Postprint: Landscape Ecological Health Assessment of Alpine Wetlands in the Heihe River Source Area Based on Vigor-Organization-Resilience

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Abstract

As a typical alpine river source wetland, the Heihe River Source National Wetland Park's ecosystem health status serves as an important basis for assessing the current and future development conditions of alpine wetlands. This study constructs a comprehensive evaluation system for alpine wetland ecological health based on land use data, incorporating the landscape ecological vulnerability index, and encompassing four dimensions: ecosystem vitality, organization, resilience, and ecosystem service value, to quantitatively evaluate the spatiotemporal dynamics of ecological health in the Heihe River source area from 2014 to 2021. The results indicate: (1) Grassland is the dominant land use type in the Heihe River source area, with high-, medium-, and low-coverage grasslands exhibiting a mosaic distribution pattern; unused land ranks second, primarily distributed along riverbanks and in the northwestern region. (2) The Heihe River source area is predominantly characterized by low and relatively low vulnerability zones, indicating low overall landscape ecological vulnerability. (3) The region is primarily healthy and moderately healthy, reflecting a relatively high overall level of ecological health. In summary, the ecosystem of the Heihe River source area remained relatively healthy during 2014–2021. Going forward, the region can prioritize ecological functions while accommodating livestock production, thereby ensuring the ecosystem develops toward a state of "ecological harmony."

Full Text

Abstract

The Heihe River source area National Wetland Park, representing a typical alpine wetland, is key for measuring the current and future development of

such ecosystems. This study uses land use data to introduce the landscape ecology vulnerability index and establish a comprehensive assessment system of the alpine wetland ecological health based on four aspects: ecosystem vitality, organization, resilience, and ecosystem service value. It quantitatively assesses the spatiotemporal change characteristics of ecological health in the Heihe River source area from 2014 to 2021. The findings reveal that (1) grassland in the Heihe River source area is the main land use type, with high, medium, and low coverage grasslands distributed in a mosaic pattern. The second type is unused land, mainly distributed on both banks of the river and in the northwest; (2) the Heihe River source area consists of both low- and low-vulnerability areas, resulting in an overall low landscape ecology vulnerability; and (3) the Heihe River source area is predominantly rated as healthy and moderately healthy, indicating a relatively high overall ecological environment health level. Throughout 2014 to 2021, the ecosystem of the Heihe River source area was relatively healthy. In the future, the Heihe River source area should prioritize ecological functions, balancing animal husbandry production and ensure the ecosystem's healthy progression toward achieving "ecological harmony."

Keywords: alpine wetland; landscape index; ecological health; land use; VOR model; the Heihe River source area

1. Study Area Overview

The Heihe River source area National Wetland Park is located in the northeastern part of Qinghai Province, on the edge of the Qinghai-Tibet Plateau, within Yeniugou Township in the northwest of Qilian County, Haibei Tibetan Autonomous Prefecture. It serves as an important water source for Qilian County and its downstream regions, as well as a critical ecological barrier for northeastern Qinghai, Gansu Province, and the Inner Mongolia Autonomous Region, maintaining regional water ecological security. The geographic coordinates are 99°02 34 –99°06 31 E, 38°30 31 –38°41 50 N. The terrain slopes from southeast to northwest, with elevations ranging from 3,286 to 4,049 m. The climate is semi-alpine, with an average annual temperature of -1.2°C, annual precipitation of 1364.9 mm, and annual evaporation of [MATH_0]. The Heihe River originates from the Bayi Glacier [Figure 1: see original paper]. The total area of the Heihe River source area is 63,935.62 hm^2, divided into four functional zones: ecological conservation zone, restoration and reconstruction zone, rational utilization zone, and management service zone.

2. Data and Methods

2.1 Data Sources

This study obtained GF-1 (GF1_{WFV}) satellite imagery with 16 m spatial resolution from the China Center for Resources Satellite Data and Application (https://data.cresda.cn/#/home), using monthly-scale remote sensing images as the data source. Based on the land resource characteristics and research

objectives of the study area, combined with field investigations, land use types were classified into shrub forest, grassland (high-coverage, medium-coverage, and low-coverage grassland), water bodies, construction land, and unused land. The classification accuracy was verified through Kappa coefficient testing and field validation, meeting research requirements.

