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Ecological Evaluation of Land Resources in the Yangtze River Delta Region by Remote Sensing Observation

Yanlong Guo [1,*], Peiyu He [1], Pengyu Chen [1] and Linfu Zhang [2]

[1] Social Innovation Design Research Center, Anhui University, Hefei 203106, China
[2] Faculty of Arts and Social Sciences, Lancaster University, Lancaster LA1 4 YW, UK
* Correspondence: 20106@ahu.edu.cn; Tel.: +86-15256556306

Abstract: The evaluation of land ecological security (LES) evaluates how human activity and land use affect land ecosystems. Its ultimate objective is to provide guidance and assistance for decision making in order to preserve and restore the efficacy and health of terrestrial ecosystems. The assessment model presented in this article is comprehensive and integrates the advantages of both subjective and objective weighting techniques. This study extends the "Pressure–State–Response" (PSR) model to "Driver–Pressure–State-Impact–Response" (DPSIR) and combines it with TOPSISI to determine the weights of each contributing component. Furthermore, the geographical and temporal distribution patterns of regional land ecological security levels were investigated using GIS geostatistical approaches. According to this study, (1) the Yangtze River Delta region's LES index, with a mean value in the fairly safe range, is generally safe. The year 2019 marks an inflection point for the index, with the highest level of ecological safety on land. The primary element is the modification of environmental policies that are enacted by the government. (2) The LES status is divided into two stages during the course of this study. The Yangtze River Delta region's LES quickly develops throughout the first stage (2012–2019), which sees a shift in the safety rating from IV to II. The second stage (2019–2023) sees a progressive improvement in the LES index and a shift in the safety category from Class II to Class I. (3) Important variables influencing the geographical distribution of LES in the Yangtze River Delta region include barrier elements, including soil and water erosion areas, flood disaster areas, grain planting areas, urban green covering areas, and effective irrigation areas of farmland.

Keywords: land resources; ecological security; evaluation index system; PSR model; Yangtze River Delta region

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1. Introduction

When ecosystems are able to fulfill human civilizations' demands for sustainable development while preserving their fundamental worth and ability to operate normally, this is known as ecological security [1]. Land, as an essential component of ecosystems, is a key material carrier for the fulfillment of ecological functions [2,3]. Land resources are necessary for human survival and labor resources and are essential for the security and comprehensive development of the country [4]. Nonetheless, the backdrop of urbanization and global industrialization in recent times has spurred the Yangtze River Delta region's explosive growth in China [5–7]. Over the past 40 years, a sizable portion of natural terrain has been transformed into artificial surfaces in the Yangtze River Delta region [8]. This conversion resulted in changes in land use patterns, and the irrational use of land resources has led to an imbalance in land resource ecosystems [9,10]. Conflicts between ecological conservation and human land-use activities are becoming increasingly evident and pose a major threat to regional ecological security [11]. Therefore, maintaining the ecological security of land resources is an important foundation and a necessary condition for achieving the lasting development and utilization of land assets. Good land ecology helps to maintain the

long-term balance of natural, economic, and social ecosystems [12]. It can provide a basic reference for achieving the optimal trade-off between human construction activities and the ecological security of land resources [13].

Land ecological security has become a hot topic for scholars in the 21st century [14]. Existing studies have concentrated on the socioeconomic effects of land resource use on the environment [15]. Humans are changing the face of the world by expanding agricultural manufacturing, increasing urban areas, and decreasing the use of ecological land such as forests, grasslands, and woodlands [16]. While land use around the world may vary in terms of specific uses, the end result is similar: a certain economic value is gained from the consumption of land resources through their exploitation [17]. Salavati et al. (2018) claimed that changes in urban planning and land usage sprawl have a direct impact on socioeconomic functions and urban structure [18]. Numerous investigations have furthermore demonstrated the consequences of land usage on global warming, worldwide ecosystems, disturbance degradation of biodiversity [19,20], water resources [21], and the global carbon cycle [19]. It can be seen that land ecosystems play a vital role in maintaining the health of natural ecosystems and the balance of social structures. It also provides stable, balanced, and abundant natural resources to promote the development of natural ecosystems and socioeconomic and other complexes [22].

At present, scholars have conducted many studies on the evaluation of land ecological security, and in the world, early warning studies on ecological security have focused on land quality, land fertility, and soil degradation [23]. China has mainly focused on the study areas of the northwest and southwest [24–26]. The study object is mainly lakes [27], arable land [28], plateaus [29], and mountainous areas. In terms of the research domain, less research has been conducted on the YRD region [30]. Currently, there exist several techniques to assess land ecological security; the most popular ones are the fuzzy comprehensive assessment approach and the composite index method [1]. However, the composite index method is highly subjective in evaluating the quality of the soil environment, and the results can only qualitatively judge the severity of the pollution without determining the level of land ecological quality attributed to the criteria [31]. Although a fuzzy comprehensive assessment technique can solve the influence of fuzzy boundaries of evaluation criteria and detection errors on the evaluation results, the use of the algorithm of taking the greater and the lesser in its method leads to a weaker degree of synthesis and the loss of more information [32]. Therefore, it is necessary to explore a new, scientific method for evaluating the land resources' ecological security.

Land resources are a complex and variable system involving the interaction of many factors, and the results of land environment monitoring are multifaceted, thus the evaluation of the ecological quality of land resources requires a thorough analysis of several indicators [33]. The entropy weight technique is an objective way of determining the information-entropy-theory-based weights of the indicators. It determines the weight of each indicator according to the amount of information it provides, avoiding the bias brought by subjective judgment. In the evaluation of regional ecological security, the importance of different indicators is often difficult to directly quantify, and the entropy weighting method can provide us with a relatively objective and scientific weight allocation scheme. The multiobjective TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) model, a multiobjective decision analysis technique, ranks evaluation items according to how close they are to both a positive and negative ideal solution [34]. The TOPSIS technique is often used in the multiobjective decision analysis of finite programmers and is widely used in areas such as benefit assessment, health decision making, resource management, and natural disaster analysis [35,36]. Combining the entropy weight method with the TOPSIS model can give full play to the advantages of both. The entropy weight method provides us with an objective weight allocation scheme, while the TOPSIS model is able to provide a comprehensive evaluation and ranking of evaluation objects based on these weights. This combination makes our evaluation results more scientific, reasonable,

and reliable [37]. Therefore, the TOPSIS method is applicable to assessing the ecological security status of land resources and can give objective and reasonable evaluation results.

2. Research Field and Approach

2.1. Yangtze River Delta Area

The Yangtze River Delta region area was the study's primary focus (Figure 1), which includes Shanghai, Jiangsu, Zhejiang, and Anhui Provinces and spans 35.8 × 104 km^2 between 114°~123° E and 27°~35° N. The Yangtze River Delta region has a flat topography with a declining tendency from southwest to northeast. Plains dominate the center and northern regions of the Yangtze River Delta, while the southern half is hilly and mountainous. The majority of the YRD region has warm, humid subtropical monsoon weather with a reasonably even seasonal distribution.

