

Article

Investigating the Influence of Land Ecological Environment Quality on Sustainable Development Goals: A Case Study of 31 Provinces in China

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Abstract

Land resources constitute the fundamental basis for human survival and a core element of social development. The quantity, quality, and ecological condition of land resources are crucial for human well-being and sustainable development, and they make significant contributions to achieving the United Nations Sustainable Development Goals (SDGs). However, the influence of land ecological quality on the implementation of the SDGs has not yet been fully clarified. This study utilizes 1 km spatial resolution geospatial data and statistical data to construct a land ecological environment quality evaluation index system based on the Pressure–State–Response (PSR) model, analyzing the spatiotemporal dynamics of land ecological environment quality in China from 2010 to 2020 (with five-year intervals). In addition, the Spearman correlation coefficient was employed to examine the relationships between the land ecological environment quality index (LEEQI), pressure index (PI), state index (SI), response index (RI), and the implementation of SDGs 6, 11, 12, and 15, and to further explore how geographical economic zones influence the effects of these indices on the achievement of the SDGs. The results indicate that land ecological quality in China shows a strong north–south gradient, while the east–west differentiation is relatively weak, and the overall trend is increasing. The LEEQI values ranged from 0.16 to 0.48; the PI values ranged from 0.00 to 0.24; the SI values ranged from 0.03 to 0.29; and the RI values ranged from 0.01 to 0.26. The LEEQI gap between the western and northeastern regions narrowed significantly, from 0.10 to 0.07. LEEQI and RI promote the achievement of all four SDGs, whereas PI and SI mainly promote the realization of SDGs 6, 11, and 12. The synergistic effects of the four indices on the SDGs are observed in the central, eastern, and western regions, with the most significant effects occurring in western China. Specifically, LEEQI shows the strongest correlation with SDG 6; both PI and SI exhibit synergistic effects with SDGs 12 and 15; and RI demonstrates synergistic effects with all four SDGs. These findings suggest that improving land ecological quality is crucial for advancing the achievement of the SDGs. Furthermore, given that land ecological environment quality and its dimensions exert different influences on the implementation of the SDGs across geographical economic regions, it is necessary to develop tailored and region-specific strategies, particularly in western China, where maximizing improvements in land ecological quality is crucial for promoting sustainable development.



Academic Editor: Alejandro Rescia

Received: 20 February 2026

Revised: 5 March 2026

Accepted: 11 March 2026

Published: 13 March 2026

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Keywords: land ecological environment quality; sustainable development goals; trade-off and synergy; geographical and economic zones

1. Introduction

Land is the fundamental basis for human survival and development and is a non-renewable natural resource [1]. However, using land resources results in significant ecological consequences despite providing essential goods and services to meet human demands [2–4]. For instance, tropical deforestation has led to biodiversity loss and heightened carbon dioxide emissions, exacerbating global warming [5,6]. Urbanization and its associated land cover changes have resulted in habitat loss and posed significant threats to biodiversity [7]. In recent decades, rapid population growth and socio-economic development have exacerbated ecological issues such as soil erosion, land desertification, and habitat fragmentation [8–10], which have constrained the sustainable use of resources and the sustainable development of the economy and society [11]. In the growing conflict between human land use and ecological protection [12], safeguarding land ecosystems to meet human needs is paramount. As a fundamental task in ecological construction and environmental protection, the importance of ecological environment quality assessment is growing daily. Concurrently, in alignment with the United Nations 2030 Agenda for Sustainable Development, the protection and sustainable management of land ecosystems have emerged as critical global concerns. From a sustainable development perspective, many scholars have conducted in-depth studies on the Sustainable Development Goals (SDGs) at multiple levels. These studies cover a wide range of scales, including national and subnational levels [13–15], and employ various methods, including quantitative assessments and big data analysis [16,17]. For example, Yu et al. [18] evaluated 16 SDGs for 31 provinces in China from 2000 to 2020 and found that the SDG index in China had improved, with most provinces making progress on most SDGs. The average scores for SDGs 3, 6, 11, and 16 in 2020 showed an increase compared to 2010, with increases of 22.36, 13.40, 15.21, and 25.11, respectively. However, the study found that the average scores for SDGs 12 and 15 decreased by 13.26 and 1.37, respectively. Therefore, how to effectively promote the achievement of the SDGs warrants careful consideration. Studies indicate that the achievement of numerous SDGs is intricately linked to land ecological quality. For example, land resources are critical for food security [19], and the protection of soil health through sustainable land management enhances food production efficiency, strengthens food security, and contributes to the attainment of SDG 2. A healthy land-use environment fosters sustainable economic activities and promotes ecotourism [20], thus contributing to the achievement of SDG 8. Maintaining and enhancing the ecological quality of land ecosystems ensures the sustainability of terrestrial ecosystems [21], thus contributing to the achievement of SDG 15. Land ecological environment quality is closely related to the sustainable development goals associated with environment, energy, and economic development.

In recent years, the realization of rational and sustainable land resource utilization has increasingly become a central focus for scholars both domestically and internationally [22]. Scholars primarily focus on the sustainability of land use to discuss its significance in achieving the SDGs. For instance, Lu et al. [23] developed a Sustainable Land Use (SLU) evaluation framework based on the SDGs, examining spatial and temporal variations in SLU levels across Chinese provinces and revealing an imbalance in sustainable development across regions. Nziguheba et al. [24] introduced a framework for SLU assessment, incorporating indirect quantitative indicators for agricultural practices. This framework is crucial for mitigating land degradation, enhancing food production efficiency, and safeguarding land resources. Qu et al. [25] conducted a comparative analysis of ecological land use changes in 282 urban and rural areas in China from 2009 to 2016 using statistical data. They found that, during the study period, the overall average change in urban ecological land use was 5.73%, while the overall average change in rural ecological land use was 4.52%.

They concluded that the sustainability of urban and rural land largely depends on land ecology. These studies highlight the importance of land use change in achieving the SDGs, yet they primarily focus on land itself [26,27], whereas the land ecological environment quality is the core and foundation of the sustainable use of land resources. Existing studies have yet to comprehensively explore how land ecological environment quality influences the achievement of SDGs. Therefore, this study expands the application scope of land ecological environment quality research from a new research perspective by integrating it with the SDGs. It provides a new perspective for understanding the relationship between land ecological quality and sustainable development, and offers valuable insights for China and other developing countries to promote the achievement of the SDGs from the perspective of land ecological environment, thereby contributing to China's overall sustainable development. In terms of establishing a land ecological environment quality evaluation system, existing frameworks primarily include the revised "Sustainable Land Use Evaluation Framework" by the Food and Agriculture Organization of the United Nations [28], the "Pressure-State-Response" (PSR) model-based evaluation system [29], the land ecological quality evaluation index system improved based on the "economic-environmental-social" model [30]. Among these, the PSR model, which emphasizes the human-land relationship and integrates social, economic, and environmental dimensions, offers the advantages of flexible indicator selection and a coherent, logical framework. Consequently, the PSR model was adopted in this study to construct the land ecological environment quality evaluation framework. Previous studies have combined statistical data with geospatial data in land ecological assessments, which enables a more comprehensive representation of both socio-economic activities and the spatial patterns of ecological environments, thereby improving the reliability and spatial explanatory power of land ecological evaluations [31,32]. Therefore, this study constructs the evaluation index system based on these two types of data to better capture the spatial variations in land ecological conditions. Several studies have highlighted the interactions between SDGs and other development factors [33]. Scholars suggest that synergies (positive correlations) and trade-offs (negative correlations) are useful for identifying these interactions [34]. Hegre et al. [35] employed principal component analysis to examine the interactions between SDGs, finding that SDGs 1–8 were strongly and positively correlated with SDG 11 (sustainable cities and communities), while SDG 10 (reduced inequalities) exhibited a trade-off relationship with most other goals. Song et al. [36] investigated the impact of land use efficiency on SDGs, observing that it exhibits a synergistic effect with nine of the SDGs. Previous research has demonstrated that synergies and trade-offs are effective tools for assessing the interactions between land ecological environment quality and the SDGs. Among the 17 SDGs outlined in the 2030 Agenda for Sustainable Development, at least four are directly linked to land. SDG 6 addresses the sustainable management of water resources and their availability, with land cover change impacting the quality and quantity of water resources [37]. SDG 11 is focused on urban sustainability to make cities and human settlements inclusive, safe, resilient, and sustainable. It includes 11 indicators across areas such as housing, transportation, architecture, culture, disaster risk reduction, the environment, and public space [38]. Land-use efficiency is closely linked to these indicators [39]. SDG 12 highlights the importance of responsible production and consumption, with land use playing a critical role in addressing the global resource crisis [40]. Specifically, SDG 15 underscores the crucial role of promoting terrestrial ecosystems' conservation, restoration, and sustainable management, which are directly linked to land use types and contribute to preserving natural habitats and biodiversity [41]. Consequently, this study concentrates on these four SDGs to investigate the synergistic or trade-off relationships between land ecological environment quality and the SDGs. The innovation of this study lies in combining land ecological environment quality

with the SDGs, exploring the synergies and trade-offs between the two, and providing a regional perspective for sustainable development in China.

Based on the above discussion, the present study chose 31 provinces in China to investigate interactions between the land ecological environment quality, pressure dimension, status dimension, response dimension, and SDGs (i.e., synergies and trade-offs) from 2010 to 2020. The research objectives can be summarized as follows:

- Construct a land ecological environment quality evaluation system based on the PSR model and analyze the evolutionary characteristics of land ecological environment quality in China from 2010 to 2020.
- Study the impact of land ecological environment quality and its pressure, state, and response dimensions on SDGs 6, 11, 12, and 15.
- Conduct an in-depth exploration of the synergies and trade-offs between land ecological environment quality, its pressure, state, and response dimensions, and SDGs 6, 11, 12, and 15 in different geographical and economic regions.

