Ecosystem Health Assessment of World Natural Heritage Sites Based on Remote Sensing and Field Sampling Verification: Bayanbulak as Case Study

Zhi Wang 1,2, Zhaoping Yang 1*, Hui Shi 1, Fang Han 1, Qin Liu 1,2, Jianwei Qi 1,2 and Yayan Lu 1,2

1 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; wangzhi115@mails.ucas.ac.cn (Z.W.); shihui@ms.xjb.ac.cn (H.S.); hanfang@ms.xjb.ac.cn (F.H.); liuqin115@mails.ucas.ac.cn (Q.L.); qijianwei16@mails.ucas.ac.cn (J.Q.); luyayan16@mails.ucas.ac.cn (Y.L)

2 University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence: yangzp@ms.xjb.ac.cn; Tel.: +86-991-788-5349

Received: 4 March 2020; Accepted: 23 March 2020; Published: 25 March 2020

Abstract: Monitoring the ecosystem health for world natural heritage sites is essential for protecting them and benefits the formulation of more targeted protection policies. This study used Bayanbulak world natural heritage site as a case, established a framework for assessing the ecosystem health through remote sensing based on the parameters of ecosystem vigour, organization, resilience, and services. Then, we verified the obtained results through field sampling. The results show that the ecosystem health in the overall study area had declined over time, however, the health within the property zone remained at high levels and stable. The area proportion of low health was low and primarily distributed in the buffer zone. Thus, in general, the ecosystem in the study area was healthy. Besides, the ecosystem health exhibited distinct spatial agglomeration characteristics, and the degree of agglomeration enhanced over time. In addition, the field vegetation samplings were consistent with the changes in the ecosystem health levels, therefore, the result of RS monitoring of ecosystem health were credible. Thus, this study provides a scientific basis for heritage managers to formulate suitable ecological protection policies and should aid further research on the ecological monitoring of heritage sites.

Keywords: world natural heritage conservation; heritage monitoring; spatial autocorrelation; field vegetation verification; VORS model

1. Introduction

World natural heritage (WNH) sites are natural areas with global outstanding universal value, and serve as regional and background references for mankind’s cognition with respect to evolution of natural, biodiversity, bioecological processes, and natural landscape beauty [1]. Thus, they are of great significance for protecting biodiversity, maintaining ecological health, and striking a balance between human development and the environment [2]. However, WNH sites face many threats from human activities and natural disasters, such as development and construction, the overutilization of resources, environmental pollution, pests and diseases, earthquakes, and mudslides [3,4]. Therefore, United Nations Educational, Scientific and Cultural Organization has strengthened the monitoring of WNH sites and added those with significant problems to the “Endangered World Heritage List” to urge the countries where these sites are located to take necessary measures to restore and protect them. By 2018, this list contained 16 WNH sites from around the world [5]. Given these facts, the ecological health assessment and monitoring of WNH sites is attracting a lot of research interest, in order to develop scientific methods for providing early warnings to protect these sites [6,7].
The concept of ecosystem health, which focuses on ecosystem stability and sustainability, has evolved since it was first proposed by Rapport et al. [8]. Then Costanza et al. (1992) defined it as the ability of an ecosystem to maintain its organisational structure and recover after interference through self-regulation processes [9]. In 1998, Rapport et al. suggested ecosystem health should be combined with human value [10]. In 2012, Costanza considered ecosystem health to be sustainable and self-sustaining of ecosystem, and to provide the stability of ecosystem function service value at a certain space-time scale [11]. Therefore, a healthy ecosystem should not only be able to maintain and renew itself, but should also provide ecological services to human society that effectively reflect the functional value of the ecosystem [12].

Ecosystem consists of multiple interactive relationships, which may be highly complex [13], and several research methods and indicators have been developed for ecosystem health assessment (EHA). In general, multicriteria-based evaluation models are used in EHA research, including the index of biotic integrity [14,15], direct measurement method (DMM) [16], ecological modelling method (EMM) [17], the pressure-state-response (PSR) model [18,19], the analytic hierarchy process model [20], and vigour, organisation, and resilience (VOR) model [10,11,21]. Among these models, the VOR is the one used most widely for EHA. This model evaluates ecosystem health based on the ecosystem vigour (EV), ecosystem organisation (EO), and ecosystem resilience (ER). However, it emphasises the natural properties of the ecosystem and has certain limitations. Hence, scholars have developed the vigour, organisation, resilience, and service (VORS) model on the basis of the VOR model [12,22]. The VORS model takes into account the ecosystem’s ability to serve humans. In other words, it considers the services provided by the ecosystem, that is, the direct and indirect ecological functions served by it for humans [23]. Research on the health of ecosystems also involves different scales, which can include the global scale, regional scales with administrative units, and scales specific to the ecosystem in question [24–32]. At present, most studies on EHA are performed on the large-to-medium regional scale, allowing one to understand the trends in ecosystem health. However, it is easy to ignore the correlations that exist within the local characteristics of ecosystems, making it difficult to formulate locally relevant policies. On the other hand, small-scale studies can compensate for these deficiencies and facilitate the formulation of suitable local protection policies. However, there is a distinct lack of research on small-scale regional studies on EHA.

As a part of Xinjiang Tianshan, Bayanbulak was successfully listed in the WNH List in 2013. Bayanbulak is a typical example of an alpine wetland ecosystem in a temperate arid region, and is the largest swan breeding site in China. Thus, it has immense natural heritage value, and protecting its environment is of great importance. Therefore, there have been numerous studies on this area, including on the evolution characteristics of its landscape patterns [33], its ecological carrying capacity and sustainable development [34], and its grassland vegetation community [35]. In addition, several ecological risk analyses [36] and ecological environmental assessments [37] have also been performed on the ecosystem. However, these studies did not provide a systematic assessment of ecosystem health at the WNH of Bayanbulak from the perspective of ecological health. Meanwhile, a previous study found that Bayanbulak faces several ecological problems such as grassland degradation [38] and the spread of harmful grasses [39], which threaten its heritage value to varying degrees. Therefore, monitoring the ecosystem health of Bayanbulak is necessary to protect the heritage site.

Therefore, in this study, we considered the WNH site of Bayanbulak as the study area and attempted to use remote sensing (RS) and geographic information system (GIS) technologies to study its ecosystem health based on the parameters of EV, EO, ER, and ecosystem services (ES). This was done with the aim of developing an EHA model for quantitatively evaluating the health of the ecosystems at WNH sites. The process involved analysing the space–time evolution characteristics and spatial aggregation effects of the ecosystem health on the analysed grid in the study area. We also collected samples of the field vegetation to evaluate the results obtained during the RS monitoring of the ecosystem health. We hope that this study will serve as a reference for heritage managers and help them formulate suitable policies for protecting endangered ecosystems.
2. Materials and Methods

2.1. Study Area

Bayanbulak is located in the bottom swampland of the Youerdusi Basin in the middle of Xinjiang Tianshan (Figure 1). It belongs to the Kaidu River basin, and is the upriver catchment area of the river. It is the best representative of the large intermontane basins of the Tianshan Mountains, and is a typical example of an alpine wetland ecosystem in the arid temperate zone. It is also an excellent example of the beautiful landscape of the Tianshan Mountains, consisting of bending rivers and marshes. The topography of Bayanbulak is gentle, with that in the west being slightly higher. The highest altitude is 2600 m, while the lowest is 2390 m, and the vertical relief is only 210 m. It is surrounded by mountains and has a temperate continental arid climate. The annual average temperature is \(-4.6\) °C, and the extreme high and low temperatures are 28.3 °C and \(-48.1\) °C, respectively. The annual average precipitation is 276 mm and mainly occurs from June to August, which account for 50–70% of the total. Snowfall is concentrated between January and March, and the annual average snowfall is 70.5 mm. The annual evaporation is 1128 mm, while the average relative humidity is 69% [40]. The soil in the region is predominantly alpine basin swamp soil. Because of the frosty climate and frozen soil, there are few large trees in the region, with the primary vegetation being typical alpine swamps and meadows. However, abundant species of birds are present, and it is the largest National Nature Reserve (NNR) for swans in China.

