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SPATIAL-TEMPORAL EVOLUTION OF LAND ECOLOGICAL HEALTH AND INFLUENCING FACTORS IN CHINA'S ECOLOGICAL CIVILIZATION PILOT AREA

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Highlights:

- optimized the land ecosystem health index system;
- constructed an improved PSR-EES model;
- investigated the temporal and spatial evolution of LEH and the influencing factors;
- selected a typical and representative study area.

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Abstract. It is crucial to assess the land ecosystem health (LEH) in China's national pilot zones (NPZ) for ecological conservation and identify the primary factors that impact it. This is crucial for developing China's ecological civilization and fostering sustainable, eco-friendly economic development. The study utilizes the pressure-state-response (PSR) and environment-economy-society (EES) model, relying on the panel data of 11 cities of Jiangxi in the NPZ for ecological conservation from 2005 to 2020, measuring the LEH in the national ecological civilization pilot zone using the comprehensive index evaluation method. The main contribution of this study is to optimize the land ecological health index system, construct an improved PSR-NES theoretical model that is more suitable for NPZ, reveal the spatial and temporal evolution characteristics of LEH in NPZ from the city scale, and refine the key driving factors. Results show that (1) The LEH exhibited a general shift from a state of "less healthy" level to the "healthier" level; (2) Differences in LEH evolution in different cities. The overall trend of "north to south and east to west" is gradually improving. (3) Urbanization has a strong role in the promotion of LEH, and economic development shows a significant dampening effect.

Keywords: land ecosystem health, spatial-temporal evolution, influencing factors, national pilot zones for ecological conservation, sustainable, Jiangxi Province.

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1. Introduction

Economic development and social progress rely heavily on the utilization of natural resources, with land serving as the foundation for these resources. Land ecosystem health (LEH) refers to a land ecosystem's ability to maintain structural and functional stability while possessing a strong self-restoration capacity in response to natural and socio-economic disruptions. This ensures it can meet the demands of human socio-economic development (Wang et al., 2021; Wu et al., 2018; Xiao et al., 2019). Additionally, recent studies highlight the critical role of land use policy in addressing demographic changes, such as aging rural populations, and their impact on agricultural carbon emissions in China (Fan et al., 2021; Huang et al., 2024). As industrialization and urbanization continue to advance, the population size is gradually increasing, and the level of natural resource extraction is escalating, which have led to ecological problems, such as desertification, pollution of land, and extensive soil erosion. According to the first China Water Census in 2012, the extent of soil erosion in China has encompassed a vast area of 294.91 million square kilometers, which corresponds to approximately 30.72% of the overall land area. Serious soil pollution was reported in some areas of China in 2014, with an overall point exceedance rate of 16.1% nationwide. LEH is one of the important dimensions to achieve ecological security, which is one of the five major security measures in China and the basis for sustainable national development. In the context of the increasing potential threats to China's land ecology, China included Jiangxi, Fujian, and Guizhou, which have good ecological resources, in the first batch of the NPZ for ecological conservation in 2016 to solve the LEH problem and accelerate the construction of ecological civilization. Research on the LEH in the NPZ for ecological conservation can facilitate the sustainable utilization of land resources, and exploring the construction of ecological civilization and promoting green economic development are of great practical significance.

"Health" was first used in the medical field to describe the physical and psychological state of the human body. The concept gradually extended to the field of land with the progress of society and economy, along with the intensification of land use. The American ecologist Aldo Leopold introduced the concept of "land health" in 1941 (Aldo, 1941). However, land health has not been studied in depth. In 1989, Canadian scholar Rapport first clarified the concept of ecosystem health (Rapport, 1989). Subsequently, many scholars conducted in-depth studies on coastal (Agboola et al., 2016; Song et al., 2022; Tang et al., 2015; Yanes et al., 2019), wetland (Chi et al., 2018; Das et al., 2020; Khatun & Das, 2022; Sahana et al., 2022), and land ecosystem health (Safaei et al., 2023). LEH is gradually becoming one of the research hot spots in ecology and geography (Are et al., 2018; Berkes et al., 2012; Li et al., 2023). In terms of research content, the current research primarily focuses is on land ecological health diagnosis and evaluation and the analysis of spatial and temporal patterns. However, limited research has been carried out on the factors that influence and drive the dynamic evolutionary traits of LEH. In terms of research scales, the existing literature mainly include the provincial (Meng et al., 2018), urban (Li et al., 2021; Peng et al., 2017), and watershed scales (Ahn & Kim, 2017; Yuan et al., 2021). Among them, urban-scale land ecological health studies are the most abundant. Currently, the research is shifting from a single urban scale to city cluster and provincial scale (Gao et al., 2022; Qiao & Huang, 2022; Uriarte et al., 2011). In terms of research methods, the primary approaches encompass the fuzzy comprehensive evaluation method (J. B. Chen et al., 2019; H. R. Cheng et al., 2022), the comprehensive index method (S. J. Chen et al., 2023; X. Cheng et al., 2018), and gray model prediction (Xu et al., 2014). The comprehensive index method is widely applied and has become the mainstream method for LEH evaluation.

