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An Improved Habitat Quality Assessment Model Considering Vegetation Growth Status: A Case Study of the Qinghai–Tibet Plateau

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ABSTRACT. Habitat quality is a key indicator of ecosystem services. However, current habitat quality assessment methods mainly depend on land-use types, which ignore the differences within the specific land-use type and have difficulty reflecting the actual situation of an ecosystem. Therefore, this study proposes an improved habitat quality assessment method that incorporates vegetation growth status by introducing the leaf area index (LAI). This method first uses the LAI to assess pixel-level habitat suitability and then incorporates threat indicators for refined habitat quality evaluation. Finally, the proposed method is used to assess habitat quality and its changes on the Qinghai–Tibet Plateau (QTP). The results show that the proposed method can effectively distinguish habitat suitability differences among pixels with the same land use type, enabling a more reasonable and precise evaluation of habitat quality. Habitat quality assessment on the QTP revealed that most regions improved between 2000 and 2020, except for urban areas, southeastern forests, and the Qiangtang region, where significant declines occurred. In particular, the Ruoergai Wetland, Qilian Mountains, Datong Beichuan River Source, and Yellow River Source exhibited greater improvements, with net habitat quality growth exceeding 30%. Furthermore, the proposed method has great potential for habitat quality assessment in other regions with various vegetation growth conditions, which will provide further support for environmental management.

Keywords: habitat quality, LAI, Qinghai–Tibet Plateau, vegetation growth status, ecological restoration

1. Introduction

Habitat quality is defined as the ability of an ecosystem to provide suitable conditions for the sustained survival and development of individuals and populations. It is a continuous variable ranging from low to high, primarily determined by resource availability for survival, reproduction, and population persistence (Hall et al., 1997; Su et al., 2021). Most existing studies assess habitat quality through models integrating land-use data with biodiversity threat factors (Sallustio et al., 2017; Cao et al., 2024; Huang et al., 2024). Among these, assigning habitat suitability values based on land use type is a key input for habitat quality assessment. However, although land use types can reflect common regional characteristics to a certain extent, differences and changes in specific geographical locations still exist, affecting the adaptation and survival of organisms. For example, the habitat suitability of grasslands or forests with different vegetation covers often varies significantly. Moreover, the habitat suitability values for different land use types rely on expert scoring and statistical data, making habitat suitability highly susceptible to subjective human influence. Therefore, assigning habitat suitability solely based on land use data makes it difficult to accurately and reasonably quantify the habitat quality of an ecosystem.

As a core component of terrestrial ecosystems, vegetation plays a crucial role in maintaining ecological balance, regulating the climate, conserving biodiversity, and ensuring the sustainable development of habitats. Vegetation can respond sensitively to climate change and human disturbances (Xia et al., 2021). Additionally, changes in vegetation directly impact a region's climate, hydrology, and soil conditions through ecological processes such as photosynthesis, plant decomposition, and transpiration (Ukkola et al., 2016; Yang et al., 2018). High-quality vegetation growth can significantly enhance regional biodiversity, ecosystem services, carrying capacity, and resilience, thereby providing habitats with a greater capacity to adapt to climatic or external disturbances (Xia et al., 2021). Accordingly, the vegetation growth status can effectively reflect the ecological environment and has potential for sustainable development, which can serve as a key indicator for assessing habitat quality. Therefore, incorporating vegetation growth is a potential way to im-

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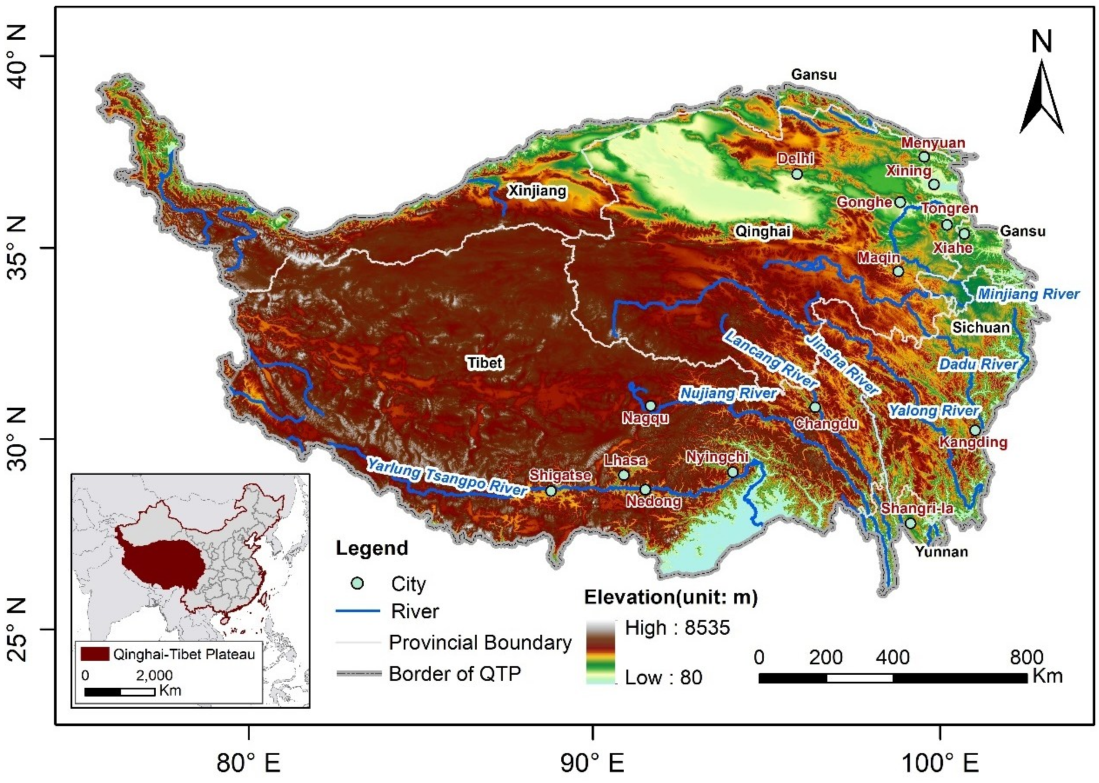

Figure 1. The geographical location of the Qinghai–Tibet Plateau.

prove habitat quality assessment rather than depending only on the land use type.

The Qinghai–Tibet Plateau (QTP), often renowned as the "Third Pole of the Earth" and the "Water Tower of Asia", serves crucial functions in water conservation, soil preservation, wind erosion control, carbon sequestration, and biodiversity protection (Liu et al., 2018). The habitat quality and ecological functional status of the QTP have a direct and significant impact on the ecological security of China (Fu et al., 2021). Given the fragile ecosystem of the QTP, which is characterized by high sensitivity and rapid fluctuations, the region is particularly vulnerable to disturbances from global climate change and human activities (Liu and Chen, 2000; Sun et al., 2020). The region's climatic characteristics and habitat quality are prone to obvious alterations, such as soil erosion (Li et al., 2019), grassland degradation (Xiong et al., 2016), and biodiversity loss (Li et al., 2023), which pose significant threats to ecological security and human well-being. In response to increasingly pressing ecological issues, national and local governments have implemented a series of ecological protection measures to safeguard the plateau's ecological security, such as establishing national parks (Foggin, 2018) and nature reserve systems (Li et al., 2018). However, whether these measures have improved the habitat quality of the QTP remains uncertain. Therefore, clarifying the crucial role of ecological protection measures in improving habitat quality is highly important for further promoting ecological protection and high-quality development on QTP.