![Figure 1. The location of Bayanbulak. Source: Authors.](image-url)
The study area of Bayanbulak included the property zone and its surrounding buffer zone (Figure 1). The property zone covers the best-preserved areas of the alpine wetland ecosystem and falls with the boundaries of the Bayanbulak NNR. To better protect the integrity of the heritage site, a protective transition zone (i.e., a buffer zone) has been set up around the property zone. In addition, the property zone is divided into a prohibited zone, a restricted zone, and an exhibition zone based on the distribution characteristics and sensitivity of the protected entities [40]. Among these zones, the prohibited zone is the core area where both the heritage value and degree of vulnerability are very high, and all potentially destructive activities are strictly prohibited. On the other hand, the restricted zone is an area with high bioecological value and relatively high ecological vulnerability. While activities related to ecotourism and science education can be carried out here, the originality and integrity of the area must be maintained. Finally, the exhibition zone is where indigenous people are allowed live. In addition, sightseeing by tourists is also permitted. However, all activities must be carried out while ensuring that the ecological environment in the zone is protected.

2.2. Data Source and Processing

2.2.1. Data Sources

The data used in this study included spatial data and field sampling data. Spatial data: World natural heritage boundary of Bayanbulak comes from Xinjiang Tianshan World Natural Heritage Declaration [39]; digital elevation model (DEM) (the resolution was 30 meter) was downloaded from Geospatial Data Cloud (http://www.gscloud.cn); and Landsat thematic mapper/enhanced thematic mapper RS images of the Bayanbulak WNH site for 2000, 2011, and 2018 (the resolution was 30 meter) were obtained from the United States Geological Survey (http://glovis.usgs.gov). Field sampling data: The data was collected from the field sampling of vegetation in 2018 and 2019.

2.2.2. Data Processing

We used the software packages ENVI 5.3 and ArcGIS 10.5 to pre-process the RS image data, which were subjected to band synthesis, radiometric corrections, atmospheric corrections, mosaic making, and cutting. To make the spatial data matched perfectly, we used ArcGIS 10.5 to define and project the spatial data layers in the same coordinate system (WGS_1984_UTM_45N), and used the spatial analysis function of ArcGIS 10.5 for spatial overlays analysis of EHA results and spatial display of EHA indicators. To obtained ecosystem landscape types, a supervised classification method was used in combination with the DEM and normalised difference vegetation index (NDVI), and the field data in 2018 and 2019 as auxiliary data for manual visual interpretation. The study area was divided into swamp grassland, high-coverage grassland, medium-coverage grassland, and low-coverage grassland, water, riverbed, construction land, sand, and bare land, and the ecosystem landscape types in 2000, 2011, and 2018 were determined. The landscape pattern index was calculated using Fragstats 4.2. The field sampling data were processed using Microsoft Excel. Correlation analyses were performed using SPSS 25.0. Spatial autocorrelation analysis was calculated using the software Geoda.

2.3. Method

2.3.1. Ecosystem Health Assessment Framework

Based on previous studies, we divided the research scales of EHA into three levels scale, e.g., large, medium, and small scale. The large-scale research refers to the study with global or national as evaluation units [24,27]; the medium-scale research was taking provincial or municipal administrative district as evaluation units [25,31]; and the small-scale research was based on the evaluation unit of a specific nature conservation site [41]. Our study is the world natural heritage of Bayanbulak, and belongs to the small-scale ecosystem health assessment. We used the VORS model to establish an EHA framework for the Bayanbulak WNH site based on previous studies [12,42,43]. The framework
includes the following parts: Establishing an indicators system for EHA, analysing the space–time evolution of the ecosystem health and the effects of spatial agglomeration, and evaluating the accuracy of obtained results by comparing it with field vegetation sampling data (Figure 2).

Figure 2. EHA framework in Bayanbulak. Source: Previous researches [12,42,43] and our combined study.

Note: Ecosystem health assessment (EHA), ecosystem vigour (EV), ecosystem organization (EO), ecosystem resilience (ER), ecosystem service (ES), landscape heterogeneity (LH), landscape connectivity (LC), connectivity of patches with important ecological functionality (IC). RS data is remote sensing image data; landscape types data comes from remote sensing image.

2.3.2. Ecosystem Health Assessment

- Ecosystem Health Assessment Model

The VORS model uses the parameters EV, EO, ER, and ES to determine the level of ecosystem health. Owing to the complexity of evaluating these indicators and the differences in the properties and dimensions of the data involved, the various indicators had to be made comparable. For this, different standardisations methods were employed, based on the role of indicators in the ecosystem [44,45].

Indicators with positive correlation effects, the standardized formula is:

$$X_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)}$$  \hspace{1cm} (1)$$

Indicators with negative correlation effects, the standardized formula is:

$$X_i = \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)}$$  \hspace{1cm} (2)$$

Based on the actual conditions of the study area, a 1 km × 1 km grid was selected for monitoring and evaluating the ecosystem health in the study area. Since each factor is indispensable for assessing the ecosystem health, the four factors were multiplied. In addition, because the size of the standardised data after the four multiplications was too small, and given that the differences between the data...
would be reduced after the multiplication process, the fourth root of the product was taken [12,46].

The formula is:

$$EH = \sqrt[4]{EV \times EO \times ER \times ES}$$  \hspace{1cm} (3)

where, $EH$ is ecosystem health value; $EV$ is ecosystem vigour; $EO$ is ecosystem organization; $ER$ is ecosystem resilience; $ES$ is ecosystem service value.

Finally, the ecosystem health was divided into 5 levels by natural fracture method: Poor (0–0.2), relatively poor (0.2–0.35), ordinary (0.35–0.5), relatively good (0.5–0.7), and good (0.7–0.9).

- Ecosystem Health Assessment Indicators

The indicators system of EHA as showed Table 1.

| Indices | Indicators | Description |
|---------|------------|-------------|
| $EV$    | NDVI       | $EV$ refers to the primary productivity of the ecosystem. $NDVI$ is widely used in ecosystem primary productivity evaluation. |
|         | landscape heterogeneity ($LH$) | Shannon’s diversity index ($SHDI$) |
| $EO$    | landscape connectivity ($LC$) | landscape fragmentation ($FN$) |
|         | connectivity of patches with important ecological functionality ($IC$) | Swamp grassland fragmentation ($FNI$) |
|         | swamp grassland patch cohesion index ($COHESION$) |
| $ER$    | resilience coefficient |
| $ES$    | ecosystem service value |

Note: Source: Authors.

$EV$ refers to the energy input and nutrient cycle capacity of the ecosystem, and can be expressed as the metabolism or primary productivity of the ecosystem [10]. On the other hand, the $NDVI$ reflects the space–time dynamics of the vegetation distribution and productivity [49]. Previous studies have shown that the $NDVI$ is highly positively correlated with vegetation productivity [50–52]. Therefore, we used the $NDVI$ as an indicator of $EV$. The formula is:

$$NDVI = (NIR - RED)/(NIR + RED)$$  \hspace{1cm} (4)

where, $NIR$ is the near infrared band; $RED$ is the infrared band.

$EO$ represents the structural stability of the ecosystem, describes the interrelationships among its components, and reflects the complexity of its structure, including its diversity and connectivity [11]. Landscape ecology emphasises the interactions between spatial patterns and ecological processes and
is of great significance to the ecosystem, providing an effective way of monitoring and assessing its health [21,53]. It is usually measured using the landscape pattern indices, including the landscape heterogeneity (LH), landscape connectivity (LC), and connectivity of patches with important ecological functionality (IC). LH is maintained through landscape diversity [54] and can be quantified using Shannon’s diversity index. LC is quantified through landscape fragmentation. Since wetlands play an important role in determining the ecosystem functionality in Bayanbulak, we used the swamp grassland fragmentation index and the patch cohesion index to quantify the IC.

The weight coefficient model was used to quantify the EO [55]. Ecosystem health is affected by LH and LC, which describe different aspects of the ecosystem structure and thus are equally important [12,56]. Moreover, the weights assigned to IC should not be higher than that for the overall patch connectivity [12]. Thus, the weights assigned to LH, LC, and IC were 0.35, 0.35, and 0.3, respectively. The degree of fragmentation is the core metric that determines the connectivity, and the weight assigned to the fragmentation degree should be higher than that for the patch cohesion index [42]. Thus, the swamp grassland fragmentation degree and patch cohesion index were assigned weights of 0.2 and 0.1, respectively. The formula is:

$$EO = 0.35 \times LH + 0.35 \times LC + 0.3 \times IC$$ \hspace{1cm} (5)$$

where, LH is landscape heterogeneity; LC is landscape connectivity; IC is connectivity of patches with important ecological functionality; SHDI is Shannon’s diversity index; FN is overall landscape fragmentation; FN1 is swamp grassland landscape fragmentation; COHESION is swamp grassland patch cohesion index.