An NPZ for ecological conservation can serve as an experimental ground for the creation of an ecological civilization (Fan et al., 2022). NPZ experience has demonstration importance for the entire country and other developing countries. Research on ecological civilization pilot areas focuses mainly on the ecological efficiency of an industry, such as forestry (Hou et al., 2022), marine (Gao et al., 2024), mining (Guo et al., 2020), and tourism (Wen & Changrong, 2018), as well as green economic development (Zhang et al., 2025), environmental governance (Zhang et al., 2024), and carbon emissions (Xu et al., 2024), and studies on the land ecological health (LEH) of ecological civilization pilot areas are few. Jiangxi Province is a pioneer ecological civilization pilot area in Central China. Jiangxi Province's ecological environment is unique and diverse, covering economically underdeveloped (e.g., Gannan) and developed (e.g., Nanchang) regions but struggling with problems, such as land pollution and development, brought about by industrialization and urbanization. The LEH problems of Jiangxi Province reflect those common in the development of Central China, which are typical and universal. Therefore, this paper considers the urban scale, taking the first batch of the NPZ for ecological conservation in Jiangxi Province as an example. The pressure–state–response and environment–economy–society (PSR-EES) model was adopted, the LEH evaluation index system was constructed, and the LEH of cities in Jiangxi Province was measured and analyzed to explore the spatial and temporal evolution process of the LEH in the national ecological civilization pilot zone and extract its main influencing factors using principal component analysis.

The possible contributions of this study are as follow: (1) To a certain extent, the research gap on the LEH in the NPZ for ecological conservation is bridged. It can provide reference for the construction of ecological civilization in other areas of China and other developing countries. (2) By utilizing the enhanced PSR-EES framework model, the LEH indicator system has been optimized to better adapt to the NPZ for ecological conservation. (3) This study explors the spatial-temporal evolution of LEH, identifies its influencing factors, and expands its research content.

The remaining portion of this paper is structured in the following manner. Section 2 provides the regional overview and the data sources. Section 3 discusses the index system construction and the research method. The results and analysis are presented in Section 4. In Section 5, the results, suggested policies, limitations, and future research are examined. Section 6 presents the conclusions drawn from the results.

2. Study area and data sources

2.1. Study area

Jiangxi Province is located in the eastern part of Southeast China and an important part of the Yangtze River Economic Belt. In the northern part of the province, the terrain is level, while mountains encircle the southeastern and western regions. The central area is characterized by hills, and the climate is a subtropical humid monsoon. The average temperature in 2020 was 19.1 °C, accompanied by a total precipitation of 1,960 millimeters. In China, the province is home to five primary rivers and the largest freshwater lake called Poyang Lake. Jiangxi has 159 nature reserves, encompassing 6.4% of the province's total land area. Jiangxi is rich in forest and lake resources, and their ecological function has great potential. In 2020, the resident population in Jiangxi Province was 46.661 million, with an annual gross product of 256.95 billion yuan. Since the 21st century, urbanization and industrialization have developed rapidly with the continuous growth of population, resulting in remarkable social and economic achievements. However, the province also faces serious challenges, such as ecological degradation and over-exploitation of resources. Jiangxi Province is included in the first batch of the NPZ for ecological conservation in China. Researching the province's LEH is typical and representative and can provide a useful experience and a policy reference for promoting ecological civilization in other regions of China (Figure 1).