2.2 Methods

2.2.1 Land Use Classification Random Forest is a machine learning method based on the bagging framework proposed by Breiman Leo, which can achieve high classification accuracy. An interpretation signature database was established according to land use classification standards, and human-computer interactive interpretation was performed to extract land use information from remote sensing images, which was then validated through field verification.

2.2.2 Landscape Ecological Indices Landscape pattern and its changes result from the combined effects of natural and human factors, representing a comprehensive reflection of the regional ecological environment system. To appropriately describe the landscape ecological effects of land use changes in the Heihe River source area, this study calculated various landscape pattern indices using Fragstats 4.2, including Patch Richness Density Index (PRD), Shannon Diversity Index (SHDI), Shannon Evenness Index (SHEI), landscape fragmentation index (Ci), landscape disturbance index (Ui), and landscape pattern vulnerability (LSV) .

2.2.3 Construction of the Ecological Health Assessment Index System Natural factors are the primary drivers affecting ecosystem quality in the Qilian Mountains region, and the Heihe River source area is relatively less affected by human activities. Therefore, this study constructed the ecological health assessment index system mainly from natural factors . **Vitality (V)** refers to the energy input and nutrient cycling capacity of the ecosystem, measured using the Normalized Difference Vegetation Index (NDVI) to obtain the vitality value of the Heihe River source area. **Organization (O)** describes ecosystem complexity, using three indicators: landscape ecological vulnerability, vegetation coverage, and mean patch area. Landscape ecological vulnerability represents the fragility of landscape pattern and ecological processes under natural or human disturbances—lower values indicate more stable ecosystems less prone to damage, while higher values indicate greater instability. Mean patch area reflects the average area of all patches, intuitively representing landscape heterogeneity. **Resilience (R)** refers to the ability of ecosystems to self-regulate and recover under external disturbances, measured using elevation and ecosystem elasticity to obtain the resilience value. **Ecosystem Service Value (ESV)** represents the monetary value of benefits humans obtain directly or indirectly from ecosystem services.

2.2.4 Standardization of Assessment Indicators Since evaluation indicators differ in magnitude and cannot be directly compared, normalization is required to standardize all indicators to the range [0,1]. For indicators with positive health significance: Y = (X - X_{min})/(X_{max} - X_{min}). For indicators with negative health significance: Y = (X_{max} - X)/(X_{max} - X_{min}). Where Y is the standardized value, X is the sample value, X_{max} is the sample maximum, and X_{min} is the sample minimum.

2.2.5 Determination of Indicator Weights Traditional expert scoring methods like the Analytic Hierarchy Process introduce significant subjectivity and uncertainty. Therefore, this study employed the entropy method to determine indicator weights, reducing the impact of subjective judgment.

2.2.6 Ecological Health Assessment Model Based on the four assessment factors—vitality, organization, resilience, and ecosystem service value—this study constructed the ecosystem health index (EHI) for the Heihe River source area: EHI = V + O + R + ESV, where V, O, R, and ESV represent vitality, organization, resilience, and ecosystem service value, respectively.

2.2.7 Classification of Landscape Ecological Health Levels The ecosystem health index (EHI) ranges from 0 to 1. Based on the actual conditions of the Heihe River source area and using ArcGIS, the ecosystem health assessment was divided into five levels : Very Healthy ($ $0.13), Healthy [0.10–0.13), Moderately Healthy [0.07–0.10), Unhealthy [0.04–0.07), and Deteriorated (<0.04).

3. Results

3.1 Land Use Spatial Distribution and Transfer Changes

From 2014 to 2021, grassland (high-, medium-, and low-coverage) was the primary land use type in the Heihe River source area, accounting for over half of the total area, with the three grassland types distributed in a mosaic pattern. In 2014, high-, medium-, and low-coverage grasslands covered 160.52 km^2, 205.57 km^2, and 65.84 km^2, respectively, representing 25.1%, 32.13%, and 10.4% of the total area. The second major type was unused land, covering 119.53 km^2 (18.7%), mainly distributed along river banks and in the northwest. Unused land area showed an increasing trend in the northwestern part of the study area from 2014 to 2021. Other land use types accounted for relatively small proportions.

Analysis of the land use transfer matrix from 2014 to 2021 [Figure 3: see original paper] revealed that in terms of transfer-out, medium-coverage grassland was the primary source, with 46.9% converting to unused land and 33.5% to low-coverage grassland. High-coverage grassland also showed significant conversion to medium-coverage grassland and unused land (18.43 km^2 and 13.49 km^2,

respectively). In terms of transfer-in, unused land was the main recipient, primarily converted from medium-coverage grassland (65.7%) and high-coverage grassland (21.6%). Medium-coverage grassland was the second major transfer-in type, mainly from high-coverage grassland and unused land (18.43 km^2 and 18.61 km^2, respectively).