2. Study Area and Data

2.1. Study Area

The study area spans across 31 provinces in China, excluding Hong Kong, Macao, and Taiwan (Figure 1). It extends over a vast geographical range from 73° E to 135° E longitude and 4° N to 53° N latitude. China has a highly complex natural environment and an extensive land area covering approximately 9.6 million km². The climate transitions progressively from humid and semi-humid zones to monsoonal and semi-arid/arid climates, accompanying a rich diversity of land types. As the largest developing country, China has made remarkable achievements in economic development over the past decade. Since implementing the reform and opening-up policy, China has markedly enhanced its economic strength, modernized its agricultural and industrial sectors, intensified land use, and ensured consistent growth in food production. China's GDP rose from 41.21 trillion yuan in 2010 to 101.60 trillion yuan in 2020, reflecting an average annual growth rate exceeding 7%. Concurrent with economic growth, the standard of living in China has significantly improved, with per capita disposable income rising by 4.7% in 2020 relative to the previous year, while educational attainment has also experienced substantial gains. Nonetheless, the tension between economic growth and environmental protection remains significant [42], manifesting in various ecological challenges such as soil erosion, land desertification, and drought, which pose risks to China's sustainable development [43–45]. Therefore, investigating the relationship between land ecological environment quality and the SDGs can contribute to China's sustainable development.

Based upon the zoning guidelines issued by the National Bureau of Statistics of China (https://www.stats.gov.cn/zt_18555/zthd/sjtjr/dejtjkfr/tjkp/202302/t20230216_1909741.htm, accessed on 12 November 2025), China's 31 selected provinces are categorized into four primary geographical and economic zones: Northeastern, Eastern, Central, and Western regions. Employing this zoning strategy as a research framework represents a scientifically sound decision that systematically accounts for ecological features, socio-economic disparities, and policy implementation requirements across China's terrestrial ecological environments. This approach not only aligns with the intricate complexity of China's geographical landscape but also precisely elucidates regional variations and collaborative pathways between LEEQI and SDGs. Comprehensive details on the four major geo-economic regions are provided in Table S1.



Figure 1. Overview of the study area.

2.2. Data Source

Multiple datasets were employed to assess land ecological environment quality (LEEQ) over the period 2000–2020, utilizing five-year temporal intervals. Key data sources included land use, socioeconomic statistics, vegetation indices, ecological parameters (Table 1). Land use data formed the basis for calculating landscape pattern metrics. Supplementary Materials Table S2 details the land use classification system utilized in this study. The socio-economic data consist of gridded population density data and statistical data. Ecological data were derived from the spatial distribution dataset of plantation and natural forests in China. Vegetation data consist of normalized difference vegetation index (NDVI), fractional vegetation cover (FVC), leaf area index (LAI), and gross primary productivity (GPP). Both LAI and GPP datasets were resampled to a 1 km spatial resolution using the Google Earth Engine (GEE) platform.

Table 1. Data used in the study.

Data	Spatial Resolution	Data Source	Index
Multi period land use remote sensing monitoring dataset in China (CNLUCC)	1 km × 1 km	Resource and Environmental Science Data Registration and Publishing System (https://www.resdc.cn/Default.aspx , accessed on 30 December 2025)	Land use
China Population Spatial Distribution Kilometer Grid Dataset	1 km × 1 km	Resource and Environmental Science Data Registration and Publishing System (https://www.resdc.cn/Default.aspx , accessed on 30 December 2025)	Population density
Planted and natural forest maps in China from 1990 to 2020	1 km × 1 km	National Ecosystem Science Data Center (http://www.nesdc.org.cn , accessed on 30 December 2025)	Planted forest area

Table 1. *Cont.*

Data	Spatial Resolution	Data Source	Index
Annual NDVI and EVI 1 KM datasets in China	1 km × 1 km	Resource and Environmental Science Data Registration and Publishing System (https://www.resdc.cn/Default.aspx , accessed on 30 December 2025)	NDVI
Annual Vegetation Coverage (FVC) Dataset with a Resolution of 1000 m Nationwide	1 km × 1 km	Geographic Data Sharing Infrastructure, global resources data cloud (http://www.gis5g.com , accessed on 30 December 2025)	FVC
MODIS/Terra Leaf Area Index/FPAR 8-Day L4 Global 500 m SIN Grid V061 dataset	500 m × 500 m	National Aeronautics and Space Administration (NASA) (https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod15a2h-061 , accessed on 30 December 2025)	LAI
MODIS/Terra Net Primary Production Gap-Filled Yearly L4 Global 500 m SIN Grid V061 dataset	500 m × 500 m	National Aeronautics and Space Administration (NASA) (https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod17a3hgf-061 , accessed on 30 December 2025)	GPP
Statistical yearbook data	-	China Statistical Yearbook (https://data.stats.gov.cn , accessed on 30 December 2025)/China Statistical Yearbook on Environment (National Bureau of Statistics of the People's Republic of China & Ministry of Environmental Protection of the People's Republic of China, 2001–2022)/Finance Yearbook of China (Ministry of Finance of the People's Republic of China, 2001–2021)	Urbanization rate, Amount of fertilizer use in agriculture, Industrial solid waste generation, Environmental protection expenditure, The harmless treatment rate of domestic solid waste, Effective irrigated area, Comprehensive utilization of industrial solid waste, Wetland area

We employed the SDG scores derived from our prior research to assess their interactions with land ecological environmental quality (LEEQ). Following earlier research, the SDGs were classified into three major categories: ecological sustainability goals, economic sustainability goals, and social sustainability goals [36,46], as shown in Table S3. This study particularly focuses on environmental and economic aspects. The environmental indicators include SDG 6 (clean water and sanitation) and SDG 15 (life on land), while the economic indicators comprise SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production). The score data utilized in this study includes values for 2010, 2015, and 2020. Supplementary Figure S1 provides further detailed information on the SDG scores. The SDG evaluation provided a foundational framework for assessing the localization of the SDGs at the provincial level in China. The dataset integrates 174 indicators aligned with 96 specific targets across all 17 goals. SDG scores were calculated using a combination of the independent weighting coefficient method and averaging, which improves both the accuracy and stability of the results [47]. This has laid a solid foundation for the present study.

3. Method

3.1. Overview of the Methodology

Figure 2 outlines the analytical framework of this study. Firstly, we conducted data collection and processing, and developed a land ecological environment quality index (LEEQI) system grounded in the Pressure–State–Response (PSR) conceptual model. This

framework constructed three sub-indices—the pressure index (PI), state index (SI), and response index (RI)—which were integrated to form the comprehensive LEEQI. Subsequently, we assessed LEEQ in China through spatio-temporal pattern analysis, encompassing both temporal evolution and hotspot analysis. Thereafter, the spearman’s model was used to explore the associations between LEEQI (as well as PI, SI, and RI) and environmental and economic SDG scores for 6, 11, 12, and 15. To elucidate regional variations, we conducted a subnational analysis examining the interplay between land ecological conditions and progress toward specific SDGs across China’s major economic subregions. Our approach aimed to uncover context-dependent trade-offs and synergies shaping sustainable development outcomes.

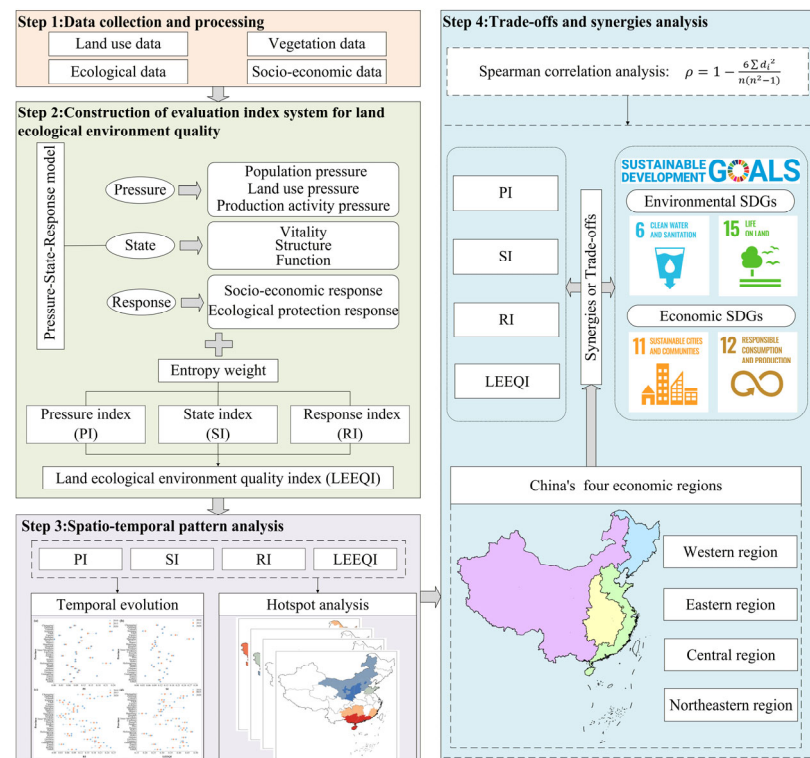


Figure 2. The analytical process of the study (In step four, purple represents the western region, blue represents the northeastern region, yellow represents the central region, and green represents the eastern region).

3.2. Indicator System Construction

The PSR model, proposed by the Organization for Economic Co-operation and Development (OECD), is a framework that describes the causes, specific manifestations, and response measures within a system by analyzing the interactions between pressure and state [48,49]. The PSR model delineates a continuous feedback loop between human activities and environmental conditions across three dimensions: the pressure dimension quantifies the impact of human activities on the environment; the state dimension reflects the prevailing environmental conditions under such pressures; and the response dimension emphasizes human actions aimed at mitigating or preventing adverse environmental impacts [50]. The PSR model offers a systematic framework for selecting relevant indicators across various dimensions and is well-suited for constructing comprehensive evaluation systems for assessing land ecological environment quality [51]. By the PSR framework, an evaluation index system for land ecological environment quality was developed through an extensive review of the literature, adhering to the principles of objectivity, comprehensiveness, operability, and data availability (Table 2). The weights of each evaluation

index are provided in Supplementary Table S4. As shown in the table, from the criteria layer perspective, the response dimension has the highest weight. Among the evaluation indicators, the area of afforested land and wetland area have the highest weights, indicating that their impact on land ecological quality is relatively greater.

Table 2. Evaluation index system for land ecological environment quality in 31 provinces of China.