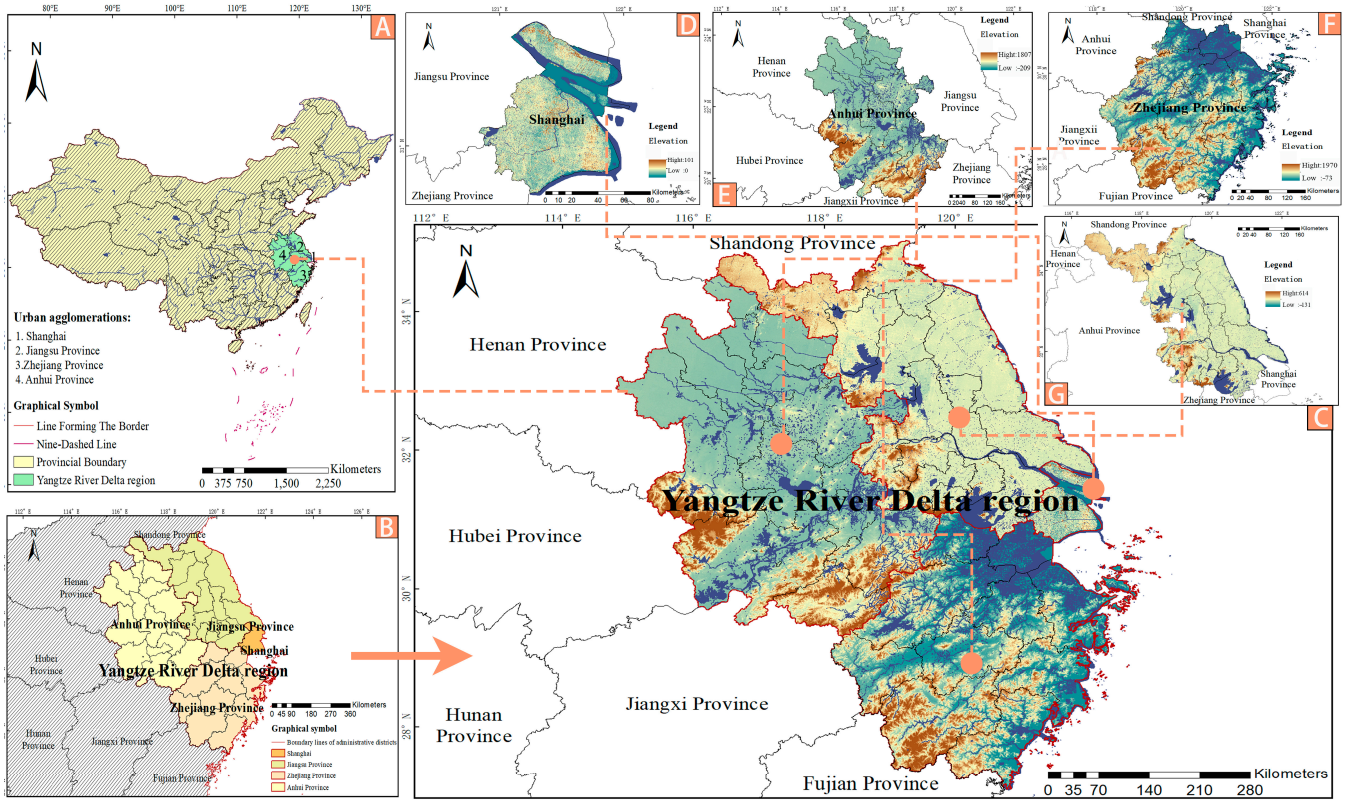


Figure 1. Geographic scope and location of the Yangtze River Delta region. (**A**) Map of China's Administrative Districts; (**B**) Map of the Yangtze River Delta Administrative Region; (**C**) Elevation map of the Yangtze River Delta; (**D**) Elevation map of Shanghai; (**E**) Elevation map of Anhui Province; (**F**) Elevation map of Zhejiang Province; (**G**) Elevation map of Jiangsu Province.

2.2. Sources of Data for the Research Field

The data for each year required for the study of ecological stability of the Yangtze River Delta region's land resources were obtained from China Water Resources Yearbook (2012–2023), China Urban Statistics Yearbook (2012–2023), China Energy Statistical Yearbook (2012–2023), and Jiangsu Statistical Yearbook (2012–2023), Zhejiang Statistical Yearbook (2012–2023), Anhui Statistical Yearbook (2012–2023), Shanghai Statistical, official data published by the provinces and cities of Shanghai, Jiangsu, Zhejiang, and Anhui provinces, as well as the bulletins on the evolution of social statistics and the country's financial system in the aforementioned provinces and cities. Provincial boundary vectors and municipal vectors of the Yangtze River Delta region were obtained from the China Basic Geographic Information Database (CBGID), and elevation information was acquired from the Chinese Academy of Sciences' Resource and Environment Science Data Center (RESDC)

(Table 1). The choice of 2012–2023 as the assessment period is significant for our study. To begin, this time span encompasses a number of significant policy and environmental event cycles, allowing for a fuller reflection of the interplay between policy, environment, and socioeconomic aspects. Second, by examining data from this time span, we may more correctly identify the important elements and mechanisms influencing ecological security, thereby providing a scientific foundation for the development of targeted policies. Finally, this time period coincides with current hotspots and research orientations in the academic and policy sectors on ecological security challenges, allowing our study findings to be more extensively identified and used. For some of the missing data, the multiple interpolation and average growth rate methods are used for calculation so as to effectively fill in the missing data and make the evaluation results more complete and more accurate.

Table 1. The comparable worth of ecological system services for each unit area of terrestrial ecological systems in China.

Data Name	Year	Description	Data Sources
DEM	2023	Digital elevation model with 30 m spatial resolution	https://www.resdc.cn/ "URL (accessed on 24 May 2024)"
Data on administrative divisions	2023	Used to extract study area boundaries	http://www.geodata.cn/ "URL (accessed on 24 May 2024)"
Data on municipal administrative centers	2023	Used to identify regional administrative centers	http://www.ngcc.cn/ "URL (accessed on 25 May 2024)"
Statistical data on objective status	2012–2023	Contains data on population, land, economy, etc.	Shanghai Statistical Yearbook, Jiangsu Statistical Yearbook, Anhui Statistical Yearbook, Zhejiang Statistical Yearbook, etc.

2.3. Ecological Security of Land Resources Assessment Model

The PSR framework was created in the late 1980s based on studies conducted by the Canadian government by the United Nations Environment Programmer (UNEP) and the Organization for Economic Cooperation and Development (OECD) [38]. In order to make the study more comprehensive, this study adds two additional dimensions to the PSR framework to optimize the composition of the DPSIR framework. The DPSIR (Driving Forces-Pressures-States-Impacts-Responses) framework is an integrated and systematic environmental management tool that analyses environmental problems from multiple dimensions [28]. The framework not only focuses on the immediate causes of environmental problems (e.g., pressures) but also analyzes the underlying drivers and impacts of changes in the status of the environment, and ultimately, points to the responses of human society. This comprehensive analytical approach enables a more holistic understanding of the complexity and multilayered nature of regional ecological security issues. By identifying and analyzing key factors and links, ecological protection and management policies can be formulated and implemented in a more targeted manner.

The framework is based on human society and natural ecosystems and organizes and classifies ecological and environmental indicators in which a certain type of ecological and environmental problem could be represented by five distinct but related categories of indicators: the driving force indicator reveals the social factors that contribute to the increase or decrease in the carrying pressure on the regional system; the pressure indicator shows the root cause of the crisis of the land ecosystems; the state indicator characterizes the real situation of resources from nature, as well as the state of the environment and ecological security under the action of pressure factors; and the impact indicator refers to the outcome due to the environmental condition. State indicators characterize the reality of natural resources and the state of the environment and ecological security in the face of pressure factors. Impact indicators refer to outcomes due to the state of the environment and represent observable positive or negative outcomes. Response indicators indicate

various reactions from people to environmental degradation or to prevent damage to resources (Figure 2).