Leaf area index (LAI) is a crucial vegetation parameter that characterizes the structural properties and growth status of vegetation, which serves as a vital indicator for net primary production, carbon storage, ecosystem health evaluation, and agricultural monitoring (Sadeh et al., 2021; Marandi et al., 2022; Jiang et al., 2023a; Jiang et al., 2023b). Therefore, this study selected the LAI to reflect vegetation growth status and aimed to develop an improved habitat quality assessment model. To demonstrate its application, the Qinghai–Tibet Plateau was selected as a case study to analyze habitat quality changes and to clarify the ecological restoration benefits of establishing national parks and nature reserves. This study is expected to provide a more accurate and universally applicable habitat quality assessment model and is anticipated to offer valuable reference data for promoting sustainable development, ecosystem management, and informed decision-making on the QTP.

2. Study Area

2.1. Qinghai–Tibet Plateau

Located at the southwest border of China, the Qinghai–Tibet Plateau (29°00′ ~ 39°47′N, 73°19′ ~ 104°47′E) covers a total area of 2.6 million km^2, with an average elevation of more than 4,000 meters above sea level. The QTP encompasses the entire Tibet Autonomous Region and Qinghai Province, as well as parts of the Xinjiang Uygur Autonomous Region and the Sichuan, Gansu, and Yunnan provinces of China (Figure 1). There are large differences in elevation, topography, climate and vegetation among the different regions, and the fragile ecosystem

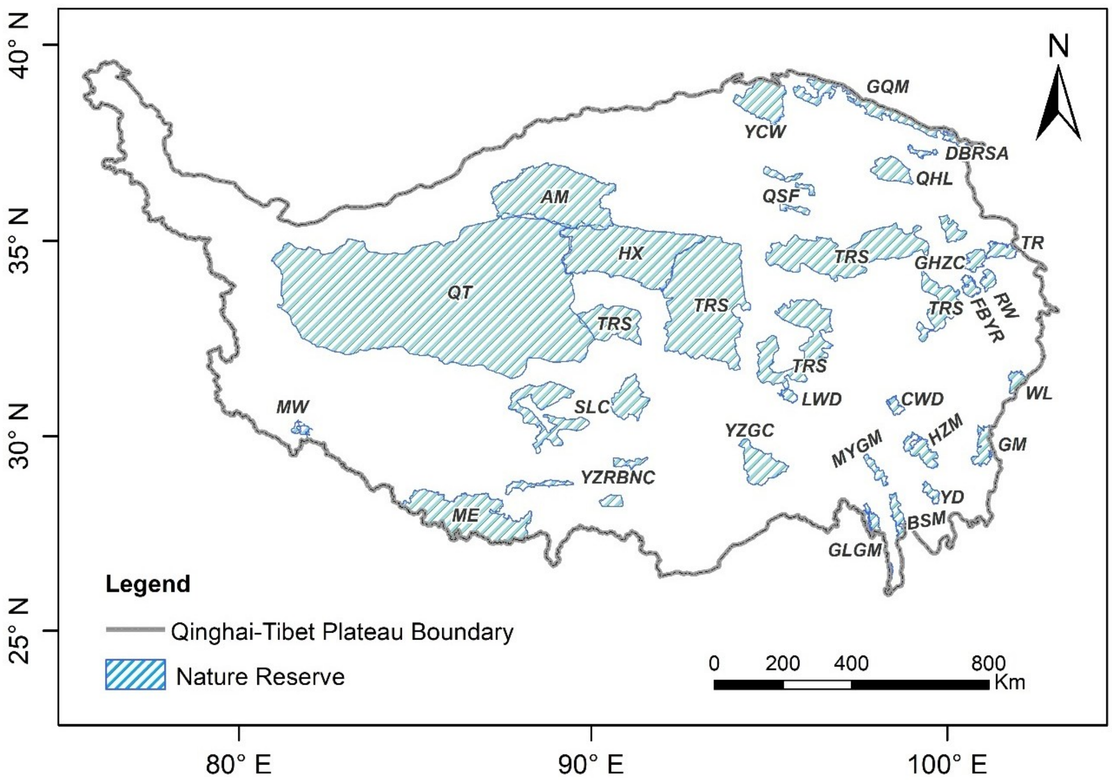

Figure 2. Distribution of National Reserves on the Qinghai–Tibet Plateau. AM, Altun Mountains; BSM, Baima Snow Mountain; QSF, Qaidam Saxaul Forest; CWD, Chaqungsongduo White-Lipped Deer; DBRSA, Datong Beichuan River Source Area; GHZC, Gahai-Zecha; QM, Gansu Qilian Mountains; GLGM, Gaoligong Mountain; GM, Gongga Mountain; HZM, Haizi Mountain; FBYR, First Bend of the Yellow River; HX, Hoh Xil; LWD, Leiwuqi Deer; MW, Mapangyongcuo Wetland; MYGM, Mangkang Yunnan Golden Monkey; QT, Qiangtang; QHL, Qinghai Lake; RW, Ruoergai Wetland; TRS, Three-River-Source; SLC, Selincuo; TR, Tao River; WL, Wolong; YD, Yading; YZGC, Yarlung Zangbo Grand Canyon; YZRBNC, Yarlung Zangbo River Black-necked Crane; YCW, Yanchiwan; and ME, Mount Everest.

on the QTP is vulnerable to interference from global climate change and human activities, making the QTP an "indicator" and "regulator" of climate change in China and even Asia (Sun et al., 2012). In general, the QTP has a unique natural environment, complex ecosystems, abundant water resources, rich biodiversity and diverse vegetation types, and the quality of its regional habitats is highly important for maintaining national ecological security and sustainable development.

2.2. Nature Reserves

Nature reserves are legally protected areas established to conserve representative natural ecosystems, endangered species, and ecologically significant features (Howard et al., 2000; Radeloff et al., 2010; Zhu et al., 2018). The establishment of nature reserves is a crucial strategy for the protection of natural habitats and biodiversity (Stein et al., 2008). In 1963, the QTP established China's first national nature reserve, initiating a phase of steady progress in the development of nature reserves across the region. As of 2021, 52 national-level nature reserves have been established in the QTP, covering a total area of 903,000 km^2, which constitutes 35.5% of the total area of the plateau (Fu et al., 2021). Among these reserves, 27 nature reserves exceed 1,000 km^2 in size, with a total area of 698,600 km^2, representing 26.66% of the plateau's total area. This study focused on analyzing the habitat quality within these 27 nature reserves (Figure 2).

