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Assessment of the Impact of Road Construction on the Ecological Environment

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Abstract: In recent years, China has made remarkable progress in infrastructure construction, which has greatly contributed to the development of the regional economy. However, the impacts of construction on the ecological environment are of increasing concern. This study aimed to quantitatively assess the ecological environment of two expressways (the Chanliu Expressway and the Linghua Expressway) constructed during different time periods, to assess the impact of road construction on the ecosystem and the effectiveness of the Chinese government's efforts in environmental protection. The pressure–state–response (PSR) model was adopted, which integrates a variety of remote sensing indicators. The ecological pressure, ecological state, and ecological response in the pre-, mid-, and post-construction periods of the road were assessed. The results reveal that the impacts of the construction of the Chanliu (1999–2002) and Linghua Expressways (2019–2023) on ecosystems are different. For the Chanliu Expressway, the ecological pressure continually increased, and the ecological state significantly declined during the construction period. When the road construction was finished, the environment continuously deteriorated. This was due to the lack of effective ecological protective measures during its construction. In contrast, the Linghua Expressway experienced reduced ecological pressure during the construction period, with the ecological state remaining relatively stable, as more protective measures were implemented. However, it later relied on natural recovery, which led to an increase in ecological pressure in the post-construction period. The results indicate that China's ecological protective measures in road construction have achieved significant progress in recent years. In the future, it is essential to maintain long-term ecological health by strengthening ecological restoration management and continuous environmental monitoring.

Keywords: expressway construction; ecological environment; pressure–state–response model; remote sensing indicators; ecological protective measures

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1. Introduction

The ecological environment, which includes human society and surrounding natural factors, is the foundation of human survival and development [1,2]. Human activities and climate change may have impacts on the environment, such as ecological degradation, extreme weather, and water crises [3–6]. Changes in the ecological environment pose significant challenges to human survival and socio-economic development. Therefore, it is crucial to accurately monitor the quality and changes in the ecological environment [7].

Expressways, with their high speed, convenience, and wide coverage, have become an important part of modern transportation systems and a key driver of regional economic growth [8–10]. The construction process tends to have adverse effects on the ecological environment along the expressway, including soil erosion, biodiversity reduction, drastic desertification, and ecological degradation [11–13]. Conducting an ecological environment assessment for expressway construction is very important. Jia et al. [14] proposed a comprehensive ecological environment evaluation model with multiple indices to determine the impact of the Zhadao highway construction on the ecological environment of the Qinghai–Tibet Plateau. Their results reveal that the ecological environment in the study area was obviously affected by highway construction. Zhang et al. [15] developed a numerical method to assess the landscape ecological risk of a particular portion of the Phnom Penh–Sihanoukville Expressway in Cambodia. Their results reveal an overall decline in the quality of the ecological environment. Qin et al. [16] constructed a comprehensive post-assessment system of the ecological environmental impact of highway construction projects to evaluate the Changbai Mountain Ring Road. These results imply that highway construction significantly affects local animal populations and ecosystem structure.

Compared with traditional methods, remote sensing technology enables large-scale, long-term dynamic ecological quality monitoring and provides a new perspective for assessing ecological quality [17–19]. Remote sensing indices, including the normalized difference vegetation index (NDVI), leaf area index (LAI), and land surface temperature (LST), have been widely employed to assess and monitor ecological quality [20–22]. Owing to the complexity of the ecological environment, a single remote sensing index cannot accurately reflect regional ecological quality. A comprehensive assessment of ecological quality by integrating multiple indicators is an effective way to overcome this shortcoming [23]. Xiong et al. [24] utilized a remote sensing ecological index (RSEI) to assess the spatial–temporal changes in the quality of the ecological environment in the Erhai Lake Basin. Their results reveal that the ecological quality decreased from 1999 to 2009 and increased from 2009 to 2019. Zhang et al. [25] used the RSEI to analyze the ecological environmental quality of the Chang–Zhu–Tan metropolitan circle in central China from 2000 to 2020. Their results reveal that the mean value of the RSEI in the study area exhibited an increasing trend. Zhang et al. [26] used the RSEI to assess the spatio–temporal variations in the ecological quality of Northeast China from 2000 to 2022 and reported that the ecological quality generally exhibited a fluctuating downward trend.

The pressure–state–response (PSR) model, driving force–state response (DSR) model, to measure the impact of tourism holistically and driving force–pressure–state–impact–response (DPSIR) model are widely used for ecological quality assessment [27–29]. Wang et al. [30] conducted research at the Zhejiang Natural History Museum in China using the DSR model, aiming to establish an evaluation framework for museum sustainability. Li et al. [31] used a sustainability analysis framework based on the PSR model to evaluate the impact of tourism activities on the environment in China's Water National Parks (WNPs). Malekmohammadi et al. [32] used the DPSIR model to assess wetland vulnerability in the Choghakhor international wetland landscape in southwestern Iran. Compared with other models, the PSR model emphasizes the causal logic of the ecological impact process and reveals the impact of natural and human factors on the ecological environment; this model has been widely used in areas such as ecological safety and environmental health [33–35].

In 2013, the Ministry of Transport of the People's Republic of China issued the guiding opinions on accelerating the development of green circulation and low carbon transportation, and three years later issued the guidance on green highway construction [36]. In recent decades, China has achieved remarkable progress in road construction and has made outstanding contributions to rapid economic development [37]. With increasing awareness of ecological environment protection and economic development, the Chinese government is paying increasing attention in road construction technology improvement in terms of materials and construction methods including carbon-neutral materials [38] self-healing asphalt [39], and cold in-place recycling techniques [40]. In addition, green highway construction policy was implemented [41] to improve ecological protection and restoration in road construction [42]. Qu et al. [43] reported that land use changes caused by ecological restoration projects were the main driving factor for improving vegetation conditions in the Yangtze River Basin. Zhang et al. [44] noted that National Key Forestry Ecology Projects significantly contributed to the vegetation carbon storage of China's forests. Huang et al. [45] reported that the post-implementation activities of the Yangtze River Conservation Project enhanced overall vegetation coverage.

The objective of this study was to quantitatively evaluate the effectiveness of the Chinese government's efforts in road construction and environmental protection. Two roads constructed at different times under similar natural environments were selected, and an integrated evaluation model was applied to comprehensively evaluate the impact of road construction on the ecological environment and the restoration effect after construction.

2. Materials and Data

2.1. Study Area

Two expressways were selected for comparative analysis to assess the effectiveness of environmental protection in road construction projects. The Chanliu Expressway represents a typical case constructed in 2000, whereas the Linghua Expressway is a new project built after 2020.

Both expressways are in the Gansu Province, which has a temperate, continental climate influenced by monsoons. The annual temperatures range from 0 °C to 15 °C [46], and the elevation varies from 1500 m to 3000 m. The temperature fluctuations are significant, with ample sunlight and large diurnal temperature differences [47].

The Chanliu Expressway lies in southeastern Gansu Province, connecting the Chankou and Liugou Rivers in Lanzhou, with a geographic range of 103°53′–104°33′E and 35°40′–36°04′N. The road has a total width of 24.5 m and a length of approximately 77.7 km. The route starts at Shibalipu, approximately 10 km east of Chankou. It passes through the northwestern of Chankou, Liangjiaping, Huangjiachuan, Tujiawan, Gancaodian, Qingshuiyi, Triangle City, and Dingyuan Town to Liugouhe. The construction of the Chanliu Expressway began on 26 September 1999 and was completed in 2002.

The Linghua Expressway (106°45′–107°27′E, 35°05′–35°19′N), located in the eastern border area of Gansu Province, is the first expressway constructed within Lingtai County. This road covers a total area of approximately 11,000 km^2, with a length of approximately 68 km. The main line of the Linghua Expressway starts at Shuichuan Village, in the western part of Lingtai County within Pingliang City. It passes through Chongxin County and Lingtai County, ending in Huating County. The construction of the Linghua Expressway began in November 2019 and was completed on 25 December 2023.