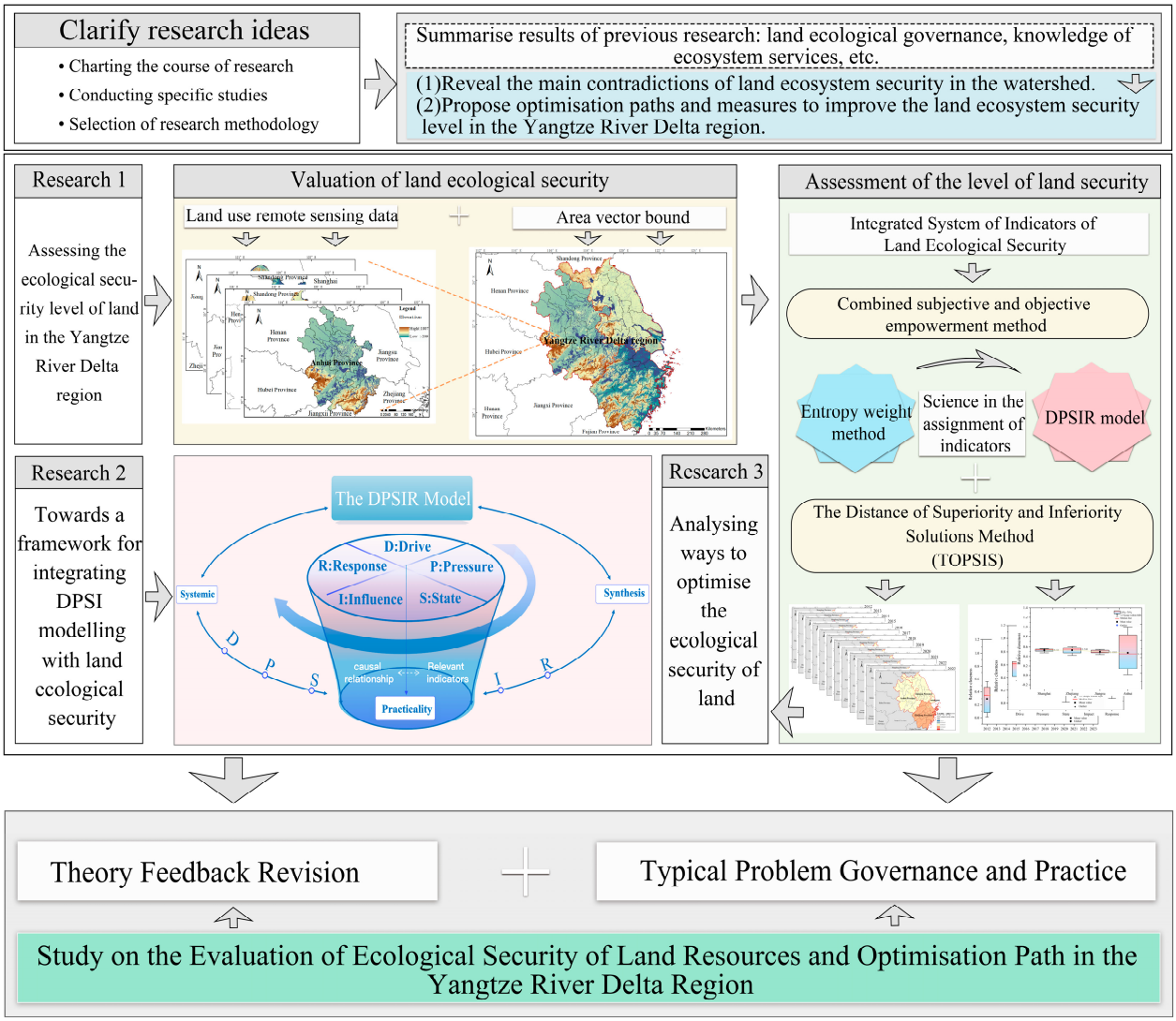


Figure 2. Logical framework for the evaluation study of ecological security of land resources in the Yangtze River Delta region.

Building an Assessment Framework for Ecological Security of Land Resources in the YRD Area

Land is a complicated entity, so the study of the ecological security of land resources in the Yangtze River Delta region is performed according to the DPSIR model (Figure 3), combining the principles of regionality, system city, scientificity, and quantifiability, as well as combining the actual situation of the Yangtze River Delta region with the summary of the literature [1,3,38], to construct the assessment of the land's ecological security covering 25 factors, starting from environmental, resource, and social dimensions, in addition to the economic and environmental ones. The indicator system is presented in Table 2.

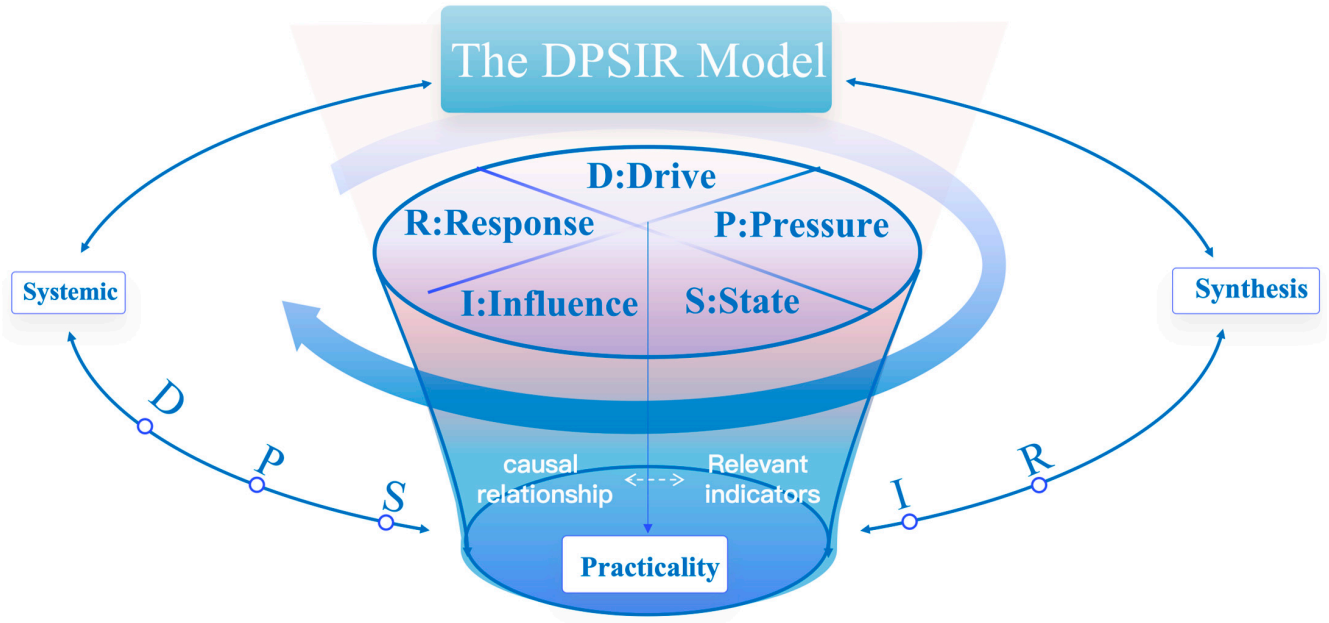


Figure 3. Evaluation indicators of land ecological security in the Yangtze River Delta region.