Objective Layer	Criteria Layer	Factor Layer	Index Layer	Unit	Calculation/Connotation	References
Land ecological environment quality evaluation	Pressure	Population pressure	Population density (–)	Person/km ²	Total population/Land area	[31]
			Urbanization rate (–)	%	Urban population/Total population	[52]
		Land use pressure	Proportion of built-up land area (–)	%	Area of built-up land/Land area	[53]
			Comprehensive land use degree index (–)	/	$L = 100 \times \sum_{i=1}^{i=n} (A_i \times C_i)$ where A_i is the land use degree grading index, and C_i is the proportion of the corresponding land use type area.	[54]
		Production activity pressure	Amount of fertilizer use in agriculture (–)	kt	Fertilizer application calculated in terms of active ingredients.	[31]
			Industrial solid waste generation (–)	kt	The total amount of solid, semi-solid, and high-concentration liquid wastes generated by enterprises during the production process.	[55]
	State	Vegetation vitality	Normalized difference vegetation index (+)	/	$NDVI = \frac{1}{n_i} \sum_{j=1}^{n_i} NDVI_{ij}$ where $NDVI_{ij}$ is the $NDVI$ value of the j -th pixel within province i , and n_i is the total number of valid $NDVI$ pixels in province i .	[56]
			Shannon diversity index (+)	/	$SHDI = -\sum_{i=1}^m (p_i \times \ln p_i)$ where p_i is the proportion of landscape area of patch type i ; m is the total number of patch types.	[54,57]
			Landscape shape index (+)	/	$LSI = \frac{0.25E}{A} \times 100$ where E is the total perimeter of all patches in the landscape; A is the total landscape area.	[54,57]
		Structure	Largest patch index (+)	/	$LPI = \frac{a_{max}}{A} \times 100$ where a_{max} denotes the area of the largest patch within a landscape or of a specific patch type.	[54,57]
			Contagion index (+)	/	$CONTAG = \left[1 + \frac{\sum_{i=1}^m \sum_{k=1}^m \left(p_i \left(\frac{g_{ik}}{\sum_{k=1}^m g_{ik}} \right) \right) \left[\ln \left(p_i \left(\frac{g_{ik}}{\sum_{k=1}^m g_{ik}} \right) \right) \right] \right]}{2 \ln(m)} \right]$ where p_i is the proportion of the landscape area occupied by patch type i ; g_{ik} is the number of adjacencies between patch types i and k ; m is the total number of patch types.	[54,57]
		Function	Ecological function index (+)	/	$EFI = \frac{1}{3} \times \frac{FVC_{ij}}{FVC_{max}} + \frac{1}{3} \times \frac{LAI_{ij}}{LAI_{max}} + \frac{1}{3} \times \frac{GPP_{ij}}{GPP_{max}}$ where FVC_{ij} , LAI_{ij} , and GPP_{ij} represent the FVC , LAI , and GPP of pixel j in year i , respectively; FVC_{max} , LAI_{max} , and GPP_{max} are the maximum values of FVC , LAI , and GPP , respectively.	[58]
			Biological abundance index (+)	/	$BAI = A_{bio} \times \sum_{i=1}^n (P_i \times A_i)$ where A_{bio} is the normalization coefficient of the biological abundance index; p_i is the biological weight assigned to land use type i ; A_i is the area proportion of land use type i ; n is the total number of land use types.	[59]
		Response	Environmental protection expenditure (+)	$\times 10^4$ yuan	The proportion of government fiscal budget expenditures allocated to environmental protection.	[52]
			The harmless treatment rate of domestic solid waste (+)	%	Harmlessly treated domestic solid waste/Generated domestic solid waste	[31]
			Effective irrigated area (+)	ha	The total area of paddy fields and irrigated land capable of normal irrigation.	[31]
			Comprehensive utilization of industrial solid waste (+)	kt	The amount of solid waste from which enterprises recover or convert resources, energy, and other raw materials through recycling, processing, reuse, or exchange.	[60]
			Planted forest area (+)	km ²	$PFA = \sum_{j=1}^{n_i} A_{ij} \times I_{ij}$ where A_{ij} represents the area of the j -th pixel within province i , and I_{ij} is an indicator function, where $I_{ij} = 1$ if the pixel is classified as artificial forest, and $I_{ij} = 0$ otherwise. n_i denotes the total number of forest-related pixels within province i .	[61]
			Artificial wetland area (+)	$\times 10^4$ ha	The total area occupied by artificial wetland within a given region.	[59]

Note: “+” denotes a positive indicator; “–” denotes a negative indicator.

- **Pressure system**

We developed a set of pressure indicators encompassing population, land use, and production activities. Population density and urbanization rate were selected to represent population pressure, as increasing population and urbanization elevate the demand for land resources, potentially degrading land ecological conditions. Land use pressure was captured using the comprehensive land use intensity index and the proportion of construction land, reflecting the intensity of land development and its stress on ecosystems. The application of agricultural fertilizers can lead to soil acidification [62], water eutrophication and loss of biodiversity [63], while industrial pollutants cause a decline in land ecological quality by contaminating the soil, releasing harmful substances, and disrupting the land structure. Accordingly, the amount of fertilizer applied in agriculture and the generation of industrial solid waste were chosen to represent the pressures exerted on the land environment by human production activities.

- **State system**

Within the state dimension, we employed the widely recognized “vitality–structure–function” framework, which is commonly utilized in ecosystem assessments. The vitality indicator serves as a measure of the productivity and resilience of land ecosystems, with the NDVI selected as its representative metric. The structure indicators, designed to depict the spatial stability of ecosystems, encompass the SHDI, LSI, LPI and CONTAG. Collectively, these metrics capture three pivotal facets of landscape patterns: landscape patch area, patch shape, and patch spatial structure [64]. The functional indicators were chosen based on an EFI constructed from FVC, LAI, and GPP, facilitating a comprehensive, multidimensional portrayal of ecosystem functional status. The BAI was also selected as a functional indicator because it directly reflects the level of biodiversity and the health of ecosystem functions.

- **Response system**

In alignment with China’s ecological construction policies, the areas of artificial forests and wetlands were selected as ecological protection response indicators to reflect the effectiveness of conservation measures. From a socio-economic response perspective, environmental protection expenditure, domestic waste treatment rate, effective irrigated area, and comprehensive utilization of industrial solid waste were chosen to represent human actions addressing land ecological and environmental issues, encompassing both the economic capacity to support environmental sustainability and efforts to mitigate and alleviate pollution from industrial and agricultural activities.

3.3. LEEQI Calculation

The calculation of the LEEQI is crucial for quantifying the weights assigned to each indicator. The entropy weight method is a broadly recognized technique for determining these weights, as it effectively reduces the subjectivity associated with manual weight assignments and objectively reflects the relative significance of each indicator in comprehensive evaluations [65]. Therefore, we utilized the entropy weight method to quantify the weights of the selected indicators. Following this, the comprehensive value of land ecological environment quality was computed based upon the indicator weights derived through the entropy weight method.

- **Data normalization**

To mitigate the effects of inconsistencies in the data scales of various indicators, the data were normalized, with each indicator’s values scaled to the [0–1] range. The

evaluation indicators for land ecological environment quality are categorized into positive and negative indicators, with the specific normalization formulas provided below:

$$\text{Positive indicator : } x'_{ij} = \frac{x_{ij} - x_{jmin}}{x_{jmax} - x_{jmin}} \quad (1)$$

$$\text{Negative indicator : } x'_{ij} = \frac{x_{jmax} - x_{ij}}{x_{jmax} - x_{jmin}} \quad (2)$$

where i denotes the i -th ($1 \leq i \leq m$) province; j denotes the j -th ($1 \leq j \leq n$) evaluation indicator; x_{jmax} and x_{jmin} are the minimum and maximum values of the j -th evaluation indicator, respectively; x'_{ij} is the normalized processing result of the evaluation indicator value.

• Entropy calculation

In order to calculate the information entropy of each indicator, a probability parameter is needed. Here the probability parameter is specified as the proportion (p_{ij}): the value of the j -th indicator for the i -th province (x'_{ij})/the sum of the j -th indicator values for all provinces ($\sum_1^n x'_{ij}$). Then the Shannon entropy formula [66] was used to calculate the information entropy of the j -th indicator (H_j), as follows:

$$\begin{cases} H_j = -k \sum_{i=1}^n p_{ij} \times \ln p_{ij} \\ k = \frac{1}{\ln n} \\ p_{ij} = \frac{x'_{ij}}{\sum_1^n x'_{ij}} \end{cases} \quad (3)$$

• Weight quantification

An indicator with greater Shannon entropy means more uncertainty, so the weight of an indicator is negatively proportional to its Shannon entropy. The formula for quantifying the weight (w_j) of j -th indicator is as follows:

$$w_j = \frac{1 - H_j}{\sum_1^n 1 - H_j} \quad (4)$$

• Calculation of the integrated index

Individual indicators can only reflect certain aspects of the land ecological environment quality, thus a comprehensive evaluation method is employed. Certain indicators only reflect specific aspects of land ecological environment quality, so a comprehensive evaluation method is used. Within the land ecological environment quality framework of 31 provinces in China, the pressure, state, and response indices, as well as the composite index, are calculated using the following formulas, with the specific values provided in Supplementary Table S5.

$$Z = \sum_{j=1}^n w_j x'_{ij} \quad (5)$$

where Z represents the comprehensive evaluation value, which is a dimensionless index with a range from 0 to 1; w_j is the weight coefficient of the j -th indicator; x'_{ij} is the normalized processing result of the evaluation indicator value; n represents the number of indicators.

3.4. Hot Spot Analysis

The approach employed to investigate the distributional characteristics of local clusters was hot spot analysis, which pinpoints statistically significant high and low values in the spatial distribution of land ecological environment quality. We utilized the Getis-Ord G^* index in ArcGIS 10.7 to delineate the cold and hot spots of LEEQ across China [67]. This statistic compares the sum of the LEEQI of a unit and its surrounding units with

the total LEEQI of all units, and is used to analyze the spatial clustering of LEEQI in a local area. A notably positive G^* value denotes an agglomeration of high values in land ecological environment quality, whereas a significantly negative G^* value indicates an agglomeration of low values, corresponding to hot and cold spots, respectively [68]. The formula is presented as follows:

$$G_i^* = \frac{\sum_{j=1}^n w_{ij}x_j - \bar{x}\sum_{j=1}^n w_{ij}}{S\sqrt{\frac{n\sum_{j=1}^n w_{ij}^2 - \left(\sum_{j=1}^n w_{ij}\right)^2}{n-1}}} \quad (6)$$

where x_j represents the LEEQI of province j ; w_{ij} denotes the spatial weight matrix between province i and province j (calculated using the Queen's contiguity rule), if i and j are adjacent, the spatial weight is 1, otherwise, it is 0; $\bar{x}$ is the mean LEEQI; S is the standard deviation of LEEQI; n is the number of provinces.

