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# Spatial (Mis)Matches Between Biodiversity and Habitat Quality Under Multi-Scenarios: A Case Study in Shandong Province, Eastern China

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**Abstract:** Despite declines in biodiversity and habitat quality (HQ) at a global scale, our understanding of the HQ and matches between HQ and biodiversity under management scenarios is incomplete. To address this deficiency, the study examined trends in HQ and (mis)matches between biodiversity and HQ over four decades in Shandong province, China, identified the key drivers, and assessed the effectiveness of ecological policies, including Ecological Redlines (ERLs) and the Grain for Green (GG) program. During the 40-year period, HQ and matching degrees (indicated by related coefficients) between biodiversity and HQ decreased obviously. Correlation analysis showed that related coefficients between HQ and four biodiversity indices (vertebrate, vascular plant, and vegetation formation type richness, and comprehensive biodiversity index) were all significant ($p < 0.01$), and coefficients were highest for the biodiversity composite index. An analysis of relative importance by the random forest algorithm indicated significant variation in driving factors for spatial distribution of HQ, biodiversity, and matches between them. The key determinants of biodiversity distribution were biophysical factors, such as NDVI (normalized difference vegetation index), DEM (digital elevation model), and temperature. However, the main drivers of HQ distribution were social factors, such as the accessibility of anthropogenic activities, urbanization, and population density. Ecological policy scenarios, ERLs and GG, are clearly effective and could improve HQ and the matching degree between HQ and biodiversity significantly. Furthermore, the improvement in HQ under ERLs was less than that under GG, while the increase in the matching degree was opposite. The results of this study can be integrated by ecological managers and planners for biodiversity conservation.

**Keywords:** habitat quality; InVEST model; biodiversity; ecosystem services; ecological redlines; Grain for Green

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**Citation:** Sun, X.; Shan, R.; Luan, Q.; Zhang, Y.; Chen, Z. Spatial (Mis)Matches Between Biodiversity and Habitat Quality Under Multi-Scenarios: A Case Study in Shandong Province, Eastern China. *Land* **2024**, *13*, 2215. https://doi.org/10.3390/land13122215

Academic Editors: Xi Li, Yuejing Rong, Kai Li, Hao Xia and Ruhong Xin

Received: 27 November 2024
Revised: 13 December 2024
Accepted: 16 December 2024
Published: 18 December 2024



## 1. Introduction

Increases in human activities generally exert pressure on natural habitats and lead to a decline in biodiversity. Globally, activities such as deforestation [1,2], road construction through wildlife habitats [3,4], and land use and land cover (LULC) changes [5] result in habitat loss, degradation, and fragmentation. As a consequence, the spatial distribution of biodiversity across a landscape can be estimated by species habitat suitability, which, simulated by analyzing maps of LULC in conjunction with threats to species' habitat [6], and habitat quality (HQ) based on this method, can be treated as proxies for biodiversity. Nowadays, the evaluation of habitat quality has become an important topic in ecosystem services and biodiversity conservation, especially since the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established [7]. In China, a variety of strategies have been proposed for the protection of biodiversity within the framework of landscape management, including policies such as the Ecological Redlines initiative and the establishment of national parks. China has introduced the concept of collaboratively forging a community of life on Earth, vigorously advocating for ecological civilization and actively safeguarding biodiversity. To this end, it is quite necessary to explore the spatio-temporal trends of HQ on local and global scales and, further, to identify variations in HQ under future scenarios of conservation policies or land use development, which can provide a scientific basis for ecological protection and policy-making.

HQ is related to the ability of a habitat to provide a stable environment for species survival, which is simulated by the InVEST-Habitat Quality model. The InVEST model is a spatially explicit assessment tool to estimate HQ as a function of anthropogenic threats under the framework of a land use scenario analysis, which can assess the HQ over large spatial and temporal scales [8]. Therefore, the InVEST model was widely applied in North America [9], Europe [10], and China [8,11] and other countries [12]. Although, as a proxy for biodiversity, relatively little assessment of HQ simulated by the InVEST model is calibrated or verified by species diversity data. The results of HQ assessment are uncertain because the scores of parameters related to threat factor and habitat suitability are all based on expert judgment [6]. Therefore, an investigation into the relationship between HQ and the biodiversity index and their drivers is needed to gain an accurate and credible assessment.

Declines in biodiversity are not simply the result of development but also reflect poor spatial planning and conservation strategies [13]. The question of how best to enact biodiversity conservation in modern societies has promoted extensive ecological research over the past few decades. In China, numerous massive ecological strategies have been applied nationwide, and these have restored degraded ecological environments and improved critical ecosystem service provisions substantially [14]. These ecological strategies include the Ecological Redlines (ERLs) policy, Grain for Green (GG) project, and so on. The ERLs policy, targeting the maintenance of biodiversity, important ecological functions, and ecosystem services, was introduced nationally to ensure that no net change in land cover and no net loss of biodiversity or degradation of ecosystem services occurs within specific areas [15]. Several studies have examined the effectiveness of this policy for key ecosystem services [16–19]; however, the impacts of ERLs on HQ and matches between HQ and biodiversity are poorly explored. The GG is another important ecological construction program in China aimed at addressing soil erosion by converting farmland in mountainous areas to forest or grassland. Many ecosystem services benefited from the GG project [20–22]. Although biodiversity conservation is not the primary objective of these policies, ancillary conservation outcomes can be achieved, and analyses of their effectiveness for biodiversity can provide important information to local managers. Above all, prediction habitat quality at a regional scale under ecological policies scenarios, such as ERL and GG, can provide a theoretical support for policy makers.

Shandong province, located in eastern China, is a major economic province, with the third highest ranked gross domestic product (GDP) in China. However, in recent years, biodiversity maintenance, including habitat provision and biodiversity status, has degraded significantly as a result of rapid economic development and intensive land use. For example, there are 80 and 24 endangered vertebrate and vascular plant species, respectively, accounting for 3.75–6.76% of all species in the province [23]. Although several policies and regulations have been implemented in Shandong to strengthen the protection of species and habitats, the declines in biodiversity and suitable habitats have not been effectively controlled. For example, the ERLs policy of Shandong province was implemented in 2016 over a total area of 2,084,790 $hm^2$, covering 13.2% of the whole province. The crucial ecological functions of the ERLs included biodiversity maintenance, freshwater conservation, soil conservation, wind prevention, and sand fixation. However, the effectiveness of ERLs was uncertain. Moreover, there are still knowledge and policy gaps with respect to biodiversity conservation in complex human and natural systems. Thus, it is necessary to gain a more comprehensive understanding of biodiversity maintenance service under economic development and land use change.

The objectives of the study were to (i) analyze the spatial-temporal dynamics of HQ using the InVEST-Habitat Quality module from 1980 to 2020 in Shandong province;

(ii) explore the spatial distribution of common plants and animals species including vertebrate, vascular plant, vegetation formation types and total biodiversity index; (iii) examine the (mis)matches between HQ and aforementioned four biodiversity indices; (iv) analyze the key drivers of HQ, biodiversity, and matches between them by a random forest algorithm; and (v) evaluate the effectiveness of ERLs policy and the GG project scenarios with respect to HQ and matches between HQ and biodiversity.