3.2 Landscape Ecological Vulnerability

After standardization, landscape ecological vulnerability was classified into five levels: Low Vulnerability ($ 0.20), $LowerVulnerability$(0.20–0.40), $MediumVulnerability$(0.40–0.60), $HigherV$
The spatial distribution of landscape ecological vulnerability [Figure 4: see original paper] showed that the overall vulnerability index remained in the low vulnerability zone, indicating a relatively stable landscape ecological state.

From 2014 to 2021, low vulnerability areas dominated, accounting for 67.9% and 60.2% of the total area in 2014 and 2021, respectively. Low and lower vulnerability areas decreased by 7.69 km^2 and 7.25 km^2, respectively, while medium, higher, and high vulnerability areas increased to varying degrees [Figure 5: see original paper]. Among different functional zones, all four zones exhibited increasing vulnerability indices . In 2014, all zones were in the low or lower vulnerability categories. By 2021, the ecological conservation zone remained in the low vulnerability category, while the restoration and reconstruction zone, rational utilization zone, and management service zone all shifted from low to lower vulnerability. The ecological conservation zone consistently showed the lowest vulnerability index, while the management service zone showed the highest.

3.3 Landscape Ecosystem Health Assessment

3.3.1 Ecosystem Vitality From 2014 to 2021, ecosystem vitality in the Heihe River source area was primarily healthy and moderately healthy, with relatively stable vitality values. In 2014, healthy and moderately healthy areas were widely distributed, accounting for 53.93% and 38.47% of the total area, respectively. Very healthy areas were distributed along the southeastern edge of the ecological conservation zone. By 2021, the northwestern ecosystem vitality improved to primarily healthy levels, while areas east of the river and the eastern section decreased from healthy to moderately healthy levels [Figure 6: see original paper]. The overall vitality remained relatively stable across different functional zones [Figure 7: see original paper].

3.3.2 Ecosystem Organization From 2014 to 2021, overall ecosystem organization in the Heihe River source area was dominated by healthy, moderately healthy, and unhealthy levels, with a general shift toward moderately healthy and unhealthy levels [Figure 8: see original paper]. In 2014, unhealthy and deteriorated areas accounted for 23.1% of the total area, increasing to 34.8% by 2021. The ecological conservation zone showed an increase in healthy and above-level areas, primarily in the northwestern region, which improved from moderately healthy to healthy and moderately healthy levels. The middle reaches of the

Heihe River and its banks maintained healthy and above levels, while other areas shifted from healthy to moderately healthy or from moderately healthy to unhealthy. The restoration and reconstruction zone showed a clear decreasing trend in healthy and moderately healthy areas (decreasing by 4.81 km^2 and 13.19 km^2, respectively), with deteriorated areas increasing by 1.47% of the zone's total area. The management service zone and rational utilization zone were dominated by healthy and moderately healthy levels [Figure 9: see original paper].

3.3.3 Ecosystem Resilience From 2014 to 2021, overall ecosystem resilience in the Heihe River source area was dominated by healthy and moderately healthy levels. The average ecosystem health index values were 0.13 in 2014 and 0.12 in 2021, both indicating healthy overall conditions. Spatial distribution of different health levels showed similarity across years, with very healthy areas mainly in the northwestern and scattered central regions, healthy and moderately healthy areas widely distributed, unhealthy areas primarily in central and northern regions, and deteriorated areas relatively small [Figure 10: see original paper]. The ecological conservation zone showed very healthy and healthy areas north of the Heihe River and in the northwest, with other areas dominated by healthy and moderately healthy levels. The restoration and reconstruction zone exhibited a pattern dominated by moderately healthy and unhealthy levels [Figure 11: see original paper].

