttime light, $X_5$ is the population density, $X_6$ is the proximity to settlements, $X_7$ is the annual precipitation, $X_8$ is the proximity to rivers, $X_9$ is the proximity to roads, $X_{10}$ is the slope, and $X_{11}$ is the average annual temperature.

## 4. Discussion

### *4.1. Ecological Risk of the Nature Reserve*

The results of the ecological risk assessment almost indicated that the ecological risks of nature reserves are all at a relatively low level. According to a study by Tang et al. [38], which focused on the Yaoluoping Nature Reserve in the Anhui Province of China, the ecological risks of nearly 90% of the area were at a medium or low level. Wang et al. [39] found that the proportion of the Baishuijiang National Nature Reserve comprising the lowest-risk and lower-risk areas was 97%. This study showed that the ecological risk levels of the Lushan National Nature Reserve tended to be low and medium, accounting for 91.03% of the total area. Overall, its ecological risk was still at a relatively low level. However, the proportion of the area with a medium risk in the nature reserve was relatively high, at 33.56%, and the proportion of the areas with the higher or highest risk was 8.97%. This indicates that there is still some ecological risk in the nature reserve.

The reason for this is closely related to the uniqueness of Lushan Mountain. With this area being one of the earliest tourist attractions in China, most of the area in the nature reserve overlaps with the Lushan Mountain Scenic Area [40]. A large number of studies have shown that, to some extent, ecological risks are impacted by tourism, as the roads and infrastructure required for tourism development lead to vegetation degradation, which causes ecological risks; additionally, a large number of tourists and tourism-related activities can place pressure on and adversely affect the natural landscape's resources, such as forests and the ecological environment. A study by Mann et al. [41] showed that areas close to infrastructure, including roads, were at a greater ecological risk. Facilities such as roads and cableways isolated the natural vegetation and ecosystem of the nature reserve [23]. Moreover, roads directly or indirectly accelerated habitat fragmentation and degradation, ultimately leading to an increase in landscape ecological risks [10]. Yang et al. [42] studied the impact of ecotourism on the ecological risks within the Jiuzhaigou UNESCO World Heritage site, and they showed that ecotourism contributed to the increased ecological risks in Jiuzhaigou. Brant et al. [43] also found that ecotourism can, to some extent, cause some forest losses. Although roads and infrastructure can promote tourism development, and indeed, tourism can promote social economic development, the ecological risks caused by these tourism-related factors, especially in nature reserves, cannot be ignored. Therefore, when ecotourism occurs in nature reserves, it is necessary to properly strike a balance between protection and utilization, so as to minimize the ecological risks caused by the adverse effects of tourism facilities and activities on the natural landscape.

Regarding ecological risks in different functional zones, the areas within the Lushan Nature Reserve according to their ecological risks, from low to high, were in the order of core zone, buffer zone, and experimental zone. This is consistent with the results obtained by Wang et al. [39] in their study focusing on the Baishuijiang National Nature Reserve. The results showed that the ecological risk of the core zone was the lowest, followed by the buffer zone; however, the risk of the experimental zone was the highest. This was mainly because there are significant differences in the degree of integrity, the protection intensity, and the vegetation interference level in different functional zones. The core zone is generally rich in landscape resources, and human activities are prohibited there. As the periphery of the core zone, the buffer zone also preserves a relatively intact vegetation ecosystem with fewer human activities, while the experimental zone is the area with more frequent human activities. However, there still exists a study showing that, for the proportion of medium- and high-risk areas, the core zone had the highest proportion while the experimental zone had the lowest proportion. For example, in a study on the Yaoluoping Nature Reserve in the Anhui Province of China, except for the lowest-risk area, the ecological risk level in the core zone was the lowest, whereas other levels of ecological risk in the core zone of the Yaoluoping Nature Reserve were greater than those in the buffer zone; furthermore, the levels of medium and medium-high ecological risk in the buffer zone were greater than those in the experimental zone. This research suggested that the ecological risks in the core zone and buffer zone are not optimistic [38]. Although the core zone of the Lushan National Nature Reserve is not at the highest level of risk, the higher-risk area accounted for 9.71% of the core zone, with the medium-risk area accounting for 28.97%. This also indicates that there is still some risk in the core zone, which is mainly related to factors such as the composition and spatial pattern of forest landscape types in the core zone, as well as human factors such as tourism development. Therefore, it is necessary to further strengthen the protection intensity of the core area, so as to reduce the ecological risk.