## 2. Methods and Data Sources

### 2.1. Study Area

Shandong province is located in the eastern coastal region of China (34°23′ to 38°24′ N, 114°48′ to 122°42′ E), covering an area of 157,900 km$^2$. Shandong province can be divided into three regions based on topography: a western plain region, central mountainous region, and eastern hilly region (Figure 1). Since the reform and opening up in 1978, the GDP in Shandong province has increased rapidly, and reached $1.24 trillion in 2021. The population in the region exceeded 100 million, ranking first in eastern China and second in China. In recent decades, local ecosystems and habitats are facing severe pressure due to rapid economic development and intensive land use. For example, the natural wetland area in Shandong province declined 37.89% from 1996 to 2014, and the abundance and distribution of 150–200 vascular plant species decreased significantly, with some species on the verge of extinction [23].

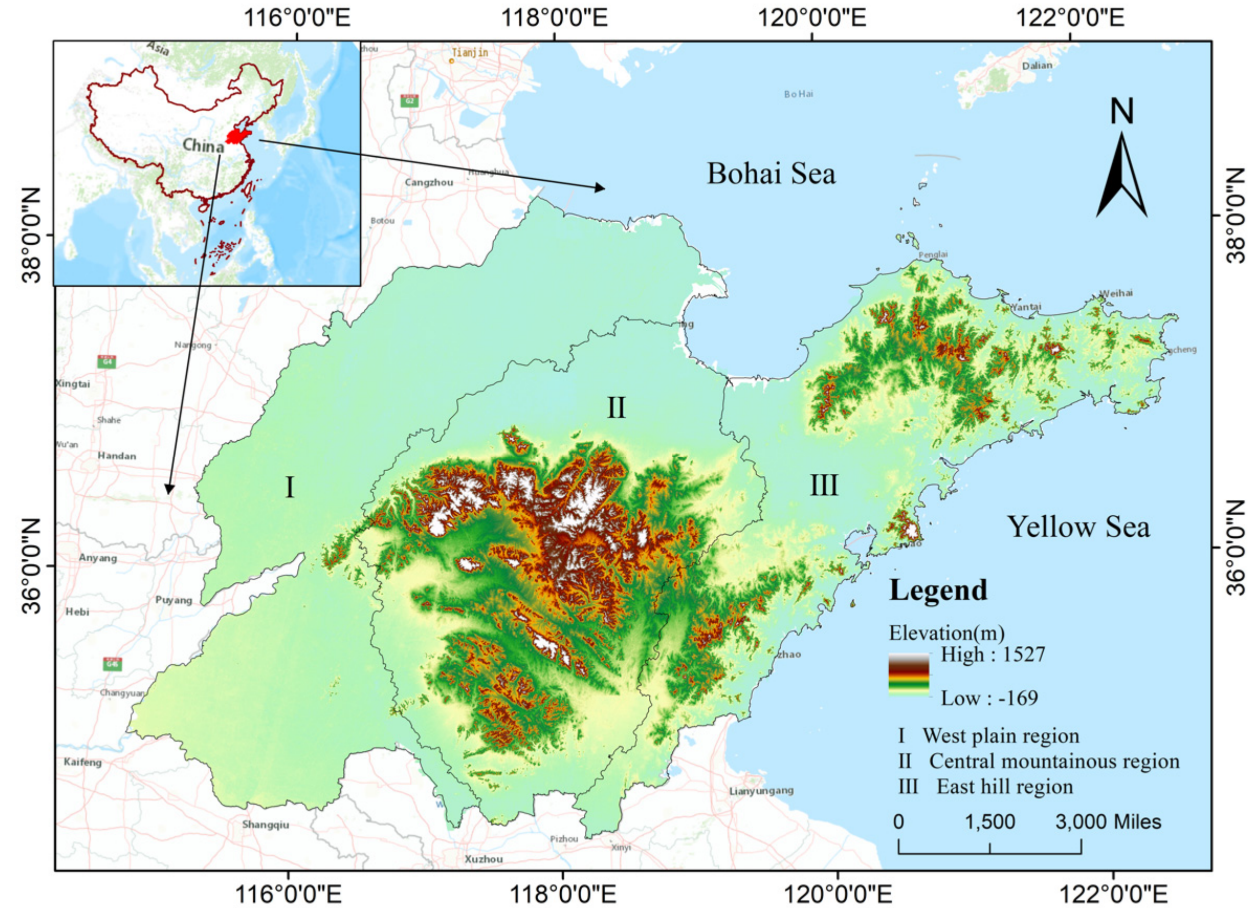


**Figure 1.** Location and topographic subregions of Shandong province in China.

### 2.2. Data Types and Sources

Land use data, digital elevation model (DEM), biodiversity data, population density, Gross Domestic Product (GDP), and other data were used. The land use data for 1980, 1990, 2000, 2010, and 2020 (30 m × 30 m resolution) were provided by the Data Center for

Resources and Environmental Sciences from the Chinese Academy of Sciences (RESDC, https://www.resdc.cn (accessed on 12 March 2024)). According to the remote sensing monitoring data classification system for multi-period land use/land cover, land use types were divided into seven first-level categories and 25 s-level types. DEM data (30 m × 30 m resolution) were obtained from the Shuttle Radar Topography Mission (SRTM) (http://srtm.csi.cgiar.org/srtmdata/ (accessed on 12 March 2024)). Biodiversity data were obtained from a biodiversity assessment of Shandong province at the county scale [23]. The population density and gross regional product data (1 km × 1 km resolution) for Shandong province in 2020 were obtained from the statistical yearbook of Shandong Province. Vector data for the county administrative boundary were obtained from RESDC. The normalized difference vegetation index (NDVI) in 2020 (1 km × 1 km resolution), annual mean temperature (1 km × 1 km resolution), and annual mean precipitation (1 km × 1 km resolution) data were also obtained from RESDC. DEM, population density, GDP, NDVI, annual mean temperature, and precipitation were the driving factors for the spatial distribution of HQ, biodiversity, and the matches between them, which were calculated and analyzed by a random forest algorithm.

### 2.3. Methods

#### 2.3.1. InVEST-Habitat Quality Model

The InVEST-Habitat Quality (HQ) model was used to evaluate habitat quality in Shandong Province. The HQ module assesses habitat quality and sustainability by combining land use and land cover (LULC) and threats to species habitat. Different land use types were considered disturbance factors for corresponding ecosystem types, and the spatial distribution of habitat quality was simulated and evaluated according to the habitat suitability of each ecosystem type and the threat intensity of human disturbance factors [6]. The HQ was calculated as follows:

$$Q_{xj} = H_j\left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right) \tag{1}$$

where $Q_{xj}$ is the HQ of raster $x$ for land use type $j$, $D_{xj}$ is the threat level of raster $x$ for land use type $j$, $H_j$ is the habitat suitability for land use type $j$, and $k$ is half the saturation constant (i.e., half of the maximum value of $D_x$; in this study, $k$ = 0.5), and z refers to (we hard code $z$ = 2.5) scaling parameters (or constants).