3.4 Overall Ecological Health Assessment

From 2014 to 2021, the overall ecological health level of the Heihe River source area was healthy, with healthy and moderately healthy areas widely distributed. In terms of land use, very healthy areas primarily existed in unused land, while unhealthy or deteriorated areas were mostly in construction land or low-coverage grassland. Water bodies were generally healthy or moderately healthy, and medium-coverage grassland showed some conversion from healthy to moderately healthy levels [Figure 12: see original paper]. Different functional zones showed varying spatial patterns of ecological health. The management service zone was dominated by healthy and moderately healthy levels, while the rational utilization zone shifted from healthy to moderately healthy dominance. The total area of healthy and above-level regions accounted for 53.93% and 38.47% of the Heihe River source area in 2014 and 2021, respectively, showing strong spatial heterogeneity [Figure 13: see original paper].

4. Discussion

The Heihe River source area National Wetland Park is located on the southern slope of the middle Qilian Mountains. Grassland is the dominant land use type, while construction land accounts for the smallest proportion. Water bodies and grassland show decreasing trends, while unused land and construction land show increasing trends, consistent with findings by Fu et al. [MATH_1]. Wet-

land ecosystems are sensitive to climate change, and alpine wetlands are among the most vulnerable ecosystems. Temperature is the dominant climatic factor affecting alpine wetland ecological conditions [MATH_2]. In recent decades, temperatures in the Qilian Mountains have shown an increasing trend [MATH_3], leading to increased landscape fragmentation and heterogeneity, reduced overall landscape connectivity, and decreased landscape stability [MATH_4]. This has caused small-scale fluctuations in ecological vulnerability across different periods in the Qilian Mountains, though low vulnerability areas remain dominant overall [MATH_5], consistent with our results.

Although precipitation in the Qilian Mountains region has increased in recent years, this cannot compensate for the adverse effects of rising temperatures on wetland ecosystems [MATH_6]. Once damaged, alpine wetlands are difficult to restore in the short term. Zhang [MATH_7] found that wetland ecological quality in the Qilian Mountains was generally moderate, but after the National Development and Reform Commission officially approved the "Qilian Mountains Ecological Protection and Comprehensive Management Plan (2013–2020)" and the Qilian Mountains Qinghai area was included in the first batch of national ecological protection and restoration pilots in 2017, the Heihe River source area implemented a series of ecological protection and construction projects [MATH_8]. These efforts have led to fluctuating but overall increasing vegetation trends [MATH_9], effectively curbing grassland degradation and significantly improving grassland productivity, demonstrating that ecological health in the Heihe River source area has improved since 2017, though still influenced by natural conditions.

Ecological health is positively correlated with ecological environmental quality—higher quality indicates better health [MATH_{10}]. Yang [MATH_{11}] found that ecological environmental quality in the Qilian Mountains region is generally at moderate health level or above, with relatively stable changes. Ecological health is negatively correlated with ecological risk and sensitivity—higher sensitivity indicates poorer health [MATH_{12}]. Ma [MATH_{13}] found that the upper Heihe River basin is dominated by low and relatively low risk areas, with overall stable ecological security. Xu et al. [MATH_{14}] found that the eastern Qilian Mountains have low overall ecological sensitivity but a trend toward moderate sensitivity. These findings are consistent with our study.

5. Conclusion

This study constructed a landscape ecological health assessment index system for the Heihe River source area National Wetland Park based on the VOR model, analyzing the landscape ecological health status from 2014 to 2021. The main conclusions are:

1. From 2014 to 2021, grassland was the dominant land use type in the Heihe River source area. Grassland and water body areas decreased, while unused land and construction land increased. Shrub forest accounted for

a small proportion with minimal change.

2. The landscape ecological vulnerability index showed an increasing trend from 0.17 to 0.21, but remained in the low vulnerability zone, indicating low landscape ecological vulnerability and low degree of damage. The overall landscape ecological health assessment index showed a slight decreasing trend from 0.13 to 0.12, but remained at a healthy level, indicating good overall ecological health status. Overall, ecological health in the Heihe River source area showed a pattern of "overall stability with slight local decline," with the landscape ecology in a relatively stable state.

3. Different health level areas showed similar spatial distribution patterns across years. Very healthy areas were mainly distributed in the northwestern and scattered central regions. Healthy and moderately healthy areas were widely distributed. Unhealthy areas were primarily in central and northern regions. Deteriorated areas were relatively small.

This study enriches research on ecological health in the Heihe River source area National Wetland Park and provides important implications for regional ecological environmental protection and restoration. Future protection of the Heihe River source area National Wetland Park should prioritize ecological functions while balancing animal husbandry production to ensure the alpine wetland ecosystem develops toward "ecological harmony."

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Note: Figure translations are in progress. See original paper for figures.