ER refers to the ability of the ecosystem to maintain its structure and patterns when subjected to external interference and is reflective of its resistance to external disturbances, as well as its ability to recover [57]. A healthy ecosystem should be resilient enough to be able to withstand various small-scale disturbances, and different types of ecosystems will have different ecosystem resilience coefficients. In this study, the ecosystem resilience coefficient was determined based on previous studies and expert knowledge (Table 2) [12,27,42,56]. We used area-weighted ecosystem resilience coefficients for all the ecosystem types quantified. The formula is:

$$ER = \sum_{i=1}^{n} A_i \times RC_i$$ \hspace{1cm} (6)$$

where, $A_i$ is area ratio of ecosystem type $i$; $RC_i$ is resilience coefficient of ecosystem type $i$; $n$ is the number of ecosystem type.

### Table 2. Ecosystem types resilience coefficient

| Ecosystem Type   | Swamp Grassland | HCG | MCG | LCG | Water | Riverbed | Construction Land | Sand | Bare Land |
|------------------|-----------------|-----|-----|-----|-------|----------|-------------------|------|-----------|
| RC               | 0.9             | 0.8 | 0.7 | 0.6 | 0.8   | 0.5      | 0.2               | 0.1  | 0.2       |

Note: Resilience coefficient (RC), high-coverage grassland (HCG), medium-coverage grassland (MCG), low-coverage grassland (LCG). Source: Previous researches [12,27,42,56].

Finally, ES refers to the life support products and services that are directly or indirectly available because of the structure, processes, and functions of an ecosystem [58]. A healthy ecosystem should have a high ES supply capacity. In this study, we used the value equivalent method to evaluate the ES value; this method distinguishes between the different types of ES functions and quantifiable standards to calculate the value equivalents for the various service functions in different types of ecosystems and then combines them with its area for the entire ecosystem [59,60]. The construction of the value equivalents of the ecological service functions is the key to determining their values. Based on the work
of Xie et al. [47,48] and the actual conditions in the study area, we were able to determine the value equivalent for the ES functions in the study area (Table 3). The formula is:

$$ES = \sum_{i=1}^{k} \sum_{j=1}^{f} A_i \times VC_{ij}$$  \hspace{1cm} (7)

where, $ES$ is the total ecosystem service value; $A_i$ is the area of ecosystem type $i$; $VC_{ij}$ is the $j$ type of ecosystem service value of ecosystem type $i$.

### Table 3. Ecosystem service value equivalent per unit area in different ecosystem types (yuan/hm$^2$).

| Service Type | Food Production | Raw Material | Water Supply | Gas Regulation | Climate Regulation | Purify Environment | Soil Maintenance | Biodiversity | Landscape Aesthetics |
|--------------|-----------------|--------------|--------------|----------------|--------------------|--------------------|------------------|--------------|---------------------|
| SWG          | 1146.40         | 1123.93      | 5821.93      | 4270.92        | 8092.26            | 5192.54            | 17690.59        | 10632.33     |                     |
| HCG          | 674.36          | 899.14       | 1775.80      | 3102.03        | 7395.43            | 3776.39            | 6676.12         | 3664.00      | 2198.40             |
| MCG          | 539.48          | 719.31       | 1420.64      | 2481.63        | 5916.34            | 3021.11            | 5340.89         | 2931.20      | 1461.10             |
| LCG          | 404.61          | 539.48       | 1065.48      | 4437.26        | 2279.32            | 2023.07            | 2023.07         | 1461.10      |                     |
| water        | 1798.28         | 517.01       | 18634.68     | 12475.57       | 2090.50            | 7532.02            | 2428.44         | 323.20       |                     |
| riverbed     | 606.92          | 202.31       | 6226.55      | 4473.22        | 809.23             | 2023.07            | 2023.07         | 1461.10      |                     |
| CL           | 0.00            | 0.00         | 0.00         | 0.00           | 0.00               | 0.00               | 0.00            | 0.00         | 0.00                |
| sand         | 22.48           | 67.44        | 44.96        | 44.96          | 44.96              | 44.96              | 44.96           | 22.48        |                     |
| bare land    | 0.00            | 0.00         | 0.00         | 0.00           | 0.00               | 0.00               | 0.00            | 0.00         | 0.00                |

Note: Swamp grassland (SWG), high-coverage grassland (HCG), medium-coverage grassland (MCG), low-coverage grassland (LCG), construction land (CL). Source: Previous researches [47,48].

#### 2.3.3. Spatial Autocorrelation Analysis

Spatial autocorrelation analyses were performed to study the spatial dependence and agglomeration patterns of the ecosystem health for Bayanbulak. This included both global and local spatial autocorrelation analyses. Global spatial autocorrelation reveals the overall trends in the global spatial correlation by calculating the global Moran’s $I$ index, whose range is $[-1,1]$. Index values greater than 0 indicate that the spatial correlation is positive; the larger the value, the more positive the correlation and hence the stronger the spatial agglomeration. On the other hand, index values lower than 0 indicate that the spatial correlation is negative; the smaller the value, the more negative the correlation and the greater the spatial difference. Finally, an index value of 0 means that there is no spatial correlation and that the spatial units are randomly distributed. The local spatial autocorrelation reflects the local characteristics of the spatial correlation and is determined by calculating the local Moran’s $I$ index (LISA). Index values greater than 0 mean that the spatial units exhibit high-high or low-low agglomeration, while values smaller than 0 mean that the spatial units exhibit high-low or low-high agglomeration. The formulas are listed as followed [61,62]:

$$Moran’s \ I = \frac{\sum_{i=1}^{n} \sum_{j \neq i}^{n} W_{ij} (x_i - \bar{x}) (x_j - \bar{x})}{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \left( \sum_{i=1}^{n} \sum_{j \neq i}^{n} W_{ij} \right)}$$  \hspace{1cm} (8)

$$Local Moran’s \ I = \frac{(x_i - \bar{x}) \sum_{j \neq i}^{n} W_{ij} (x_j - \bar{x})}{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$  \hspace{1cm} (9)

where, $n$ is the number of units in the study area; $x_i$ is the value of the spatial unit $i$; $x_j$ is the value of the spatial unit $j$; $W_{ij}$ is the spatial matrix of spatial autocorrelation; $\bar{x}$ is the mean value.

#### 2.3.4. Verification Based on Field Data

In order to further verify the accuracy and effectiveness of the proposed EHA model, we used the field vegetation sampling data to indirectly evaluate the accuracy of the model with respect to the study area. We collected field vegetation samples in the study area in July 2018 and July 2019, based on the accessibility of the roads. Samples from a total of 47 plots were collected. Next, as per previous
studies [63–66], the EHA results were verified based on the vegetation coverage, diversity, richness, and evenness of the field vegetation. We used Spearman rank correlation coefficient to elucidate the relationship between the EHA results and the biodiversity of the field vegetation, with the aim of determining the accuracy of the EHA results.

We selected the Vegetation Coverage, Simpson Diversity Index, Shannon-Wiener Diversity Index, Margalef Richness Index, Pielou Evenness Index as the field vegetation biodiversity. The formula is [67]:

\[
\text{Simpson diversity index} = 1 - \sum P_i^2
\]

\[
\text{Shannon-Wiener diversity index} = -\sum P_i \ln P_i
\]

\[
\text{Margalef richness index} = (S-1) / \ln N
\]

\[
\text{Pielou evenness index} = -\sum P_i \ln P_i / \ln S
\]

where, \( P_i = N_i / N \), \( N_i \) is the number of vegetation species \( i \); \( N \) is the total number of sample species; \( S \) is the total number of vegetation in the sample.