The parameters in the InVEST model were set according to the model guidance manual (Sharp et al., 2022) and previous studies [8]. Based on previous investigation and the ecological characteristics of Shandong province, plain agriculture, mountain agriculture, urban, industry, and rural residents were selected as the main threat factors in Shandong province, and the maximum impact distance and weight of different threat factors were determined. The HQ levels in 1980, 1990, 2000, 2010, and 2020 were simulated with land use data for corresponding years.

#### 2.3.2. Assessment of Biodiversity

Vertebrates, vascular plants, vegetation formation types, and the total biodiversity composite index were selected to assess biodiversity levels at county scale. The richness of vertebrates, vascular plants, and vegetation formation types refers to the number of species or vegetation types recorded in a region, which was obtained by field survey from 2015 to 2017 [23]. The total biodiversity composite index combines the above indicators to suggest the level of total biodiversity. The total biodiversity composite index (BI) was calculated as follows:

$$\mathrm{BI} = \mathrm{VE} \times 0.2 + \mathrm{VA} \times 0.2 + \mathrm{PF} \times 0.2 + \mathrm{SS} \times 0.2 + \mathrm{RT} \times 0.1 + (100 - \mathrm{IS}) \times 0.1 \tag{2}$$

where VE is the normalized richness of vertebrate species, VA is the normalized richness of wild vascular species, PF is the normalized richness of vegetation formation types, SS is the normalized species specificity, RT is the normalized richness of threatened species, and IS represents the normalized invasive species.

#### 2.3.3. (Mis)Matches Between Habitat Quality and Biodiversity

HQ was used as proxy for the biodiversity maintenance service and the total comprehensive biodiversity index (BI) was used as an indicator to match to HQ. The matching degree was calculated by dividing HQ by the total comprehensive biodiversity index after data normalization. Values of less than 1 indicated that the HQ does not match the biodiversity.

#### 2.3.4. Scenarios for Ecological Redline and Grain for Green Policies

In this study, the ERLs' areas were limited to areas with human activity and accessibility; these areas were set to zero during HQ simulation. Map data of ERLs came from the *Ecological red line protection plan of Shandong Province (2016–2020)*. The scenario for the GG policy supposed that all farmland located in areas with a slope of greater than 25 degrees was converted to forest. To evaluate the effectiveness of ecological policies, HQ simulations were performed under scenarios corresponding to these two policies.

### *2.4. Data Analysis*

Spatial and temporal dynamics of HQ were performed using ArcGIS 10.2. Slope was calculated from DEM using ArcMap's spatial analyst tools. Z-score standardization of HQ and biodiversity indices and their correlations was performed using SPSS 21. A Spearman correlation analysis was conducted to evaluate relationships between HQ and four biodiversity indicators from 1980 to 2020 to obtain the matching degree. The random forest algorithm (implemented in the randomForest package in R) was used to quantify the relative importance of impact factors. The impact factors included NDVI, DEM, temperature, precipitation, GDP, slope, urbanization rate, and population density. The biodiversity data and impact factors were analyzed in county units.

## 3. Results

### *3.1. Spatiotemporal Dynamics of Habitat Quality from 1980 to 2020*

The average HQ value in Shandong province was low, ranging from 0.231251 to 0.250954, and decreased by 7.80% from 1980 to 2020. HQ was divided into five categories: poor (0–0.2), low (0.2–0.4), medium (0.4–0.6), good (0.6–0.8), and high (0.8–1.0). In 2020, areas with a poor HQ accounted for 81.59% of the whole province, while only 10.08% of the region was classified as high HQ (Table 1). From 1980 to 2020, the area of poor HQ increased by 3.78%; however, areas classified as low, moderate, and good decreased substantially. The proportion of areas classified as high HQ increased slightly. Therefore, the habitat quality across Shandong province has declined over the last 40 years.

**Table 1.** Area and relative frequency of each HQ level and changes between 1980 and 2020.

| HQ Level | 1980 | | 1990 | | 2000 | | 2010 | | 2020 | | Change from 1980 to 2020 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ha | % | ha | % | ha | % | ha | % | ha | % | ha | % |
| Poor | 12,236,732.28 | 77.81% | 12,266,630.10 | 78.20% | 12,221,918.01 | 78.01% | 12,769,637.94 | 81.50% | 12,784,761.90 | 81.59% | 548,029.62 | 3.78% |
| Low | 517,549.50 | 3.29% | 518,255.73 | 3.30% | 516,263.67 | 3.30% | 291,661.92 | 1.86% | 292,216.68 | 1.86% | −225,332.82 | −1.43% |
| Moderate | 1,057,994.73 | 6.73% | 1,067,850.45 | 6.81% | 1,066,630.14 | 6.81% | 753,553.71 | 4.81% | 750,085.47 | 4.79% | −307,909.26 | −1.94% |
| Good | 400,248.27 | 2.55% | 407,177.10 | 2.60% | 402,693.48 | 2.57% | 263,699.46 | 1.68% | 263,158.92 | 1.68% | −137,089.35 | −0.87% |
| High | 1,513,876.86 | 9.63% | 1,425,491.10 | 9.09% | 1,460,041.83 | 9.32% | 1,590,085.08 | 10.15% | 1,579,661.82 | 10.08% | 65,784.96 | 0.45% |

Figure 2 shows the spatial distribution of HQ in Shandong province in 1980–2020. The HQ was highest in the central mountainous region, followed by the eastern hilly region, and the HQ was lowest in the western plain region. In 2020, the HQ values in the western plain region, central mountainous region, and eastern hilly region were 0.199160, 0.251109, and 0.244988, respectively. From 1980 to 2020, the HQ in the western plain region remained nearly unchanged, while the HQ in the central mountainous region and eastern hilly region declined significantly, i.e., 7.80% and 12.42%, respectively (Figure 2f).