For each expressway, a 1 km buffer zone was selected as the study area. The main land use and cover types for the Chanliu Expressway research area are cropland, forest, grassland, marsh, flooded flat, impervious surfaces, bare areas, unconsolidated bare areas, and water body. The average elevation is 1858 m. The main land use and cover types for the Linghua Expressway research area are water, trees, flooded vegetation, crops, built area, bare ground, and rangeland. The average elevation is 1305 m. The research area and two expressways are shown in Figure 1.

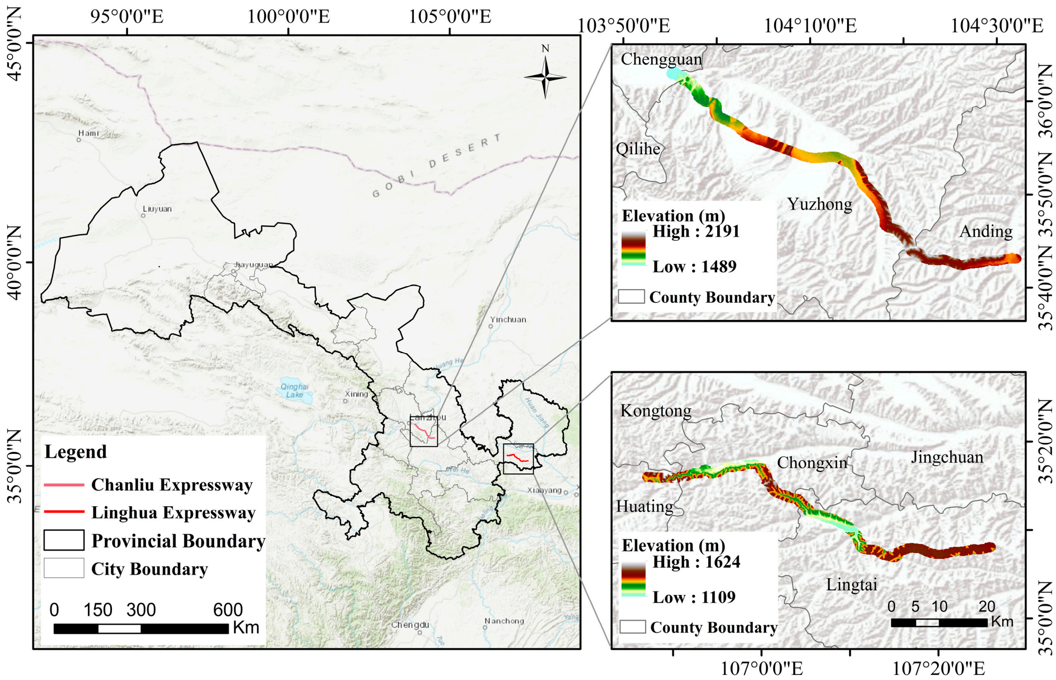

Figure 1. The location and overview of the study area.

2.2. Data

The 30 m and even higher spatial resolution data were used for assessment. Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) data were downloaded from the Earth Explorer platform provided by the United States Geological Survey (USGS). For each expressway, data from the pre-construction, mid-construction, and post-construction periods were selected. Details of the data are provided in Table 1.

Table 1. The data used for the two expressways.

Expressway	Sensor	Pre-Construction	Mid-Construction	Post-Construction
Chanliu	Landsat 5 TM	21 June 1998	29 June 2001	21 June 2004
Linghua	Landsat 8 OLI	14 June 2018	3 July 2022	14 June 2024

The GLC_FCS30D and ESRI 10 m datasets were used for Chanliu and Linghua according to their availability. The GLC_FCS30D dataset spans from 1985 to 2022, providing a spatial resolution of 30 m and an overall accuracy of 80.88% [48]. Land use data for the years 1995, 2001, and 2004 were selected for the Chanliu Expressway (https://doi.org/10.5281/zenodo.8239305, accessed on 10 September 2024). The dataset had an update cycle of every five years before 2000, so data from 1995 was selected to represent the pre-construction phase. The ESRI provides annual global 10 m land cover data from 2017 to 2023 with an overall accuracy of 85% [49]; data from 2018, 2022, and 2023 were selected for the Linghua Expressway. Since 2023 is the latest available year in the ESRI dataset, it was used as a substitute for 2024 to approximate the current land use conditions.

Digital elevation model (DEM) data with a 30 m resolution from the Geospatial Data Cloud (https://www.gscloud.cn, accessed on 10 September 2024) were also used in this study to extract slope and terrain relief.

3. Method

The PSR framework was first proposed by the Canadian statisticians Tony Friend and David Rapport [50] and then modified by the Organization for Economic Cooperation and Development (OECD) in the 1970s [51]. The PSR model includes three components:

pressures, states, and responses. In the pressure–state–response framework, pressure indicators refer to factors that exert pressure on ecosystems and social systems from natural or human sources. State indicators represent the ecosystem's current state and reveal its health condition. Response indicators refer to the strategies and measures that can be taken when the system faces risks and pressures [7,52,53]. The framework of this study is shown in Figure 2.

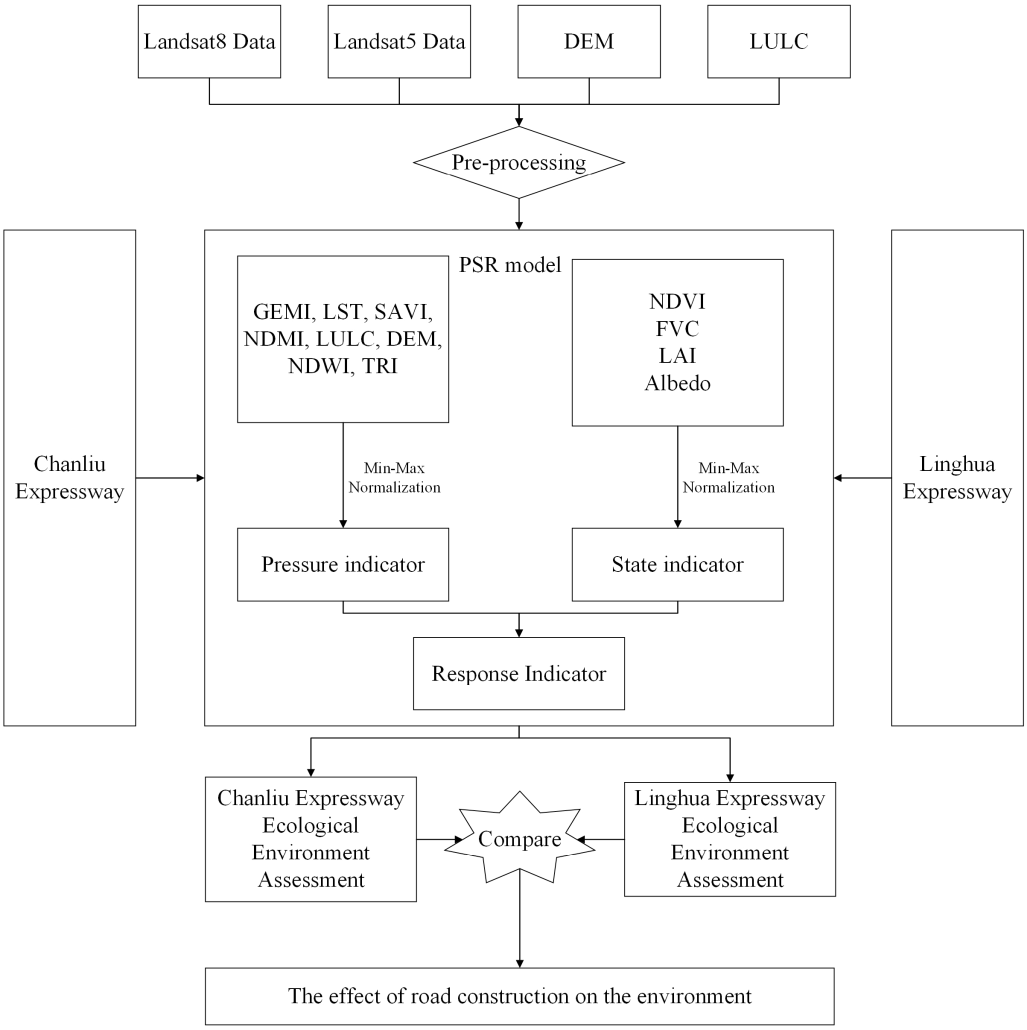

Figure 2. Framework of the road ecological environment assessment. (DEM: digital elevation model; LULC: land use/land cover; GEMI: global environment monitoring index; LST: land surface temperature; SAVI: soil-adjusted vegetation index; NDMI: normalized difference moisture index; NDWI: normalized difference water index; TRI: terrain gauging index; NDVI: normalized difference vegetation index; FVC: fractional vegetation cover; LAI: leaf area index).