### *4.2. Ecological Risk of Different Types of Forest Landscapes*

Many studies have shown that the ecological risks of zonal climax communities and mixed forest landscapes are lower than those of coniferous forests, whereas the ecological risks of natural forest landscapes are lower than those of plantation landscapes [44,45]. However, for the ecological risk levels of various forest landscape types in the Lushan National Nature Reserve, the results did not totally align with those findings. In this study, the ecological risks of the *Cunninghamia lanceolata* forest was higher than that of mixed forests, but the ecological risk of coniferous forests such as the *Pinus massoniana* forest, the *Pinus taiwanensis* forest, other pure coniferous forests, and the *Cryptomeria japonica* plantation were lower than that of mixed forests. The reasons for this need to be explored. Throughout history, the forest vegetation of Lushan Mountain has suffered serious damage, and protection and restoration measures have been taken [46]. *Cunninghamia lanceolata* is the main tree species used in afforestation for the artificial restoration of vegetation; it makes up the largest proportion of forest area, accounts for a wide distribution range of 19.17%, and is found relatively close to roads and settlements. Coniferous mixed forests, coniferous broad-leaved mixed forests, and broad-leaved mixed forests are almost all formed by secondary succession, with relatively short-term succession and wide distribution areas. In contrast, the coniferous forests of the *Pinus massoniana* forest, the *Pinus taiwanensis* forest, other pure coniferous forests, and *Cryptomeria japonica* plantations are relatively concentrated and account for only a small proportion of the area. For example, *Cryptomeria japonica* plantations are mainly distributed in U-shaped mountain nests, V-shaped valleys, and well-drained areas with altitudes ranging between 800 m and 1300 m on Lushan Mountain [47], and their surface area only accounts for 0.8% of the total area. Research has shown that the wide distribution of vegetation affects the ecological risk [44]. To some extent, the results of this study also showed that the wide distribution of vegetation area increased the ecological risk.

Furthermore, in this study, the ecological risk of other forestry land was the lowest. This is partly because its area is the smallest, and partly because there are human environments, such as other forestry land under human management, in the nature reserve, which inputs negative entropy, thus reducing the natural losses and ecological risks when resisting external interference [45].

At present, there are still some differences in the evaluation results of ecological risks for different forest landscape types in the same region, or the same forest landscape type in different regions. In addition to the differences in the areas, the spatial distribution, the succession stage of each forest type in the study area, and human factors such as the proximity to roads and settlements, the natural environment, such as the topography and climate of their location, also plays an important role in landscape ecological risk [17,45].

### *4.3. Driving Forces of Ecological Risk*

Previous studies have shown that human factors are the dominant factors causing landscape ecological risks, with human activities directly causing ecological risks [36,48]. Human activities, including the economic construction, population size, and infrastructure, increase the intensity of human disturbance and ecological risks [49,50]. The results of this study also indicate that human factors play a dominant role in the forest landscape ecological risk of the nature reserve. The surrounding residents of Lushan Mountain, the tourism industry, and tourism development infrastructure have a direct or indirect impact, to some extent, on the Lushan Mountain forest ecosystem. Therefore, the main factors that played a significant role in human factors were the proximity to roads and the proximity to settlements, which is consistent with relevant studies [48,51] suggesting that the proximity to roads and settlements is the main human factor affecting the landscape ecological risk. The proximity to roads and settlements represents the intensity of human activity. The smaller the distance, the greater the intensity of human activity, the greater the damage to the landscape, and the lower the ecological stability of the landscape [52]. Furthermore, there was a significant positive autocorrelation in the spatial distribution of forest landscape ecological risks in the Lushan National Nature Reserve, which generally tended to be aggregated, and this is consistent with the distribution of the intensity of human activity. This further indicates that human factors play a dominant role in landscape ecological risk.