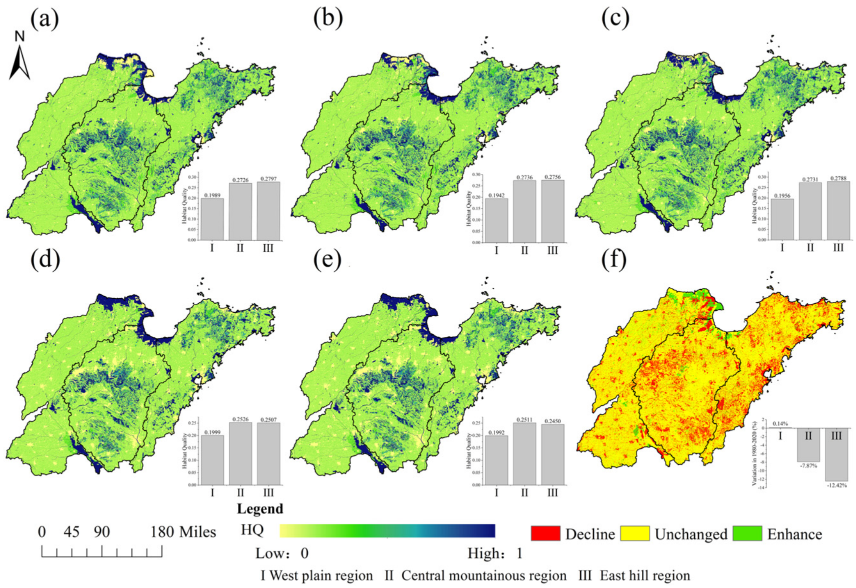


**Figure 2.** Habitat quality in 1980–2020 in Shandong Province ((**a**) 1980; (**b**) 1990; (**c**) 2000; (**d**) 2010; (**e**) 2020; (**f**) 1980–2020.).

## *3.2. Spatial Distribution of Biodiversity*

There were 594 vertebrate species in Shandong province, including 45 endangered species and 44 species endemic to China. Additionally, there were 1498 species of vascular plants, including 7 endangered species and 229 species endemic to China. There were 80 vegetation formation types in Shandong province, including coniferous forest, broad-leaved forest, bamboo forest, shrub, meadow, sandy vegetation, aquatic vegetation, and marsh vegetation.

As displayed in Figure 3, biodiversity (as estimated by richness) decreased gradually from east to west across Shandong province. The richness of vertebrate species and the biodiversity composite index in the eastern, central, and western parts clearly decreased. However, the richness values for vascular plants and vegetation formation types were highest in the central mountainous region, followed by the eastern and western regions.

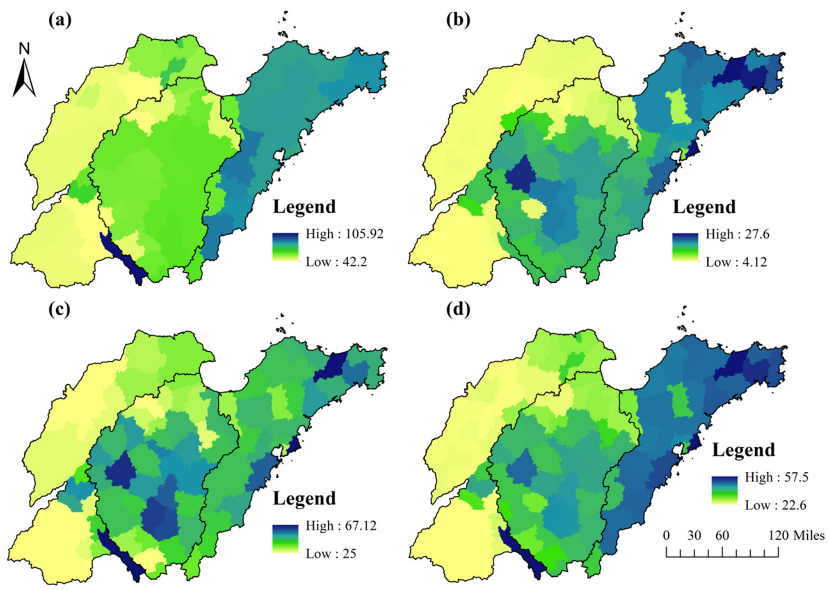


**Figure 3.** Distribution of biodiversity indices in Shandong province ((**a**) Vertebrates; (**b**) Vascular plants; (**c**) Vegetation formations; (**d**) Biodiversity index.).

### *3.3. (Mis)Match Between Habitat Quality and Biodiversity*

The coefficients for relationships between HQ and biodiversity indices were obtained to evaluate the matching degree. All of the correlations were significant ($p < 0.01$), as displayed in Table 2. Furthermore, the matching degree between HQ and biodiversity declined from 1980 to 2020 based on correlation coefficients. From 1980 to 2020, the matching degrees for vertebrates, vascular plants, vegetation formations, and the biodiversity composite index decreased by 17.66%, 15.03%, 10.71%, and 12.90%, respectively. Among the four biodiversity indices, correlation coefficients were highest for the biodiversity composite index, followed by vegetation formations, vascular plants, and vertebrates.

**Table 2.** Correlations between habitat quality and biodiversity.

| Habitat Quality | Vertebrate Species | Vascular Plant Species | Vegetation Formations | Biodiversity Composite Index |
|---|---|---|---|---|
| 1980 | 0.589 ** | 0.692 ** | 0.691 ** | 0.713 ** |
| 1990 | 0.588 ** | 0.695 ** | 0.690 ** | 0.714 ** |
| 2000 | 0.584 ** | 0.680 ** | 0.680 ** | 0.702 ** |
| 2010 | 0.496 ** | 0.594 ** | 0.622 ** | 0.628 ** |
| 2020 | 0.485 ** | 0.588 ** | 0.617 ** | 0.621 ** |
| ERLs | 0.487 ** | 0.590 ** | 0.619 ** | 0.623 ** |
| GG | 0.486 ** | 0.589 ** | 0.617 ** | 0.621 ** |

** Correlation is significant at the 0.01 level (2-tailed).

The (mis)matches between HQ and biodiversity (BI) could be classified into four categories: high HQ–high BI, low HQ–low BI, low HQ–high BI, and high HQ–low BI. The relative frequencies of these categories in 2020 are displayed in Table 3. For vertebrates, low HQ–low BI type was the largest category (37.79%), followed by high HQ–low BI (26.37%), high HQ–high BI (22.51%), and low HQ–high BI (13.33%) (Table 3). However, the proportions of the four match types for vascular plants, vegetation formations, and the biodiversity composite index decreased in the following order: high HQ–high BI, low HQ–low BI, low HQ–high BI, and high HQ–low BI. It is worth noting that the low HQ–high BI type accounted for 13.33–21.37% (average 17.62%) of the province, indicating that the habitat provision was insufficient.

**Table 3.** Proportion of different match types in Shandong province.

| Match Type | Vertebrates | Vascular Plants | Vegetation Formations | Biodiversity Composite Index |
|---|---|---|---|---|
| High HQ–High BI | 22.51% | 37.62% | 38.62% | 37.66% |
| Low HQ–High BI | 13.33% | 21.37% | 17.71% | 18.06% |
| Low HQ–Low BI | 37.79% | 29.75% | 33.41% | 33.06% |
| High HQ–Low BI | 26.37% | 11.26% | 10.26% | 11.22% |

Spatial distributions of different categories of matches are summarized in Figure 4. High HQ–high BI areas were distributed mainly in eastern coastal areas and central mountainous areas. The high HQ–low BI type was located mainly in the northern part of the province and central mountainous areas. The low HQ–high BI type was mainly concentrated in areas with flat terrain in the transition zones of the central mountainous region and the eastern hilly region. In addition, low HQ–high BI areas were distributed in parts of the transition zones between the western plain and central mountainous regions. The low HQ–low BI type was mainly concentrated in western plain (Figure 4).