3.1. Pressure Indicator (PI)

The pressure indicators of the road ecological environment refer to external activities that affect the road ecosystem and cause changes in its factors, which are the fundamental reasons for system changes. To quantify the pressure in this study, the following 8 key indicators were selected: the global environmental monitoring index (GEMI), LST, soil adjusted vegetation index (SAVI), normalized difference moisture index (NDMI), land use/land cover (LULC), digital elevation model (DEM), normalized difference water index (NDWI), and terrain ruggedness index (TRI). The GEMI quantifies the pressure of road construction or human activities on the vegetation ecosystem. The LST describes the changes in the thermal environment of road areas. The SAVI reflects the pressure caused by soil exposure due to road construction. The NDMI detects moisture changes caused by road construction. Land use/land cover reveals changes in land use and land cover. The DEM and TRI evaluate the pressure of road construction on terrain. The NDWI is used to assess the pressure on water bodies. The combination of these indicators can directly reflect external pressures and quantify the degree of disturbance to ecosystems caused by human activities or environmental changes. Previous studies have identified these indicators as the main factors contributing to pressure on the ecological environment [34,54]. Table 2 lists the PI calculation formulas.

Table 2. Formula for calculating pressure indices.

Submodule	Index	Formula	Reference
Pressure	GEMI	$GEMI = eta\times(1 - 0.25\times eta) - \left(\frac{B_R - 0.125}{1 - B_R}\right)$ $eta=\frac{2\times\left({B_{NIR}}^2 - {B_R}^2\right)+1.5\times B_{NIR} + 0.5\times B_R}{B_{NIR} + B_R + 0.5}$	[55]
	LST	$LST=K_1\times B_{ST}+K_2$	[56,57]
	SAVI	$SAVI=\frac{(B_{NIR} - B_R)}{(B_{NIR} + B_R + L)}\times(1 + L)$	[58]
	NDMI	$NDMI=(B_{NIR} - B_{SWIR1})/(B_{NIR} + B_{SWIR1})$	[59]
	LULC	-	
	DEM	-	
	NDWI	$NDWI=(B_G - B_{NIR})/(B_G + B_{NIR})$	[60]
	TRI	$TRI=\frac{\text{Mean elevation} - \text{Min elevation}}{\text{Max elevation} - \text{Min elevation}}$	[54]

where B_R is the surface reflectance of the red band; B_{NIR} is the surface reflectance of the near-infrared band; B_{ST} is the surface reflectance of the thermal–infrared band; K_1 is a band-specific thermal conversion constant from the metadata; K_2 is a band-specific thermal conversion constant from the metadata; L is the soil brightness correction factor, which is defined as 0.5 to accommodate most land cover types; B_{SWIR1} is the surface reflectance of the shortwave infrared band; B_G is the surface reflectance of the green band.

The LULC data were reclassified according to the following categories. High values indicate that the utilization of land resources has reached its peak and is usually beyond further use by mankind; low values are the starting point of land resource utilization. On the basis of the above characteristics, LULC data in an ideal state are classified into different levels, and each level is assigned its corresponding category [7].

- Grade 1: Trees, Forest, Bare Ground, Grassland, Water body
- Grade 2: Flooded vegetation, Marsh, and Flooded flat
- Grade 3: Cropland, Rangeland
- Grade 4: Built area, Impervious surfaces

All pressure indicators were normalized to a range between 0 and 1 via the max–min normalization method. This approach eliminates the impact of inconsistent dimensions on the evaluation, making all indicators comparable on the same scale.

All the indicators within the study area were assigned equal weights, and the pressure index was calculated via Formula (1):

$$PI = \frac{(GEMI+LST+SAVI+NDMI+LULC+DEM+NDWI+TRI)}{8} \quad (1)$$

High values indicate high pressure and poor ecosystem conditions, whereas low values indicate low pressure and good ecosystem conditions.

3.2. State Indicator (SI)

The state index represents the health condition of the road ecosystem. Human activities that alter road ecosystem conditions can lead to a reduction in vegetation coverage and a decrease in LAI. The NDVI, LAI, and fractional vegetation cover (FVC) are the main vegetation indices used as state indicators. Vegetation health conditions also have a direct effect on albedo, with healthy vegetation having a lower albedo and degraded vegetation or bare land having higher albedo values, so albedo was also included. Table 3 lists the SI indicators used in this study.

Table 3. State index calculation formula.

Submodule	Index	Formula	Reference
State	LAI	$LAI = 0.57 \times e^{2.33 \times NDVI}$	[61]
	NDVI	$NDVI = (B_{NIR} - B_R)/(B_{NIR} + B_R)$	[62]
	FVC	$FVC = 1 - [(NDVI_{max} - NDVI) / (NDVI_{max} - NDVI_{min})]^{0.6175}$	[61]
	Albedo	$Albedo = E_{\uparrow}/E_{\downarrow}$	[63]

where B_R is the surface reflectance of the red band; B_{NIR} is the surface reflectance of the near-infrared band; $E_{\uparrow}$ is the reflected solar radiation; $E_{\downarrow}$ is the incident solar radiation.

The state index values were calculated by assigning equal weights to all the indicators in the study area, as shown in Formula (2) below:

$$SI = \frac{(NDVI + LAI + FVC + Albedo)}{4} \quad (2)$$

High values indicate a good state and healthy ecosystem. Low values represent a poor state and degraded ecosystem conditions.

3.3. Response Indicator (RI)

The response indicator reflects how a system reacts to stress or its state. It was calculated by subtracting the state indicator from the stress indicator, as shown in Formula (3) [7,54] below:

$$RI = PI - SI \quad (3)$$

A high response index means that the ecosystem is under significant stress and is in poor condition or worsening. When the response index is low, the ecosystem is more stable or has greater resistance to external stress.

4. Results

4.1. Ecological Environment Assessment of the Chanliu Expressway

4.1.1. Pressure Analysis of the Natural Ecosystem

Figure 3 shows the changes in ecosystem pressure on the Chanliu Expressway from 1998 to 2004. As shown in Figure 3a–c, the ecosystem pressure along the Chanliu Expressway increased, with the PI value following a yearly increasing trend. The average PI value increased from 0.465 in 1998 to 0.469 in 2001 and further to 0.476 in 2004 (Figure 4a). The pressure increase during the construction period (Figure 4a) was less significant than that during the post-construction period (Figure 4b), which indicates that although road construction had some impact on the ecosystem, its overall effect was limited. Natural climate changes and land-use changes have contributed significantly to ecosystem pressure [64].

At the regional scale, the ecosystem pressure in the western part of Yuzhong County and Anding County increased significantly year by year. The land-use changes and vegetation damage caused by road construction in this area have led to increasing pressure reflected in the LST, SAVI, and NDMI [65], which has caused a yearly increase in ecosystem pressure.