Table 2. Indicators for assessing land ecological security in the Yangtze River Delta region.

Target Level	Normative Layer	Indicator Layer (Unit)	Trends	Weights
Ecological Security of Land Resources in the Yangtze River Delta Region	Drive	X1: GDP per capita (Million yuan)	+	0.0417
		X2: Share of tertiary sector in GDP (%)	+	0.0285
		X3: Natural population growth rate (%)	-	0.0293
		X4: Birth rate (%)	-	0.0328
	Pressure	X5: Population density (persons/square kilometer)	-	0.0198
		X6: Land area for urban construction (10,000 square meters)	-	0.0329
		X7: Land acquisition for property development (10,000 square meters)	-	0.0257
		X8: Pesticide use on arable land (tones)	-	0.0405
		X9: Fertilizer application to arable land (tones)	-	0.0437
		X10: Urbanization rate (%)	-	0.0339
	State	X11: Forest cover (%)	+	0.0316
		X12: Grain yield per unit of arable land (kg/ha)	+	0.0454
		X13: Green areas of parks (thousands of hectares)	+	0.0403
		X14: Effective irrigated area (thousands of hectares)	+	0.0195
	Influence	X15: Land area sown with crops (thousands of hectares)	+	0.0680
		X16: Green space coverage in built-up areas (%)	+	0.0302
		X17: Area affected by crops (thousands of hectares)	-	0.5040
		X18: Area affected by geological disasters (thousands of hectares)	-	0.0277
		X19: Share of nature reserves in area under jurisdiction (%)	+	0.1304
	Response	X20: Local fiscal expenditure on environmental protection (billion yuan)	+	0.0322
		X21: Total afforestation area for the year (thousands of hectares)	+	0.0546
		X22: Centralized treatment rate of sewage treatment plants (%)	+	0.0344
		X23: Nonhazardous treatment rate of domestic waste (%)	+	0.0145
		X24: Area covered by urban greenery (thousands of hectares)	+	0.0417
		X25: Deflooded Area (thousands of hectares)	+	0.0506

Driving force indicators represent societal aspects improving land resources' ecological security in the research region, including economic elements. Pressure indications show the amount of pressure on land generated by social development and the pressure caused by natural disasters; examples include the amount of land needed for urban growth, the

number of pesticides and fertilizers used, and floods. State indicators reflect the current status of the natural environment and ecosystem functions, such as food production per unit of arable land area, forest coverage, effective irrigation area, park green space area, etc. Impact indicators refer to the results of the ecological environment, such as the area sown by crops, the area covered by green space in built-up areas, the area affected by crops, and the area affected by geological disasters. Response indicators refer to the degree of social response to ecological and environmental issues, such as the proportion of nature reserves within the jurisdiction, local financial expenditure on environmental protection, and the rate at which residential waste is safely processed, as well as the rate at which sewage treatment plants are consolidated.

2.4. Determination of Indicator Weights

2.4.1. Data Normalization for Indicators

The evaluation indicators were divided into positive and negative security tendency indicators, and the data for each indicator were normalized.

$$\text{Positive indicator}: \ R_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{1}$$

$$\text{Reverse indicator}: \ R_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \tag{2}$$

2.4.2. Calculation of the Weights of the Indicators

The entropy value technique was used to establish the indicator weights based on the various contributions made by the chosen indicators to the overall assessment.

(1) Calculation of the f_i weight of indicator j in year i

$$f_{ij} = \frac{R_{ij}}{\sum_{i=1}^{m} R_{ij}} \tag{3}$$

(2) Determine the entropy of every indicator e_j

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \left(f_{ij} \ln f_{ij} \right) \tag{4}$$

(3) Calculation of indicator weights w_j

$$W_j = \frac{\left(1 - e_j\right)}{\sum_{j=1}^{n} \left(1 - e_j\right)} \tag{5}$$

2.5. Evaluation of the Model Using the TOPSIS Method

In this study, an ecological security assessment index system for land resources in the Yangtze River Delta (YRD) area was developed using the DPSIR optimization model, and the ecological security level of those resources was analyzed using the TOPSIS approach.

(1) Establishment of a weighted normalization matrix

$$V = \left| V_{ij} \right| = W_j \times R_{ij} \tag{6}$$

(2) Determine the positive ideal solution v^+ and the negative ideal solution v^-

$$\text{Positive Ideal Solution}: \ V^+ = \left\{ \max v_{ij} \middle| i = 1, 2, 3, \cdots, m \right\} \tag{7}$$

$$\text{Negative Ideal Solution}: \ V^- = \left\{\min v_{ij} \middle| i = 1, 2, 3, \cdots, m\right\} \tag{8}$$

(3) Calculate the indicator of the positive ideal solution distance S_i^+ and negative ideal solution distance S_i^-

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(V_{ij} - V_j^+\right)^2}(i = 1, 2, \cdots, m) \tag{9}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(V_{ij} - V_j^-\right)^2}(i = 1, 2, \cdots, m) \tag{10}$$

(4) Calculation of the relative closeness of indicators c_i

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{11}$$

Based on references, when combined with the real circumstances of the region under study, the nonequal spacing method was used to classify the ecological security of land resources into five levels (Table 3).

Table 3. Evaluation metrics for ecological safety of the land in the YRD.

Closeness	[0–0.35)	[0.35–0.45)	[0.45–0.55)	[0.55–0.65)	[0.65–1.5)
Security level	Extremely unsafe (V)	Less safe (IV)	Proximity safety (III)	Safer (II)	Safety (I)

3. Statistics and Analysis of Data

Calculate the Yangtze River Delta (YRD) region's complete ecological safety metric for land resources from 2012 to 2023. Next, use Table 2 to determine the Yangtze River Delta region's ecological safety grade division of land resources. Finally, acquire the findings of the Yangtze River Delta region's ecological safety grade of land resources, as shown in Table 4, as well as the thermal correlation diagrams of the Yangtze River Delta region's ecological safety proximity, as shown in Figure 4.