2.3. National Parks

The national park concept, first proposed by George Catlin in the United States in 1832, advocates the governmental establishment of large protected areas to maintain pristine landscapes through specific conservation policies (Fancy et al., 2009). Given the unique natural and cultural landscapes of QTP, a "Third Pole National Park Cluster" framework has been established, led by flagship national parks and supported by transboundary and general parks (Jie et al., 2017). The QTP hosts a total of 20 national parks, covering an area of 353,800 km^2, which represents 13.5% of the plateau's total area (Figure 3). Of these, six flagship national parks encompass 186,800 km^2, making up 7.13% of the region's area. Additionally, there are 12 general national parks, spanning 121,700 km^2 and constituting 4.64% of the plateau. Pamir Mount Everest Transnational National Park, characterized by desert ecosystems and extensive mountain glaciers, spans 45,300 km^2 within the plateau, accounting for 1.73% of its total area. Notably, the Three-River Source National Park, which in-

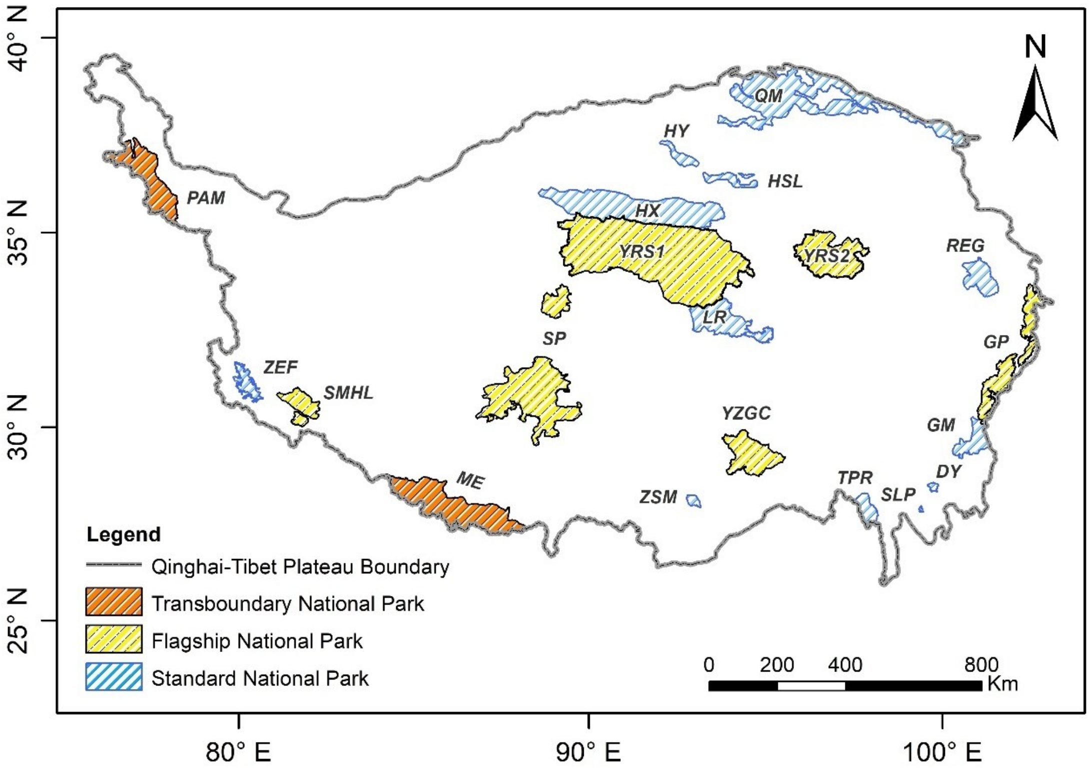

Figure 3. Distribution of national parks on the Qinghai–Tibet Plateau. Transboundary National Park (TNP): ME, Mount Everest; PAM, Pamir; Flagship National Park (FNP): GP, Giant Panda; YRS1, Yangtze River Source; YRS2, Yellow River Source; SP, Selincuo-Purogongri; SMHL, Sacred Mountains and Holy Lakes; YZGC, Yarlung Zangbo Grand Canyon. Standard National Park (SNP): DY, Daocheng Yading; GM, Gongga Mountain; ZSM, Zhari Sacred Mountain; HX, Hoh Xil; LR, Lancang River; QM, Qilian Mountains; REG, Ruoergai; TPR, Three Parallel Rivers; HY, Hydrous Yardang; SLP, Shangri-La Pudacuo; ZEF, Zhada Earth Forest; HSL, Haixi Salt Lake.

cludes Yangtze River Source National Park, Yellow River Source National Park, and Lancang River Source General National Park, is the largest national park on the QTP and the largest in China.

3. Materials and Methods

3.1. Data Collection

The data used in this study include the leaf area index (LAI) data, land use and land cover (LULC) data, road network data, and vector data for national parks and nature reserves. This study used GLASS LAI data acquired at the University of Maryland GLASS product service centre (http://www.glass.umd.edu/Download.html). The product has a temporal resolution of 8 days and a spatial resolution of 500 m. The LAI estimation was conducted using a generalized regression neural network based on time-series remote sensing data. Comparative validation based on the global distributed field survey data demonstrated the better accuracy of GLASS LAI product than the CYCLOPES and MODIS LAI products (Xiao et al., 2014). The LULC data utilized the MODIS land use product (MCD12Q1) with a spatial resolution of 500 m, which was sourced from the USGS website (https://earthexplorer.usgs.gov/). The product covers a total of 13 sets of classification standards, among which the International Geosphere Biosphere Program (IGBP) classification standard is widely used and has high classification accuracy, with an overall accuracy of 73.6% (Sulla-Menashe et al., 2019). Road data from Open StreetMaps (OSMs) (https://www.openstreetmap.org/) provide information about the primary roads and secondary roads. The boundary data of the nature reserves were obtained from the Resource and Environment Science Data Platform (https://www.resdc.cn), and the QTP national park boundary data were provided by the Department of Natural Resources of the Tibet Autonomous Region.

3.2. The Proposed Method for Habitat Quality Assessment

In this study, the LAI was introduced to characterize vegetation growth status to improve the habitat quality assessment method, and the habitat quality was assessed in combination with biodiversity threat information. The calculation formula is as follows:

$$HQ_{xf} = H_{xf}\left(1-\left(\frac{D^{z}_{xf}}{D^{z}_{xf}+K^{z}}\right)\right) \qquad (1)$$

where HQ_{xf} represents the habitat quality of pixel x in land use type f. The habitat quality index ranges from 0 to 1, with values closer to 1 indicating better habitat quality. D_{xf} refers to the total

Table 1. Sensitivity of Habitats to Threats Used in this Study

Land Use Type	Threat Factor		
	Cropland	Road	Urban
Evergreen Needleleaf Forest	0.7	0.6	0.8
Evergreen Broadleaf Forest	0.8	0.7	0.9
Deciduous Needleleaf Forest	0.7	0.6	0.8
Deciduous Broadleaf Forest	0.8	0.7	0.9
Mixed Forests	0.7	0.6	0.9
Closed Shrublands	0.6	0.5	0.7
Open Shrublands	0.5	0.4	0.6
Woody Savannas	0.4	0.5	0.7
Savannas	0.3	0.4	0.6
Grass	0.3	0.5	0.6
Cropland Natural Vegetation	0.3	0.4	0.6
Croplands	0.3	0.6	0.6
Urban	0.0	0.0	0.0
Permanent Snow	0.0	0.0	0.0
Barren	0.0	0.0	0.0
Water	0.7	0.6	0.8
Permanent Wetlands	0.8	0.7	0.9

threat stress of pixel x caused by surrounding threats. K and z are the normalized constant and half-saturation constant, which are set to 1/2 of the maximum value of D_{xf} and 2.5 by default, respectively. H_{xf} represents the habitat suitability of pixel x in land-use type f.