3. Results

3.1. Changes in Ecosystem Landscape Types

From Figures 3 and 4, we found that swamp grasslands and high- and medium-coverage grassland are the main landscape types in the study area, accounting for 95%, 95%, and 94% of the total area in 2000, 2011, and 2018, respectively; while the proportion of the construction land was relatively low, accounting for only 0.4%, 0.5%, and 0.4% of the study area. Overall, there was no change in the ecosystem landscape types structure from 2000 to 2018; however, there were some changes in the areas of the different types. Specifically, the area of medium-coverage grassland increased significantly, from 14.5% in 2000 to 22% in 2018. In addition, the area of the high-coverage grassland decreased, going from 38.5% in 2000 to 30.1% in 2018. Further, the area of the water reduced by 2.3% over the same period, while those of the other landscape types remained stable.

Figure 3. Ecosystem landscape types in 2000, 2011, and 2018. Source: Authors.
Figure 4. Changes of ecosystem landscape types in 2000, 2011, and 2018. Source: Authors. Note: High-coverage grassland (HCG), medium-coverage grassland (MCG), low-coverage grassland (LCG), construction land (CL).

The fragmentation index values for the various ecosystem landscape types in 2000, 2011, and 2018 are shown in Table 4. In general, the degree of landscape fragmentation increased in all three years. However, the extent of fragmentation remained small (0.0061–0.0084). Specifically, the fragmentation index for swamp grassland remained almost constant, while that for high-coverage grassland increased initially and then decreased. Finally, that for medium-coverage grassland fell.

| Landscape Type | Water | Swamp Grassland | Sand | HCG | MCG | LCG | Riverbed | Construction Land | Bare Land | Study Area |
|----------------|-------|-----------------|------|-----|-----|-----|----------|------------------|----------|------------|
| 2000           | 0.0058| 0.0012          | 0.2439 | 0.0022 | 0.0076 | 0.0487 | 0.0083 | 0.0705 | 0.2448 | 0.0061 |
| 2011           | 0.0218| 0.0010          | 0.2615 | 0.0048 | 0.0050 | 0.0868 | 0.0094 | 0.0525 | 0.2163 | 0.0076 |
| 2018           | 0.0367| 0.0012          | 0.2754 | 0.0037 | 0.0051 | 0.0651 | 0.0120 | 0.0566 | 0.2369 | 0.0084 |

Note: High-coverage grassland (HCG), medium-coverage grassland (MCG), low-coverage grassland (LCG). Source: Authors.

3.2. Ecosystem Health Assessment

3.2.1. Changes in EHA indicators

The spatial distributions of and changes in the EHA indicators in the overall study area during 2000, 2011, and 2018 were determined (Figure 5, Table 5). It was found that $EV$ declined from 2000 (0.7758) to 2011 (0.6927), but remained stable from 2011 to 2018 (0.7). The overall $EV$ value was high and distributed evenly during 2000. However, there was a downward trend in the northwest and western parts in 2011 and 2018. Within the property zone, the $EV$ first decreased from 2000 (0.7515) to 2011 (0.7072) and then increased from 2011 to 2018 (0.74), while its spatial distribution remained relatively stable. However, there was a significant decline in its value within the buffer zone from 2000 (0.8095) to 2011 (0.6788), then it remained stable from 2011 to 2018 (0.6638). Moreover, its spatial distribution suggested that its value declined in the southwestern part in 2011 and the western and southwestern parts in 2018.
In contrast, $EO$ remained essentially unchanged in the study area, as well as the property zone and buffer zone, during the three investigated years. Its overall value was relatively low, and the mean values for the study area, property zone, and buffer zone were 0.54, 0.63, and 0.45, respectively. Its spatial distribution also remained stable, especially within the property zone, where its value was highest, though there was a slight change in its value in the northern part of the buffer zone.

The value of $ER$ remained almost stable in the overall study area. Specifically, within the property zone, its value was generally high; it declined slightly from 2000 (0.9024) to 2011 (0.8796), but remained stable from 2011 and 2018. The spatial structure within property zone remained stable. On the other
hand, the buffer zone showed a marked decline from 2000 (0.7802) to 2011 (0.7177), and then a slight decrease in 2011–2018. Further, its spatial distribution suggested that it had declined in the northwestern part in 2011 and 2018.

In general, ES declined in the overall study during 2000–2018 and, in particular, from 2000 (0.6507) to 2011 (0.582). Further, within the property zone, which value of ES was high, had a slow trend of decline (the mean value of 2000, 2011, and 2018 was 0.7928, 0.7544, and 0.7445, respectively). However, in the buffer zone, the ES value remained low, and its rate of decline was significant, especially from 2000 (0.4881) to 2011 (0.3826), while in 2018, it fell to 0.3477. In terms of spatial distribution, it remained essentially unchanged within the property zone, while that in the buffer zone changed significantly. Compared with the case in 2000, the value in the northern and northwestern parts declined significantly during 2011, while in 2018, the value in the southwestern and northwestern parts declined significantly.

In summary, all the EHA indicators showed declining trends, with the decline in ES being the most significant. On comparing the ecosystem landscape types and the EHA indicator values for 2000, 2011, and 2018, it can be inferred that the distribution of swamp grassland and high-, medium-, and low-coverage grassland is the primary factor influencing the values of the EHA indicators in the study area.

3.2.2. Changes in Ecosystem Health

The overall ecosystem health in Bayanbulak also showed a declining trend during the investigated periods (Table 5). For instance, it declined from 0.6802 in 2000 to 0.6251 in 2018, with the decline occurring primarily from 2000 (0.6802) to 2011 (0.6324). While the variations within the property zone were small, there was a slight decline here as well, however, the overall health remained stable. Therefore, the changes in the overall study area were mainly caused by the changes within the buffer zone, with the decline from 2000 (0.6046) to 2011 (0.5284) being especially significant, however, the rate of decline became smaller from 2011 (0.5284) to 2018 (0.5075).

In terms of proportions of area in ecosystem health levels (Figure 6). The proportions of the area with “good” ecosystem health in 2000, 2011, and 2018 were 47%, 44%, and 44%, respectively, thus it remained stable. However, the proportion of the area with “relatively good” health declined significantly, from 47% in 2000 to 26% in 2018; the rate of decline from 2000 to 2011 was 15%. In addition, the proportion of the area with “ordinary” health showed an increase, going from 6% in 2000 to 27% in 2018, with most of the increase occurring during 2000–2011 and the rate of increase being 17%. Finally, the proportions of the area with “poor” and “relatively poor” health remained almost unchanged.

![Figure 6. The area proportion of ecosystem health levels in 2000, 2011, and 2018. Source: Authors.](image-url)
The spatial distribution of the ecosystem health in Bayanbulak is shown in Figure 7. In general, the ecosystem health levels within the property zone remained stable trend, while those within the buffer zone changed significantly. Specifically, the areas with “good” health are mainly distributed within the property zone; however, there was a decline in the health level of some sections of the northern part of the property zone in 2011. The “relatively good” health areas were mostly distributed in the buffer zone during 2000, and in the southern and eastern parts of the zone in 2011 and 2018. The areas with “ordinary” health were sporadically distributed in 2000, but their proportion increased significantly in 2011 and 2018, and they were observed in the western and northwestern parts of the study area in the buffer zone. The “poor” and “relatively poor” health areas were mainly distributed within the buffer zone while they showed dot sporadic distribution and distributed less, however, their proportion increased slightly in 2018.

![Figure 7](image_url)

Figure 7. The spatial distribution of ecosystem health in 2000, 2011, and 2018. Source: Authors.

In summary, although the ecosystem health declined in the study area, it generally remained high. Most of the changes in the ecosystem health occurred within the buffer zone, with the health level changing from “relatively good” to “ordinary.” However, the proportions of the area with “poor” and “relatively poor” health remained low. Therefore, on the whole, the ecosystem in the study area was found to be in the healthy state.

3.3. Spatial Autocorrelation Analysis

The global Moran’s I index values in 2000, 2011, and 2018 were 0.762, 0.809, and 0.821, respectively, and they were all greater than 0 and showed an upward trend (Figure 8). These results were indicative of a significant positive spatial autocorrelation. Further, the spatial distributions of the ecosystem health levels showed obvious agglomeration characteristics, with the degree of agglomeration increasing over time.

![Figure 8](image_url)

Figure 8. Moran scatter plots of ecosystem health value in 2000, 2011, and 2018. Source: Authors.