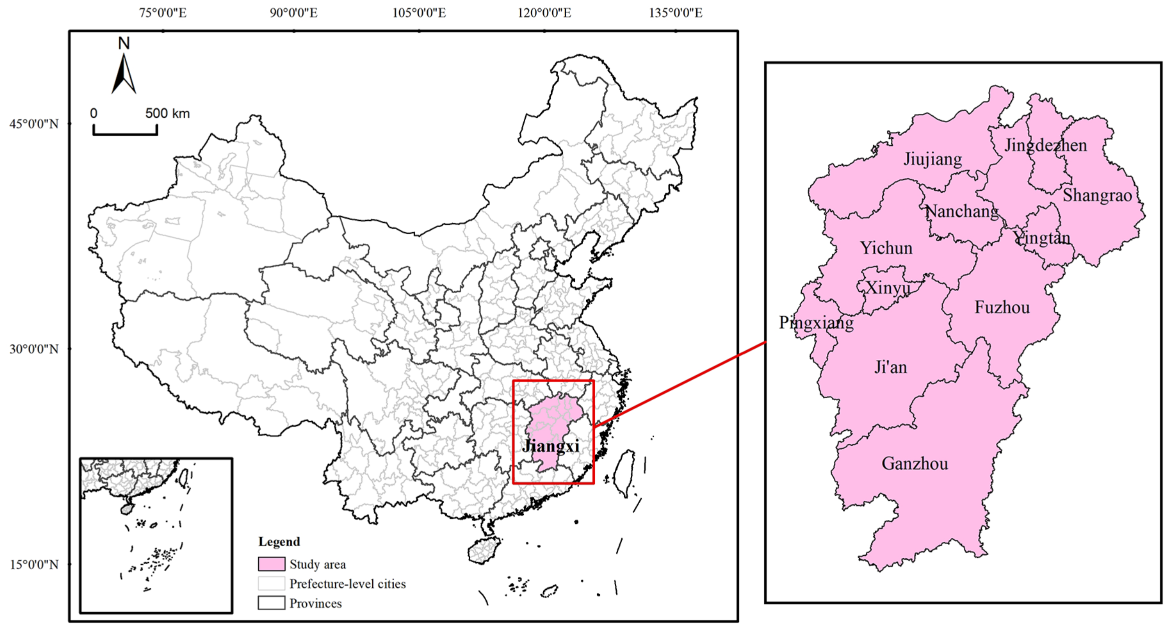

Figure 1. Study area

2.2. Data source

The focus of this study is on 11 cities located in Jiangxi Province, The initial information of the relevant metrics primarily came from the Jiangxi Statistical Yearbook within the study timeframe, he Municipal Statistical Yearbook and National Economic and Social Development Statistical Bulletin, China's Reclamation Statistical Yearbook, China's Environmental Statistical Yearbook, China's Urban Statistical Yearbook, the Jiangxi Department of Ecology and Environment, and the Jiangxi Provincial Bureau of Statistics website, a few missing or anomalous data were completed using linear interpolation.

3. Index system and methods

3.1. Index system construction

The Pressure-State-Response (PSR) framework was proposed by the Organisation for Economic Co-operation and Development (1993). The PSR framework is simple and easy to explain to the public and is widely recognized by many organizations around the world (Hazbavi et al., 2019). Its primary purpose is to assess the extent of human activities' influence on the ecological environment. Among them, Pressure indicators primarily reflect the influence of human socio-economic activities on land ecology; State indicators indicate the state of the land ecology in response to changes in various external factors; Response indicators represent the set of measures taken by humans to restore the state of LEH to normal levels after it has been negatively affected by stress. The concept environment-economy-society (EES) stems from that land ecosystems are complex systems of coupled environmental, economic, and social systems. The status and processes of land ecosystem should be adequately reflected in LEH assessments, in particular, the impact of human beings on the environment should be reflected. Therefore, when studying the LEH, the impacts, status and responses of environment, economic and social influences on land ecosystems should be considered in an integrated manner. This paper is utilizes the principles of scientificity, objectivity and accessibility, taking into account the specific conditions of the study area, based on the relevant references (Guo et al., 2021; Meng et al., 2014; Yang et al., 2020), the evaluation index system was constructed using the PSR-EES framework model (Table 1).

Pressure index. Crop sown area per capita and construction land area per capita represent the pressure of land development and utilization on land ecology; The amount of pesticide used Pesticide use per unit sown area and the amount of Fertilizer use per unit sown area of sowing surface characterize the load of land use on the land ecological environment. The annual growth rate of fixed asset investment and population density characterize the pressure of population and economic development on the land ecological environment.

Status indicators. GDP per unit of construction land, the land reclamation index, and the unit yield of the grain sown area characterize the status of resource consumption and utilization efficiency during the land use process; the per capita disposable income of rural residents, the urbanization level, the per capita water resources, and the per capita public green space area characterize the status of the regional economic development level, as well as the living environment and quality of life of urban residents.

Response indicators. The effective irrigated area represents the response to improving the stability of regional agricultural production. The proportion of the secondary industry in GDP, the comprehensive utilization rate of industrial solid wastes, and the reuse rate of industrial

Table 1. The index system of LEH

Target layer	Criterion layer	Elements layer	Indicator layer	Positive and inverse	Based on the weight
Land ecosystem health	Pressure (0.3063)	Environment pressure	Crop sown area per capita	+	0.1523
			Construction land area per capita	–	0.1190
			Pesticide use per unit sown area	–	0.1900
			Fertilizer use per unit sown area	–	0.1957
		Economic pressure	Annual growth rate of fixed asset investment	–	0.1078
		Social pressure	Population density	–	0.2352
	Status (0.3870)	Environment status	Land reclamation index	–	0.1494
			Water resources per capita	+	0.1373
			Grain sown area unit yield	+	0.1037
		Economic status	GDP per unit of construction land	+	0.1385
			Per capita disposable income of rural residents	+	0.1928
		Social status	Public green space per capita	+	0.1603
			Urbanization level	+	0.1180
	Response (0.3067)	Environment response	Effective irrigated area	+	0.2637
		Economic response	Share of secondary industry in GDP	–	0.2009
		Social response	Comprehensive utilization rate of industrial solid waste	+	0.1256
			Industrial wastewater reuse rate	+	0.1519
			Agricultural machinery per unit sown area	+	0.2579

wastewater represent the positive responses to controlling environmental pollution. The agricultural machinery per unit of sown area represents the degree of intensification of agricultural production.