In the InVEST model, habitat suitability is typically assigned based on different land use types, such as $H_{forest} = 0.9$ and $H_{grassland} = 0.7$. This method has difficulty distinguishing the differences in habitat suitability among different pixels of the same land use type. Therefore, this study introduced the LAI to represent the vegetation growth status and calculated the habitat suitability for each pixel. The calculation formula is as follows:

$$H_{xf} = \begin{cases} H_{i,x,f} = \dfrac{LAI_{i,x,f}}{LAI_{\max i,f}} & vetetated\ area \\ H_{xf} = 0 & non\text{-}vetetated\ area \\ H_{xf} = 0.8 & water/wetland \end{cases} \tag{2}$$

where $H_{i,x,f}$ represents the habitat suitability value of pixel x under land use type f in year i. $LAI_{i,x,f}$ is the LAI value of pixel x for land use type f in year i, and $LAI_{\max i,f}$ is the maximum LAI value for land use type f in year i. In practice, to reduce sensitivity to extreme values and enhance the robustness of the habitat suitability assessment, this study used the 95th percentile of LAI values as the effective $LAI_{\max i,f}$ rather than the absolute maximum.

The total threat stress D_{xf} for pixel x in land use type f is represented by the following formula (Sharp et al., 2018):

$$D_{xf} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{W_r}{\sum_{r=1}^{R} W_r}\right)\cdot r_y i_{rxy} S_{fr} \tag{3}$$

where r and R represent the threat factor and the number of threat factors, respectively. y refers to the pixel in threat source r. r_y is the threat factor of the pixel y. W_r is the weight of the threat factor. S_{fr} represents the sensitivity of land-use type f to threat factor r. i_{rxy} represents the impact of threat factor r in pixel x on habitat in pixel y, with the following formula:

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}}\right),\ if\ linear \tag{4}$$

$$i_{rxy} = \exp\left(-\left(\frac{2.99}{d_{rmax}}\right)d_{xy}\right),\ if\ exponential \tag{5}$$

where d_{xy} refers to the distance between pixels x and y and where d_{rmax} represents the maximum influence distance of threat factor. The linear function indicates that the threat decays linearly with distance in space, whereas the exponential function indicates that the threat decays exponentially with distance in space.

This study selected cropland, construction land, and roads as threat sources. The weights and sensitivity indices of these threat factors are shown in Tables 1 and 2, respectively (Liu et al., 2021; Song et al., 2021).

Table 2. Threat Factor Parameters Used in this Study

Threat Factor	Maximum Impact Distance/km	Weight	Decay Type
Cropland	6	0.7	Linear
Urban	10	1.0	Exponential
Road	3	0.8	Linear

3.3. Analysis of Dynamic Changes in Habitat Quality

This study employed the Theil–Sen estimation method and the Mann–Kendall trend test to analyze habitat quality changes. The Theil–Sen analysis is a robust nonparametric statistical method for trend calculation that is capable of fitting linear relationships robustly and reducing the impact of outliers (Theil, 1950; Sen, 1968; Yang et al., 2019). The Mann–Kendall test is a nonparamet-

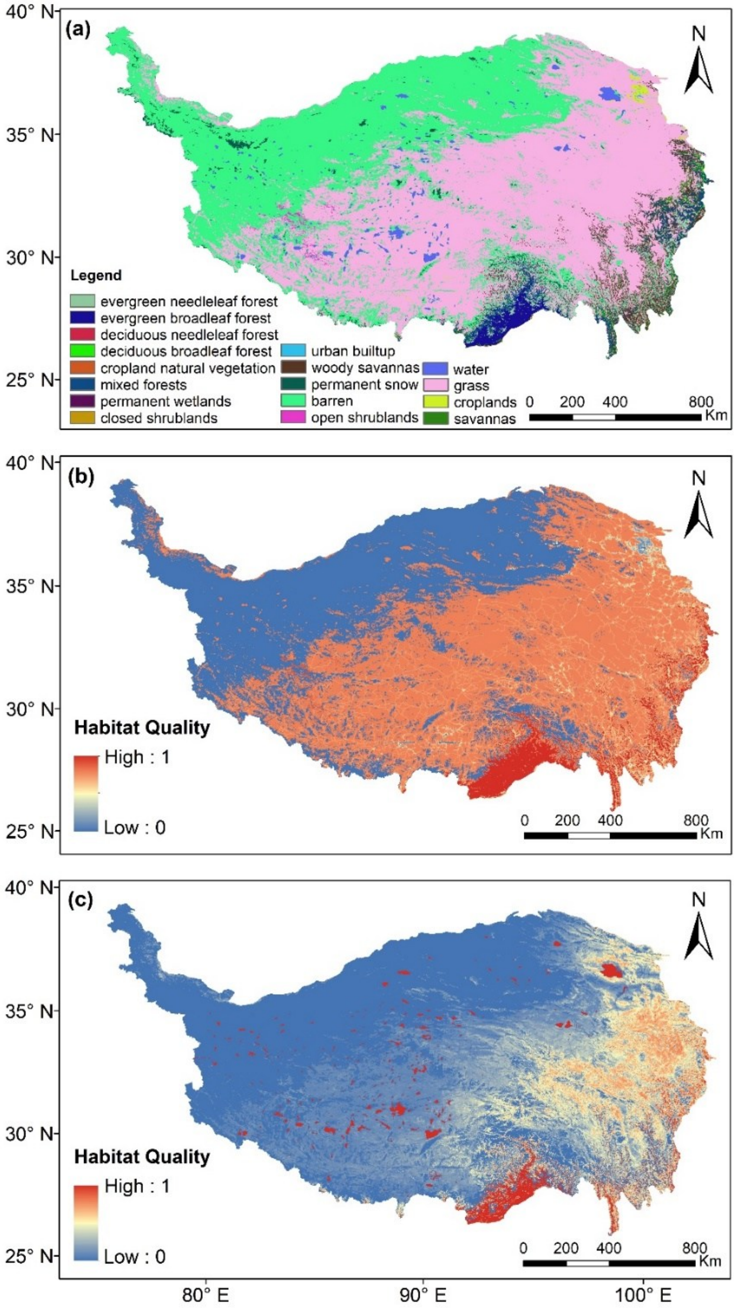

Figure 4. Habitat Quality Assessment with different methods on the Qinghai–Tibet Plateau (Year 2010). (a) LULC map of the Tibetan Plateau. (b) Habitat quality assessment using the InVEST model. (c) Modified habitat quality suitability assessment using the LAI.

ric statistical test used to determine the significance of a trend (Mann, 1945) and is commonly used to test the significance of trends in ecological indicators over time (Zhao et al., 2023; Li et al., 2024). Habitat quality trends were classified through integrated analysis of Theil-Sen median slope (β) and Mann-Kendall Z statistics at 95% confidence level ($\alpha = 0.05$). Significant degradation was defined as a negative slope with $Z < -1.96$, while restoration required a positive slope with $Z > 1.96$. Non-significant trends ($-1.96 \leq Z \leq 1.96$) were categorized as stable.