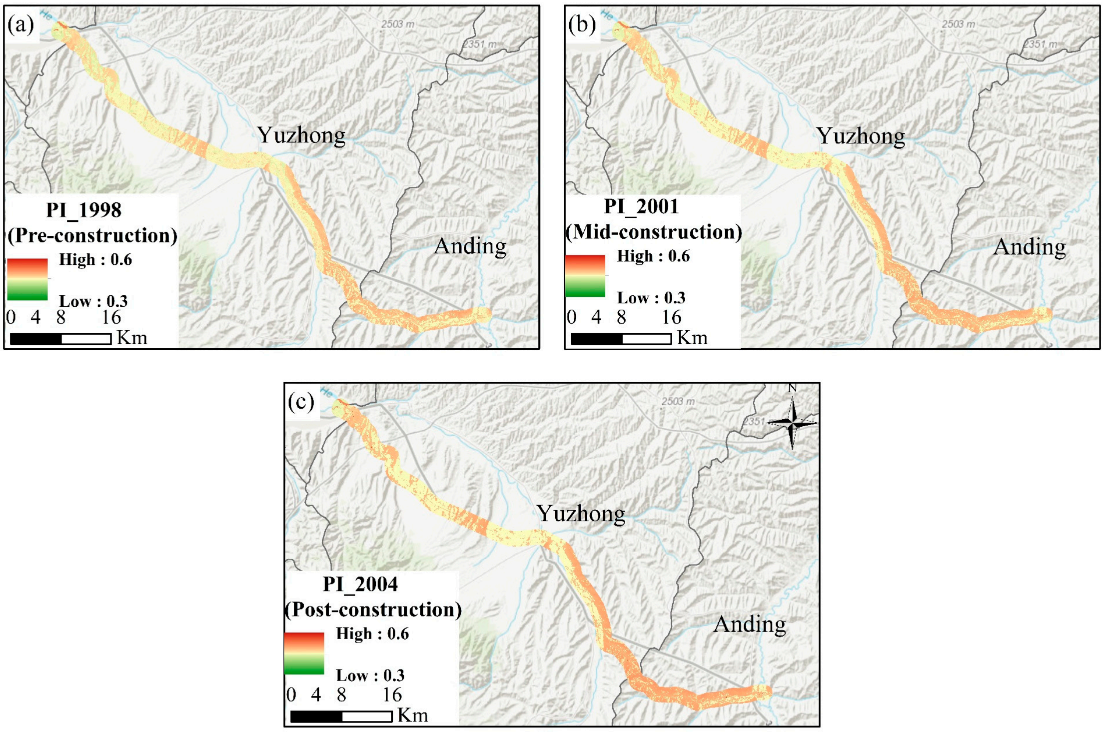

Figure 3. Pressure indicator maps of the Chanliu Expressway. (**a**) Pressure indicator map for 1998, (**b**) pressure indicator map for 2001, and (**c**) pressure indicator map for 2004.

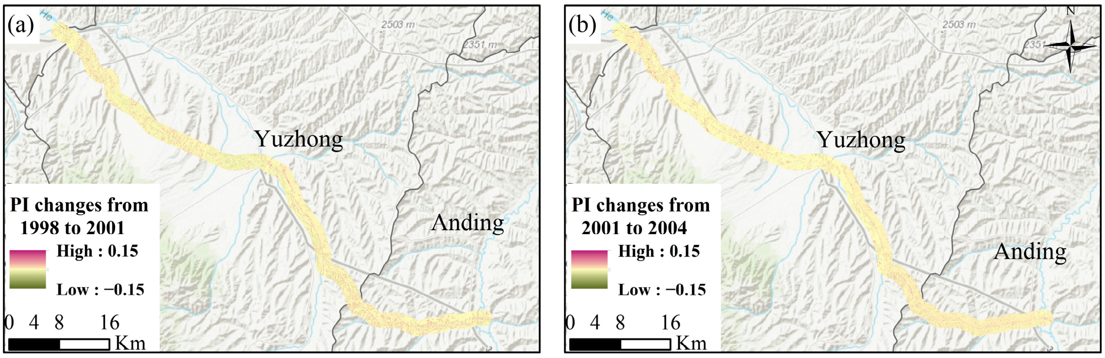

Figure 4. Pressure indicator change maps of the Chanliu Expressway. (**a**) Pressure indicator changes from 1998 to 2001, and (**b**) pressure indicator changes from 2001 to 2004.

4.1.2. State Analysis of the Natural Ecosystem

Figure 5 presents the changes in the ecosystem state along the Chanliu Expressway from 1998 to 2004. According to Figure 5a–c, the ecosystem state had a consistent yearly decline, reflecting a steady degradation in ecosystem health. The average SI value decreased from 0.441 in 1998 to 0.379 in 2001 and further decreased to 0.375 by 2004. Figure 6a,b show that the ecosystem state declined during the construction period, especially in northwestern and southeastern Yuzhong County and Anding County. The destruction of vegetation led to continuous declines in indicators of vegetation health, such as the NDVI, LAI, and FVC that resulted in a decreasing trend in SI values [66]. The ecosystem state improved after construction, indicating that post-construction recovery efforts, such as replanting vegetation and reducing land-use disturbances, helped the ecosystem recover gradually [67].

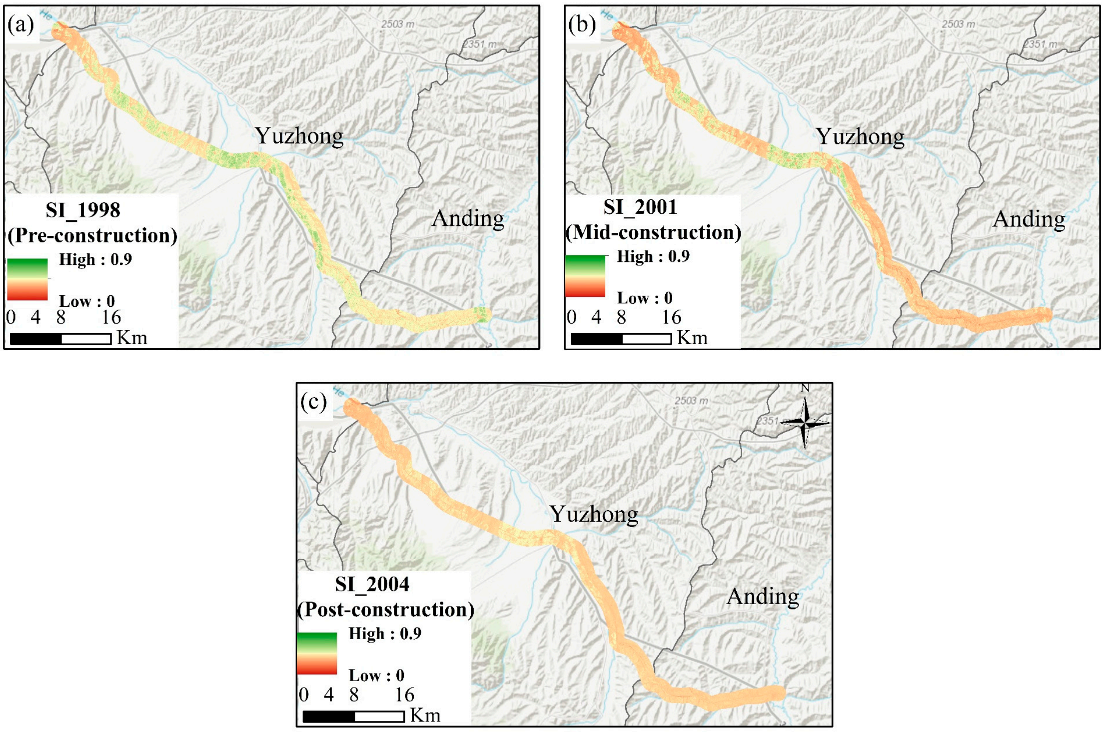

Figure 5. State indicator maps of the Chanliu Expressway. (**a**) State indicator map for 1998, (**b**) State indicator map for 2001, and (**c**) State indicator map for 2004.