3.2. Methods

Based on the PSR-EES framework model, this study uses the comprehensive index evaluation method to measure the LEH of Jiangxi Province. According to the principles of scientificity, integrity, and accessibility, this study selects 18 indicators to construct the evaluation system, which cover the three dimensions of pressure, state, and response. The specific methods used in this study are index standardization, weight calculation, comprehensive index synthesis, health classification, and driving mechanism analysis. The detailed steps are described in the next section.

3.2.1. Standardization of indicators

This paper constructs complex and diverse LEH evaluation indexes, and the nature, content, and units expressed by different indicators are different and cannot be compared. The influence of different numbers of levels and dimensions should be eliminated to make the index data comparable. In this paper, we use the extreme value method to process the evaluation index data and convert all indicator data values to values between 0 and 1. Meanwhile, to make sense of the processing of data with the value 0, all data are shifted to the right by the smallest unit value. The calculation formula is as follows.

$$\text{Positive indicator: } X'_{ij} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}}; \quad (1)$$

$$\text{Negative indicator: } X'_{ij} = \frac{x_{i\max} - x_{ij}}{x_{i\max} - x_{i\min}}, \quad (2)$$

where x_{ij} is the actual value of the i-th indicator in the j-th year; X' indicates the standard value after data processing; $x_{\min}$ is the minimum value, and $x_{\max}$ is the maximum value.

3.2.2. Entropy method

The entropy method is an objective weighting method that can determine the index weight by measuring the data dispersion degree through information entropy, and the higher the data dispersion, the more the index information, and the greater the weight. The entropy method steps are as follows:

1. Calculate the proportion of features y_{ij}, as follows:

$$y_{ij} = \frac{X'_{ij}}{\sum_{j=1}^{m} x_{ij}}, \quad (3)$$

where X'_{ij} is the standardized index value, which is used mainly to eliminate the dimensional difference and make the data comparable; and y_{ij} is used to calculate the characteristic proportion of the i year index under the j index, which reflects the relative proportion of the index data in the entire year.

2. Calculate the entropy values E_i.

$$E_i = -\frac{1}{\ln m} \sum_{j=1}^{m} y_{ij} \ln y_{ij}, \quad (4)$$

The entropy value E_i measures the amount of information in the index, and the closer the value to 1, the lower the dispersion of the index data, and the less the information provided. Conversely, the closer to 0, the higher the dispersion, and the more the information provided.

3. Determine the differentiation factor f_i.

$$f_i = 1 - E_i. \quad (5)$$

In the formula, the difference coefficient f_i is inversely related to the entropy value E_i. The difference coefficient f_i reflects the amount of information in the index data, and the larger the value, the more the contribution of the index to the comprehensive evaluation.

4. Determine the indicator weights W_i.

$$W_i = \frac{f_i}{\sum_{n=1}^{n} d_i}, \quad (6)$$

where i represents the serial number of the indicator, and n is the number of indicators (i = 1, 2, 3..., n); j represents the year (j =1, 2, 3..., m); $0 \le E_i \le 1$; $0 \le W_i \le 1$; and $\sum_{n=1}^{n} W_i = 1$, where data-based W_i can ensure the objectivity and data-driven nature of the weights.

3.2.3. Comprehensive index

The composite index is calculated by weighting and accumulating the weights of each indicator: F.

$$F = \sum_{i=1}^{n} W_j \sum_{j=1}^{m} W_i y_{ij}, \quad (7)$$

where F represents the land ecological health composite index; W_j represents the weight of each element in the criterion layer; and y_{ij} represents the weight of the characteristics of each element in the indicator layer. The closer F is to 1, the better the LEH is.

3.2.4. Classification of LEH

At present, no clear standard for the classification of LEH evaluation exists. In order to enhance the comprehensibility and clarity of the evaluation results. Based on the combination of related research results (Ran et al., 2021; Xie et al., 2021; Yang et al., 2023), this study classified the evaluation results into five levels according to equal spacing (Table 2).

3.2.5. Driving mechanism analysis method

LEH can be affected by numerous factors, many of which may be correlated with one another. Such correlation may interfere with the accurate judgment of the influence of a single factor, and the use of numerous variables can increase the complexity of the analysis. To reduce the dimensions effectively and analyze the influence of various factors on LEH accurately, this study combines PCA with multiple linear regression:

Principal component analysis (PCA)

PCA can extract a few comprehensive variables, namely, the principal components, from many related variables to simplify the data structure and retain the key information. Before PCA can be conducted, the suitability of the data must be tested. By using the SPSS 26.0 statistical software, this study conducts a Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity on the 18 selected indicators. The result of the KMO test is >0.6, and the significance of Bartlett's test is $p < 0.01$, which indicate that the data are suitable for factor analysis.