4. Results

4.1. Habitat Quality Assessment of the Qinghai–Tibet Plateau

To clearly illustrate the advantages of the habitat quality assessment method, which considers vegetation growth conditions compared with the traditional method, this study selected a specific year as a typical example for method comparison (Figure 4). The standard InVEST model's habitat quality assessment (Fig-

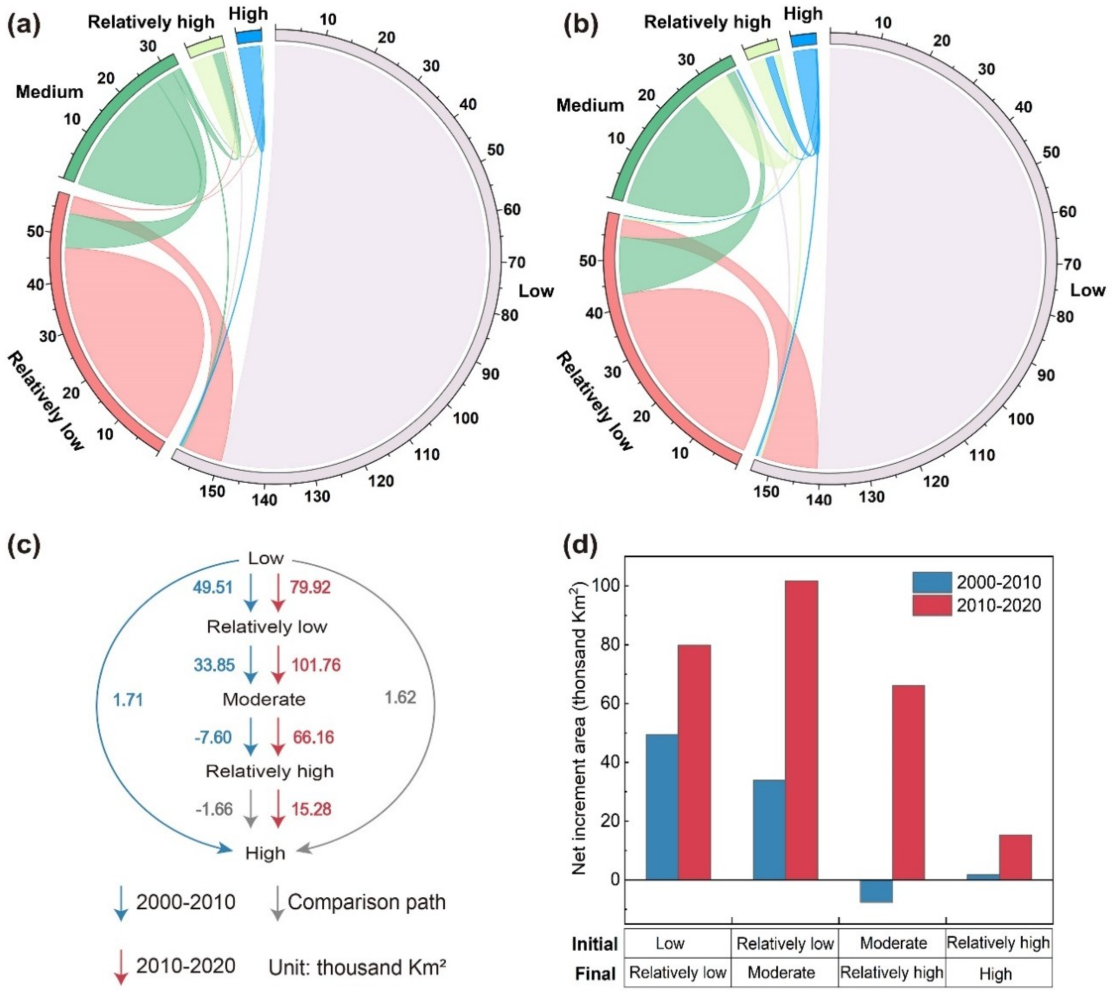

Figure 5. Transitions of different habitat quality levels on the Qinghai–Tibet Plateau (2000 ~ 2020). (a) Chord diagram of habitat quality changes (2000 ~ 2010); (b) Chord diagram of habitat quality changes (2010 ~ 2020); (c) Optimal increment pathways of habitat quality transitions d. Comparison of optimal increment pathways of habitat quality between 2000 ~ 2010 and 2010 ~ 2020.

ure 4b) is strongly influenced by land use categories without accounting for variations within each category. For example, the InVEST model assigned a uniform habitat suitability value to grasslands, resulting in relatively high habitat quality scores across the QTP's extensive grassland areas. However, this approach did not distinguish between low-vegetation grasslands with fewer resources and high-vegetation grasslands with rich resources, which have distinct differences in their ecological characteristics. This limitation underscores the model's reliance on land use types, which can obscure important habitat suitability variations within the same land category, potentially reducing the accuracy of habitat quality assessments.

The modified model (Figure 4c), which incorporates the LAI to represent vegetation growth and habitat suitability on a pixel-by-pixel basis, provides a more refined habitat quality assessment. This approach highlights variations within land use types, particularly in grasslands, by assigning accurate habitat quality values to areas with vegetation. As a result, the modified model addresses the InVEST model's limitations by accounting for resource abundance differences within the same land use type, offering a more nuanced view of habitat suitability. This pixel-level differentiation is crucial for informing conservation and management efforts, as it allows for targeted protection of ecologically significant areas, especially in heterogeneous landscapes such as the Tibetan Plateau, where vegetation cover and resource availability varies widely. Finally, this study generated annual habitat quality datasets for the QTP from 2000 to 2020 based on the improved habitat quality estimation model.

4.2. Characteristics of Habitat Quality Levels on the Qinghai–Tibet Plateau

The natural breaks method was employed to classify habitat quality into five levels: low, relatively low, moderate, relatively high, and high. The overall habitat quality of the QTP exhibited a distribution pattern with higher habitat quality in the southeast and lower habitat quality in the northwest, which progressively decreased from southeast to northwest. The northwest region is dominated by barren land, resulting in low habitat quality. Conversely, the southeastern region, which is located in the

Table 3. Habitat Quality Levels on the Qinghai–Tibet Plateau in 2000, 2010, and 2020

Habitat quality level	Year 2000		Year 2010		Year 2020		Year 2000 ~ 2020
	Area (k·km^2)	Proportion (%)	Area (k·km^2)	Proportion (%)	Area (k·km^2)	Proportion (%)	Rangeability
Low	1589.09	60.65%	1536.89	58.65%	1457.66	55.63%	−8.27%
Relatively low	579.34	22.11%	595.2	22.72%	567.94	21.68%	−1.97%
Moderate	328.81	12.55%	371.59	14.18%	403.17	15.39%	22.61%
Relatively high	72.95	2.78%	66.71	2.55%	123.09	4.70%	68.73%
High	50.04	1.91%	49.84	1.90%	68.37	2.61%	36.63%

Note: "k·km^2" represents thousand square kilometres.