The LISA agglomeration chart for the local spatial autocorrelation of the ecosystem health levels is shown in Figure 9. The high-high type clusters were mainly distributed within the property zone, and their proportion increased during 2000–2018. The low-low type clusters were mainly distributed within the buffer zone, the spatial distributions during 2000 and 2011 were similar, but there was a decrease in the southern and northeastern parts in 2018, while the western and northwestern parts
exhibited relatively stable distributions. In addition, the high-low and low-high type clusters were sporadically distributed.

Figure 9. Local spatial autocorrelation LISA agglomeration chart. Source: Authors.

3.4. Field Verification

The distribution of the field vegetation sampling plots in Bayanbulak is shown in Figure 1. Since none of the sampling plots were located in the areas with “poor” health, the “poor” level was not included in the field verification process. We calculated the vegetation index values for the sampling plots in each zone based on the ecosystem health levels (Table 6). The results showed that the vegetation coverage, Simpson diversity index, Shannon-Wiener diversity index, and Margalef richness index values were consistent with the changes in the ecosystem health levels in that the higher the level of ecosystem health, the higher the values of the various vegetation indices were. The only exception was Pielou’s evenness index.

Table 6. The vegetation index of field sampling in different levels of EHA.

| Vegetation Index         | Good          | Relatively Good | Ordinary      | Relatively Poor |
|--------------------------|---------------|-----------------|---------------|----------------|
| vegetation coverage      | 92.22 ± 1.88  | 80.58 ± 5.28    | 72.90 ± 3.75  | 39.50 ± 5.5    |
| Simpson diversity index  | 0.71 ± 0.04   | 0.64 ± 0.05     | 0.63 ± 0.02   | 0.53 ± 0.10    |
| Shannon-Wiener           | 1.56 ± 0.12   | 1.43 ± 0.12     | 1.31 ± 0.07   | 1.12 ± 0.23    |
| diversity index          |               |                 |               |                |
| Margalef richness index  | 1.39 ± 0.17   | 1.44 ± 0.16     | 1.21 ± 0.11   | 1.08 ± 0.08    |
| Pielou evenness index    | 0.68 ± 0.02   | 0.63 ± 0.04     | 0.65 ± 0.02   | 0.60 ± 0.08    |

Note: Source: Authors.

Table 7 shows the results of the correlation analysis of the various vegetation indices and the ecosystem health levels performed using the Spearman rank correlation method. It was found that the \( r_s \) value was greater than 0 in all the cases, indicating that the results of the field vegetation sampling process were positively correlated with the ecosystem health. The \( P \) values for the vegetation coverage, Simpson diversity index, and Shannon-Wiener diversity index were 0.019, 0.035, and 0.038, respectively. Thus, all three indices were significantly correlated with the ecosystem health.

Table 7. The results of Spearman Rank Correlation analysis in Bayanbulak

| Vegetation Index          | \( r_s \) | \( P \) value |
|---------------------------|-----------|--------------|
| vegetation coverage       | 0.341     | 0.019        |
| Simpson diversity index   | 0.323     | 0.035        |
| Shannon-Wiener            | 0.318     | 0.038        |
| diversity index           |           |              |
| Margalef richness index   | 0.170     | 0.277        |
| Pielou evenness index     | 0.149     | 0.341        |

Note: Source: Authors.

To sum up, the vegetation index values were consistent with the changes in the ecosystem health levels, and the various vegetation indices were positively correlated with the ecosystem health values. Thus, the results of RS monitoring of ecosystem health were credible.
4. Discussion

The health of an ecosystem is reflective of its overall state. However, absolutely healthy ecosystems do not exist, and the focus of EHA is to determine the differences in the spatial distributions in ecosystem health that occur over time [68]. The ecological effect of the land cover is a key factor in ecological protection, and has a determining effect on the health of the ecosystem [42,68,69]. The current trend in EHA research is to consider the land cover in studies on ecological health [43,44,70]. Assessing ecosystem health based on the changes in the landscape types of the ecosystem allows one to spatially understand the dynamic changes in the health levels [43]. Therefore, in this study, we focused on analysing the spatial differences and dynamic changes in ecosystem health based on the changes in the spatial distributions of the ecosystem landscape types.

4.1. Ecosystem Health Assessment model

Monitoring world heritage sites is essential for protecting them, the key to which is the construction of monitoring model [71,72]. Ecosystems are often complex, each ecosystem (such as water ecosystem and the grassland ecosystem) has different basic features [73], and the structure and function of ecological system may also be different under different space-time, therefore, many model methods have been proposed to assess the ecosystem health, and the most common methods are DMM, EMM, PSR, and VOR. Each model has different advantages and disadvantages, and they are suitable for different research areas.

DMM is based on the direct measurement and indirect calculate the value to assess ecosystem health [73], and it is often used to assess the water quality of rivers in small scale, or to assess the health of a single ecosystem [15,16]. This model could reflect the ecosystem health accurately, but it needs a lot of measured data, meaning it is unsuitable for integrated ecosystem health assessment. EMM has high requirements on the establishment of ecosystem model and the setting of model parameters [17], and it is also unsuitable for the integrated ecosystem health assessment. PSR focuses on the ecosystem state and the impact of human activities on the ecosystem and their interaction [29], it is suitable for large-medium scale region ecosystem, which is greatly affected by human activities. VOR pays more attention to the health of the ecosystem’s own structure [9]. The above model often assesses health through the state of the ecosystem itself and external disturbance, and ignores the ability of the ecosystem to provide services to humans [12,27]. However, in the case of health ecosystem, it needs to meet human’s reasonable requirements and keep the sustainability of itself [12]. VORS model combined the structure of the ecosystem itself and its ecosystem service to humans [12], and it is easy to describe in theory and conduct in practice [73], thus it is suitable for the study of nature reserve sites with strict restrictions on human activities.

The weights assigned to these indicators of VORS model have a determining effect on the assessment results. Since assessing ecosystem health involves humans making subjective judgments that should take into account human needs of ecosystem functional services [68], using subjective methods to determine the weights to be assigned to the indicators is one way of highlighting the relative importance of the different indicators. This is both scientifically reasonable and a widely accepted practice in EHA [12,27,42,43,56]. Therefore, we relied on expert knowledge and experience, as well as the actual conditions in Bayanbulak, which reflect its uniqueness, to determine the weights in this study. However, if this model was used in other place, it should be adjusted appropriately based on the actual conditions of study area.

The selection of data also has an important impact on the results of the model. RS data can be used to monitor and assess the spatial heterogeneity of ecosystem health at different space-time scales [50,74]. Hence, RS and GIS technologies are used widely in EHA [20,45]. RS large-scale data can quickly assess the space-time distribution and evolution of ecosystem health in heritage sites, but RS large-scale data have certain limitations in accurately reflecting the level of ecosystem health, thus, the ground-based field sampling small-scale data were used to verify the rationality of the results of RS large-scale data [65].
Bayanbulak covers the best-preserved areas of the alpine wetland ecosystem, and it has important ecological function value and provides important ecological function service value for human [40]. Thus, the ability of Bayanbulak’s ecosystem to provide the value of ecological functions cannot be ignored in its ecosystem health assessment. In addition, WNH site of Bayanbulak is a nature reserve which has strict protection measures and human socioeconomic activities are restricted, and the possible negative impact of human activities is relatively small, and its direct effect can even be ignored. Therefore, we used the VORS to assess the ecosystem health of our study area from the perspective of heritage protection monitoring.

In addition, in the application of data, we used RS large-scale data and GIS analysis to assess the ecosystem health in WNH of Bayanbulak, and used the ground-based sample small-scale data to verify the rationality of the results of ecosystem health level by RS large-scale data. Therefore, our study complements the research of ecosystem health in WNH of Bayanbulak and would provide a new idea and practical experience for future monitoring and protection of WNH sites.

4.2. Ecosystem Health Assessment

The regions with “good” ecosystem health were mainly distributed within the property zone, which is a typical area with high ecosystem health, and mostly remained stable from 2000 to 2018. This was because the boundary of the study area overlaps with the NNR, and this area is strictly protected and controlled as per the laws and regulations for NNRs in China. A similar phenomenon was also found in Sanjiangyuan NNR, that areas that received strict control and protection had the highest ecosystem health level [41]. In addition, those areas contain a large number of swamp grassland and water bodies with high water content, and the land utilisation intensities were extremely low for these regions. This result is consistent with that of a study of He et al. (2019), who found that the moisture index and the land utilisation intensities were the primary parameter that determines the ecosystem health [27]. This is another reason the ecosystem health level was the highest within the property zone. Meanwhile, our field sampling data also found ecosystem health level was the highest within the property zone. In addition, we observed several rare and endangered species during the field sampling process, including Orchis umbrosa, Orchis latifolia, also suggesting that the habitat conditions in the property zone were better than those in the buffer zone.