After conducting the tests to meet the conditions, this study extracts the principal component with an eigenvalue of >1. An eigenvalue that is larger than 1 indicates that the variance explained by the principal component is higher than the average variance of the original variable, which has certain explanatory power. This study uses the maximum variance method to rotate the factor load matrix to simplify the factor structure and improve the interpretability of the data. According to the rotated component matrix, this study classifies high load indices as the same factors and names them.

Multivariate linear regression

After completing the PCA to obtain the principal component factor, this study uses the LEH composite index as the dependent variable (Y) and the principal component factor score as the independent variable X_i (i = 1, 2, 3, 4, 5) to construct the regression model, as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \partial, \quad (8)$$

where Y is the LEH index; β_0 is the intercept term; β_i (i = 1, 2, 3, 4, 5) is the standardized regression coefficient; and ∂ is the error term.

Table 2. Grade of LEH in the study area

Level	Index	Characteristic
Health state (V)	[0.8, 1.0]	Characterize the vitality, structural stability and functional integrity of the land ecosystem
Healthier state (IV)	[0.6, 0.8)	Characterize the land ecosystem function is relatively well maintained and self-healing ability is relatively good
Critical state (III)	[0.4, 0.6)	Characterize the basic maintenance of land ecosystem function, its self-healing and disturbance resistance is insufficient
Less healthy state (II)	[0.2, 0.4)	Characterize the degradation of land ecosystem functions and the frequent occurrence of land ecological problems
Unhealthy state (I)	[0.0, 0.2)	Characterize land ecosystem is threatened and land ecological problems are more serious

After constructing the model, this study tests its significance. This study verifies the significance of the model by conducting an *F*-test and a *t*-test and calculates the variance inflation factor (<5) to address the issue of multicollinearity. The regression coefficient β_i reflects the direction and intensity of the influence of each factor on LEH.

4. Results and analysis

4.1. Time-Series evolutionary characteristics

4.1.1. Time series evolution of the composite index

The LEH in Jiangxi Province from 2005 to 2020 was measured through the comprehensive index method, the findings show that the comprehensive index of the land ecological health in Jiangxi Province presents the characteristics of "three-stage leapfrog fluctuation growth" (Figure 2).

The first stage is from 2005 to 2009, the LEH index rose from 0.282 to 0.361, indicating an average annual growth rate of 6.35% and a "less healthy" level. The second stage is from 2009 to 2018, in which the LEH index rose from 0.361 to 0.591, indicating an average annual growth rate of 5.64% and a "critical health" level. The third stage is from 2018 to 2020 in which the LEH index increased from 0.591 to 0.675, with an average annual growth rate of 6.83% and a "healthier" level. The three stages show an overall fluctuating growth trend.

4.1.2. Time series evolution of classification indicators

Within the study time domain, the pressure, state, and response indicators show divergent evolutionary characteristics across the cities of Jiangxi Province (Figure 2). The details are as follows.

The pressure index presents a downward and then upward trend. From 2005 to 2013, there was a decrease in the pressure index from 0.153 to 0.110, exhibiting an average annual decline rate of 4.03%. From 2013 to 2020, there was a rise in the pressure index from 0.110 to 0.187, exhibiting an average yearly growth rate of 7.91%. The trend changed because the annual growth rate of pesticide use per unit sown area and the annual growth rate of fixed asset investment present a significant upward and then downward trend.

The state index displays a fluctuating upward trend. Between 2005 and 2020, the state index increased from 0.069 to 0.283, exhibiting an average yearly growth rate of 9.89%. The index increased because the GDP per unit of construction land rose from 6.05 million yuan/hm^2 to 16.02 million yuan/hm^2. Meanwhile, the per capita disposable income of rural residents rose from 3,193.94 yuan per person to 16,981.00 yuan per person, with an average annual growth rate of 11.78%.

The index of response displays a fluctuating growth trend. Between 2005 and 2020, there was a rise in the response index from 0.060 to 0.204, exhibiting an average yearly growth rate of 8.46%. The index increased because the reuse rate of industrial wastewater and the annual industrial solid waste comprehensive utilization rate rose from 61.25% and 27.10% in 2005 to 90.15% and 44.98% in 2020, respectively. The trend shows that in the context of advocating the construction of ecological civilization, Jiangxi Province has responded positively to the problem of land ecological health to achieve the purpose of promoting the improvement of land ecological health.