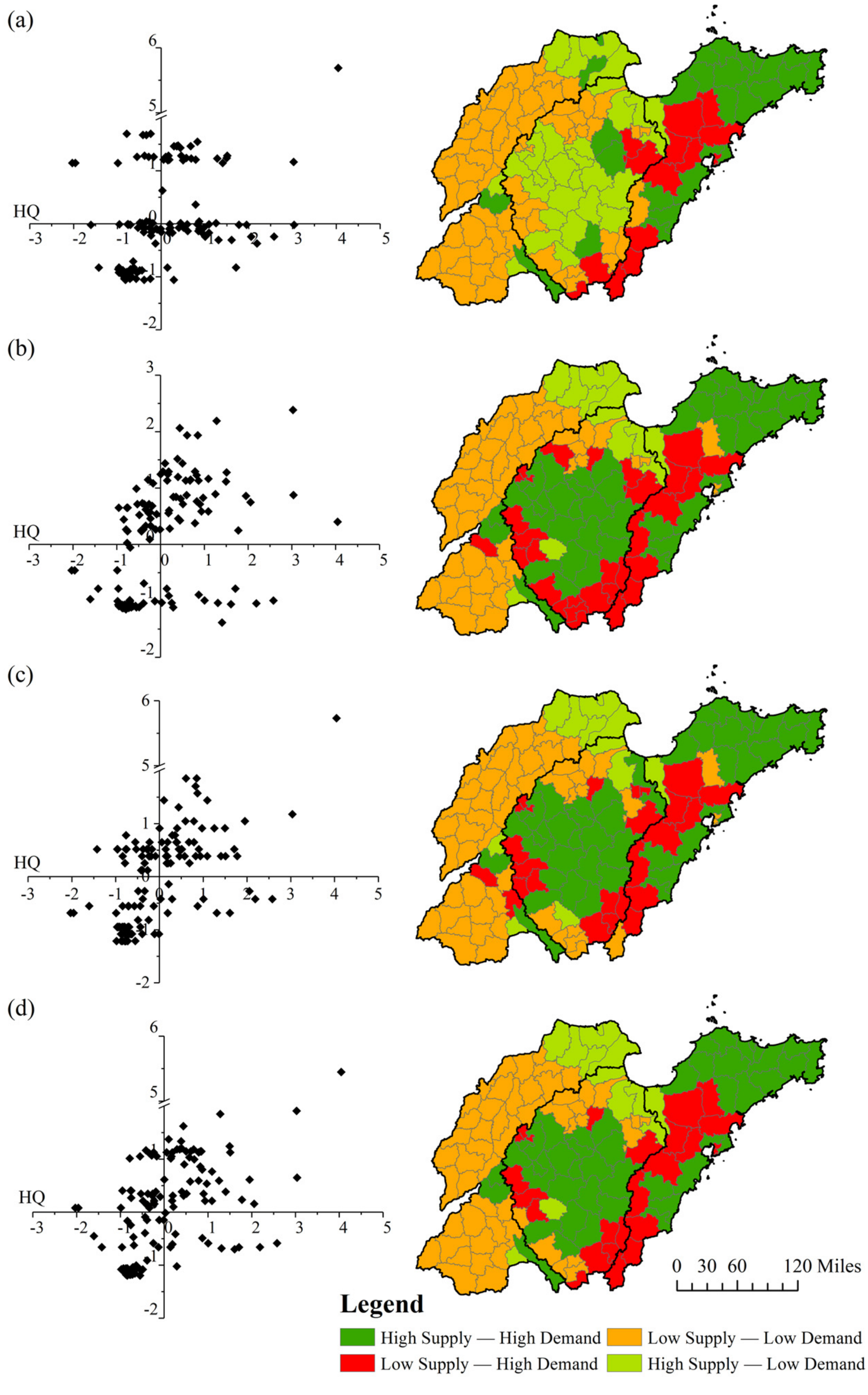


**Figure 4.** Spatial matches between HQ and biodiversity in 2020 ((**a**) Vertebrates; (**b**) Vascular plants; (**c**) Vegetation formations; (**d**) Biodiversity index.).

### *3.4. Determinants of Habitat Quality, Biodiversity and Their Matches*

The degree of urbanization (proportion of urban construction land), population density, GDP, slope, DEM, NDVI, precipitation, and temperature were included in an analysis of factors driving the spatial distribution of HQ, biodiversity and matches between them. As displayed in Figure 5, biophysical factors (e.g., NDVI, DEM, and temperature) were the key factors affecting the total biodiversity composite index, while anthropic factors were less important to biodiversity. However, slope, urbanization, and population density were the most important impact factors for HQ. Slope was a proxy for human accessibility, suggesting that anthropic activities were key factors impacting HQ. For matches between HQ and biodiversity, the top factors were NDVI, DEM, and GDP, suggesting that vegetation coverage and human economic activities were the most important driving factors (Figure 5).

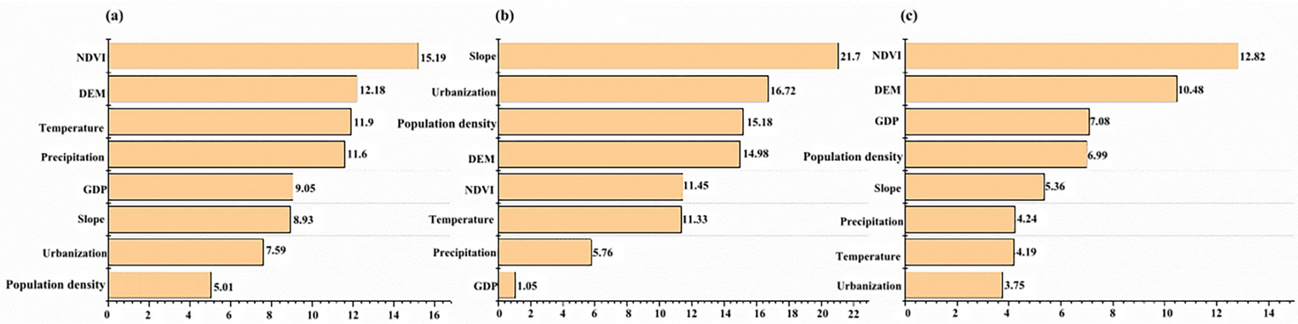


**Figure 5.** Relative importance of various factors for biodiversity, habitat quality, and matches between them ((**a**) Biodiversity; (**b**) Habitat quality; (**c**) Matches between biodiversity and habitat quality.).