However, studies have shown that the impact of human activities on ecological landscape structures has a double nature [53]. The moderate disturbance of landscape ecosystems by human activities can enhance the ecological diversity of landscape ecosystems, and the resilience of fragile ecosystems to disturbances will be improved; however, under excessive anthropogenic disturbance, the ecological risk of regional ecosystems increases due to the destruction and imbalance of the landscape structure [54,55]. Thus, it is necessary to keep the disturbance of the landscape by human activities within reasonable limits in order to maximize the diversity and resilience of the landscape against disturbances [56,57]. Conservation and development need to be scientifically planned. Human activities such as tourism should not be built beyond the carrying capacity of the environment, as human activities can help to reduce ecological risks to the landscape when decision making and planning are carried out in a prudent manner [58]. Further research should be conducted in the future to determine the most appropriate limits within which human activities should be controlled in order to reduce landscape ecological risks, increase landscape diversity and resilience, and enhance the coordination between tourism development and the eco-environment in nature reserves.

In addition, natural factors play an important role in landscape ecological risk [59]. This study indicates that the relative humidity and annual average temperature are the main natural factors that cause ecological risk; this is consistent with the conclusion drawn by the research of Wu et al. [35], who noted that the relative humidity and annual average temperature are the main factors affecting evapotranspiration in most regions of China. These factors affect vegetation growth, thereby affecting vegetation vulnerability. However, when natural and human factors interact, landscape ecological risk levels increase [60]. This study found that the interaction between natural and human factors is stronger than that between natural factors, which, to some extent, confirms the above point.

Therefore, controlling the intensity of human activities within a reasonable range and emphasizing a balance between humanity and nature will not only be beneficial for reducing the ecological risk of forest landscapes in nature reserves, but it will also increase the resilience to disturbances, as well as the ecological stability.

### *4.4. Implications*

There are some limitations that need to be improved in future studies. The study used the FRID to evaluate the ecological risk levels of the forest landscapes in the Lushan National Nature Reserve by using the current and widely used landscape ecological risk assessment method. This study validated the effectiveness of the protection in the nature reserve, but future studies could use field surveys or conduct biodiversity assessments to validate the ecological risks, so as to improve the reliability. In addition, although the study revealed the driving factors using geodetector method, the precise mechanisms underlying the interactions should be studied deeply in future studies, as this could strengthen the study's theoretical basis.

## 5. Conclusions

In general, the ecological risk level of the forest landscape in the nature reserve was relatively low. More specifically, the area comprising the lowest-, lower-, and medium-risk levels accounted for 91.03% of the total forest area, whereas the highest-risk and higher-risk areas accounted for 8.97%. In the functional zones, the ecological risk of the core zone was the lowest, followed by the buffer zone, and that of the experimental zone was the highest. This indicates that the conservation effectiveness of the nature reserve was obvious. Among all the forest landscape types, the forest type with the highest ecological risk was the *Cunninghamia lanceolata* forest, and that with the lowest was other forestry land. The ecological risk had a positive correlation in space, with high-risk (high–high) and low-risk (low–low) clusters exhibiting strong coupling with the proximity to settlements and roads. The ecological risk was mainly influenced by both human and natural factors. The effects of interactions between any two factors were stronger than those of single factors, and the interaction types were two-factor enhancement and non-linear enhancement. Human factors played a dominant role in the landscape ecological risk of the nature reserve. The proximity to roads, the proximity to settlements, the relative humidity, and the average annual temperature were the main influencing factors. This reveals that, by properly controlling the intensity of human activities, ecological risks in the nature reserve may be alleviated. This study implies that a balance between human survival and eco-environmental protection is necessary, and it provides references for improving the eco-environmental quality and forest management in the nature reserve.

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