4.2. Spatial evolution characteristics

According to the change of the land ecological health grade in various cities of Jiangxi Province, years 2005, 2010, 2015, and 2020 were selected to map the spatial

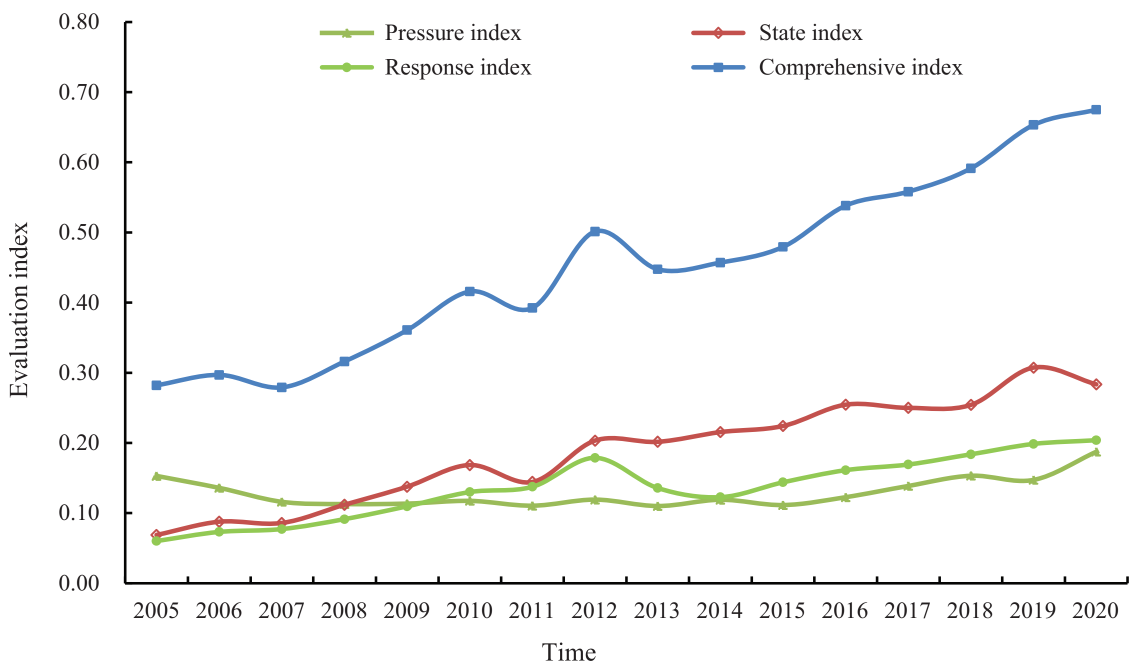

Figure 2. LEH index

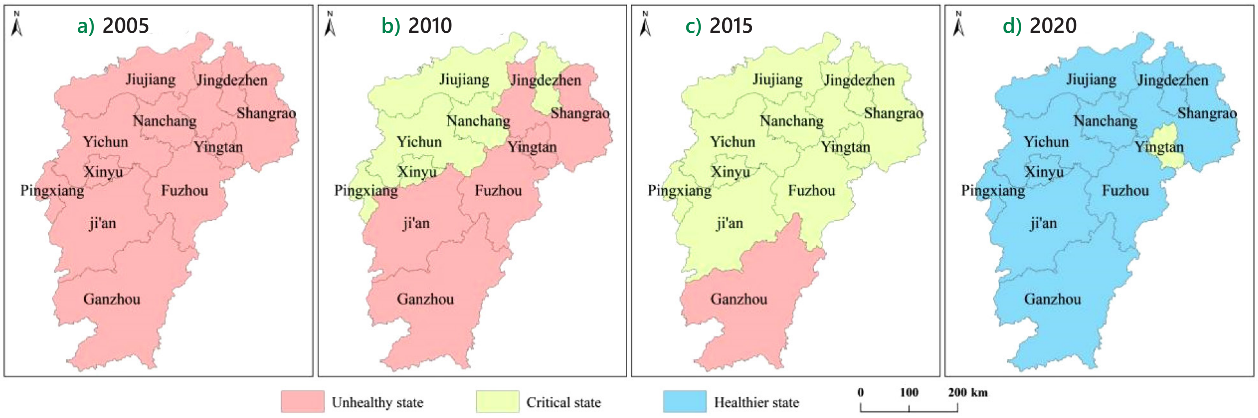

Figure 3. Spatial distribution of LEH

distribution of LEH (Figure 3). Significant regional differences in LEH exist, and the overall trend of "from west to east, from north to south" has been improving every year.

The northern region of Jiangxi consists of eight cities, including Nanchang, Jingdezhen, Pingxiang, Jiujiang, Xinyu, Yingtan, Yichun, and Shangrao. The LEH of these cities demonstrates a yearly improvement from west to east. In 2005, the average value of land ecological health in the northern part of Jiangxi was 0.279, and all the cities were in the "less healthy" level. In 2010, except for Shangrao and Yingtan in the east, which remained in the "less healthy" level, the LEH in all the cities exceeded 0.400, reaching the "critical health" level. All the eight cities entered the "critical health" level in 2015. In 2020, except for the eastern city of Yingtan, all the cities had an average LEH value of 0.669, and all of them were in the "healthier" level.