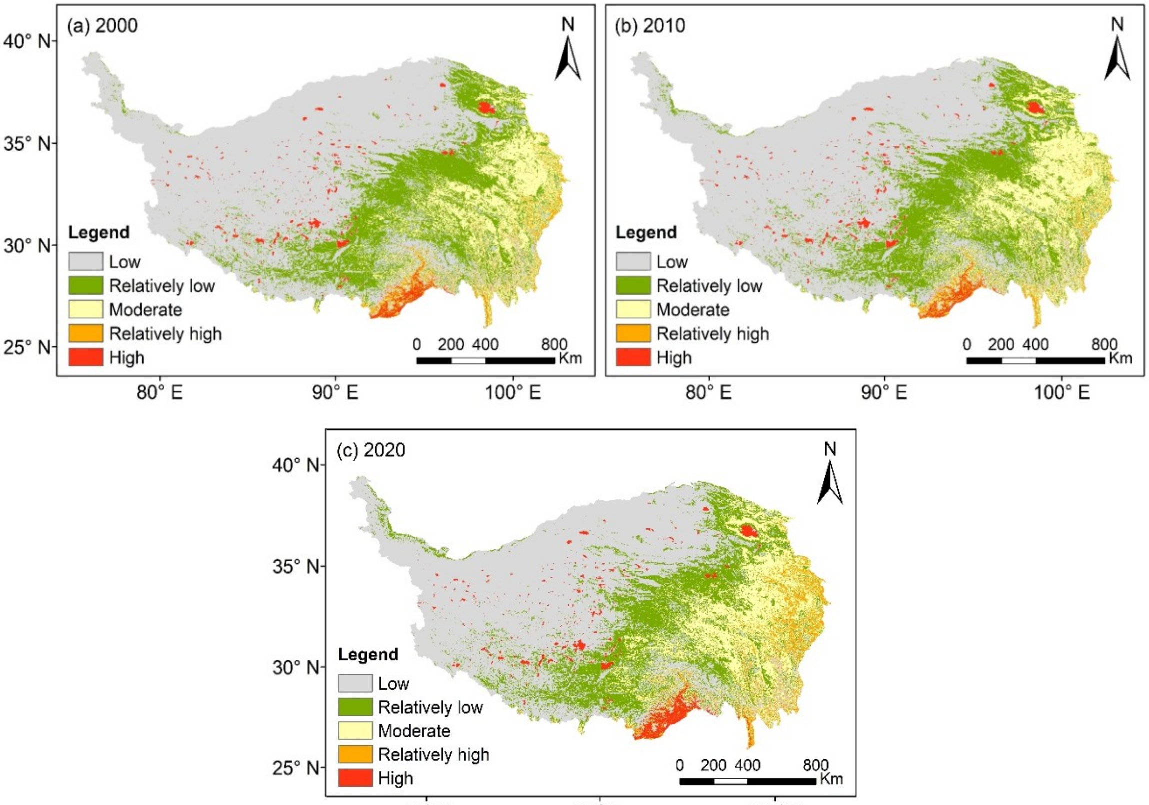

Figure 6. Spatial distribution of habitat quality at different levels on the Qinghai–Tibet Plateau.

middle-to-lower reaches of numerous rivers, presents greater vegetation cover and species richness, leading to a significant improvement in habitat quality when compared to the northwest region. The low-quality ecoregions encompass the largest area (nearly 1.5 million km^2), accounting for more than 50% of the natural habitats on the QTP. From 2000 to 2020, the overall change in habitat quality on the QTP was characterized primarily by a decrease in areas with low and relatively low habitat quality and an increase in areas with moderate, relatively high, and high habitat quality. The largest decrease was observed in the area with low habitat quality, while the area with moderate habitat quality experienced the most significant increase. The changes in habitat quality from 2000 to 2020, ranging from lowest to highest, were −8.27, 1.97, 22.61, 68.73, and 36.63%, respectively. The trend in relatively high habitat quality change was the most pronounced, whereas the change in relatively low habitat quality was the least significant (Table 3).

From the chord diagram of habitat quality transitions across different levels, it can be observed that (Figure 5), the optimal increase paths for other habitat quality levels primarily resulted from transitions from the preceding level. This trend can be seen across all time points of the diagram except for the period from 2000 to 2010, where the most significant increase in high habitat quality came from low habitat quality. The area of low habitat quality decreased substantially, primarily transitioning to relatively low habitat quality. The relatively low habitat quality remained stable because of a balance between inflows from low habitat quality and outflows to moderate habitat quality. Notably, the transition to moderate habitat quality experienced a considerable net increase, particularly from 2010 to 2020, where the improvement was approximately three times greater than that in the previous decade. The transition paths indicate a clear trend of increasing habitat quality, with substantial gains in moderate, relatively high, and high habitat quality over the two decades.

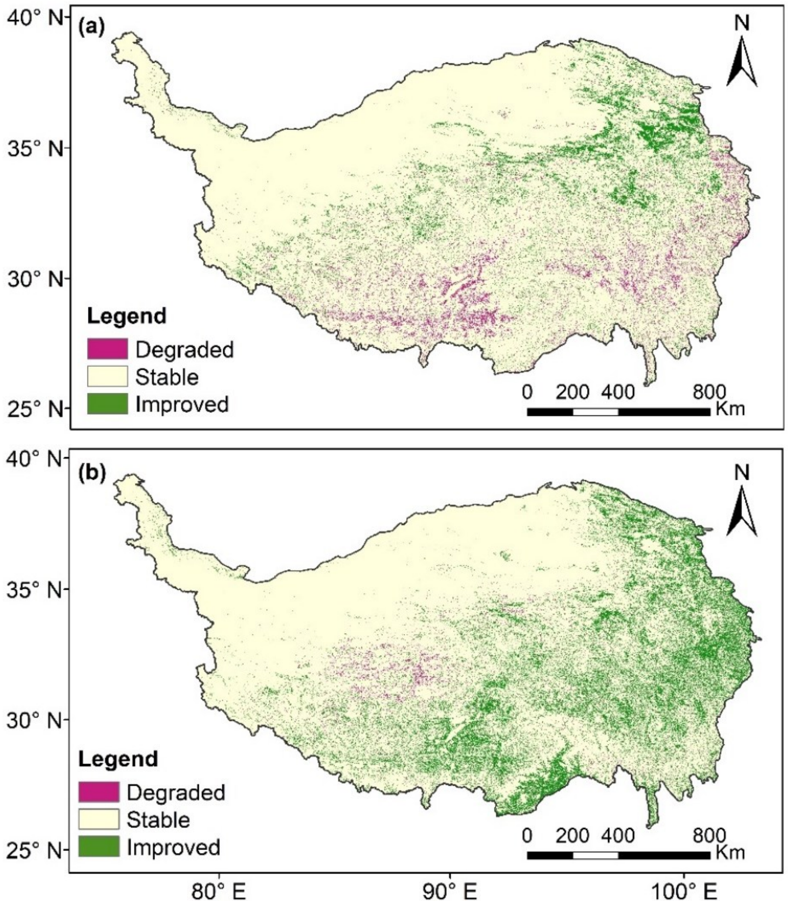

Figure 7. Habitat quality changes from 2000 to 2010 (a) and 2010 to 2020 (b).

This trend reflects the overall enhancement of the ecological environment and biodiversity on the plateau.