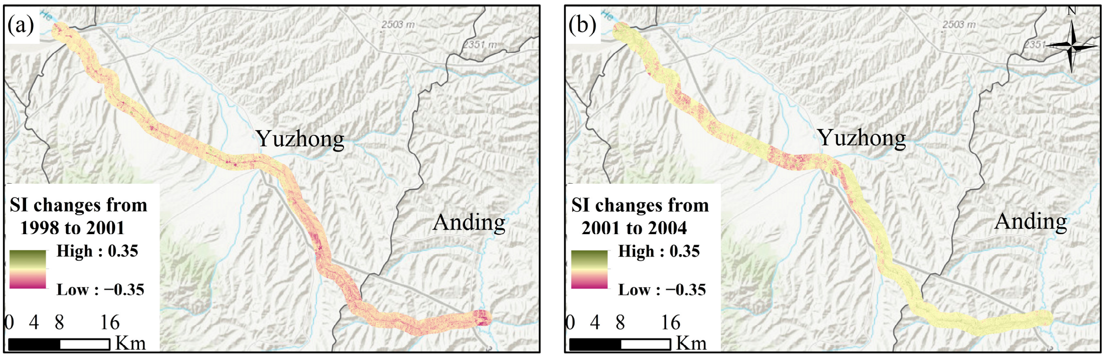

Figure 6. State indicator change maps of the Chanliu Expressway. (**a**) State indicator changes from 1998 to 2001, and (**b**) state indicator changes from 2001 to 2004.

4.1.3. Response Analysis of Changes in Ecosystem Dynamics

Figure 7 shows the changes in ecosystem response along the Chanliu Expressway from 1998 to 2004. As shown in Figure 7a–c, the RI values increased each year, reflecting the growing response of the ecosystem to external pressures. The average RI value increased from 0.024 in 1998 to 0.090 in 2001 and further to 0.101 in 2004. The ecosystem response increased significantly during the construction period (Figure 8a), especially in the northwestern and southeastern parts of Yuzhong County, as well as in Anding County. Large-scale disturbances such as heavy machinery and vegetation clearing during construction greatly weaken the resistance of the ecosystem, leading to a decrease in vegetation cover and an increase in water stress, thus weakening the ability of the ecosystem to regulate and leading to a continuous increase in RI values [68]. The ecological recovery in the post-construction period was limited (Figure 8b). Although ecological restoration measures were implemented during the recovery period, long-term damage to the soil structure has led to slow recovery of the ecosystem [69].

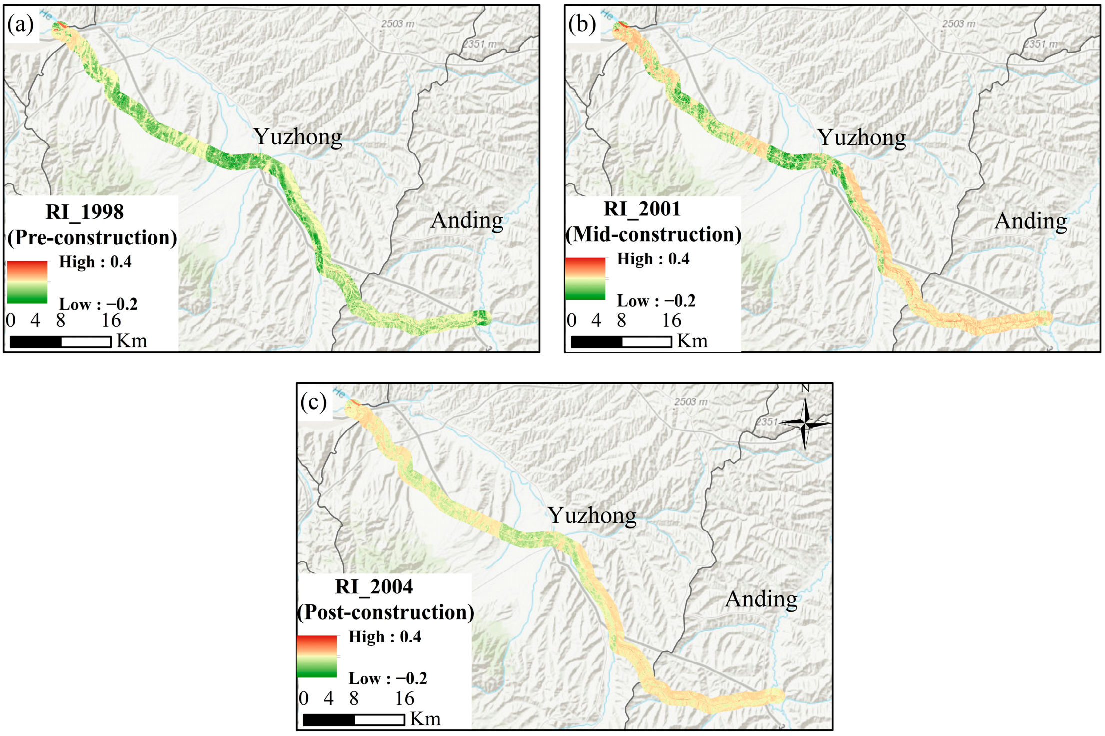

Figure 7. Response indicator maps of the Chanliu Expressway. (**a**) Response indicator map for 1998, (**b**) response indicator map for 2001, and (**c**) response indicator map for 2004

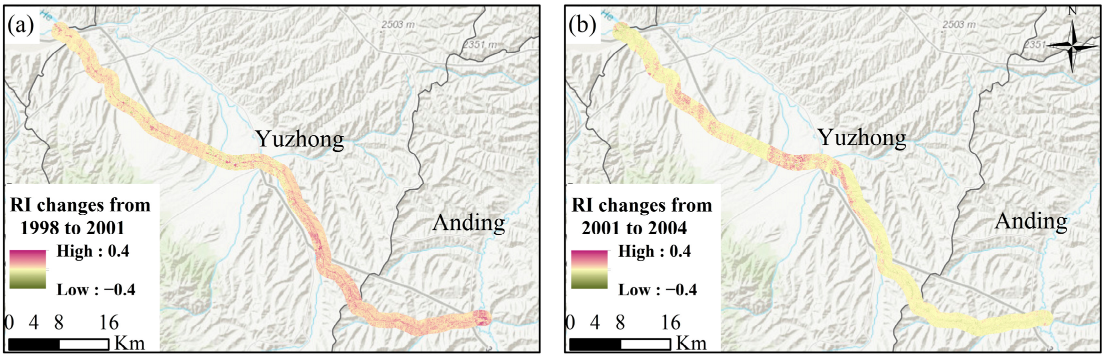

Figure 8. Response indicator change maps of the Chanliu Expressway. (**a**) Response indicator changes from 1998 to 2001, and (**b**) response indicator changes from 2001 to 2004.

4.2. Ecological Environment Assessment of the Linghua Expressway

4.2.1. Pressure Analysis of the Natural Ecosystem

Figure 9 shows the changes in ecosystem pressure on the Linghua Expressway from 2018 to 2024. As shown in Figure 9a–c, the ecosystem pressure along the Linghua Expressway first decreased but then increased slightly. The average PI value was 0.514 in 2018, decreased to 0.488 by 2022, and slightly increased to 0.494 in 2024. The effective environmental management measures implemented during the construction period temporarily reduced ecosystem pressure [70], which induced a decrease in pressure during this period (Figure 10a). During the post-construction period (Figure 10b), the increase in traffic, the use of new infrastructure, and changes in land use, such as commercial and residential development, induced an increase in ecological pressure [71].