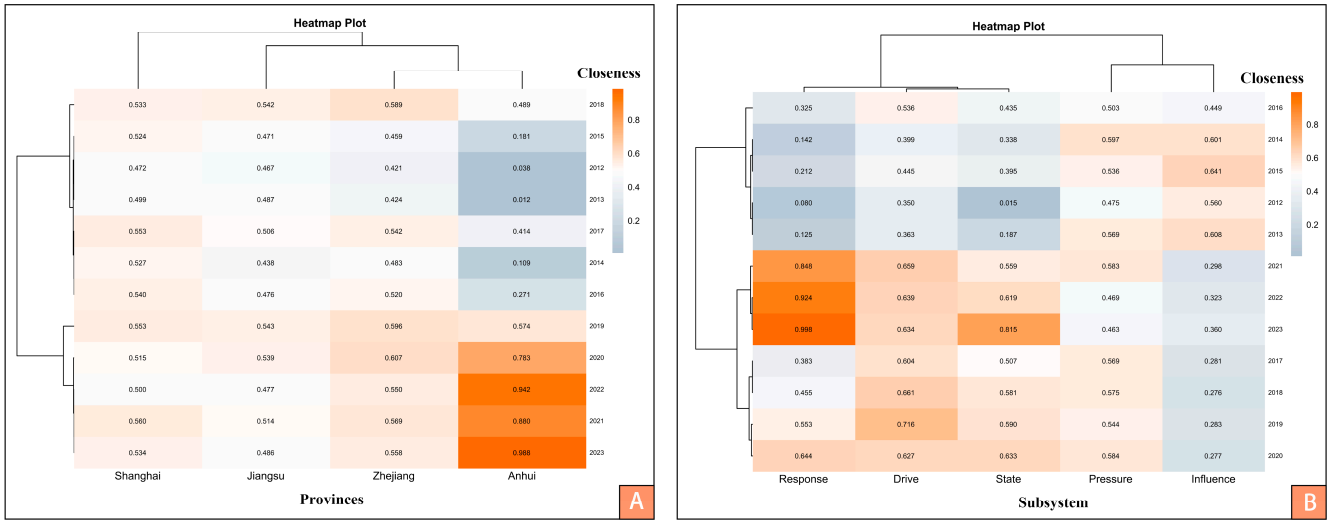


Figure 4. (**A**) Comparison of relative proximity of provinces in land resource ecological security in the Yangtze River Delta region, 2012–2023. (**B**) Comparison of relative proximity of subsystems of ecological security of land resources in the Yangtze River Delta region, 2012–2023.

Table 4. Evaluation indicators of land ecological safety in the Yangtze River Delta region.

Year	D^+	D^-	Proximity C	Drive	Pressure	State	Influence	Response	Security Level	Rank Order
2012	3.972	2.595	0.395	0.35	0.475	0.015	0.56	0.08	IV	12
2013	3.401	2.954	0.465	0.363	0.569	0.187	0.608	0.125	III	11
2014	2.948	3.063	0.51	0.399	0.597	0.338	0.601	0.142	II	8
2015	2.693	3.029	0.529	0.445	0.536	0.395	0.641	0.212	II	6
2016	2.728	2.832	0.509	0.536	0.503	0.435	0.449	0.325	II	9
2017	2.71	3.032	0.528	0.604	0.569	0.507	0.281	0.383	II	7
2018	2.524	3.121	0.553	0.661	0.575	0.581	0.276	0.455	II	3
2019	2.511	3.239	0.563	0.716	0.544	0.59	0.283	0.553	II	1
2020	2.555	3.235	0.559	0.627	0.584	0.633	0.277	0.644	II	2
2021	2.824	3.256	0.535	0.659	0.583	0.559	0.298	0.848	II	4
2022	3.096	3.11	0.501	0.639	0.469	0.619	0.323	0.924	III	10
2023	3.166	3.577	0.531	0.634	0.463	0.815	0.36	0.998	III	5

3.1. Comprehensive State Evaluation of Land Resources' Ecological Security

According to Table 4, under the overall perspective, the ecological safety level of land resources in the Yangtze River Delta region reveals a consistent rising trend from 2012 to 2023. The Yangtze River Delta region's land resources now have an ecological safety grade of Class III rather than Class IV, and their relative closeness has grown by 0.136, from 0.395 in 2012 to 0.531 by 2023. The D^+ value shows a decreasing trend from 3.972 in 2012 to 3.166 in 2023, a decrease of 0.806. The results presented by the data changes indicate that the Yangtze River Delta area's ecological safety of land resources is gradually approaching the positive ideal solution distance, and the safety level is steadily increasing. At the same time, the D^- value generally shows an upward trend from 2.595 in 2012 to 3.577 in 2023, an increase of 0.982, which indicates that the ecological safety of land resources in the Yangtze River Delta region has improved (Figure 5). Between 2012 and 2019, the ecological safety of land resources in the area increased dramatically. The relative closeness increased from 0.359 in 2012 to 0.563 in 2019, and the land safety grade increased from Grade IV to Grade II. Combined with the analysis of the yearbook data, it is concluded that during the study period, the Yangtze River Delta region earnestly promoted localized ecological development and made efforts to build an ecological barrier. From 2019 to 2023, the land ecological safety level in the Yangtze River Delta region showed a stable development trend, of which the peak was reached in 2019, with the relative proximity increasing from 0.553 to 0.563, and the safety grade was stably maintained at the level of Class II. The Yangtze River Delta region's provinces have actively responded to and promoted the policy of "taking full account Regarding the environment's and resources' carrying capacities, comprehensively promoting the construction of ecological civilization, and promoting the harmonious development of human beings and nature", in conjunction with the proposal for the establishment of an ecological civilization. This has eased part of the strain on the land and conserved its ecosystems, resulting in a benign trend of sustainable development for the land's ecological security (Figure 6).

3.2. Analysis of Ecological Security Guideline Factors for Land Resources in the Yangtze River Delta Region

Stress factors show an "M"-shaped trend of rising, then falling, then rising again. From 2012–2014, the stress index increased from 0.359 to 0.0.597. From 2014 to 2016, the stress index dropped from 0.597 to 0.520. From 2016 to 2018, the stress index increased from 0.520 to 0.694. The stress index decreased from 0.649 to 0.608 in 2018–2019. In 2019–2021, the stress index increased from 0.608 to 0.638. Combined with the yearbook data, it can be seen that fertilizer and pesticide application on arable land areas showed a slow downward trend during the study period. Fertilizer application on arable land area reduced from 767.62 tones in 2012 to 635.14 tones in 2021. Pesticide application on arable land areas decreased from 26.91 tones in 2012 to 18.42 tones in 2021. The land in the area has seen far

less ecological stress. In summary, the ecological security pressure index of land resources in the Yangtze River Delta region is generally trending upward and is situated between Level I and Level II.

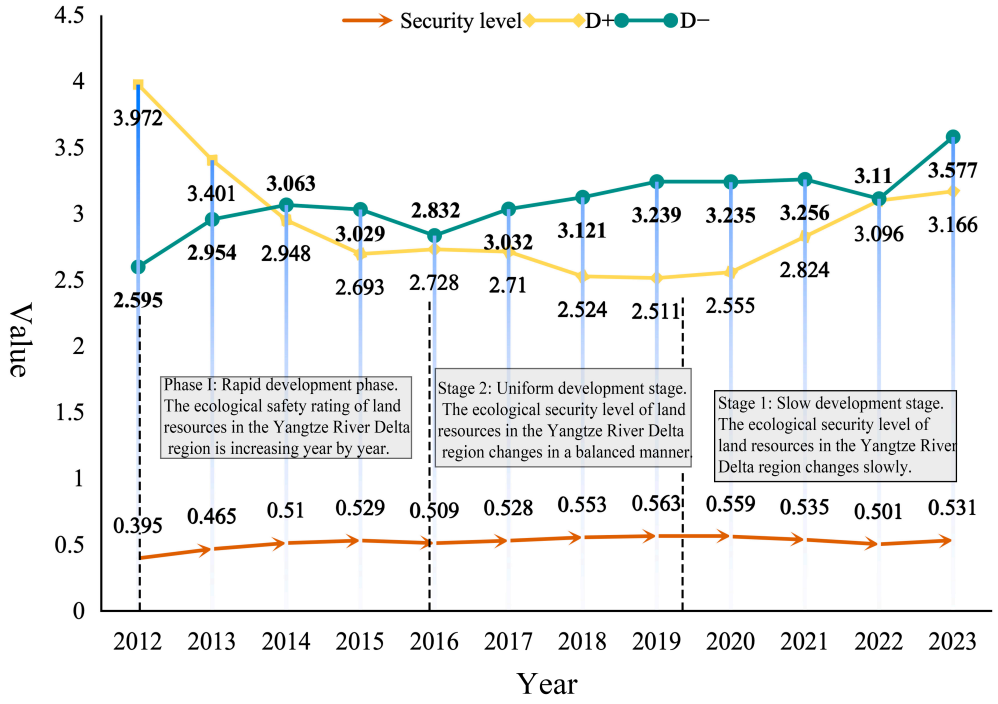


Figure 5. Trend of ecological security closeness of land resources and D^+, D^- development trend of the Yangtze River Delta region.