Based on the spatial distribution of habitat quality (Figure 6), it is evident that from 2000 to 2010, the relatively low-habitat-quality areas in the central QTP expanded westwards into low-habitat-quality regions and transitioned eastwards into moderate-habitat-quality regions. These areas are primarily distributed in the Qilian Mountains region, the southern part of Qinghai Lake, and the Three-River Source region. From 2010 to 2020, the moderate habitat quality areas mainly transitioned to relatively high habitat quality areas in the east, particularly in the Zoige region and the Hengduan Mountains in the eastern part of the plateau. The westwards expansion continued, replacing relatively low-habitat-quality areas, especially in the Three Rivers Source Region and the middle reaches of the Yarlung Tsangpo River, where habitat quality improved. Additionally, the habitat quality in and around the cities of Lhasa and Nagqu showed a positive trend.

4.3. Spatiotemporal Changes in Habitat Quality on the Qinghai–Tibet Plateau

The changes in habitat quality, coefficients of variation, and distributions of significantly changed areas on the QTP are illustrated in Figure 7. Overall, the habitat quality on the QTP has improved significantly, with the effectiveness of habitat quality improvements from 2010 to 2020 surpassing that from 2000 to 2010. Regarding the distribution of significant changes in habitat quality changes, the areas showing an increase, stability, and decreases in habitat quality from 2000 to 2010 were 7.13, 88.11, and 4.76%, respectively. From 2010 to 2020, these areas were 16.13, 82.45, and 1.42%, respectively. Most areas on the QTP presented stable habitat quality; however, in regions where significant vegetation changes occurred, the areas with improved habitat quality far exceeded those with decreased habitat quality. From 2010 to 2020, the area of increased habitat quality was approximately 11 times greater than the area of decreased habitat quality.

Based on the spatial distribution of changes in habitat quality and the coefficient of variation on the QTP, a trend towards overall improvement alongside localized degradation was observed. From 2000 to 2010, significant improvements in habitat quality were primarily concentrated in the Three-River Source Region of Qinghai Province, particularly in the Yellow River source area, where the improvements were most pronounced. Areas of declining habitat quality were located mainly in the central and southeastern parts of the plateau. Notably, the midstream valleys of the Yarlung Tsangpo River, surrounded by cities such as Lhasa, Shannan, and Shigatse, experienced significant declines, likely due to geological disasters and urban expansion. Additionally, the southeastern riverine forest regions of the Nu-

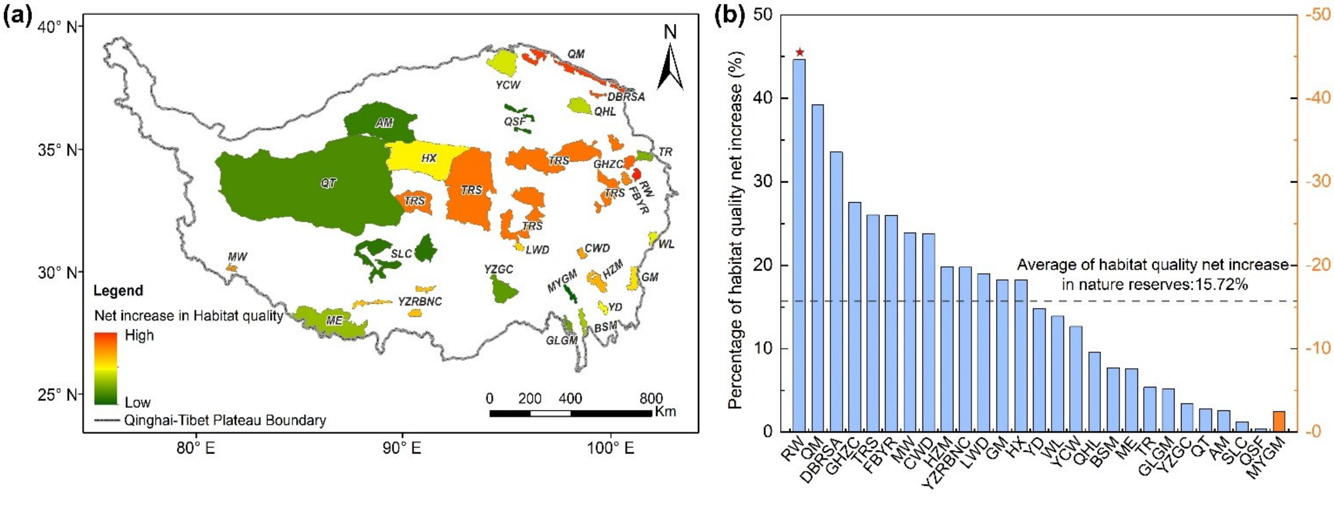

Figure 8. Spatial distribution (a) and percentage of habitat quality net increase (b) in the Nature Reserves on the Qinghai–Tibet Plateau (2000 ~ 2020).

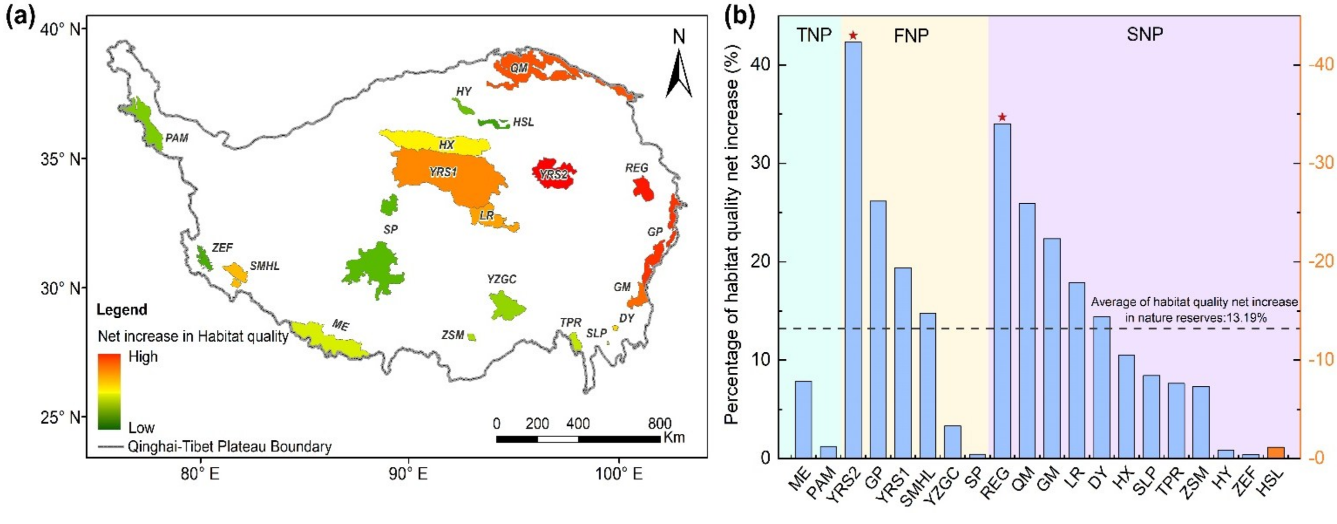

Figure 9. Spatial distribution (a) and percentage of habitat quality net increase (b) in the National Parks on the Qinghai–Tibet Plateau (2000 ~ 2020).

jiang, Lancang, Jinsha, Yalong, and Minjiang Rivers also exhibited significant declines. From 2010 to 2020, significant improvements in habitat quality were observed not only in the Three-River Source Region but also in areas that had experienced significant declines during the previous decade, with these showing marked recovery. Only parts of southern Qiangtang displayed a significant decline.