3.5. Trade-Off and Synergies Analysis

To explore the impact of ecological environment quality on the attainment of SDGs, we examined the synergies and trade-offs, denoted by positive correlations (which facilitate SDG achievement) and negative correlations (which hinder SDG progress), respectively. We opted for the nonparametric Spearman's rank correlation coefficient (ρ) in SPSS 27.0 to ascertain the presence of synergy or trade-off between the LEEQI (along with PI, SI, and RI) and SDGs 6, 11, 12, and 15 [69].

The Spearman correlation coefficient provides an effective means of measuring the monotonic relationship between any two sets of data [70]. Unlike the Pearson correlation coefficient, Spearman's model does not require the variables to follow a normal distribution or be on the same scale. It is capable of detecting nonlinear relationships and exhibits reduced sensitivity to outliers [71]. Consequently, it is extensively utilized to investigate general associations between variables that extend beyond linear correlation. The correlation coefficient spans from -1 to $+1$, signifying either positive or negative associations. A coefficient of 0 denotes the absence of correlation, although this does not necessarily imply independence between the variables. The p -value quantifies the probability that the observed correlation arose by chance. If the p -value is near zero and falls below the significance threshold (p -value = 0.05), it suggests that the probability of no correlation existing is exceedingly low. Pradhan et al. [69] determined that a positive correlation (indicative of a synergistic relationship) between two SDGs can be established when the ρ -value exceeds 0.6. Conversely, negative correlations (indicative of trade-off relationships) can be identified when the ρ -value is less than -0.6 . In this study, we used the Spearman coefficient, i.e., the positive or negative of ρ -value, represents the synergies and trade-offs between LEEQI and SDGs. The formula is presented as follows:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)} \quad (7)$$

where ρ represents the Spearman correlation coefficient; d_i denotes the difference in rank values of the i -th data pair; n represents the total number of observations. According to the significance test, the value of ρ is considered meaningful when $p \leq 0.05$, indicating a significant correlation between LEEQI (PI, SI, and RI) and the SDGs.

4. Results

4.1. Spatiotemporal Pattern Analysis of Land Ecological Environment Quality

4.1.1. Temporal Evolution of LEEQI and Its Three Subdimensions

Figure 3 depicts the temporal evolution of the LEEQ Index across 31 Chinese provinces from 2010 to 2020, encompassing three sub-indices: pressure index (PI), state index (SI), and response index (RI). As demonstrated in Figure 3a, in the past decade, the range of PI values was between 0.00 and 0.24, and the PI values of all provinces showed a declining trend. Notably, the initial negative indicators for the PI calculation were processed using the reverse Min-Max normalization method—where higher normalized values correspond to lower actual environmental pressure. Consequently, the observed decrease in PI values signifies an escalation in land ecological environmental pressure within the LEEQ framework. The most significant declines in PI values were recorded in economically advanced eastern regions, including Tianjin (22% decrease), Beijing (12%), Jiangsu (17%), and Shandong (13%). These reductions reflect heightened land ecological pressures linked to high population density, industrial activities, and rapid urbanization—hallmarks of densely populated, developed areas. In contrast, Tibet and Heilongjiang demonstrated contrasting trends. Tibet's PI value rose from 0.14 in 2010 to 0.17 in 2020 (a 21% increase), signifying a notable easing of land ecological stress and relatively intact ecosystems, likely owing to low population density and effective conservation efforts. Similarly, Heilongjiang's PI value increased from 0.20 to 0.23 (15%), driven by the implementation of targeted ecological protection policies, which have facilitated ecosystem recovery and enhancement. To explore the long-term trends of LEEQI, PI, SI, and RI in China during the study period, we calculated the average values of the four indices for 2010, 2015, and 2020, and classified them into five categories using the equal interval method. Detailed information can be found in Supplementary Tables S5 and S6. We can see that the average PI values for the provinces ranged from 0.00 to 0.24. There were 4 provinces with lower values, 13 provinces with low values, 7 provinces with medium values, 4 provinces with high values, and 3 provinces with higher values. This result indicates that the land ecological pressure in most provinces was relatively low.

Figure 3b shows that between 2010 and 2020, the SI values for most provinces in China fluctuated minimally, with the SI range from 0.03 in Xinjiang to 0.29 in Shanghai. Notably, Shanghai exhibited the most significant improvement, with its SI rising from 0.26 in 2010 to 0.29 in 2020. This enhancement stems from science-based land-use planning, a substantial proportion of ecological space allocation, efficient land administration systems, and targeted policy interventions—collectively positioning Shanghai's land structure at the forefront of national optimality. In contrast, Tianjin exhibited the most pronounced decline in its SI value, dropping from 0.21 in 2010 to 0.17 in 2020—a reduction of 19.0% over the decade. The SI in Tianjin decline stems from industrial-urban trade-offs: rapid urbanization fragmented natural landscapes, reduced ecological connectivity (via LSI/NP changes), and degraded wetland-driven services. Unlike Shanghai's science-based planning, Tianjin's expansion prioritized industrial/built-up land over ecological conservation, exacerbating Shannon diversity's artificial bias and weakening landscape resilience. These structural shifts, coupled with policy gaps in green space protection and pollution control, collectively eroded SI, highlighting the need for balanced land-use policies to reconcile development and sustainability. According to Tables S5 and S6, the average SI values for the provinces ranged from 0.04 to 0.27. There were 6 provinces with lower values, 15 provinces with low values, 6 provinces with medium values, 3 provinces with high values, and 1 province with a higher value. This result indicates that the land ecological status in most provinces was relatively low, with a concentration in the low-value category.

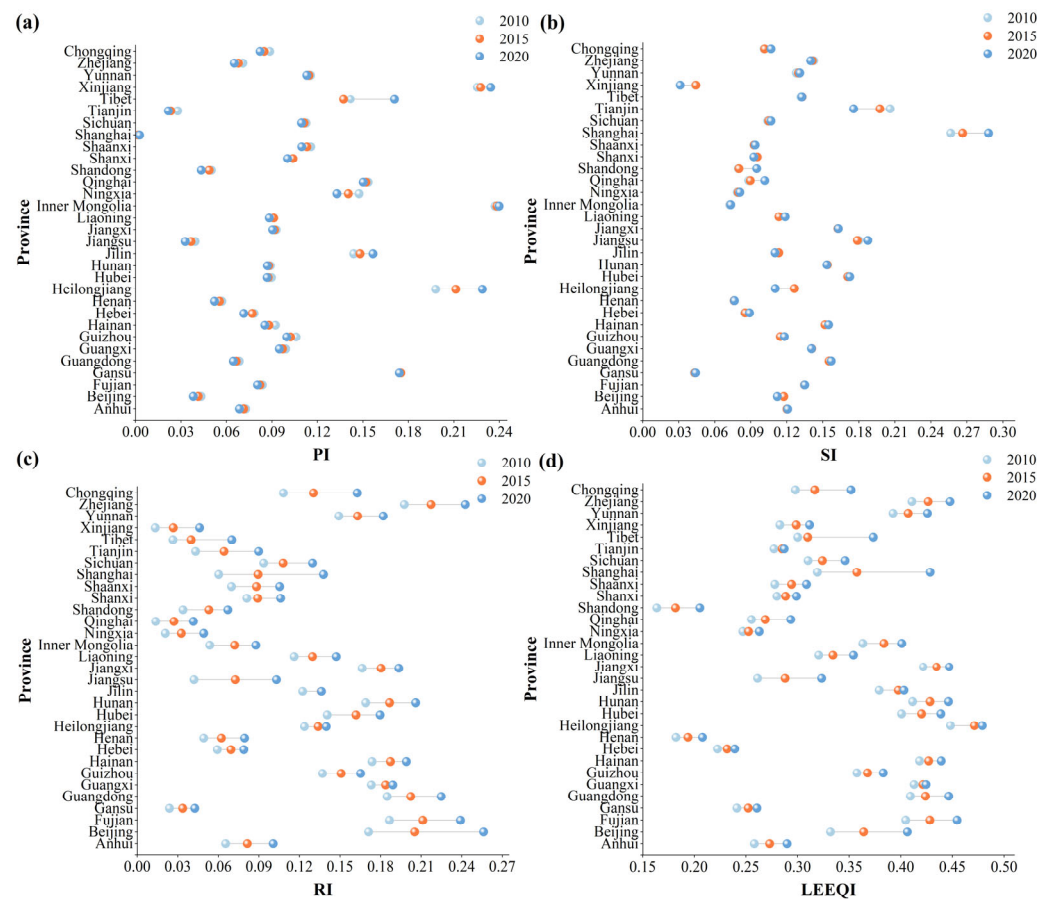


Figure 3. Temporal evolution of LEEQI across 31 Chinese provinces from 2010 to 2020: (a) PI, (b) SI, (c) RI, and (d) LEEQI.

Figure 3c shows that between 2010 and 2020, the RI values for all provinces in China ranged from 0.01 to 0.26, exhibiting a steady upward trend, with significant inter-provincial differences in the rate of increase. It underscores the heterogeneous nature of regional sustainability responses, emphasizing the need for province-specific strategies to amplify positive trends and address lagging areas. Beijing (+0.09), Shanghai (+0.08), and Jiangsu (+0.06) exhibited the most pronounced increases in RI values—surpassing the national average by 2–4 times—reflecting targeted ecological interventions and regional development strategies. This substantial increase manifests a marked enhancement in land ecosystem regulation and recovery capacity, rooted in intensive ecological restoration initiatives. Beijing’s RI growth is linked to afforestation under the “Three-North Shelterbelt Program” and urban green space expansion (e.g., 30% increase in green areas), which enhanced carbon sequestration and reduced PM_{2.5} levels by 40% [72,73]. Shanghai’s Yangtze River Delta Ecological Corridor restored 1200 km of coastal wetlands, improving flood resilience and biodiversity [74]. Jiangsu’s Jianchuan Project rehabilitated 12,000 hectares of wetlands, boosting water source protection and achieving a 9.36 benefit–cost ratio in ecological restoration [75]. According to Tables S5 and S6, the average RI values for the provinces ranged from 0.03 to 0.22. There were 7 provinces with lower values, 8 provinces with low values, 5 provinces with medium values, 5 provinces with high values, and 6 provinces with higher values. This result indicates that the response levels in most provinces were relatively high.