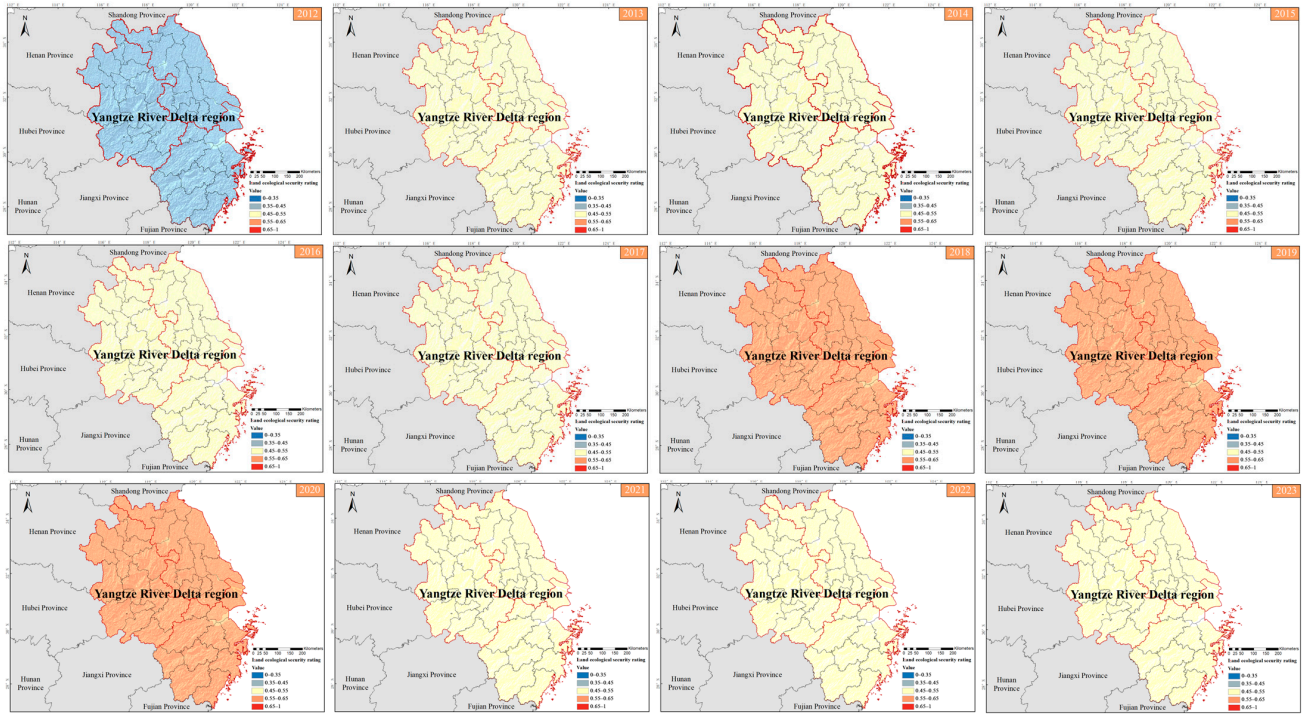


Figure 6. The 2012–2023 changes in the distribution of comprehensive evaluation levels of ecological security of land resources in the Yangtze River Delta region.

The relative progress of the state factor was at the lowest level in 2012 and then showed continuous and stable growth. The Yangtze River Delta region's land safety status index

rose over the research period from 0.015 in 2012 to 0.815 in 2023, and its land ecological safety status system as a whole showed a favorable development trend, with its safety level rising from Level IV to Level I. The land safety status index of the Yangtze River Delta region is also a good indicator of the ecological safety of the region. Analyzing the data from the yearbook, it is concluded that with the continuous improvement of the ecological environment in the YRD region, the greening rate of the city has increased year by year, and the scientific crop cultivation mode has contributed to the increase in grain output from 24,103.67 tones in 2012 to 28,334.49 tones in 2023. To a certain extent, these initiatives have eased the pressure on land bearing and promoted the development of land ecological security in the Yangtze River Delta region.

The relative closeness of the response factors shows a steady upward trend, with the response index increasing from 0.08 to 0.998 from 2012 to 2023, and the safety level increasing from Level IV to Level I. This is mainly because the Yangtze River Delta region has seen an increase in investments in environmental protection and governance, afforestation areas, centralized sewage treatment rates, harmless treatment rates of household waste, waterlogging areas, and urban greening areas as a result of sustained and rapid socioeconomic development, as well as the adjustment and upgrading of industrial structures. The government and the state have introduced a series of policies and measures to strengthen the protection of the ecological environment; for example, the centralized sewage treatment rate will increase from 91.93% in 2012 to 97.95% in 2023, and the amount of investment in environmental protection and governance will increase from 56.304 billion yuan in 2012 to 96.115 billion yuan in 2023. These corresponding measures have, to a certain extent, mitigated the damage to land ecological security caused by a series of social activities carried out by human beings for the purpose of obtaining economic benefits and laid the foundation for the land ecology in the Yangtze River Delta region to have a healthy development trend.

3.3. An Examination of Land Ecological Security in the Yangtze River Delta Region's Provinces and Cities

Using the TOPSIS model calculation, the relative posting progress of the ecological security of land resources in each province (city) was derived (Figure 7), and the spatial and temporal evolution characteristics of the carrying capacity of the land environment in the Yangtze River Delta region were compared (Figure 8) to analyze the state of the ecological security of land resources in the Yangtze River Delta region in each province (city).

In the Yangtze River Delta region, the provinces'/cities' land ecological safety posting progress from 2012 to 2023 are presented in decreasing order: Shanghai (0.472), Jiangsu Province (0.467), Zhejiang Province (0.421), Anhui Province (0.038), and Anhui Province (0.988). By 2023, Anhui Province (0.558), Zhejiang Province (0.558), Shanghai Municipality (0.534), and Jiangsu Province (0.486). Anhui Province's land ecological security status is steadily improving, and it now ranks first with a Class I security rating. Zhejiang Province is at the level of Class II. Zhejiang Province is at level II, and Jiangsu Province and Shanghai Municipality are at safety level III. It can be seen that the difference in land ecological security status in the Yangtze River Delta region is relatively significant. Jiangsu Province is the region with the lowest ecological safety coefficient of land resources in the Yangtze River Delta region, which is mainly due to the high pressure of economic growth in the region, as well as the challenges of land ecological safety caused by the problems of population density, agricultural production, and transformation and upgrading of the industrial structure, as shown in the data of the Yearbook. Anhui Province's land ecological security index presents the most significant changes in the Yangtze River Delta region. From 2012 to 2023, Zhejiang Province's land ecological security sticker progressed from 0.038 to 0.988, an increase of 0.95, and the land ecological security level went from level V to level I. From a comprehensive data yearbook analysis, it can be seen that the total environmental protection expenditure in Zhejiang Province increased from 10.439 billion yuan in 2012 to 18.295 billion yuan in 2023; the centralized sewage treatment rate increased

from 94.53% in 2012 to 98.1% in 2023. This shows that Anhui Province has accomplished amazing things in earnestly promoting the construction of an ecological civilization and actively promoting the construction of a "beautiful provincial capital".