However, the northern part of the property zone exhibited a decline in ecosystem health in 2011, and the declined areas were distributed in the restricted and exhibition zones within the property zone. A possible explanation is that those areas are close to Bayanbulak town and vulnerable to tourism and grazing activities, which would decrease the ecosystem health [75]. Jia et al. (2011) and Qian et al. (2016) also found the low ecosystem health level areas were easier to be affected by human activities in Sanjiangyuan and Dongting Lake wetland, respectively [41,76]. In addition, Bayanbulak wetland areas had begun to degenerate and shrink in 2010 [33], leading to the decline of ecosystem health in the northern part of the property zone.

The ecosystem health of the buffer zone was lower than the property zone and exhibited obvious spatial changes. We found the ecosystem health within the buffer zone in the southwestern, western, and northwestern parts were lower than the other part of the buffer zone in 2011 and 2018. This was probably because of the seasonal grazing activities in these areas from June to September. In addition, the northwestern part is adjacent to Bayinguoleng town and National Road 217. Hence, it is likely that extensive human activities in the area resulted in lower vegetation coverage [35]. In addition, we also found that the vegetation index values in the northwestern part of the study area were lower than those in the southeastern part. This was consistent with the results of RS monitoring. However, most of the buffer zone exhibited “relatively good” health and “ordinary”, and there were few areas with “poor” ecosystem health, indicating that the overall health of the buffer zone was relative good. During field sampling, we found that the buffer zone contains abundance of Pedicularis kansuensis, which has low nutrient requirements and semi-parasitic characteristics [77], which would result in large-scale outbreaks and threaten the balance of the grassland ecosystem.
4.3. Limitations and Future Prospects

In this study, we established an integrated model for EHA based on the space–time changes in the ecosystem landscape types. Further, by combining RS imaging data with field sampling data, we evaluated the suitability of the proposed EHA model. However, the study has a few limitations. For instance, during the field sampling process for verifying the EHA model, the data were not collected spatially uniformly from the study area. This was owing to the inaccessibility of the wetlands. In addition, the study area shares a boundary with the Bayanbulak NNR, and the protection policy in the study area prohibited access to some of its parts. Hence, some of the sampling plots could not be accessed during the sampling process. We also found that even though the study area has strict controls and protection management measures in place, grazing and tourism activities do occur in the restricted, exhibition, and buffer zones to different degrees, which may affect the ecosystem health of Heritage. In addition, we used the RS data of 2000, 2011, and 2018 to assess the ecosystem health of Bayanbulak, and used the field data of 2018 and 2019 to verified the results of ecosystem health in 2018. As the field vegetation sampling was only conducted in 2018 and 2019, meaning we could not verify the results of ecosystem health in 2000 and 2011, which is the shortcoming of our study.

Therefore, future studies should try to ensure that the sampling plots are distributed uniformly in the study area, and the grazing and tourism activities should be accounted for within the frameworks for the assessment of heritage sites. Finally, continued efforts should be made to explore the factors driving ecological health as well as their impact mechanisms. In addition, integrated sky-space-ground monitoring systems are expected to allow for the comprehensive and focused monitoring of heritage sites at different space-time scales and provide a scientific basis for the establishment of suitable protection measures.

5. Conclusions

In this study, we established an indicator-based framework for the EHA of WNH sites and evaluated it using Bayanbulak in China as a test case for the periods of 2000, 2011, and 2018. We analysed the space–time evolution characteristics and spatial agglomeration effects of the ecosystem health levels based on the changes in the ecosystem landscape types from 2000 to 2018. The primary results of this study can be summarised as follows:

- While changes were observed in the area proportions of the various ecosystem landscape types from 2000 to 2018, the overall landscape structure did not change. The fragmentation of the landscape in the study area increased in general during the three periods. However, the degree of fragmentation remained small.
- All the EHA indicators showed a decline, with the decline in ES being the most significant. Thus, the overall ecosystem health in the study area also declined. However, the ecosystem health within the property zone remained high and essentially unchanged. Further, the area proportions of poor health were extremely low and were mostly distributed within the buffer zone. Therefore, in general, the ecosystem of the study area was in a healthy state.
- The spatial distribution of the ecosystem health exhibited obvious agglomeration characteristics, with the degree of agglomeration increasing over time. With respect to the local spatial autocorrelation, the high-high clusters were mainly distributed within the property zone, and the degree of agglomeration enhanced over time. On the other hand, the low-low clusters were mainly distributed in the buffer zone, and the degree weaken over time.
- The results of EHA obtained through RS monitoring were positively correlated with those of the field sampling of the vegetation in the study area. The areas with high levels of ecosystem health also exhibited high sampling vegetation index values. This confirmed the suitability of using RS imaging for monitoring ecosystem health.

We diagnosed the ecosystem health level in WNH of Bayanbulak and analyzed the characteristics of its space-time evolution, which helps local heritage managers to formulate precise protection
measures for different regions with different ecosystem health levels, and provided guiding significance for the protection of Bayanbulak. In addition, we established an EHA framework in the WNH sites, which could be applied to other nature reserve sites for their better protection in the future. However, the RS data used to assess the ecosystem health were large-scale data, which may affect the accuracy of results, so we used small-scale field data to verify its rationality. However, due to the lack of field sampling data in 2000 and 2011, the accuracy of EHA was not fully verified. In the future, we could increase the accuracy of EHA framework in WNH by using more ground-based sample small-scale data and unmanned Aerial Vehicle medium-scale data.

Author Contributions: Writing—original draft, Z.W.; funding acquisition, Z.Y. and F.H.; writing—review and editing, H.S.; methodology, Z.W. and H.S.; software, Q.L.; data acquisition, J.Q. and Y.L.; supervision, Z.Y. and F.H. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Key Research and Development Program of China (No. 2016YFC0503306) and the National Natural Science Foundation of China (No. 41971192) and the Provincial Natural Science Foundation of Xinjiang Uyghur autonomous region (No. 2019D01A96).

Acknowledgments: We are very grateful to Sachin for useful suggestions and remarks and great help in English editing and enhancement of this manuscript. We also express gratitude to Xiyong Wang for his great help in the process of data collection in the field survey.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNESCO. Operational Guidelines for the Implementation of the World Heritage Convention; UNESCO: Paris, France, 2017.

2. Jokilehto, J. World Heritage: Defining the outstanding universal value. City Time 2006, 2, 1.

3. Wang, Z.; Yang, Z.; Du, X. Analysis on the threats and spatiotemporal distribution pattern of security in World Natural Heritage Sites. Environ. Monit. Assess. 2015, 187, 4143. [CrossRef]

4. Allan, J.R.; Venter, O.; Maxwell, S.; Bertzky, B.; Jones, K.; Shi, Y.; Watson, J.E. Recent increases in human pressure and forest loss threaten many natural world heritage sites. Biol. Conserv. 2017, 206, 47–55. [CrossRef]

5. UNESCO. Available online: http://www.unesco.org (accessed on 4 March 2020).

6. Hedge, P.; Molloy, E.; Sweatman, H.; Hayes, K.R.; Dambacher, J.M.; Chandler, J.; Bax, N.; Gooch, M.; Anthony, K.; Elliot, B. An integrated monitoring framework for the great barrier reef world heritage area. Mar. Policy 2017, 77, 90–96. [CrossRef]

7. Du, X.; Wang, Z. Optimizing monitoring locations using a combination of GIS and fuzzy multi criteria decision analysis, a case study from the Tomur World Natural Heritage site. J. Nat. Conserv. 2018, 43, 67–74. [CrossRef]

8. Rapport, D.J.; Regier, H.A.; Hutchinson, T.C. Ecosystem behavior under stress. Am. Nat. 1985, 125, 617–640. [CrossRef]

9. Costanza, R. Toward an operational definition of ecosystem health. In Ecosystem Health: New Goals for Environmental Management; Costanza, R., Norton, B.G., Haskett, B.D., Eds.; Island Press: Washington, DC, USA, 1992; pp. 239–256.