The south-central region of Jiangxi consists of three cities, including Ji'an, Fuzhou, and Ganzhou, their LEH shows a trend of improvement from north to south year by year. Between 2005 and 2010, the average LEH value for them rose from 0.291 to 0.357, experiencing a yearly growth rate of 4.12%. However, the municipalities still remained at the "less healthy" threshold. The overall evolution of the south-central region of Jiangxi is better than that of the same period in Northern Jiangxi. In 2005, in addition to Ganzhou City, Ji'an and Fuzhou were in the "critical health" level. The LEH index of the entire south-central region in Jiangxi reached 0.729 in 2020. Achieved to overtake the northern part of Jiangxi, showing rapid growth, with Fuzhou and Ganzhou ranking among the top 2 in the province in terms of LEH value. Compared with that in 2015, Ganzhou City's LEH in 2020 grew at a rate of 13.87%, which was the fastest growth rate in the province, achieving a leapfrog growth from the "less healthy" level to the "healthier" level.

4.3. Analysis of factors influencing LEH

This paper analyzes the data with the help of spass 26.0. Feasibility study testing is a necessary process to perform principal component analysis. SPSS 26.0 was used to perform the KMO statistical test and Bartlett's sphericity test on the previous data. If the calculated KMO statistics exceed 0.6, then the statistics are generally considered to be acceptable for principal component analysis. The KMO statistical test value is 0.664 > 0.600, and the Bartlett's sphericity test value is 0.000 < 0.010. The results suggest that a factor analysis of the indicators is appropriate. After the factor extraction of the 18 indicators, we obtained five component factors with eigenvalues greater than 1. The cumulative contribution of these five factors was 75.085%, indicating that most of the information of the indicators was retained, and these five factors can characterize the 18 original indicators information well. According to related literature (Sun, 2019; Wang et al., 2018), the dimensionality of the influencing factors of land ecological health was reduced based on principal component analysis. The factor component matrix was rotated by the Kaiser Normalized Maximum variance method, resulting in a rotated component matrix (Table 3).

Table 3 shows that Factor "a" has high loadings on the urbanization level, the common green space per capita, the construction land area per capita, and the effective irrigation area. Factor "b" has high loadings on population density, the land reclamation index, and the water resources per capita. Factor "c" has high loadings on the annual growth rate of fixed asset investment, the per capita disposable income of rural residents, the share of secondary industry in the GDP, and the agricultural machinery per unit sown area. Factor "d" has high loadings on the fertilizer use per unit sown area, the crop sown area per capita, and the pesticide use per unit sown area. Factor "e" has a high loading on the comprehensive utilization rate of industrial solid waste. On the basis of the results of factor analysis, Factors "a–e" are named urbanization (X_1), social development (X_2), economic development (X_3), arable land security (X_4), and environmental governance (X_5), respectively.

The LEH index was selected as dependent variable Y. Linear regression analysis was performed on the five factors extracted by Stata16, and the F-test value was 64.454, the p-value was 0.000, and the linear regression R^2 was

Table 3. Rotated component matrix

Criterion layer	Elements layer	Elements layer	Factor a	Factor b	Factor c	Factor d	Factor e
Pressure	Environment pressure	Crop sown area per capita	–0.455	–0.243	–0.090	0.684	0.312
		Construction land area per capita	0.820	0.090	–0.009	–0.181	0.338
		Pesticide use per unit sown area	–0.317	–0.073	0.279	–0.440	–0.427
		Fertilizer use per unit sown area	–0.058	0.098	0.064	–0.873	0.114
	Economic pressure	Annual growth rate of fixed asset investment	–0.218	0.016	0.755	–0.032	–0.140
	Social pressure	Population density	0.284	0.869	0.012	–0.170	0.219
Status	Environment status	Land reclamation index	–0.050	0.748	–0.012	0.316	0.435
		Water resources per capita	–0.241	–0.713	–0.151	0.243	0.088
		Grain sown area unit yield	0.187	0.348	0.037	–0.057	0.551
	Economic status	GDP per unit of construction land	–0.317	0.132	–0.475	0.549	–0.192
		Per capita disposable income of rural residents	0.457	0.218	–0.696	0.248	0.229
	Social status	Public green space per capita	0.734	0.192	–0.143	–0.145	0.376
		Urbanization level	0.705	0.493	–0.298	0.000	0.280
Response	Environment response	Effective irrigated area	–0.856	–0.089	–0.347	0.086	–0.074
	Economic response	Share of secondary industry in GDP	0.445	0.281	0.715	0.078	0.096
	Social response	Comprehensive utilization rate of industrial solid waste	0.165	0.041	0.041	–0.011	0.871
		Industrial wastewater reuse rate	0.717	0.475	0.010	0.298	–0.187
		Agricultural machinery per unit sown area	0.241	0.082	0.558	–0.185	0.189