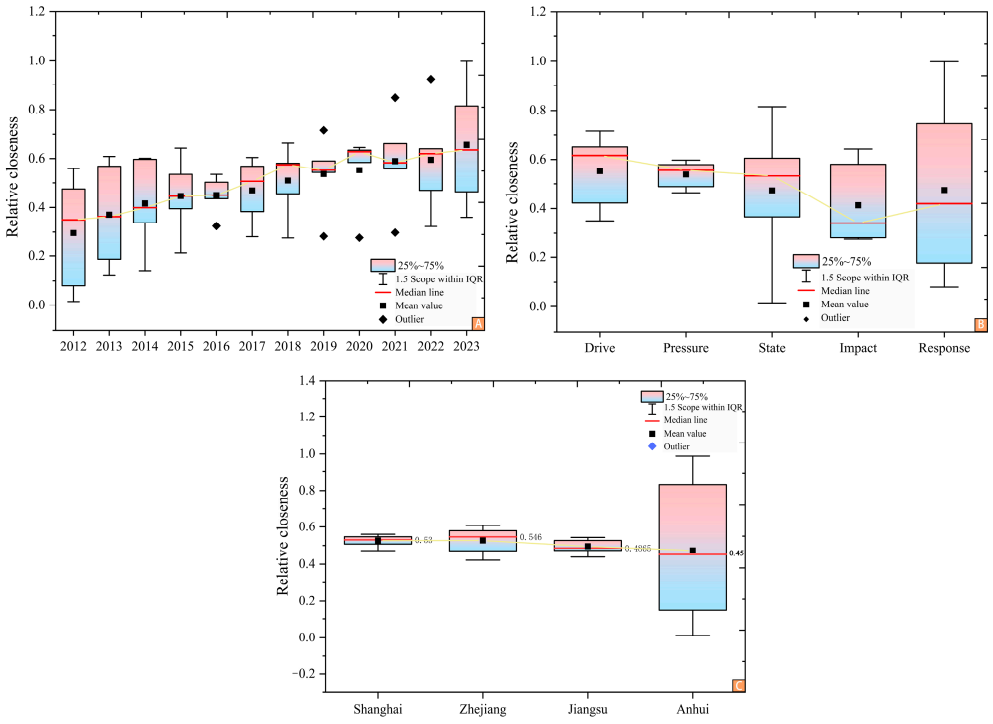


Figure 7. Distribution of LRES assessment scores in the YRD region, 2012–2023. (**A**) Changes in the relative posting rate of land ecological security in the Yangtze River Delta region from 2012 to 2023. (**B**) Comparison of relative posting progress of individual subsystems. (**C**) Comparison of the relative posting progress of land ecological security in the Yangtze River Delta provinces.

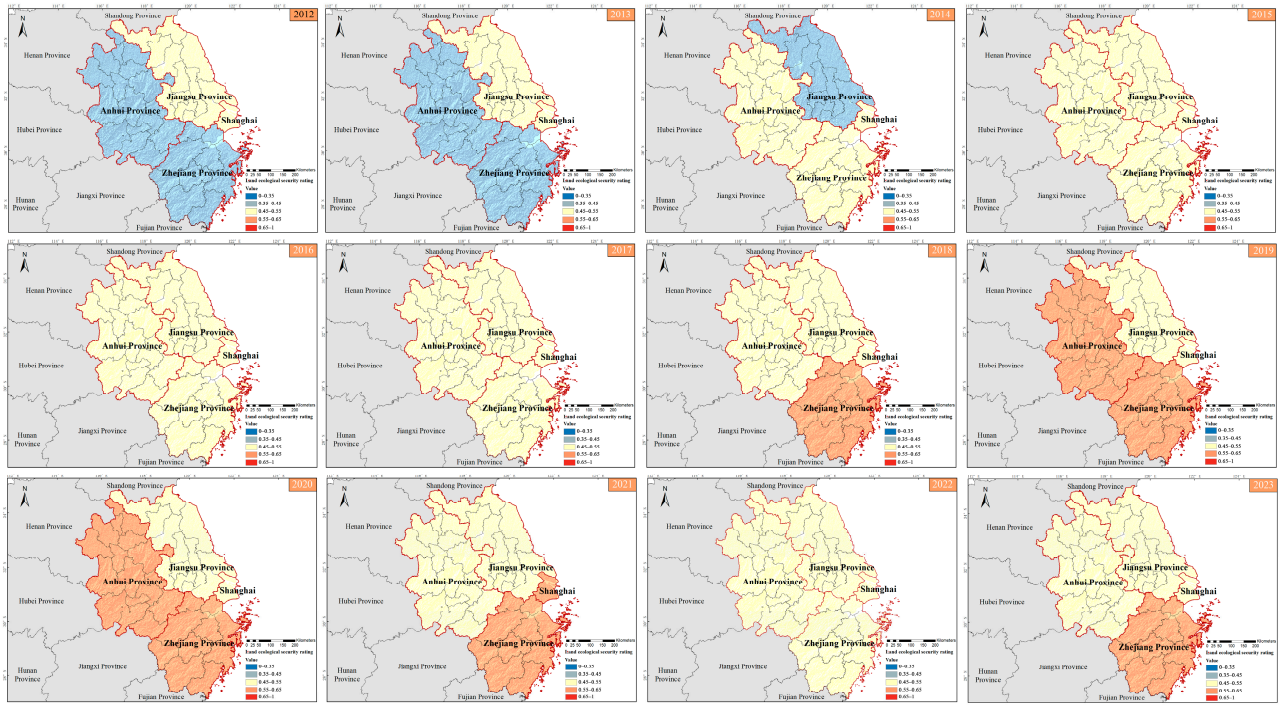


Figure 8. Changes in the distribution of land ecological safety assessment ratings by provinces in the Yangtze River Delta region, 2012–2023.

4. Discussion

The following are the ways in which this study adds to the body of current literature:

(1) The selection of environmental, resource, and social elements to establish indicators. Compared with the single-dimension or fewer-dimension land ecological security evaluations, the DPSIR approach for analysis is more persuasive and impartial. Using a connected socioeconomic–environmental framework, this study technique provides a full examination of area ecological security, allowing us to identify potential barriers to ecological security [28,39]. This is especially crucial when applying our study's findings to guide land use decisions that promote ecological security while maintaining long-term social and economic growth.

(2) The TOPSISI method is used to empirically evaluate land use and land ecological security in the YRD region of China, demonstrating the complimentary benefits of several assessment techniques. In order to provide a basic reference point for attaining an ideal trade-off between construction activities and the ecological security of land resources in the Yangtze River Delta region, it examines the important factors impacting land ecological security in the area.