10. Rapport, D.J.; Costanza, R.; McMichael, A.J. Assessing ecosystem health. Trends Ecol. Evol. 1998, 13, 397–402. [CrossRef]

11. Costanza, R. Ecosystem health and ecological engineering. Ecol. Eng. 2012, 45, 24–29. [CrossRef]

12. Peng, J.; Liu, Y.; Wu, J.; Lv, H.; Hu, X. Linking ecosystem services and landscape patterns to assess urban ecosystem health: A case study in Shenzhen City, China. Landsc. Urban Plan. 2015, 143, 56–68. [CrossRef]

13. Pan, Y.; Xu, Z.; Yu, C.; Tu, Y.; Li, Y.; Wu, J. Spatiotemporal variation of interacting relationships among multiple provisioning and regulating services of Tibet grassland ecosystem. Acta Ecol. Sin. 2013, 33, 5794–5801.

14. Yang, W.; You, Q.; Fang, N.; Xu, L.; Zhou, Y.; Wu, N.; Ni, C.; Liu, Y.; Liu, G.; Yang, T.; et al. Assessment of wetland health status of Poyang Lake using vegetation-based indices of biotic integrity. Ecol. Indic. 2018, 90, 79–89. [CrossRef]

15. Zhao, C.; Shao, N.; Yang, S.; Ren, H.; Ge, Y.; Zhang, Z.; Zhao, Y.; Yin, X. Integrated assessment of ecosystem health using multiple indicator species. Ecol. Eng. 2019, 130, 157–168. [CrossRef]
16. Young, R.G.; Matthaei, C.D.; Townsend, C.R. Organic matter breakdown and ecosystem metabolism: Functional indicators for assessing river ecosystem health. J. N. Am. Benthol. Soc. 2008, 27, 605–625. [CrossRef]
17. Xu, F.; Dawson, R.W.; Tao, S.; Cao, J.; Li, B. A method for lake ecosystem health assessment: An Ecological Modeling Method (EMM) and its application. Hydrobiologia 2001, 443, 159–175. [CrossRef]
18. Liu, D.; Hao, S. Ecosystem health assessment at county-scale using the pressure-state-response framework on the Loess Plateau, China. Int. J. Environ. Res. Public Health 2017, 14, 2. [CrossRef]
19. Sun, B.; Tang, J.; Yu, D.; Song, Z.; Wang, P. Ecosystem health assessment: A PSR analysis combining AHP and FCE methods for Jiaozhou Bay, China. Ocean Coastal. Manag. 2019, 168, 41–50. [CrossRef]
20. Song, D.; Gao, Z.; Zhang, H.; Xu, F.; Zheng, X.; Ai, J.; Hu, X.; Huang, G.; Zhang, H. GIS-based health assessment of the marine ecosystem in Laizhou Bay, China. Mar. Pollut. Bull. 2017, 125, 242–249. [CrossRef]
21. Suo, A.; Xiong, Y.; Wang, T.; Yue, D.; Ge, J. Ecosystem health assessment of the Jinghe River watershed on the Huangtu Plateau. EcoHealth 2008, 5, 127–136. [CrossRef]
22. Wu, L.; You, W.; Ji, Z.; Xiao, S.; He, D. Ecosystem health assessment of Dongshan Island based on its ability to provide ecological services that regulate heavy rainfall. Ecol. Indic. 2018, 84, 393–403.
23. Costanza, R.; De Groot, R.; Sutton, P.; Van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. Glob. Environ. Chang. 2014, 26, 152–158. [CrossRef]
24. Halpern, B.S.; Longo, C.; Hardy, D.; McLeod, K.L.; Samhouri, J.F.; Katona, S.K.; Kleisner, K.; Lester, S.E.; O’Leary, J.; Ranelletti, M.; et al. An index to assess the health and benefits of the global ocean. Nature 2012, 488, 615–620. [CrossRef]
25. Meng, L.; Huang, J.; Dong, J. Assessment of rural ecosystem health and type classification in Jiangsu province, China. Sci. Total Environ. 2018, 615, 1218–1228. [CrossRef]
26. De Toro, P.; Iodice, S. Ecosystem Health Assessment in urban contexts: A proposal for the Metropolitan Area of Naples (Italy). Aestimatum 2018, 72, 39–59.
27. He, J.; Pan, Z.; Liu, D.; Guo, X. Exploring the regional differences of ecosystem health and its driving factors in China. Sci. Total Environ. 2019, 673, 553–564. [CrossRef] [PubMed]
28. Yan, Y.; Zhao, C.; Wang, C.; Shan, P.; Zhang, Y.; Wu, G. Ecosystem health assessment of the Liao River Basin upstream region based on ecosystem services. Acta Ecol. Sin. 2016, 36, 294–300. [CrossRef]
29. Sun, T.; Lin, W.; Chen, G.; Guo, P.; Zeng, Y. Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. Sci. Total Environ. 2016, 566, 627–640. [CrossRef] [PubMed]
30. Singh, P.K.; Saxena, S. Towards developing a river health index. Ecol. Indic. 2018, 85, 999–1011. [CrossRef]
31. Chen, W.; Cao, C.; Liu, D.; Tian, R.; Wu, C.; Wang, Y.; Qian, Y.; Ma, G.; Bao, D. An evaluating system for assessing lake ecosystem health: A case study on nineteen major wetlands in Beijing-Tianjin-Hebei region, China. Sci. Total Environ. 2019, 666, 1080–1088. [CrossRef] [PubMed]
32. Wu, N.; Liu, A.; Wang, Y.; Li, L.; Chao, L.; Liu, G. An Assessment Framework for Grassland Ecosystem Health with Consideration of Natural Succession: A Case Study in Bayinxile, China. Sustainability 2019, 11, 1096. [CrossRef]
33. Xu, X.; Wang, X.; Zhu, X.; Jia, H.; Han, D. Landscape pattern changes in alpine wetland of Bayanbulak Swan Lake during 1996–2015. J. Nat. Resour. 2018, 33, 1897–1911.
34. Zhang, M.; Xu, D.; You, G. Ecological carrying capacity and sustainable development of grassland and wetland in Bayanbulak national alpine grassland nature reserve. Biol. Disaster Sci. 2018, 41, 101–107.
35. Lv, C.; Pan, X.; Feng, C.; Qian, J. Spectral models for estimating vegetation coverage and its application on Bayanbulak grassland. Bull. Soil Water Conserv. 2016, 36, 62–67.
36. Shi, H.; Yang, Z.; Han, F.; Shi, T.; Li, D. Assessing landscape ecological risk for a world natural heritage site: A case study of Bayanbulak in China. Pol. J. Environ. Stud. 2015, 24, 269–283. [CrossRef]
37. Liu, Q.; Yang, Z.; Han, F.; Shi, H.; Wang, Z.; Chen, X. Ecological environment assessment in world natural heritage site based on remote-sensing data. A case study from the Bayinbuluke. Sustainability 2019, 11, 6385. [CrossRef]
38. Ayimin, B.; An, S.; Dong, Y.; Yang, J.; Zhang, A. Soil stoichiometry characteristics in different degradation stages of alpine steppe in Bayanbulak. Xinjiang Agric. Sci. 2018, 55, 957–965.
39. Liu, Y. Ecological Factors of Pedicularis kansuensis Maxim. Expansion in Bayanbulak Grassland. Ph.D. Thesis, Xinjiang University, Urumqi, China, 2018.
40. Yang, Z.; Zhang, X.; Xu, X.; Han, F.; Zhang, Y.; Yang, W.; Yan, S.; Hai, Y.; Yin, L.; Zhao, X.; et al. *World Natural Heritage of Xinjiang Tianshan*: Science Press: Beijing, China, 2017.

41. Jia, H.; Cao, C.; Ma, G.; Bao, D.; Wu, X.; Xu, M.; Zhao, J.; Tian, R. Assessment of wetland ecosystem health in the source region of Yangtze, Yellow and Yalu Tsangpo Rivers of Qinghai province. *Wetl. Sci.* **2011**, *9*, 209–217.