### *3.5. Effectiveness of ERLs and GG*

Compared to HQ in 2020, the areas of low, moderate, and good HQ level under the ERLs policy scenario decreased significantly, while the area classified as high grade increased (Table 4). On the whole, the average HQ under the ERLs scenario in Shandong province improved by 0.16%. Furthermore, the matching degrees for vertebrates, vascular plants, vegetation formations, and the biodiversity composite index increased by 0.41%, 0.34%, 0.32%, and 0.32%, respectively (Table 2). Under the GG policy scenario, the area of poor HQ decreased by 0.26% (40,539.42 ha), while the area of low HQ increased by 0.26% compared to those in 2020 (Table 4). The average HQ improved by 0.29%. However, no significant changes in the supply-demand matching degree were detected under the scenario corresponding to the GG policy (Table 2). In general, the improvement in the average HQ under the GG scenario exceeded that under the ERL scenario, while improvements in the matching degree under the GG scenario were lower than those under the ERL scenario (Table 2).

**Table 4.** Area and ratio of each HQ level under ecological policy scenarios.

| HQ Level | Ecological Redlines | | Variation HQ from 2020 | | Grain for Green | | Variation HQ from 2020 | |
|---|---|---|---|---|---|---|---|---|
| | ha | % | ha | % | ha | % | ha | % |
| Poor | 12,757,931.73 | 82.03% | 0 | 0.00% | 12,744,222.48 | 81.33% | −40,539.42 | −0.26% |
| Low | 281,728.62 | 1.81% | −10,008.63 | −0.06% | 332,756.1 | 2.12% | 40,539.42 | 0.26% |
| Moderate | 671,178.96 | 4.32% | −77,053.05 | −0.49% | 750,085.47 | 4.79% | 0.005 | 0.00% |
| Good | 240,434.01 | 1.55% | −22,549.68 | −0.14% | 263,158.92 | 1.68% | 0.00 | 0.00% |
| High | 1,601,423.37 | 10.30% | 109,611.36 | 0.70% | 1,579,661.82 | 10.08% | 0.00 | 0.00% |

Under the ERL scenario, areas with improved HQ were mainly distributed in central mountainous regions and eastern coastal regions (Figure 6). The area in which HQ improved accounted for 11.62% of the whole province. Under the GG scenario, areas with improved HQ were scattered throughout the western, central, and eastern parts of the province with slopes exceeding 25 degrees. The area in which HQ improved accounted for 3.86% of the whole province.

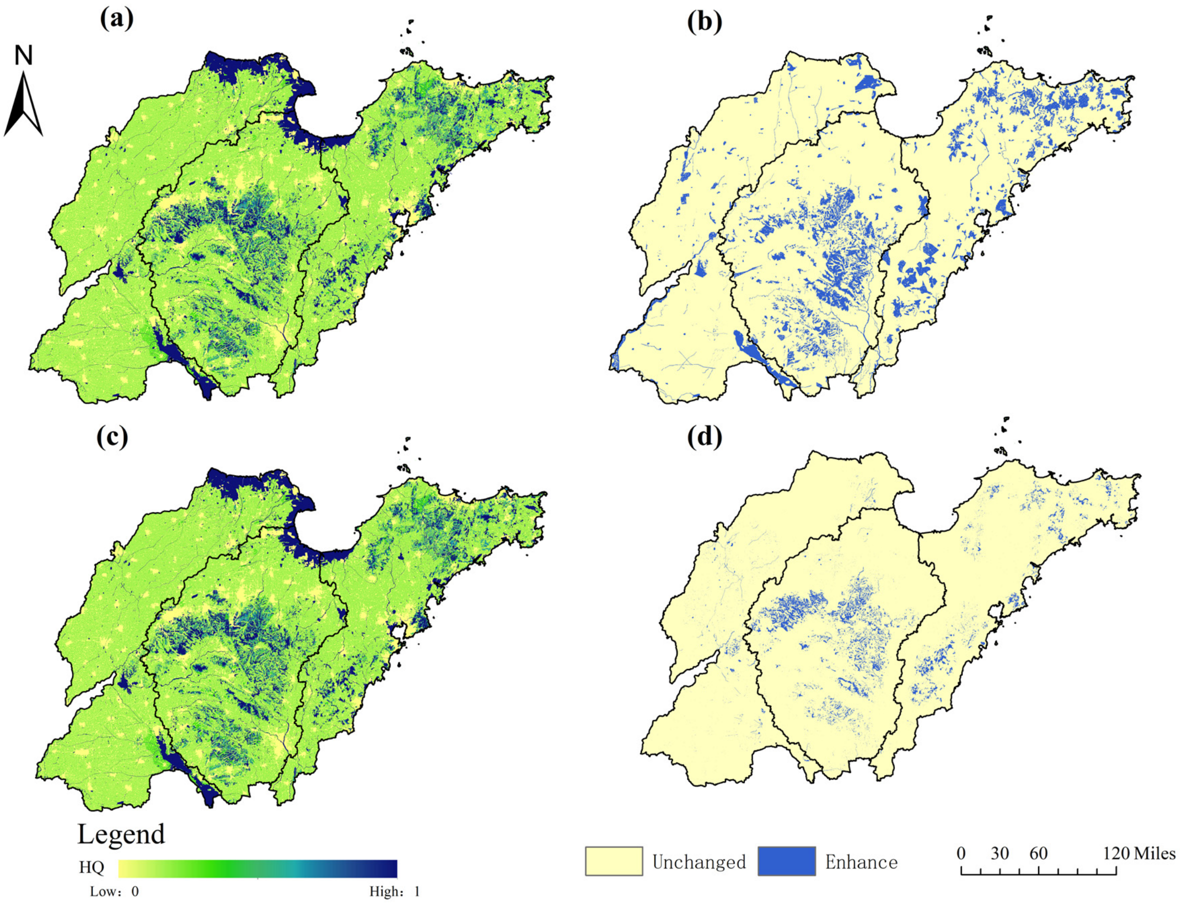


**Figure 6.** Variations in habitat quality under ecological policy scenarios ((**a**) Ecological redlines; (**b**) Variations from 2020; (**c**) Grain for Green; (**d**) variation from 2020.).

## 4. Discussion

### *4.1. Matches Between Habitat Quality and Biodiversity*

Many studies have investigated HQ by the InVEST model [24–26]; however, relatively little assessment of HQ is calibrated or verified by species data. The study performed calibration of HQ simulation using four biodiversity indices, including vertebrate, vascular plant, and vegetation formation type richness, and the total biodiversity index. Correlation analysis based on county units suggested that related coefficients between HQ and four biodiversity indices, under multi-scenario indices, were all significant ($p$ < 0.01), and coefficients were highest for the total comprehensive biodiversity composite index (Table 2). The results indicated that HQ is more consistent with total comprehensive biodiversity than individual species diversity, and so HQ as simulated by the InVEST model was more suitable to indicate the comprehensive biodiversity of the whole ecosystem. In addition, the HQ matching degree for plants species (vegetation formations and vascular plants) was more than that for animal species. Above all, HQ simulated by the InVEST model can act as preferable proxy of biodiversity maintenance service, and the spatial distribution of HQ at the regional scale correlates closely with biodiversity patterns.