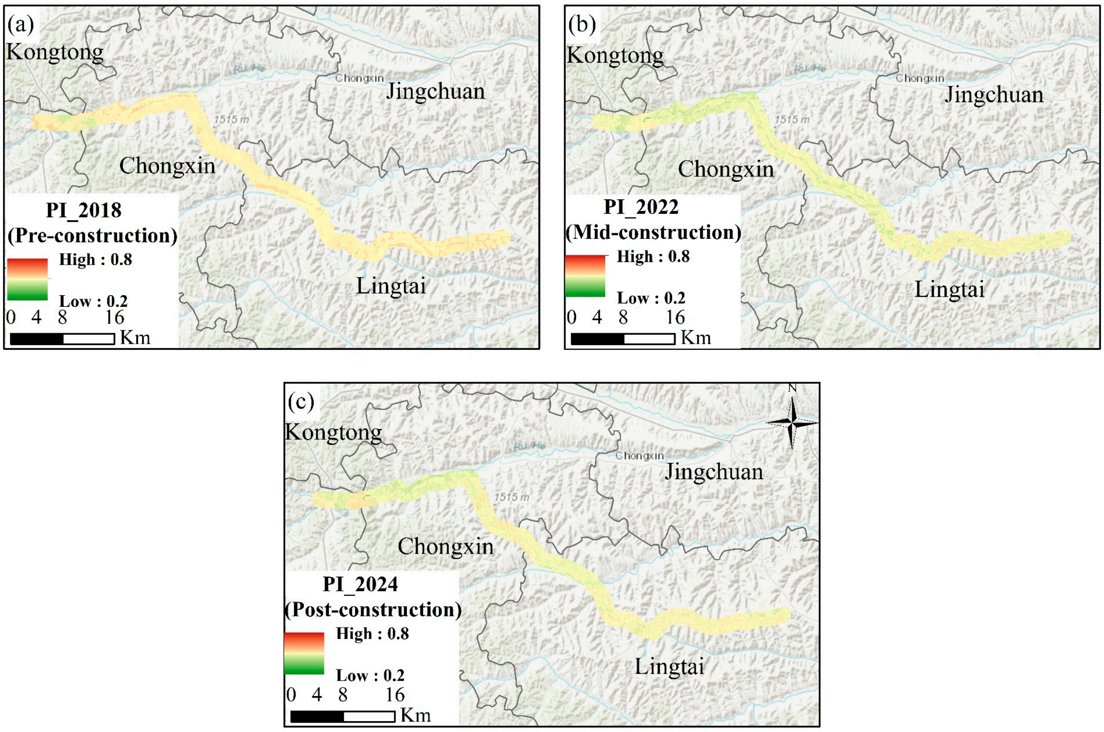

Figure 9. Pressure indicator maps of the Linghua Expressway. (**a**) Pressure indicator map for 2018, (**b**) pressure indicator map for 2022, and (**c**) pressure indicator map for 2024.

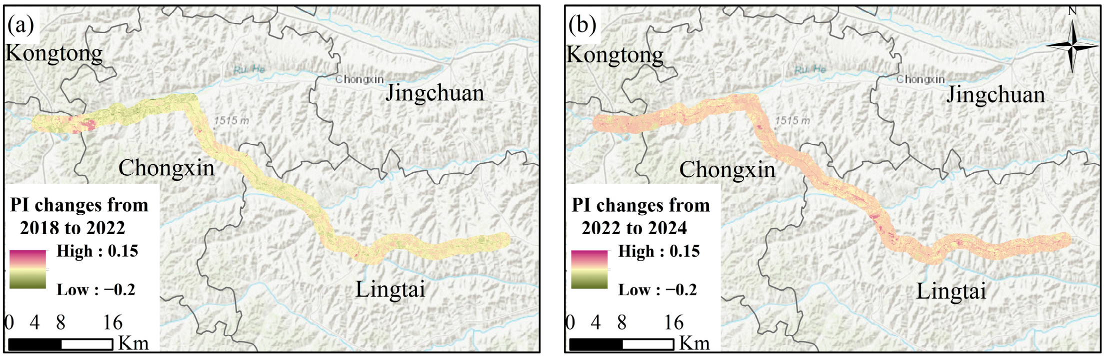

Figure 10. Pressure indicator change maps of the Linghua Expressway. (**a**) Pressure indicator changes from 2018 to 2022, and (**b**) pressure indicator changes from 2022 to 2024.

4.2.2. State Analysis of the Natural Ecosystem

Figure 11a–c illustrate the changes in the ecosystem state from 2018 to 2024 along the Linghua Expressway. As shown in the figures, the ecological conditions were declining, with the SI value decreasing from 0.321 in 2018 to 0.313 in 2022 and further to 0.288 in 2024. The degree of deterioration of the ecosystem state during the construction period (Figure 12a) was less than that during the post-construction period (Figure 12b). The active interventions during the construction period, such as habitat restoration efforts and reforestation programs, were more effective in maintaining or improving the ecological state than the natural recovery processes were [72].

In the central part of Chongxin County and southern part of Kongtong County, the ecosystem values continuously declined. The increased ecological pressure caused by human activities, such as increased traffic flow, land use changes, and ecosystem fragmentation induced further ecological degradation [73].

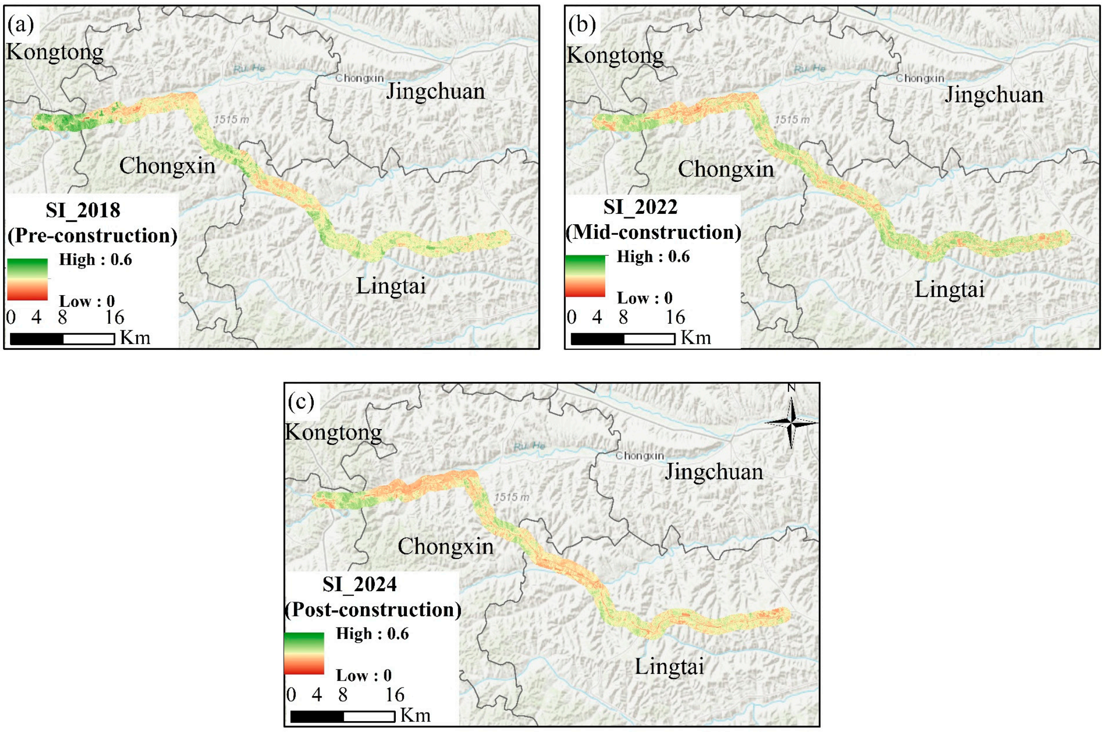

Figure 11. State indicator maps of the Linghua Expressway. (**a**) State indicator map for 2018, (**b**) state indicator map for 2022, and (**c**) state indicator map for 2024.