4.4. Habitat Quality Characteristics of Nature Reserves and National Parks on the QTP

The analysis of the net increase in habitat quality across nature reserves on the QTP revealed significant variability in ecological recovery (Figure 8). The Ruoergai Wetland leads with a 44.64% improvement, followed by the Gansu Qilian Mountains (39.26%) and the Datong Beichuan River (33.55%). These regions have benefited from effective conservation strategies, particularly in sensitive wetland and water source areas. Nature reserves such as Gahai-Zecha, First Bend of the Yellow River, and Three-River Source had moderate habitat quality increases of 23 to 28%, respectively. Concentrating in upstream river areas on the QTP, these regions benefit from abundant water resources, which support better ecological conditions. Several nature reserves, such as Yarlung Tsangpo Middle Valley, Haizi Mountain, and Gongga Mountain, which are largely located in downstream river areas on the QTP, had modest increases in habitat quality, ranging from 18 to nearly 20%. In contrast, reserves such as those in Qiangtang (2.80%), the Altun Mountains (2.58%), and the Qaidam Saxaul Forest (0.38%) had minimal increases, likely due to harsher environmental conditions and limited conservation resources. The Mangkang Yunnan Golden Monkey (−2.44%)

experienced a negative net change.

The national parks on the QTP are classified into three categories based on different conservation strategies and regional distributions (Figure 9). Based on the categorization, the Flagship National Park (FNP) category reserves, such as Yellow River Source National Park (42.32%), Giant Panda (26.15%), Yangtze River Source National Park (19.38%), and Sacred Mountains and Holy Lakes (14.75%) had greater gains in habitat quality. However, Yarlung Zangbo Grand Canyon (3.30%) and Selincuo-Purogongri (0.43%) had relatively lower habitat quality improvements. Reserves within the Standard National Park (SNP) category, such as Ruoergai National Park (34.04%), Qilian Mountains National Park (25.91%), Gongga Mountain National Park (22.34%), Lancang River National Park (17.87%), and Daocheng Yading National Park (14.39%) had significant improvements. However, other SNP reserves had habitat quality improvements below the average level. Zhada Earth Forest National Park (0.39%) and Hydrous Yardang National Park (0.82%) had very limited gains, and Haixi Salt Lake National Park even reports a negative net change (−1.15%). The Transnational National Park (TNP) reserves, including Mount Everest (7.86%) and Pamir (1.24%), had relatively lower net increases in habitat quality compared to other categories.

5. Discussion

5.1. Advantages and Limitations of the Improved Habitat Quality Assessment Method

The current habitat quality assessment methods rely on broad land-use classifications and have difficulty accounting for variations within the same land-use type. By introducing the LAI as an indicator of vegetation growth, the modified model enables pixel-level estimation of habitat suitability, providing a more nuanced and accurate evaluation of habitat quality, particularly for heterogeneous ecosystems on the QTP, such as grasslands. This modification effectively addresses the failure of current habitat quality assessment methods to reasonably distinguish between differences in habitat suitability of different likenesses under the same land use type. Compared with previous studies, the evaluation results significantly enhanced the refinement of habitat quality distribution areas (Mao et al., 2023; Yu et al., 2024).

Moreover, the proposed method demonstrates strong adaptability and scalability for assessing habitat quality across different ecosystems, especially in regions characterized by diverse vegetation growth conditions. By integrating the LAI as a key variable, this approach offers a flexible framework that can be tailored to various ecological contexts, including forests, wetlands, and agricultural landscapes. This adaptability makes it a valuable tool for supporting environmental management efforts and conservation planning in areas beyond the QTP, ensuring its broader applicability in habitat quality studies worldwide.

Additionally, the observed trend of improved habitat quality in protected areas surrounding watersheds highlights the potential significance of hydrological conditions as a key factor influencing habitat quality. While hydrological conditions are implicitly reflected in vegetation growth (Rodriguez-Iturbe, 2000; Bouaziz et al., 2022), future studies could explore the integration of additional indicators, such as soil quality or specific hydrological metrics, to refine habitat suitability assessments. Such advancements would increase the accuracy and applicability of habitat quality evaluations, contributing to more precise conservation planning and management.

5.2. Impact of Ecological Restoration and Protection Policies

The significant improvements in habitat quality across the QTP from 2000 to 2020 demonstrate the effectiveness of ecological restoration and protection policies, such as the establishment of nature reserves and national parks. For example, regions such as the Three-River Source, Ruoergai and Qilian Mountains showed remarkable improvements in habitat quality, reflecting the positive outcomes of targeted conservation efforts. However, there are still regions where habitat quality improvement has been relatively slow despite ecological measures. First, regions such as Selincuo-Purogongri, Mount Everest, Shangri-La and Qinghai Lake are popular tourist destinations, where local tourism-related economic activities are prioritized over ecological protection considerations (Jie et al., 2017). Additionally, these regions are adjacent to urban areas and are significantly affected by intense human activities. Second, some are mainly distributed in the southeastern part of the QTP, such as Zhari Sacred Mountain, Mangkang Yunnan Golden Monkey, Yarlung Zangbo Grand Canyon, and Gaoligong Mountain; these areas are affected mainly by excessive deforestation and unnecessary expansion of built-up areas (Hu et al., 2021). Finally, areas such as the Hoh Xil, Qiangtang and Altun Mountains presented minimal habitat quality improvements due to harsh environmental conditions, characterized by extreme climates and fragile ecosystems. These findings suggest that while conservation policies have largely been effective, they must be tailored to address specific challenges in vulnerable regions. Additionally, strategies to mitigate the impact of human activities and promote sustainable development in surrounding areas are crucial for long-term ecological restoration.

6. Conclusions

This study utilized an improved habitat quality assessment method that incorporates vegetation growth status by introducing the LAI. This method was used to evaluate the habitat suitability of key factors influencing habitat quality to create a pixel-by-pixel habitat suitability map, which was then combined with threat source data to create a more accurate assessment of habitat quality. This study selected the QTP as a case study using the improved habitat quality assessment model. The results that from 2000 to 2010, habitat quality increased significantly in the Three-River Source region and decreased significantly in the urban agglomerations and southeastern forested areas. In addition, from 2010 to 2020, only the Qiangtang region had a significant decrease in habitat quality, whereas the other regions recovered to varying degrees. Analysis of habitat quality trends over the past two decades identified Ruoergai Wetland, Qilian Mountains, and Datong Beichuan River Source as the most significantly recovered nature reserves, while Yellow River Source and Ruoergai National Parks showed the best restoration among the national parks. These findings underscore the positive impact of national ecological restoration policies, including the establishment of nature reserves and national parks, on improving the region's ecological environment. However, this study also found challenges in areas with harsh environmental conditions or intense human activities, such as the Qiangtang region and the Mangkang Yunnan Golden Monkey Reserve, where habitat quality changes were minimal or even negative. Additionally, localized degradation in areas such as the Yarlung Tsangpo River Valley and southeastern riverine forests indicates that urban expansion, geological instability, and ecological fragility continue to pose significant threats to habitat quality.

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