Figure 3d shows that the LEEQI for all provinces continued to increase, indicating substantial progress in land ecology and environmental protection during this period. Looking at the overall trend over the decade, the LEEQI values for the provinces ranged from 0.16

in Shandong to 0.48 in Heilongjiang. Shanghai's LEEQI exhibited a steady upward trajectory from 2010 to 2020, registering a 34% cumulative increase by 2020 relative to its 2010 baseline—a performance significantly outpacing most other regions in China. This marked improvement reflects the efficacy of targeted ecological modernization strategies aligned with national sustainability goals, particularly through the implementation of flagship initiatives such as the “Sponge City” program and “Eco-Corridor Construction” Projects. Guangxi Province's LEEQI demonstrated a moderate growth trajectory of 3% between 2010–2020, reflecting a distinct regional pattern of ecological stability rooted in its high forest coverage, robust ecological foundation, and consistent conservation strategies. This modest yet sustainable increase contrasts with more dynamic changes observed in other provinces, underscoring Guangxi's unique balance between natural capital preservation and incremental ecological improvement. According to Tables S5 and S6, the average RI values for the provinces ranged from 0.18 to 0.47. There were 3 provinces with lower values, 8 provinces with low values, 5 provinces with medium values, 6 provinces with high values, and 9 provinces with higher values. The average LEEQI for 15 provinces was in the high range, while 11 provinces had their LEEQI average in the low range. This result indicates that the land ecological environment quality in most provinces was relatively good.

Given China's expansive territorial expanse and significant regional disparities in land ecological environment quality, we undertook a comprehensive assessment of the LEEQI across four distinct geo-economic zones: Northeastern, Eastern, Central, and Western regions (Figure 4). As shown, average LEEQI values in all economic zones increased over time. In 2020, the Northeastern region (0.41 ± 0.03) exhibited the highest LEEQI, followed by the Eastern (0.37 ± 0.03) and Central regions (0.35 ± 0.04), while the Western region recorded the lowest value (0.34 ± 0.02). Notably, the disparity in LEEQI between the Western and Northeastern regions narrowed significantly—from a difference of 0.10 in 2010 to 0.07 in 2020—indicating a convergence in regional ecological quality improvements. This temporal reduction in regional gaps underscores the efficacy of targeted environmental policies and collaborative regional development strategies in promoting balanced ecological restoration across China's diverse geo-economic landscapes.

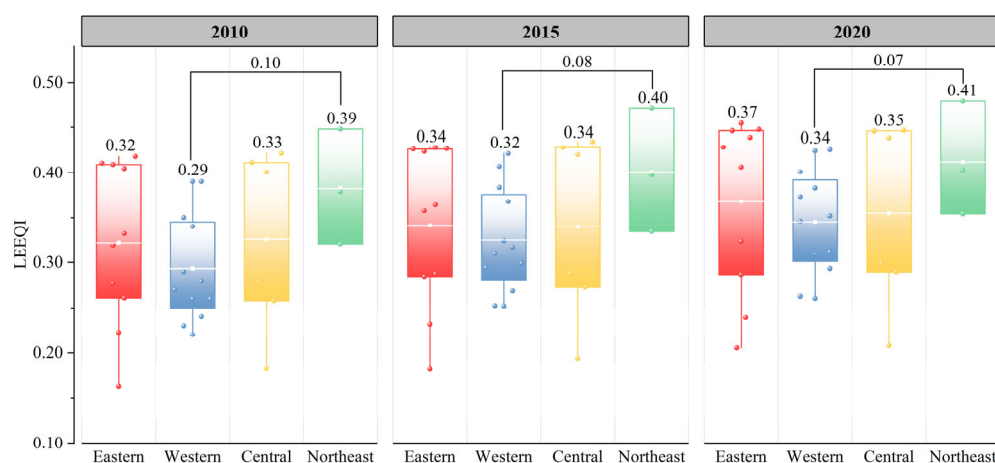


Figure 4. Temporal evolution of LEEQI across different geo-economic zones.

4.1.2. Hotspot Analysis of LEEQI and Its Three Sub-Dimensions

Figure 5 reveals the geographically distinct patterns of LEEQI and its sub-dimensions: pressure index (PI), state index (SI), and response index (RI), across regions in 2020, employing hot spot analysis to identify statistically significant clusters of high (hot spots) and low (cold spots) ecological quality in 2020. Figure 5a reveals that hotspots of the pressure index are concentrated in western regions of China, with Xinjiang and Tibet exhibiting significant spatial clustering at the 95% confidence level. This distribution pattern

indicates relatively low land ecological pressure and robust ecosystem carrying capacity in these areas, underscoring their potential for sustainable development. Xinjiang and Tibet, situated in high-altitude, cold ecological vulnerability zones, inherently experience limited human activity intensity. This reduces ecological disturbance and enhances the ecosystem's self-restoration capacity. Conversely, several eastern and central provinces emerged as ecological cold spots, signifying heightened land ecological pressure tied to dense populations and intensive land development.

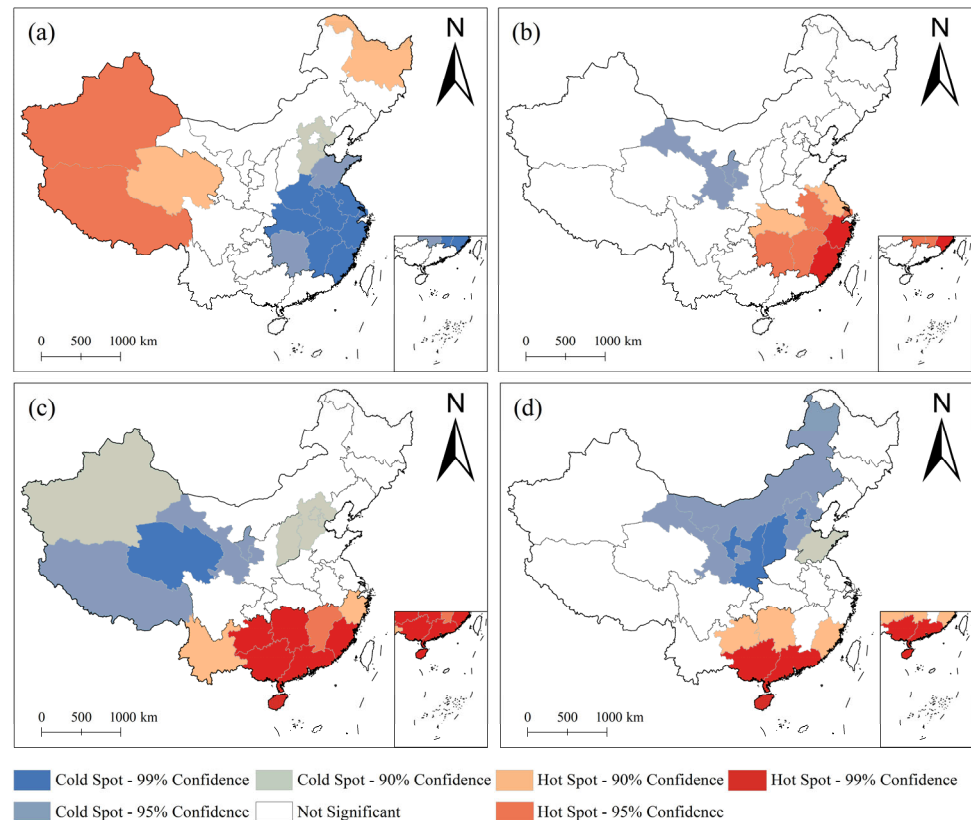


Figure 5. Spatial distribution of LEEQI across 31 provinces of China in 2020: (a) PI, (b) SI, (c) RI and (d) LEEQI.

Figure 5b shows that the hotspots of state index values were concentrated in the southeastern coastal areas and the middle and lower reaches of the Yangtze River, where favorable land structure, abundant precipitation, and high vegetation coverage support robust land state conditions. In contrast, Gansu and Ningxia were identified as ecological cold spots, underscoring severe ecosystem vulnerability and persistent challenges in ecological protection and restoration. This designation reflects a vicious cycle of ecological degradation, characterized by structural constraints (e.g., arid plateaus, fragmented river basins, and shallow soils that limit water retention and vegetation stability), functional misalignments (such as historical overexploitation for agriculture, grazing, and mining, which degrade soil quality and disrupt hydrological regulation), and biomass scarcity (exacerbated by low precipitation, high evaporation, and nutrient-poor soils, resulting in sparse vegetation cover and diminished carbon sequestration capacity). Together, these factors collectively undermine efforts toward sustainable ecological restoration, heighten susceptibility to climate change impacts, and amplify vulnerability to anthropogenic pressures—perpetuating a self-reinforcing cycle of degradation.

Figure 5c reveals that response index (RI) hotspots were predominantly concentrated in southern provinces of China. This spatial pattern profoundly reflects the synergistic effects of substantial policy investments and sustained ecological governance,

which have significantly enhanced land management and policy responsiveness in these regions. Southern provinces lead the nation in fiscal investment intensity for environmental protection, with funds prioritized for pollution control, ecological restoration, and environmental supervision. This directs hardware upgrades such as pollution treatment facilities and monitoring networks, strengthening the “capital-efficiency” conversion chain for policy execution. In addition, large-scale afforestation projects (e.g., returning farmland to forests, shelterbelt system construction) have boosted forest coverage in southern mountainous regions. This enhances soil and water conservation, carbon sequestration capacity. By contrast, cold spots emerged in underdeveloped western regions, including Qinghai and Tibet. These regions are characterized by lagging harmless treatment rates of domestic solid waste, constrained effective irrigated areas, underdeveloped comprehensive utilization of industrial solid waste, diminished planted forest areas, and reduced artificial wetland areas, collectively reflecting systemic governance gaps and ecological vulnerabilities, thereby necessitating targeted policy interventions and resource prioritization for balanced ecological stewardship.

Figure 5d reveals that the spatial distribution of LEEQI hot and cold spots in China manifests a pronounced “south-hot, north-cold” pattern, driven by climatic gradients, land-use intensification, and socioeconomic disparities, necessitating geographically differentiated ecological governance frameworks to address regional vulnerabilities. Hotspot regions were predominantly situated in southern provinces—most notably Guangdong and Guangxi—exhibiting statistical significance at the 99% confidence level. Secondary hotspot aggregation was observed in Guizhou, Hunan, and Fujian, with significance at the 90% level. These regions are characterized by favorable geographic positioning, abundant natural capital, and ecological landscape structure, which collectively contribute to their relatively elevated land ecological quality. By contrast, cold spots were predominantly concentrated in northern provinces—most notably Shanxi and Ningxia—exhibiting statistically significant clustering at the 99% confidence level. These regions are characterized by arid conditions and limited fertility, which impede vegetation growth and compromise soil stability, resulting in generally suboptimal land ecological quality.