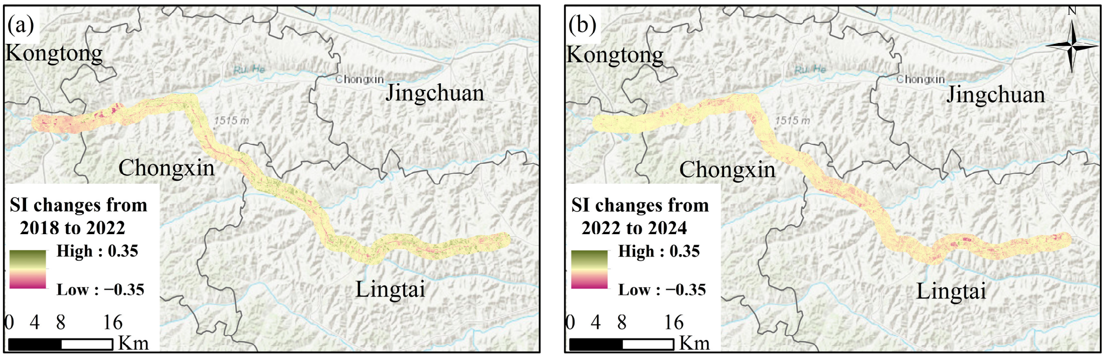

Figure 12. State indicator change maps of the Linghua Expressway. (**a**) State indicator changes from 2018 to 2022, and (**b**) state indicator changes from 2022 to 2024.

4.2.3. Response Analysis of Changes in Ecosystem Dynamics

Figure 13 shows the changes in the ecosystem response along the Linghua Expressway. As shown in Figure 13a–c, the ecosystem response to external pressures along the Linghua Expressway fluctuated. During the construction period, the RI decreased from 0.193 in 2018 to 0.175 in 2022, indicating that the construction of the Linghua Expressway did not degrade the ecological environment. Since the early 2000s, the Chinese government has made significant efforts in environmental protection, including new construction technology and green highway construction policy, to mitigate the ecological impact of large-scale infrastructure projects [74]. Environmental management during the construction period helps reduce direct ecological pressures (Figure 14a). However, intensified human activities and land-use changes have significantly increased ecosystem responses during the recovery period, placing greater stress on the environment (Figure 14b) [75]. When the road construction was finished, the RI value increased to 0.206 in 2024.

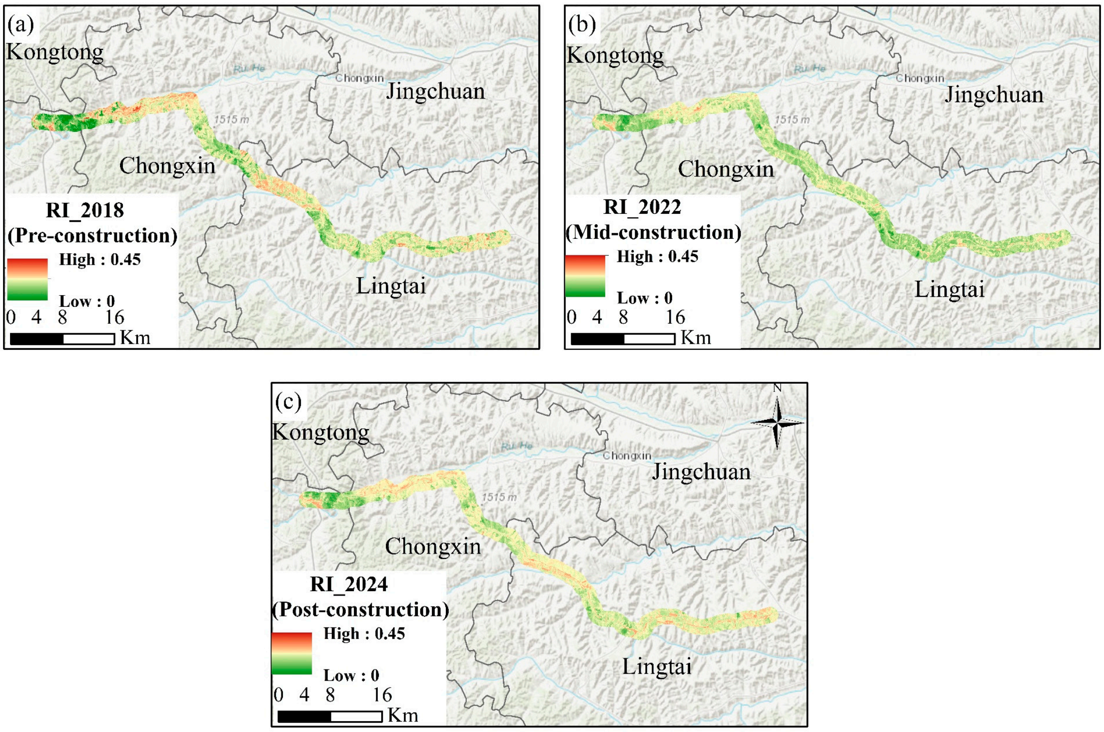

Figure 13. Response indicator maps of the Linghua Expressway. (**a**) Response indicator map for 2018, (**b**) response indicator map for 2022, and (**c**) response indicator map for 2024.

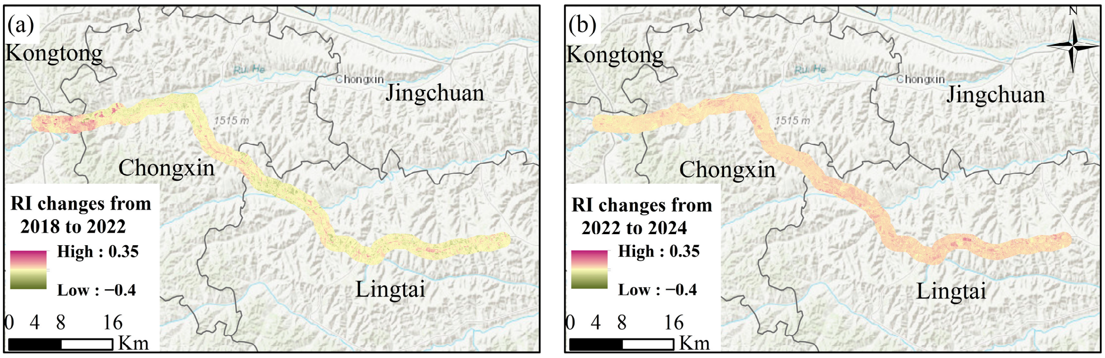

Figure 14. Response indicator change maps of the Linghua Expressway. (**a**) Response indicator changes from 2018 to 2022 and (**b**) response indicator changes from 2022 to 2024.

4.3. Comparative Analysis of the Ecological Quality of the Chanliu Expressway and the Linghua Expressway

Figure 15 and Table 4 show the comparisons of the ecological indicators across different construction periods for the Chanliu and Linghua Expressways. As shown in Table 4, the ecological pressure on the Linghua Expressway before construction (0.514) was greater than that on the Chanliu Expressway (0.465), indicating that the area faced greater environmental pressure before construction. Despite its poor ecological condition, Linghua's ecological environment was improved by the implementation of effective environmental management, such as vegetation protection, soil stabilization, and pollution control during construction. The Chanliu Expressway was constructed two decades earlier than the Linghua Expressway. At that time, the Chinese government paid less attention to ecological environment protection, especially to the environmental damage caused by large construction activities. Although the Chanliu Expressway area experienced less ecological pressure before construction, road construction had adverse effects on the ecological environment in this area. The ecological pressure and response clearly increased, and the ecological state decreased from 0.441 to 0.379.

After road construction, the ecological environment protective measures weakened, and the ecological situation deteriorated on both expressways. The degrees of deterioration differ according to the natural environment and human activities.