42. Peng, J.; Liu, Y.; Li, T.; Wu, J. Regional ecosystem health response to rural land use change: A case study in Lijiang City, China. *Ecol. Indic.* **2017**, *72*, 399–410. [CrossRef]

43. Xiao, R.; Liu, Y.; Fei, X.; Yu, W.; Zhang, Z.; Meng, Q. Ecosystem health assessment: A comprehensive and detailed analysis of the case study in coastal metropolitan region, eastern China. *Ecol. Indic.* **2019**, *98*, 363–376. [CrossRef]

44. Yu, G.; Yu, Q.; Hu, L.; Zhang, S.; Fu, T.; Zhou, X.; He, X.; Liu, Y.; Wang, S.; Jia, H. Ecosystem health assessment based on analysis of a land use database. *Appl. Geogr.* **2013**, *44*, 154–164. [CrossRef]

45. Liao, C.; Yue, Y.; Wang, K.; Fensholt, R.; Tong, X.; Brandt, M. Ecological restoration enhances ecosystem health in the karst regions of southwest China. *Ecol. Indic.* **2018**, *90*, 416–425. [CrossRef]

46. Yuan, M.; Liu, Y.; Wang, M.; Tian, L.; Peng, J. Ecosystem health assessment based on the framework of vigor, organization, resilience and contribution in Guangzhou City. *Chin. J. Ecol.* **2019**, *38*, 1249–1257.

47. Xie, G.; Zhang, C.; Zhang, L.; Chen, W.; Li, S. Improvement of the evaluation method for ecosystem service value based on per unit area. *J. Nat. Resour.* **2015**, *30*, 1243–1254.

48. Xie, G.; Zhang, C.; Zhen, L.; Zhang, L. Dynamic changes in the value of China’s ecosystem services. *Ecosyst. Serv.* **2017**, *26*, 146–154. [CrossRef]

49. Mageau, M.T. The development and initial testing of a quantitative assessment of ecosystem health. *Ecosyst. Health* **1995**, *1*, 201–213.

50. Myneni, R.B.; Ganapol, B.D.; Asrar, G. Remote sensing of vegetation canopy photosynthetic and stomatal conductance efficiencies. *Remote Sens. Environ.* **1992**, *42*, 217–238. [CrossRef]

51. Phillips, L.B.; Hansen, A.J.; Fether, C.H. Evaluating the species energy relationship with the newest measures of ecosystem energy: NDVI versus MODIS primary production. *Remote Sens. Environ.* **2008**, *112*, 4381–4392. [CrossRef]

52. Li, Z.; Xu, D.; Guo, X. Remote sensing of ecosystem health: Opportunities, challenges, and future perspectives. *Sensors* **2014**, *14*, 21117–21139. [CrossRef]

53. Rapport, D.J. Ecosystem services and management options as blanket indicators of ecosystem health. *J. Aquat. Ecosyst. Health* **1995**, *4*, 97–105. [CrossRef]

54. Turner, M.G. Landscape ecology: The effect of pattern on process. *Annu. Rev. Ecol. Syst.* **1989**, *20*, 171–197. [CrossRef]

55. Frondoni, R.; Mollo, B.; Capotorti, G. A landscape analysis of land cover change in the Municipality of Rome (Italy): Spatio-temporal characteristics and ecological implications of land cover transitions from 1954 to 2001. *Landsc. Urban Plan.* **2011**, *100*, 117–128. [CrossRef]

56. Kang, P.; Chen, W.; Hou, Y.; Li, Y. Linking ecosystem services and ecosystem health to ecological risk assessment: A case study of the Beijing-Tianjin-Hebei urban agglomeration. *Sci. Total Environ.* **2018**, *636*, 1442–1454. [CrossRef] [PubMed]

57. Holling, C.S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]

58. Lautenbach, S.; Kugel, C.; Lausch, A.; Seppelt, R. Analysis of historic changes in regional ecosystem service provisioning using land use data. *Ecol. Indic.* **2011**, *11*, 676–687. [CrossRef]

59. Costanza, R.; d’Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O’Neill, R.V.; Paruelo, J.; et al. The value of the world’s ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]

60. Xie, G.; Zhen, L.; LU, C.; Xiao, Y.; Chen, C. Expert Knowledge Based Valuation Method of Ecosystem Services in China. *J. Nat. Resour.* **2008**, *23*, 911–919.

61. Moran, P.A. Notes on continuous stochastic phenomena. *Biometrika* **1950**, *37*, 17–23. [CrossRef]

62. Anselin, L. Local indicators of spatial association—LISA. *Geogr. Anal.* **1995**, *27*, 93–115. [CrossRef]

63. Quijas, S.; Schmid, B.; Balvanera, P. Plant diversity enhances provision of ecosystem services: A new synthesis. *Basic Appl. Ecol.* **2010**, *11*, 582–593. [CrossRef]

64. Xie, H.; Wang, G.G.; Yu, M. Ecosystem multifunctionality is highly related to the shelterbelt structure and plant species diversity in mixed shelterbelts of eastern China. *Glob. Ecol. Conserv.* **2018**, *16*, e00470. [CrossRef]
65. Shi, H.; Shi, T.; Han, F.; Liu, Q.; Wang, Z.; Zhao, H. Conservation value of world natural heritage site’ outstanding universal value via multiple techniques—Bogda, Xinjiang Tianshan. *Sustainability* 2019, 11, 5953. [CrossRef]

66. Geng, S.; Shi, P.; Song, M.; Zong, N.; Zu, J.; Zhu, W. Diversity of vegetation composition enhances ecosystem stability along elevational gradients in the Taihang Mountains, China. *Ecol. Indic.* 2019, 104, 594–603. [CrossRef]

67. Magurran, A.E. *Ecological Diversity and its Measurement*; Princeton University Press: Princeton, NJ, USA, 1988.

68. Peng, J.; Wang, Y.; Wu, J.; Zhang, Y. Evaluation for regional ecosystem health: Methodology and research progress. *Acta Ecol. Sin.* 2007, 27, 4877–4885. [CrossRef]

69. Mitchell, M.G.; Suarez-Castro, A.F.; Martinez-Harms, M.; Maron, M.; McAlpine, C.; Gaston, K.J.; Johansen, K.; Rhodes, J.R. Reframing landscape fragmentation’s effects on ecosystem services. *Trends. Ecol. Evol.* 2015, 30, 190–198. [CrossRef] [PubMed]

70. Liu, R.; Dong, X.; Zhang, P.; Zhang, Y.; Wang, X.; Gao, Y. Study on the sustainable development of an arid Basin based on the coupling process of ecosystem health and human wellbeing under land use change—A case study in the Manas River Basin, Xinjiang, China. *Sustainability* 2020, 12, 1201. [CrossRef]

71. Woodhill, J. *Planning, Monitoring and Evaluating Programmes and Projects: Introduction to Key Concepts, Approaches and Terms*; World Conservation Union: Gland, Switzerland, 2000.

72. Job, H.; Becken, S.; Lane, B. Protected Areas in a neoliberal world and the role of tourism in supporting conservation and sustainable development: An assessment of strategic planning, zoning, impact monitoring, and tourism management at natural World Heritage Sites. *J. Sustain. Tour.* 2017, 25, 1697–1718. [CrossRef]

73. Kruse, M. Ecosystem health indicators. In *Encyclopedia of Ecology*, 2nd ed.; Fath, B., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 407–414.

74. Ludwig, J.A.; Bastin, G.N.; Chewings, V.H.; Eager, R.W.; Liedloff, A.C. Leakiness: A new index for monitoring the health of arid and semiarid landscapes using remotely sensed vegetation cover and elevation data. *Ecol. Indic.* 2007, 7, 442–454. [CrossRef]

75. Shi, Y.; Rui, H.; Luo, G. Temporal–Spatial distribution of ecosystem health and its response to human interference based on different terrain gradients: A case study in Gannan, China. *Sustainability* 2020, 12, 1773. [CrossRef]

76. Qian, Y.; Lou, Y.; Chu, Y.; Liu, J.; Hu, J. Ecosystem Evaluation of International Important Wetlands in Dongting Lake. *Wetl. Sci.* 2016, 14, 516–523.

77. Liu, Y.; Hu, Y.; Yu, J.; Li, K.; Gao, G.; Wang, X. Study on harmfulness of Pedicularis myriophylla and its control measures. *Arid Zone Res.* 2008, 25, 778–782.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).