Further study was performed on the linkages and matches between HQ and biodiversity, and matching degree has rarely been addressed to date. In this study, we quantified the matching degree based on correlation coefficients for the relationships between biodiversity and HQ in Shandong province, indicating a significant decrease during last four decades, corresponding to the continuous degradation of local habitat. The spatial distribution of the matching types could reveal key areas for protection or restoration. For example, areas with low HQ–high BI are priorities for restoration, and areas with high HQ–high BI should be selected for protection efforts. Accordingly, the analysis of matches could help policy makers accurately identify regional differences and develop targeted measures. Evaluations of biodiversity or HQ alone are insufficient for conservation in complex social–ecological systems.

### 4.2. Driving Factors of Habitat Quality, Biodiversity, and Their Matches

The factors driving HQ, biodiversity, and matches between them varied significantly within an area. It is well known that geomorphology, microclimate, soil, and other biophysical factors determine the spatial patterns of biodiversity. However, habitat quality (or the supply of biodiversity maintenance services) was mainly influenced by land use intensity, population density, and other social–economic activities [8,12,27] (Figure 5). In this study, the top factors impacting biodiversity were biophysical drivers, such as NDVI, DEM, and temperature, while the main factors related to HQ were anthropic activities (Figure 5). Furthermore, the important determinants of the matches between HQ and biodiversity included biophysical (e.g., NDVI and DEM) and anthropic (e.g., GDP) factors. Thus, conservation plans and ecological policies to enhance the HQ, biodiversity, and their matches need to be multi-dimensional, including ecological restoration from the perspective of biodiversity, limitation of the intensity of human activities from the perspective of HQ, and so on.

### 4.3. Effectiveness of Ecological Policies

ERLs in China are protected areas, originally proposed in 2015, with the goal of maintaining ecological security patterns, ensuring ecosystem services, and supporting sustainable economic and social development [28,29]. Areas within ERLs have special ecological functions that must be compulsorily and strictly protected. The ERLs policy is effective in maintaining and protecting ecosystem services, such as water provision, soil conservation, and biodiversity maintenance [16,18,30,31]. The results of this study were consistent with those of previous studies, which indicated that the ERLs policy could improve the supply of biodiversity maintenance services (habitat quality). Furthermore, the increase in HQ under the ERL policy scenario was less than that under the GG policy, although the ERL areas were larger than the GG areas (Figure 6). The reason is that farmland with a slope of greater than 25 degrees was converted to forestland under GG scenario, which increased the HQ score substantially. However, farmland with a slope of greater than 25 degrees was found in regions with low biodiversity, and therefore the matching degree between HQ and biodiversity under the GG policy scenario was lower than that under the ERLs scenario (Table 2). Although HQ under GG policy improved significantly, there was no obvious improvement in the matching degree. In general, the ERLs policy is more suitable for biodiversity conservation than the GG policy.

## 5. Conclusions

Economic development generally exerts great pressure on natural habitats and leads to a decline in biodiversity resources, resulting in an imbalance between habitat quality and biodiversity. Therefore, it is important to investigate the spatial matching relationship between habitat quality and biodiversity and to further identify the effectiveness of conservation planning policy scenarios. In this study, the spatial dynamics of habitat quality, biodiversity indices, and their matches in Shandong province were evaluated, the driving factors were identified, and the effectiveness of ERLs and GG policies were examined. The calibrated results of InVEST-Habitat Quality model indicated that HQ is more consistent with total comprehensive biodiversity than individual species diversity, and so HQ simulated by the model was more suitable to indicate the comprehensive biodiversity of the whole ecosystem. In addition, the HQ matching degree for plants species (vegetation formations and vascular plants) was more than that for animal species. Spatio-temporal analysis of HQ indicated that HQ and matches in Shandong province were in a state of continuous degradation. Areas with low HQ–high BI occupied 18.06% of the whole province, which was insufficient for biodiversity maintenance, and these areas were priorities for ecological restoration. An analysis of the relative importance of driving factors indicated that biodiversity was related to biophysical factors, while the main factors for HQ were social factors, such as accessibility, urbanization, and population density. Based on the difference in factors driving HQ and biodiversity, the restoration of natural habitats and the prohibition of anthropogenic activities are recommended to address the biodiversity and habitat quality sides, respectively. With respect to the effectiveness of ecological policies, the improvement in HQ under ERLs was less than that under GG, while the increase in the matching degree under ERLs was greater than that under GG. The results of this study can be integrated by ecological managers and planners for biodiversity conservation. This integration of ERLs and GG policies allows for the application of scientific insights to decision-making processes, which can lead to more informed and effective conservation efforts.

**Author Contributions:** X.S. and R.S. conceived the main idea and designed and performed the study. Q.L., Y.Z. and Z.C. made contributions to the InVEST model and data analysis. The manuscript was written by X.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China [grant numbers: 42471332].