4.2. Correlation Analyses Between Land Ecological Environment Quality and SDGs

Table 3 demonstrates the interconnections between the LEEQI—comprising its sub-indices of PI, SI, and RI—and four selected SDGs. LEEQI was positively correlated with SDG 6 (clean water and sanitation) ($\rho = 0.302^{**}$, p -value < 0.01), suggesting that a healthy land ecosystem contributed significantly to the provision and sustainable management of clean water and sanitation for all. Natural ecosystems, including terrestrial environments, play a crucial role in water storage, regulation, filtration, and purification, thus contributing to the achievement of SDG 6 [76]. A synergistic relationship between LEEQI and SDG 11 (sustainable cities and communities) was observed ($\rho = 0.339^{**}$, p -value < 0.01). Higher LEEQI scores indicated that enhanced land ecological quality fostered inclusive, safe, resilient, and sustainable urban environments. Urbanization and population growth exerted significant impacts on land ecosystems, as cities increasingly depended on the benefits derived from biodiversity and ecosystem services [77,78]. Prior research consistently demonstrated that enhancing ecosystem integrity and functionality strengthened urban resilience, thereby fostering sustainable urban development [33,79–81].

Table 3. Relationships between LEEQI and SDGs in 31 provinces of China (revealed by nonparametric Spearman's rank correlation).

Goal	LEEQI (<i>p</i> -Value)	Pressure Index (<i>p</i> -Value)	State Index (<i>p</i> -Value)	Response Index (<i>p</i> -Value)
SDG 6	0.302 **	0.340 **	0.275 **	0.355 **
SDG 11	0.339 **	0.412 **	0.337 **	0.403 **
SDG 12	0.212 *	0.646 **	0.449 **	0.468 **
SDG 15	0.335 **	0.032	0.138	0.384 **

Note: * is significant at 5% level; ** is significant at 1% level.

In addition, LEEQI was positively correlated with SDG 12 (responsible consumption and production) ($\rho = 0.212$ *, p -value < 0.05). It indicates that healthy land ecosystems play a pivotal role in advancing resource efficiency, reducing waste generation, and enabling the transition toward sustainable consumption and production systems. This interdependence underscores how ecological integrity directly supports SDG 12, such as decoupling economic growth from resource use, promoting circular economic models, and minimizing environmental footprints. A statistically significant strong positive correlation ($\rho = 0.335$ **, p -value < 0.01) existed between SDG 15 (life on land) and LEEQI, underscoring that enhancing land ecological quality is foundational to protecting, restoring, and sustainably utilizing terrestrial ecosystems while mitigating biodiversity loss. This relationship aligns logically with ecological restoration principles: rehabilitating degraded lands and reviving natural ecosystems—such as wetlands and forests—directly safeguard ecosystem health and functionality. As Hansen et al. [82] and Cao et al. [83] emphasize, such interventions are pivotal for maintaining biodiversity, regulating hydrological cycles, and sustaining carbon sequestration, thereby advancing targets of SDG 15.

Observations revealed positive correlations between the PI and SDGs 6 ($\rho = 0.340$ **, p -value < 0.01), 11 ($\rho = 0.412$ **, p -value < 0.01), and 12 ($\rho = 0.646$ **, p -value < 0.01). It indicated that reducing population, land-use, and production pressures contributed to achieving these goals. The rapid population growth, increased demand for living resources, and excessive land development had exacerbated the overuse and pollution of natural resources, thereby compromising water quality, the sustainability of urban environments, and resource efficiency. Therefore, it is essential to reasonably control population size, optimize land-use structures, and promote green production practices to advance the implementation of sustainable development goals. Synergistic relationships existed between SI and SDGs 6 ($\rho = 0.275$ **, p -value < 0.01), 11 ($\rho = 0.337$ **, p -value < 0.01), and 12 ($\rho = 0.449$ **, p -value < 0.01), underscoring that the stable land condition and robust ecological structure played a crucial role in enhancing the quality and sustainable management of water resources, as well as in fostering healthier living environments and resilient urban infrastructures. The RI had a synergistic effect with the four sustainable development goals of SDGs 6 ($\rho = 0.355$ **, p -value < 0.01), 11 ($\rho = 0.403$ **, p -value < 0.01), 12 ($\rho = 0.468$ **, p -value < 0.01), and 15 ($\rho = 0.384$ **, p -value < 0.01), suggesting that human-driven actions aimed at protecting ecosystems could significantly contribute to the realization of these SDGs. Through urban expansion and restoration efforts, coupled with the gradual enhancement of urban vegetation, substantial progress had been made, supported by sustained large-scale ecological restoration programs initiated by the Chinese government [84,85]. Our findings align with existing theoretical analyses, confirming the robustness of our results.

4.3. The Impact of LEEQI on SDG Under Varying Economic Zone Settings

Figure 6 illustrates the complex interactions between LEEQI and the four sustainable development goals (SDGs 6, 11, 12, and 15) across different economic regions. Notably, the synergistic effects of LEEQI were more pronounced in the eastern and central regions, where it exhibited a synergistic relationship with two of the sustainable development goals. This suggests that improving LEEQI in these regions can significantly promote the achievement of SDGs. This is primarily due to the higher levels of economic development and financial support in these regions, more institutionalized land use and ecological governance systems, and the national policy emphasis on urban sustainability and green transformation, enabling improvements in land ecological quality to more effectively contribute to overall progress in achieving sustainable development goals.

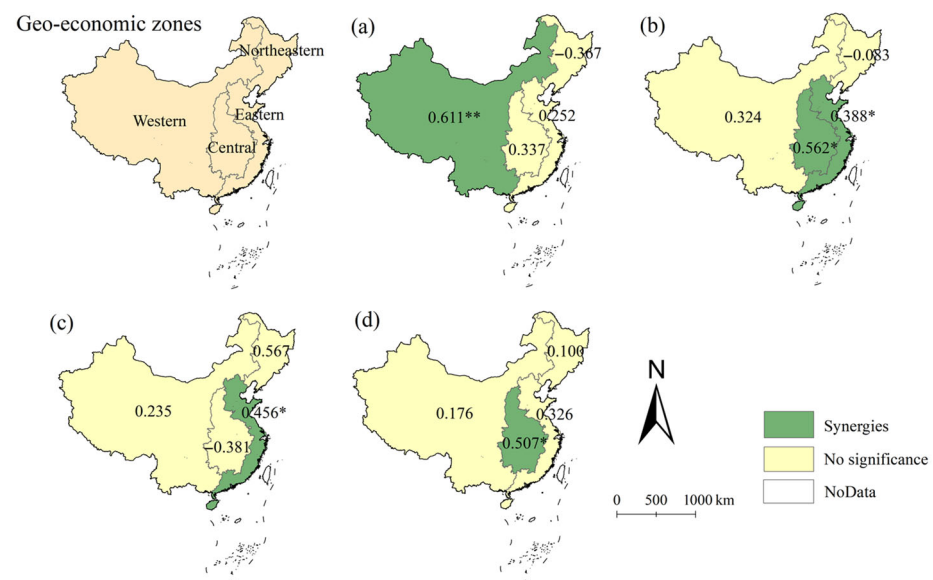


Figure 6. Relationships between LEEQI and SDGs under varying economic settings (* is significant at 5% level; ** is significant at 1% level): (a) SDG 6, (b) SDG 11, (c) SDG 12, and (d) SDG 15.

Figure 6a shows that in the western region, the synergistic effect of LEEQI on the implementation of SDG 6 was significant ($\rho = 0.611$ **, p -value < 0.01). In this region, the population density and urbanization rate were relatively low, and the direct pressure of economic activities on the ecosystem was limited. The region's favorable natural ecological conditions provided conducive conditions for water conservation and soil and water preservation. Furthermore, within the framework of the "Western Development" strategy, large-scale water conservancy and ecological restoration projects were implemented, offering both institutional and engineering support for the achievement of SDG 6. A comparison of the synergistic effects of LEEQI and the SDGs across economic zones and at the national level revealed that LEEQI in the western region contributed more significantly to SDG 6 than at the national level ($\rho = 0.302$ **, p -value < 0.01). This is attributed to western China being a key water source, where healthy river ecosystems played a critical role in improving environmental quality and safeguarding water resources [86].

Figure 6b shows that in eastern and central regions, LEEQI exhibited a synergistic effect with SDG 11, indicating that high-quality land ecosystems in these regions contributed to sustainable cities and communities [87]. This is due to the high-intensity urbanization and robust policy and financial support in eastern and central China, which had fostered a "pressure-governance-improvement" dynamic, enabling improvements in LEEQI to effectively support the achievement of urban sustainability goals. Furthermore, we observe that due to the implemented sustainable engineering in central China [88], the impact of

LEEQI on SDG 11 was stronger in the central region ($\rho = 0.562^*$, p -value < 0.05) than in the eastern region ($\rho = 0.388^*$, p -value < 0.05), suggesting that the eastern region still requires further improvement in land ecological quality to ensure urban sustainability.

Figure 6c shows that the correlation between LEEQI and SDG 12 was most significant in the eastern region ($\rho = 0.456^*$, p -value < 0.05). Although the land ecological environment in the eastern region had long been under high pressure, local governments had made relatively sufficient investments in environmental governance and resource utilization. For example, the performance of industrial solid waste recycling in the eastern region was notably higher than in the central and western regions [89], playing a key role in improving resource utilization efficiency and thus driving the coupling between LEEQI and SDG 12. Additionally, the ecological function and landscape pattern in the eastern region had been maintained under high-intensity development through the optimization of land use structure, further supporting the establishment of sustainable production and consumption patterns.

Figure 6d shows that LEEQI in central China exhibited a synergistic effect on SDG 15 ($\rho = 0.507^*$, p -value < 0.05), indicating that the region's high land ecological quality played a crucial role in promoting the protection of terrestrial biodiversity. In recent years, central China has significantly increased forest and wetland areas through large-scale afforestation and wetland protection projects, enhancing the integrity of regional ecosystems and habitat quality, which in turn supported biodiversity restoration and the improvement of ecological functions. Furthermore, national-level financial investments and the implementation of ecological redline policies had further strengthened the effectiveness of ecological protection, thereby reinforcing the synergistic effect of LEEQI on SDG 15 [90].

Figure 7 illustrates the associations between the PI and multiple SDG across China's major economic regions. The synergy was most evident in the western region, suggesting that alleviating land-use, population, and production pressures, as indicated by higher PI values played a pivotal role in advancing sustainable development in western China. Figure 7a shows a weak correlation between PI and SDG 6 across all economic regions, indicating that changes in land use pressure had yet to directly drive improvements in water resource management.