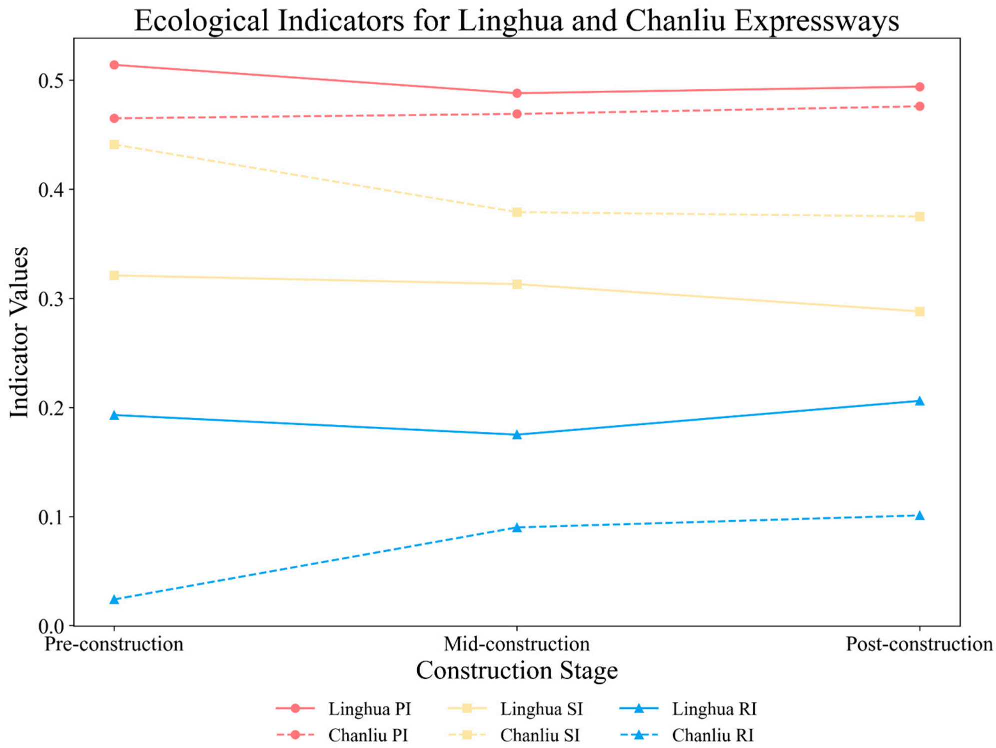

Figure 15. Ecological indicator trends for the Linghua and Chanliu Expressways across different construction stages.

Table 4. Comparison of ecological indicators in different construction periods for the Chanliu Expressway and Linghua Expressway.

Expressway	Indicator	Pre-Construction	Mid-Construction	Post-Construction
Chanliu	Pressure	0.465	0.469	0.476
	State	0.441	0.379	0.375
	Response	0.024	0.090	0.101
Linghua	Pressure	0.514	0.488	0.494
	State	0.321	0.313	0.288
	Response	0.193	0.175	0.206

5. Discussion

5.1. The Rationality of the Index System

By combining the PI, SI, and RI, the model effectively captures both the external pressures imposed on the ecosystem by road construction and the internal health status of the ecosystem in response to these pressures. The PI captures direct pressures such as soil and temperature changes due to construction, whereas the SI highlights the current health status, enabling us to monitor not only the immediate impacts, but also the longer-term effects on ecosystem resilience.

Unlike traditional ecological environment assessments, this study used spatially complete remote sensing data as the driving data for model indicators. These indicators were selected and recommended based on previous studies, providing a high level of rationality. However, there were several potential issues in its application. For example, we used the LAI, NDVI, and FVC to represent vegetation conditions. Although these indicators all reflect vegetation growth and health status, they may have certain correlations. However, each indicator represents different aspects of vegetation. The NDVI reflects vegetation vigor [76], the LAI provides structural information [77], and the FVC highlights spatial distribution characteristics [78]. The incorporation of these indicators leads to a comprehensive representation of vegetation conditions, which makes the results reliable.

5.2. Impact of Buffer Distance on Result

The buffer distance determines the size of the research area. To identify the influence of buffer distance on evaluation result, the following two buffer distances were set: 500 m and 1 km. Experiments were conducted across different construction stages (pre-construction, mid-construction, and post-construction) of the Chanliu Expressway and the Linghua Expressway. The detailed results are shown in Table 5.

Table 5. Comparative Results of Evaluation Indicators under Different Buffer Distances for Expressway Construction Stages.

Expressway	Indicator	Pre-Construction		Mid-Construction		Post-Construction	
		500 m	1 km	500 m	1 km	500 m	1 km
Chanliu	Pressure	0.4641	0.4654	0.4687	0.4698	0.4759	0.4767
	State	0.4422	0.4413	0.3746	0.3798	0.3742	0.3752
	Response	0.0222	0.0243	0.0943	0.0902	0.1018	0.1015
Linghua	Pressure	0.5142	0.5147	0.4867	0.4887	0.4940	0.4949
	State	0.3204	0.3216	0.3077	0.3135	0.2828	0.2883
	Response	0.1938	0.1930	0.1790	0.1751	0.2111	0.2064

Results indicate that for all the three indicators, the differences between the two buffer distances are not significant, and their variation trends are the same. The consistency demonstrates that the 1 km buffer distance is reasonable in this study.

5.3. Representativeness of Evaluation Work

The purpose of this study was to assess the effectiveness of China's environmental protective measures in the context of large-scale road construction. In this study, the assessment was limited to two expressways—the Chanliu Expressway and the Linghua Expressway. The reason is that both Expressways are located in Gansu Province and have comparable geographic and natural environmental conditions, but were constructed at the following different times: the Chanliu Expressway was constructed in 1999–2002, whereas the Linghua Expressway was constructed in 2019–2023, when the Chinese government paid much more attention to environmental protection. In such situations, the assessment was considered comparable. However, further studies should expand this analysis to include more expressways across diverse regions, reinforcing our conclusions to provide a more comprehensive understanding of the long-term effects of road construction on ecosystem health and the efficacy of environmental protective measures.

5.4. Potential of Remote Sensing in Ecological Environment Protection

Remote sensing technology provides real-time monitoring ability for the ecological environment, including satellite and unmanned aerial vehicle (UAV) remote sensing. Satellite observations enable large-scale, long-term monitoring, help to identify environmental change trends on a regional scale [79]. The UAV observations allow for detailed and comprehensive monitoring in relatively small areas, providing multiscale, high-resolution data for ground analysis [80]. Compared with traditional field surveys, remote sensing technology can capture changes in ecosystems promptly, providing scientific support for ecological protection [81].

This study exclusively employed remote sensing data in model applications and achieved effective high-resolution monitoring of the ecological environment over a long time series. In the future, the application of remote sensing in road monitoring should be strengthened; for example, UAVs would be used to detect potential risks in road construction more promptly. Such real-time monitoring will assist managers in taking rapid corrective measures, thereby effectively reducing the negative impact of road construction on the ecological environment.

6. Conclusions

In recent decades, China has made significant strides in road construction that have greatly contributed to its rapid economic development. With increasing awareness of environmental protection, the Chinese government has placed special emphasis on ecological preservation and restoration efforts in road infrastructure projects. In this study, the effectiveness of environmental protection initiatives was assessed on two expressways, Chanliu and Linghua, which were built during different time periods but have similar environmental conditions.

The results show that the Linghua Expressway, which was constructed more recently, benefited more from enhanced environmental management strategies during its construction period. The ecological pressure decreased from 0.514 to 0.488, and the ecological state slightly improved. Successful protective measures such as vegetation restoration and soil stabilization have greatly decreased the negative impact of infrastructure construction on ecological protection. In contrast, the Chanliu Expressway, constructed in an earlier period and with fewer environmental management strategies, experienced an increase in ecological pressure and deterioration in its ecological state during and after construction. The results indicate that the Chinese government's increasing emphasis on ecological restoration in road projects has yielded positive results.

However, both expressways demonstrated a rising trend in terms of ecological pressure and a decline in the ecological state during post-construction periods, suggesting that long-term environmental challenges remain. Although environmental protective measures during the construction period had positive effects in the short term, long-term efforts still need to be strengthened. This calls for the Chinese government to continue enhancing ecological restoration strategies during the post-construction period to maintain long-term environmental health.

In conclusion, the government has made notable progress in integrating ecological protection into road construction projects, particularly in recent developments such as the Linghua Expressway. Further efforts are still needed to ensure sustained ecological recovery and long-term environmental protection.

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