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author due to (specify the reason for the restriction).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Terrado, M.; Sabater, S.; Acuña, V. Identifying regions vulnerable to habitat degradation under future irrigation scenarios. *Environ. Res. Lett.* **2016**, *11*, 114025. [CrossRef]
2. Villarreal-Rosas, J.; Wells, J.A.; Sonter, L.J.; Possingham, H.P.; Rhodes, J.R. The impacts of land use change on flood protection services among multiple beneficiaries. *Sci. Total Environ.* **2022**, *806*, 150577. [CrossRef] [PubMed]
3. Bruschi, D.; Astiaso Garcia, D.; Gugliermetti, F.; Cumo, F. Characterizing the fragmentation level of Italian's National Parks due to transportation infrastructures. *Transp. Res. Part D Transp. Environ.* **2015**, *36*, 18–28. [CrossRef]
4. Zhang, H.; Zhang, C.; Hu, T.; Zhang, M.; Ren, X.; Hou, L. Exploration of roadway factors and habitat quality using InVEST. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102551. [CrossRef]
5. Sharma, R.; Nehren, U.; Rahman, S.; Meyer, M.; Rimal, B.; Aria Seta, G.; Baral, H. Modeling Land Use and Land Cover Changes and Their Effects on Biodiversity in Central Kalimantan, Indonesia. *Land* **2018**, *7*, 57. [CrossRef]
6. Stanford University; University of Minnesota; Chinese Academy of Sciences; The Nature Conservancy; World Wildlife Fund; Stockholm Resilience Centre; the Royal Swedish Academy of Sciences. *Natural Capital Project. InVEST 0.0*; Stanford University: Stanford, CA, USA, 2024.
7. Ruckelshaus, M.H.; Jackson, S.T.; Mooney, H.A.; Jacobs, K.L.; Kassam, K.-A.S.; Arroyo, M.T.K.; Báldi, A.; Bartuska, A.M.; Boyd, J.; Joppa, L.N.; et al. The IPBES Global Assessment: Pathways to Action. *Trends Ecol. Evol.* **2020**, *35*, 407–414. [CrossRef] [PubMed]
8. Sun, X.; Jiang, Z.; Liu, F.; Zhang, D. Monitoring spatio-temporal dynamics of habitat quality in Nansihu Lake basin, eastern China, from 1980 to 2015. *Ecol. Indic.* **2019**, *102*, 716–723. [CrossRef]
9. Upadhaya, S.; Dwivedi, P. Conversion of of forestlands to blueberries: Assessing implications for habitat quality in Alabaha river watershed in Southeastern Georgia, United States. *Land Use Policy* **2019**, *89*, 104229. [CrossRef]
10. Rahimi, L.; Malekmohammadi, B.; Yavari, A.R. Assessing and Modeling the Impacts of Wetland Land Cover Changes on Water Provision and Habitat Quality Ecosystem Services. *Nat. Resour. Res.* **2020**, *29*, 3701–3718. [CrossRef]
11. Sun, X.; Ye, D.; Shan, R.; Peng, Q.; Zhao, Z.; Sun, J. Effect of physical geographic and socioeconomic processes on interactions among ecosystem services based on machine learning. *J. Clean Prod.* **2022**, *359*, 131976. [CrossRef]
12. Gomes, E.; Inacio, M.; Bogdzevic, K.; Kalinauskas, M.; Karnauskait, D.; Pereira, P. Future scenarios impact on land use change and habitat quality in Lithuania. *Environ. Res.* **2021**, *197*, 111101. [CrossRef]
13. Soley, F.G.; Perfecto, I. A way forward for biodiversity conservation: High-quality landscapes. *Trends Ecol. Evol.* **2021**, *36*, 770–773. [CrossRef] [PubMed]
14. Wu, R.; Possingham, H.P.; Yu, G.; Jin, T.; Wang, J.; Yang, F.; Liu, S.; Ma, J.; Liu, X.; Zhao, H. Strengthening China's national biodiversity strategy to attain an ecological civilization. *Conserv. Lett.* **2019**, *12*, e12660. [CrossRef]
15. Choi, C.; Shi, X.; Shi, J.; Gan, X.; Wen, C.; Zhang, J.; Jackson, M.V.; Fuller, R.A.; Gibson, L. China's Ecological Conservation Redline policy is a new opportunity to meet post-2020 protected area targets. *Conserv. Lett.* **2022**, *15*, e12853. [CrossRef]
16. Bai, Y.; Wong, C.P.; Jiang, B.; Hughes, A.C.; Wang, M.; Wang, Q. Developing China's Ecological Redline Policy using ecosystem services assessments for land use planning. *Nat. Commun.* **2018**, *9*, 3034. [CrossRef] [PubMed]

17. Chen, D.; Pan, Y.; Jin, X.; Du, H.; Li, M.; Jiang, P. The delineation of ecological redline area for catchment sustainable management from the perspective of ecosystem services and social needs: A case study of the Xiangjiang watershed, China. *Ecol. Indic.* **2021**, *121*, 107130. [CrossRef]
18. Wang, X.; Wen, Y.; Liu, X.; Wen, D.; Long, Y.; Zhao, P.; Liu, P.; Zhong, J. Protection Effect and Vacancy of the Ecological Protection Redline: A Case Study in Guangdong–Hong Kong–Macao Greater Bay Area, China. *Remote. Sens.* **2021**, *13*, 5171. [CrossRef]
19. Wang, Y.; Gao, J.; Zou, C.; Xu, D.; Lin, N.; Zhang, K.; Wang, L. Ecological Conservation Redline will promote harmony between humans and nature in the future. *Ambio* **2021**, *50*, 726–727. [CrossRef]
20. Deng, L.; Liu, S.; Kim, D.G.; Peng, C.; Sweeney, S.; Shangguan, Z. Past and future carbon sequestration benefits of China's grain for green program. *Glob. Environ. Chang.* **2017**, *47*, 13–20. [CrossRef]
21. Ma, S.; Wang, L.; Wang, H.; Zhang, X.; Jiang, J. Spatial heterogeneity of ecosystem services in response to landscape patterns under the Grain for Green Program: A case-study in Kaihua County, China. *Land Degrad. Dev.* **2022**, *33*, 1901–1916. [CrossRef]
22. Zhang, Y.; Li, C.; Wang, M. National-Scale Meta-Analysis of Soil Carbon and Nitrogen Accumulation Potential in China's Grain for Green Program. *Eurasian Soil Sci.* **2020**, *53*, 892–901. [CrossRef]
23. Tian, G.; Song, Y.; Liu, Q.; Zong, X.; Zhang, X.; Meng, X.; Geng, D.; Cao, Z. Investigation and evaluation of endangered diversity in Shandong province. *Ecol. Environ. Sci.* **2012**, *21*, 27–32. [CrossRef]
24. Aznarez, C.; Svenning, J.-C.; Taveira, G.; Baró, F.; Pascual, U. Wildness and habitat quality drive spatial patterns of urban biodiversity. *Landsc. Urban Plan.* **2022**, *228*, 104570. [CrossRef]
25. Chen, X.; Yu, L.; Cao, Y.; Xu, Y.; Zhao, Z.; Zhuang, Y.; Liu, X.; Du, Z.; Liu, T.; Yang, B.; et al. Habitat quality dynamics in China?s first group of national parks in recent four decades: Evidence from land use and land cover changes. *J. Environ. Manag.* **2023**, *325*, 116505. [CrossRef]
26. Zhu, S.; Li, L.; Wu, G.; Liu, J.; Slate, T.J.; Guo, H.; Li, D. Assessing the Impact of Village Development on the Habitat Quality of Yunnan Snub-Nosed Monkeys Using the INVEST Model. *Biology* **2022**, *11*, 1487. [CrossRef] [PubMed]
27. Mengist, W.; Soromessa, T.; Feyisa, G.L. Landscape change effects on habitat quality in a forest biosphere reserve: Implications for the conservation of native habitats. *J. Clean Prod.* **2021**, *329*, 129778. [CrossRef]
28. Bai, Y.; Jiang, B.; Wang, M.; Li, H.; Alatalo, J.M.; Huang, S. New ecological redline policy (ERP) to secure ecosystem services in China. *Land Use Policy* **2016**, *55*, 348–351. [CrossRef]
29. Jiang, B.; Bai, Y.; Wong, C.P.; Xu, X.; Alatalo, J.M. China's ecological civilization program-Implementing ecological redline policy. *Land Use Policy* **2019**, *81*, 111–114. [CrossRef]
30. Chen, H. The ecosystem service value of maintaining and expanding terrestrial protected areas in China. *Sci. Total Environ.* **2021**, *781*, 146768. [CrossRef]
31. Hu, T.; Peng, J.; Liu, Y.; Wu, J.; Li, W.; Zhou, B. Evidence of green space sparing to ecosystem service improvement in urban regions: A case study of China's Ecological Red Line policy. *J. Clean Prod.* **2020**, *251*, 119678. [CrossRef]