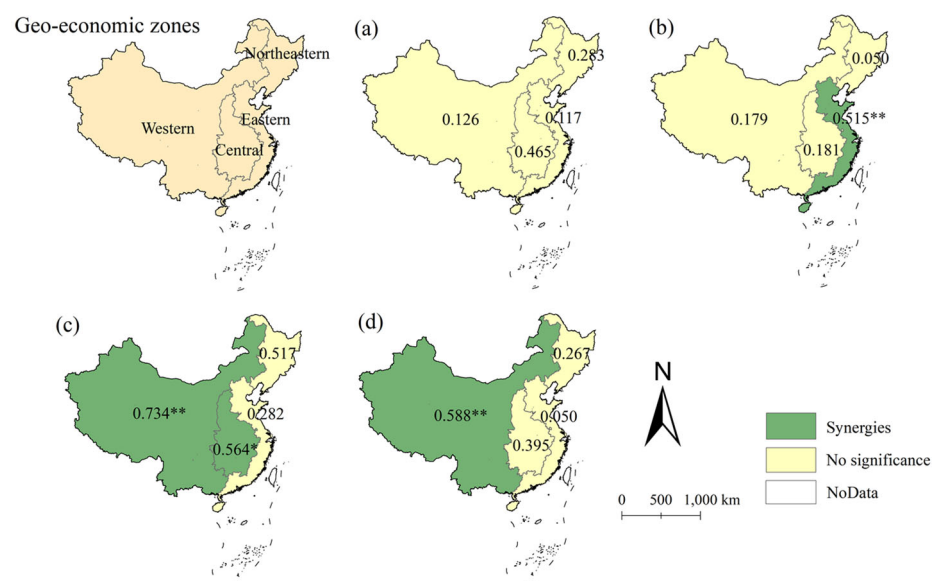


Figure 7. Relationships between PI and SDGs under varying economic settings (* is significant at 5% level; ** is significant at 1% level): (a) SDG 6, (b) SDG 11, (c) SDG 12, and (d) SDG 15.

Figure 7b shows a synergy between PI and SDG 11 ($\rho = 0.515^{**}$, p -value < 0.01) in the eastern region. This is likely due to the pressure on the ecological environment caused by factors such as urban expansion and infrastructure development during the high-intensity urbanization process, which in turn impeded sustainable urban development [91,92]. This aligns with the reality faced by large cities in eastern China, where ecological space was generally limited. Alleviating land-use pressures associated with urbanization, as reflected by higher PI values, was therefore critical to advancing sustainable urban development in the eastern region.

Figure 7c shows a significant positive correlation between PI and SDG 12 in the western region ($\rho = 0.743^{**}$, p -value < 0.01) and the central region ($\rho = 0.564^{*}$, p -value < 0.05). This indicates that in regions with relatively fragile resource and environmental carrying capacities, lower land-ecological pressure (higher PI values) more strongly promoted the transition toward sustainable production and consumption patterns. The ecological environment in the western region was fragile, with widespread desertification and combined with underdeveloped economies and unsustainable land use and human activities, these factors continued to pose significant barriers to the sustainable development of these areas [93,94]. It is therefore essential to alleviate these pressures to better advance the implementation of sustainable development goals.

Figure 7d shows a strong positive correlation between PI and SDG 15 ($\rho = 0.588^{**}$, p -value < 0.01) in the western region, indicating that lower land-use pressure had a significant positive effect on ecosystem protection. Given that these areas encompassed a large portion of China's forests, grasslands, and wetland ecosystems, reducing land-use pressure often directly enhanced the integrity of biological habitats and the provision of ecosystem services [95–97]. Specifically, our findings highlighted the need for greater attention to the land ecological pressures faced by cities in the western region to effectively promote the achievement of sustainable development goals.

Figure 8 illustrates the relationship between the SI and various sustainable development goals across different economic regions. It is evident that the SI had a more significant impact on sustainable development goals in the western region. Figure 8a,b show that the correlation between SI and SDG 6, SDG 11 was generally weak across different economic regions, with no significant synergistic or trade-off effects observed.

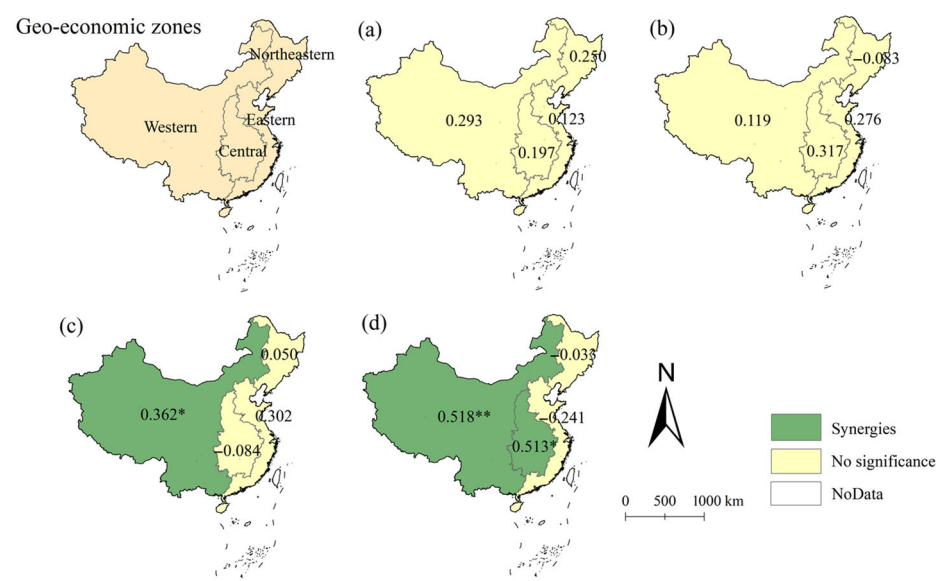


Figure 8. Relationships between SI and SDGs under varying economic settings (* is significant at 5% level; ** is significant at 1% level): (a) SDG 6, (b) SDG 11, (c) SDG 12, and (d) SDG 15.

Figure 8c shows a significant positive correlation between SI and SDG 12 in the western region ($\rho = 0.362^*$, p -value < 0.05), indicating that a healthier land ecological state contributed to improving resource utilization efficiency and fostering sustainable production patterns. This is linked to the region's diverse natural landscape and relatively strong ecological connectivity. The varied land use patterns not only enhanced ecosystem resilience and reduced the environmental risks associated with monocultural development, but also mitigated the pressures caused by overdevelopment. Furthermore, by promoting sustainable production models, these factors played a key role in supporting the achievement of SDG 12.

Figure 8d shows a significant positive correlation between SI and SDG 15 in both the western ($\rho = 0.518^{**}$, p -value < 0.01) and central ($\rho = 0.513^*$, p -value < 0.05) regions, indicating that a healthy land resource environment may foster terrestrial life. In the western region, the concentration of forests, grasslands, and wetlands, along with the maintenance of high landscape integrity, was crucial for the protection of biological habitats. Through effective land use planning, the central region enhanced landscape connectivity, enabling species to migrate and inhabit more effectively, thus promoting biodiversity conservation.

Figure 9 illustrates the impact of the RI on the SDGs across different economic regions. It is evident that the RI in the western region exhibited a synergistic effect on SDGs 6, 11, 12, and 15. The ecological environment in western China is more vulnerable [98], and the series of actions taken to protect the environment can significantly contribute to the achievement of sustainable development goals.

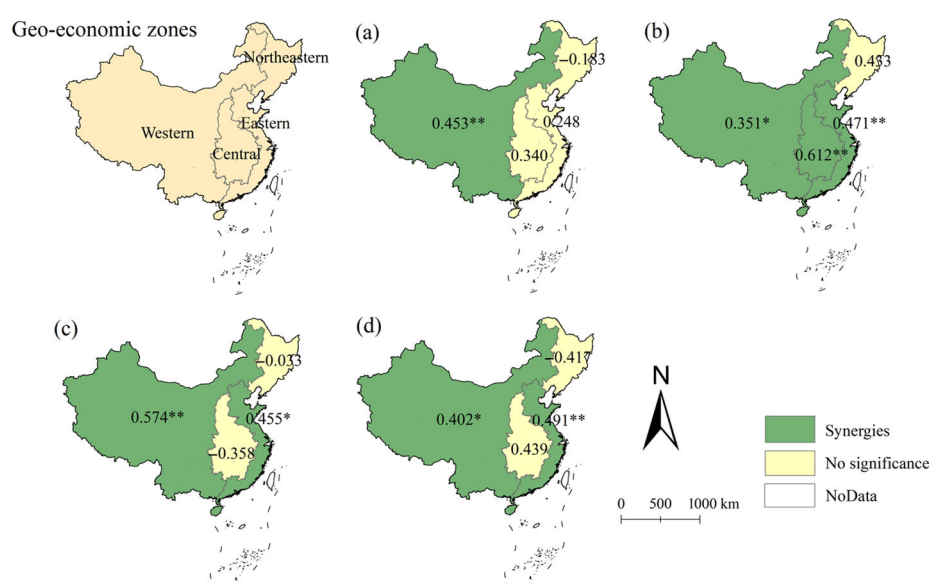


Figure 9. Relationships between RI and SDGs under varying economic settings (* is significant at 5% level; ** is significant at 1% level): (a) SDG 6, (b) SDG 11, (c) SDG 12, and (d) SDG 15.

Figure 9a shows a significant synergistic effect between RI and SDG 6 ($\rho = 0.453^{**}$, p -value < 0.01) in the western region, suggesting that policy and engineering responses, such as wetland restoration and the renovation of water conservancy infrastructure, could directly improve water resources and, in turn, facilitated the achievement of SDG 6.

Figure 9b shows a positive correlation between RI and SDG 11 across most economic regions in the country, with the central region being particularly prominent ($\rho = 0.612^{**}$, p -value < 0.01), indicating that environmental response measures generally promoted urban sustainability. National-level policies on new urbanization and spatial planning reforms had further strengthened the policy drive for sustainable urban development.

These measures had effectively alleviated environmental pressures while enhancing urban livability and resilience, thereby advancing the achievement of SDG 11 [99,100].