(3) This study measures the current status of ecological security of land resources in the YRD region of China from a macroperspective. So far, there is little literature presenting empirical work on the evaluation of land resource security in the Yangtze River Delta. China is a vast country with a strong correlation between land use in different provinces or cities. The Yangtze River Delta region, which is identified in the Outline of the Development Plan for the Integrated Development of the Yangtze River Delta Region as one of the regions in China with the most active economic development, the highest degree of openness, and the strongest capacity for innovation, holds an important strategic position in the overall situation of national construction and the overall pattern of opening up. Therefore, analyzing China's regional land ecological security issues by taking the Yangtze River Delta region as an example helps to closely link regional land ecological safety.

In the course of this study, we also found a series of problems and shortcomings, including two aspects: (1) Some of the indicator data are not available, and there is still room for improvement in the indicator system's architecture. Due to the different statistical data of different administrative regions in China, the corresponding indicator data of some regions cannot be obtained, or there are no relevant data statistics. (2) The ecological security level of land resources is revealed at the macrolevel in this research using the objective evaluation technique, the DPSIR theory, and the entropy TOPSIS model. The subjective opinions of individuals on the quality of the environment are not included in the assessment study. The subjective evaluation requires the use of questionnaires to obtain people's experiences and feelings and transform them into visualized data.

Because of this, in order to make up for the lack of subjectivity in data samples, we will need to perform more microlevel social interviews and field surveys in the future. To ensure the objectivity and reasonableness of the research results, we will continue to monitor the research program in the future, adding human subjective judgment into the study [40]. Additionally, we will incorporate field research to obtain more comprehensive and accurate data. This will allow us to look more closely at the ecological security of land resources in the Yangtze River Delta area.

5. Conclusions

From its social, ecological, and economic perspectives, this study introduces the coherence factor in DPSIR theory into the measurement of the ecological security level of land resources in the Yangtze River Delta region, adopts the entropy-weighted TOPSIS model to coordinate the data samples, and carries out a comprehensive evaluation of the ecological security of land resources in the Yangtze River Delta region in 2012–2023 and then reveals the impact of "DPSIR" on the ecological security of land resources in the Yangtze River Delta region. Unlike previous study findings that offer large-scale ecological security

decision-making tools so that locally grounded, economically feasible, and ecologically safe policies may be achieved, this study's findings not only highlight the urgent need for remediation but also advance our knowledge of the biological processes behind land degradation in the Yangtze River Delta region of China. The findings of this study indicate the following.

Firstly, the development of land ecological security in the Yangtze River Delta region from 2012 to 2021 is good, and the land security grade is stable at level III. The study period is roughly divided into a rapid increase stage (2012–2019) and a stable and slow increase stage (2019–2023). However, there are differences between provinces (municipalities), with the largest increase in the land ecological safety coefficient in Anhui Province (0.988), followed by Zhejiang Province (0.558), Shanghai Municipality (0.534), and Jiangsu Province (0.486). When combined with the data yearbook, it is clear that the provinces (municipalities) in the Yangtze River Delta area differ in terms of economic development, industrial structure, population density, natural environment, and other characteristics. These differences explain the vast bulk of the variation in the region's level of land ecological security. Furthermore, there are variations in the extent to which provinces (cities) respond to and execute land ecological security policies and ecological civilization construction. Therefore, Zhejiang Province, a region with a substantial urbanization rate and industrialization and a relatively low share of agriculture, should fully understand the law between economic development and environmental protection, establish the awareness that "green water and green mountains are golden silver mountains", and take advantage of the dual advantages of economy and ecology in order to build a green recycling economic system. Anhui Province, a province with developed agriculture, should strictly implement the policy of land ecological security. Provinces with developed agriculture, such as Anhui Province, should strictly implement the system of arable land protection and the system of balancing the occupation and replenishment of arable land, strive to improve the quality of arable land, and introduce scientific planting modes to increase the output of crops per unit of arable land so as to promote conservation and extensive land use.

Secondly, in terms of the change index of each subsystem, the state system has the largest change, followed by the response system, pressure system, and impact system, and the driver system has the smallest change. Evidently, during the study period, the Yangtze River Delta region actively responded to land ecological security policies and ecological civilization construction, and the ecological security status of land resources has been significantly improved, but focusing on alleviating the pressure of land entry and actively responding to the feedback land security construction are still the key points of the land ecological security protection work.

Thirdly, the Yangtze River Delta region's land ecological security evaluation method reveals that parameters such as total area of afforestation in the current year, population density, and arable land area per capita have grown in importance to land ecological security. These changes are determined by the degree of change in each index in the indicator layer, as well as the weight coefficients of parameters such as GDP per capita, tertiary industry's share of GDP, and investment in environmental protection and governance. Therefore, the following recommendations are made to perpetuate and enhance the ecological security of land resources in the YRD region:

(1) Agriculture, forestry, animal husbandry, and industry are all subject to unified planning. Reasonable use and management of soil resources ensure that the soil's production inputs and outputs are balanced and that its productivity and carrying capacity are optimized. Control of pollutant sources: Control land contamination from industrial 'three wastes', urban inhabitants' living waste, agricultural chemicals, and animal and poultry breeding waste. Increase environmental protection oversight and enforcement and crack down on pollution. Treatment and rehabilitation of contaminated land: Depending on the kind and severity of pollution, physical, chemical, or biological approaches are utilized to remediate and restore soil productivity and ecological function. Implement ecological restoration initiatives in environmentally

sensitive locations, such as mountain sealing and tree and grass planting in places prone to soil erosion. Vegetation restoration and soil enhancement promote ecosystem stability and resistance.

(2) To maximize the benefits of urban–rural integration, rules and regulations should be strengthened to create a system for coordinating urban and rural land resources in order to promote sustainable development. This has to be enhanced, as does macrocontrol. Furthermore, urbanization should be scientifically supported, and current information technology should be employed to improve the efficiency and quality of urban and rural land resource management. Rural areas should utilize the advantages of urban capital and technology to develop green-development-friendly industrial systems like tourism and agriculture.

(3) In the Yangtze River Delta region's integrated land resource development, inter-regional collaboration should be strengthened, scientific use of the asynchrony in the degree of land development between different regions should be made use of, and the complementarity of advantages in the layout of industries, especially in the relocation and introduction of industries in different regions, should be insisted on in order to pursue ecological as well as economic benefits. Encourage public engagement in land ecological conservation efforts, such as tree planting and environmental awareness campaigns. Public engagement will create a favorable environment in which the entire society pays attention to and participates in land ecological conservation. Strengthen environmental education and promote public understanding and concern about land ecological conservation. Popularize environmental protection information through school instruction, media coverage, and other ways, as well as raise public awareness and responsibility for environmental issues. It is recommended that the participation of different stakeholders of local land resources be encouraged so that decision making is widely accepted [41,42].

In general, the evaluation results of the ecological security of land resources directly affect the socioeconomic quality and natural ecological area of a region. Although the YRD region has largely achieved the status of leading the nation in ecological indicators, there are some asymmetries in the environmental pressures caused by production and life in the region, the balanced degree of urbanization development, and the ability to supply resources for people's livelihoods. Therefore, the Yangtze River Delta region should rectify local ecological problems and improve. The environmental quality of people's production and lifestyle should be balanced and coordinated in accordance with local conditions. Even though the DPSIR theory and the entropy weight TOPSIS model revealed the ecological security level of land resources at the macrolevel in this paper, we still need to conduct more field surveys and social interviews at the microlevel in order to gather more accurate data and compensate for the residents' lack of subjective initiative in the data sampling.

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