Figure 9c demonstrates a synergistic effect between RI and SDG 12 in both the western ($\rho = 0.574^{**}$, p -value < 0.01) and eastern ($\rho = 0.455^{*}$, p -value < 0.05) regions, indicating that responsive measures had enhanced resource utilization efficiency, thereby driving the achievement of SDG 12. The western region had made significant progress in addressing ecological pressures, implementing green agriculture, and transforming industries, while the eastern region had provided robust support for responsible consumption and production through technological innovation and stringent environmental policies.

Figure 9d shows a significant positive correlation between RI and SDG 15 in both the western ($\rho = 0.402^{*}$, p -value < 0.05) and eastern ($\rho = 0.491^{**}$, p -value < 0.01) regions. Notably, the promoting effect of RI on SDG 15 was stronger in the eastern region, primarily due to its stronger economic foundation, greater resource investment, and advanced technological capabilities. These factors enabled the region to allocate more resources to ecological protection and restoration, implement advanced management techniques, and enforce stringent environmental policies, all of which contributed to the achievement of sustainable development goals.

5. Discussion

5.1. Limitations and Future Research Directions

- **Data issues**

This study presents several limitations that warrant consideration. In this study, a 1 km spatial unit was selected to evaluate land ecological quality, primarily based on the spatial resolution of the available datasets [101]. Nevertheless, variations in spatial resolution may affect the results. Future research should therefore explore multi-scale analyses, integrate higher-resolution datasets, and quantify the influence of data uncertainties on the evaluation outcomes to enhance analytical accuracy. Regarding the SDG score data, while the approach proposed in the present study successfully demonstrates a significant correlation between land ecological quality and SDG scores, it only accounts for provincial SDG scores on an annual basis. This approach, however, is insufficient to underpin more detailed and region-specific strategies for ecological conservation and sustainable development. Consequently, future research should focus on acquiring more refined SDG scores at higher spatial and temporal resolutions (e.g., at the county level and on a seasonal basis).

- **Transferability**

This study investigated the influence of land ecosystem quality on the achievement of Sustainable Development Goals across 31 provinces in China. The study further explored the differential roles of land ecosystem quality in shaping individual SDGs across distinct economic regions. The findings indicate that the results possess significant applicability, particularly for developing nations like China. However, the social and ecological contexts of other countries may give rise to distinct sustainability challenges [102], potentially altering the relationship between land ecosystem quality and SDGs. For instance, land use practices, economic development models, and environmental governance frameworks in Europe and North America exhibit substantial differences compared to China, which could lead to distinct characterizations of the impacts of land ecosystem quality on SDGs in these regions. Therefore, future research should prioritize the exploration of the applicability of these findings to different countries and regions (e.g., developed nations, low-income countries, etc.).

Moreover, this study primarily concentrated on examining the impacts of land ecosystem quality on SDGs. Still, it does not fully encompass other critical factors, such as climate

change and natural disasters. As a result, the findings were insufficient in capturing the comprehensive sustainability impacts stemming from changes in land ecosystem quality. Consequently, future research should incorporate additional influencing factors and employ a broader range of analytical approaches, building upon the current framework, to more comprehensively elucidate the multifaceted sustainability impacts of changes in land ecological environment quality on SDGs, and to explore the causal mechanisms between land ecological quality and sustainable development goals in greater depth. Through these efforts, we aim to enhance the robustness and applicability of the research findings, thereby providing more precise guidance to policymakers and making a more substantial contribution to the realization of global sustainable development goals.

5.2. Policy Implications

Analyzing the interactions between LEEQI, PI, SI, RI, and the SDGs offers a novel perspective on achieving the SDGs. This study enhances the understanding of how developing countries, exemplified by China, can achieve the SDGs by improving land ecosystem quality. Given that our findings may contribute to realizing the 2030 Agenda for Sustainable Development, we propose the following policy recommendations.

The synergistic relationship between LEEQI and the SDGs indicates that higher LEEQI facilitates the achievement of the SDGs. Therefore, enhancing LEEQI is at the core of the policy framework aimed at achieving sustainable development. Policies should prioritize improving land management practices, promoting ecosystem restoration, and mitigating land pressure through sustainable agricultural practices. At the same time, scientifically sound land use planning should be implemented to ensure the effective allocation and utilization of land resources, thereby supporting China's efforts to achieve the SDGs. Ecological quality levels are often influenced by factors such as population pressure and socio-economic context. Therefore, the government should strengthen urbanization management to prevent excessive population concentration, promote the transformation of green industries, improve resource utilization efficiency, and reduce land development pressure. Given the regional differences in land ecological quality, tailored strategies are required. For example, in the western regions, where the natural environmental conditions are relatively harsh and economic infrastructure is underdeveloped, the improvement of land ecological conditions and response capacity is hindered [103]. Therefore, more attention should be given to alleviating land use pressure. These efforts should focus on the maintenance and restoration of natural ecosystems such as wetlands, forests, and grasslands, and accelerate ecological restoration work. In these regions, measures such as land leveling and the consolidation of fragmented cropland, in conjunction with soil and water conservation techniques and sustainable farming practices, can mitigate land degradation caused by over-cultivation. Moreover, excessive development should be strictly controlled, and ecological initiatives, such as converting farmland to forest, should be systematically promoted. In contrast, regions such as the eastern and central areas should promote sustainable urbanization to improve land use efficiency. The eastern economic zone holds substantial economic and technological advantages over other regions [104]. Therefore, it is essential to actively respond to management decisions. For instance, increased government support (e.g., fiscal transfers) should be allocated to infrastructure enhancement. In certain eastern coastal regions, wetland ecosystems can be rehabilitated through interventions such as developing industrial wetlands and establishing wetland protection zones. These measures can improve water quality, increase biodiversity, enhance ecological stability, and promote sustainable urban development alongside resource conservation. Additionally, regional cooperation should be encouraged, with the Eastern and Western regions shar-

ing technology and financial resources, collaborating to develop a green economy, and enhancing overall land ecological quality.

To effectively achieve the SDGs, China's land use policies should be closely aligned with broader environmental sustainability objectives. For example, integrating the Sustainable Development Goals framework into local land management policies ensures that land development is carried out in a way that protects ecological health. In addition, economic incentives for sustainable agriculture, eco-friendly industrial practices, and urban greening projects can further support the implementation of SDGs 12, 6, and 15. For different regions, in the western and eastern regions, governments must sustain investments in ecological governance and the establishment of protected areas, thereby fostering the achievement of SDG 15. Furthermore, water is essential for human development and ecosystem health, and the effective realization of nearly all SDGs is fundamentally dependent on water resources [105]. Thus, improving the resilience of fragile ecosystems and optimizing water resource management is paramount [103]. In Northwest China, environmental protection efforts, such as afforestation, have proven to be highly effective in rehabilitating desert and Gobi ecosystems, progressively transforming these regions into viable oases that support human livelihoods and ecological sustainability in arid and semi-arid areas. For instance, improving the ecological quality of regions like Inner Mongolia can significantly contribute to sustainable development [106]. Notably, central and western China should implement strategic policies to regulate population growth and industrial activities while facilitating the migration of populations to low-pressure areas. This approach will alleviate pressures in high-density regions while enhancing the carrying capacity and adaptive capacity of surrounding areas as economic development progresses. Additionally, farmland should be rationally planned to maximize its ecological functions, thereby contributing to the achievement of sustainable development goals.

6. Conclusions

Compared with previous studies, this study provided a land ecological environment quality evaluation system based on PSR model and directly linked the ecological environment quality of land to the SDGs at the provincial scale, thereby filling a significant research gap. More importantly, we first explained how economic zones regulated the consequence of LEEQI, PI, SI, RI, and SDG realizations. We systematically analyzed the synergies and trade-offs between LEEQI, PI, SI, RI, and SDGs. The conclusions can be drawn as follows.

- From 2010 to 2020, China's land ecological environment quality remained stable, with the southern regions exhibiting higher quality, and an overall upward trend, indicating substantial improvements. The spatial distribution of cold and hot spots in land ecological quality follows a "hot in the south, cold in the north" pattern. At the criterion level, the PI value shows a downward trend, the SI value fluctuates minimally, and the RI value exhibits an upward trend, reflecting an increase in land pressure, relatively stable land status, and a high response level across China. Regarding the classification of average values for LEEQI and the three subindices, the provinces with LEEQI and RI values above the medium level outnumber those with PI and SI values. Furthermore, regional differences are evident across the four major geoeconomic zones, with the gap in LEEQI between the western and northeastern regions gradually narrowing.
- Significant synergies existed between LEEQI, RI, and SDGs 6, 11, 12, and 15. At the same time, a synergistic relationship was also observed between PI, SI and SDGs 6, 11, and 12. These findings indicated that improving land ecological environmental quality, alleviating land pressures, maintaining a healthy land ecosystem, and implementing

proactive response measures could jointly facilitate the achievement of sustainable development goals.

- The synergistic effect of land ecological quality on SDG 6 was most pronounced in the western region, while in the eastern region, land ecological quality exhibited a synergistic effect with both SDG 11 and SDG 12. In the central region, land ecological quality showed a synergistic effect with SDG 11 and SDG 15, whereas no significant synergistic or trade-off effects were observed between land ecological quality and the sustainable development goals in the northeastern region. This highlighted the critical importance of improving land ecological quality to effectively promote the implementation of sustainable development goals in the western region.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18062852/s1>, Table S1. Geographical and economic zone division in China. Table S2. Classification system of Multi period Land Use Remote Sensing Monitoring Dataset in China. Table S3. SDGs classification scheme. Table S4. Evaluation index weight table. Table S5. The LEEQI, PI, SI, and RI values for China's 31 provinces from 2010 to 2020. Table S6. The average values of LEEQI, PI, SI, and RI for China's 31 provinces from 2010 to 2020. Table S7. The grading standards for the average values of LEEQI, PI, SI, and RI for China's 31 provinces from 2010 to 2020. Figure S1. Scores of SDGs 6, 11, 12, and 15 for 31 provincial-level administrative units in China from 2010 to 2020.

Author Contributions: Y.L.: Methodology, Formal analysis, Writing—review and editing, Writing—original draft, Resources, Investigation, Data curation. S.C.: Methodology, Writing—review and editing, Supervision, Resources, Conceptualization. S.W.: Writing—review and editing, Validation, Investigation, Formal analysis, Data curation. Y.Q.: Writing—review and editing, Validation, Investigation, Formal analysis, Data curation. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the National Natural Science Foundation (NSFC) of China (No. 42301394) and supported by the Young Faculty Development Program (“Qingjiao Plan”) of Beijing University of Civil Engineering and Architecture (No. X25025).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declared that they have no conflicts of interest to this work.

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