0.655. The result shows that the equation is reasonable to a high degree. The functional relationship is as follows.

$$Y = 0.453 + 0.048X_1 + 0.018X_2 - 0.083X_3 + 0.039X_4 + 0.035X_5. \quad (9)$$

Among the factors, urbanization, social development, arable land security, and environmental management have a significant positive correlation with the LEH. When they increase by 1 unit, the land ecological health index increases by 0.048, 0.018, 0.039, and 0.035 units, respectively (Table 4).

The promoting effect of urbanization (X_1) on LEH can be attributed mainly to policy intervention and technical support in the "new urbanization" path of Jiangxi Province. In the research time domain, Jiangxi Province improved its intensive land use and land use efficiency and reduced the ecological damage caused by extensive development through environmental protection and new urbanization construction. At the same time, the government increased its investment in environmental protection and improved pollution control technology. In the research time domain, Jiangxi Province increased its industrial wastewater reuse rate by 28.90% and industrial solid waste comprehensive utilization rate by 17.88%, which alleviated the pollution pressure from the urbanization process. With the increase in its per capita public green space area from 2.86 m^2/person to 5.89 m^2/person, Jiangxi Province enhanced the carbon sink capacity and the biodiversity maintenance function of its urban ecosystem, which improved its LEH. However, the promoting effect of urbanization (X_1) on LEH was not completely linear, and its promotion process may be accompanied by potential ecological risks. For example, the expansion of construction land may aggravate habitat fragmentation or cause local pollution. However, Jiangxi Province balanced development and protection effectively by limiting the disorderly spread of cities through its "multiregulation" policy and implementing ecological restoration projects.

The positive effect of social development (X_2) stemmed from the synergy of population agglomeration facilitating efficient governance, the reasonable reclamation of cultivated land to support ecological agriculture, and water resource abundance ensuring system resilience. In the research time domain, Jiangxi Province's population density increased from 259.91 people/km^2 to 280 people/km^2; its GDP per unit of construction land increased from 6.0486 million yuan/hm^2 to 1.623 million yuan/hm^2, with an increase of 165%; and its per capita public green space area increased from 2.86 m^2/person to 5.89 m^2/person, with an increase of 106%. The province's land reclamation index increased slightly from 0.317 to 0.373, with a decrease in fertilizer use per unit area (from 244.36 kg/hm^2 to 174.34 kg/hm^2), which reflected the improvement of the cultivated land quality and the effectiveness of the policy regulation. The province's adequate per capita water resources (from 3,502.7 m^3/person to 3,730.05 m^3/person) supported its ecological resilience and improved its industrial wastewater reuse rate from 61.25% to 90.15%, which alleviated the pressure from resources. Although the province's population density and reclamation index may imply the existence of pressure, the factors can be transformed into the driving force behind ecological health improvement through policy intervention and technological upgrading.

The positive effect of cultivated land security (X_4) stemmed from the synergy between chemical input control and the sustainable use of cultivated land. Although the use of chemical fertilizers and pesticides per unit area was a reverse index (a load of −0.873 and −0.440, respectively), the use intensity decreased significantly (use of chemical fertilizers decreased from 244.36 kg/hm^2 to 174.34 kg/hm^2 and use of pesticides decreased from 14.22 kg/hm^2 to 8.45 kg/hm^2), which reflected the policy-driven agricultural pollution reduction. At the same time, the per capita sown area of crops increased from 0.12 hm^2/person to 0.14 hm^2/person. The construction of high-quality farmland (a stable effective irrigation area of around 1,940 thousand hm^2) and the promotion of ecological planting can realize the "quality and quantity double protection" of cultivated land and support the improvement of the LEH index.

The positive effect of environmental management (X_5) is derived from the source reduction of land pollution by industrial solid waste recycling: the comprehensive utilization rate of industrial solid waste in Jiangxi Province increased from 27.1% in 2005 to 44.98% in 2020, and the comprehensive index of land ecological health increased from 0.282 (less healthy) to 0.675 (healthier), showing a synchronous upward trend. Regression analysis showed that for every 1% increase in solid waste utilization, the land ecological health index increased by 0.035 (p < 0.01). The data show that the efficient utilization of industrial solid waste reduces the direct pressure of pollutant accumulation on land, reduces the risk of soil pollution, alleviates the consumption of land resources through resource utilization, and enhances the stability and recovery ability of land ecosystem. This control measure has effectively suppressed the negative impact of industrialization on land ecology and has become one of the key factors to promote the improvement of land ecological health in Jiangxi Province.

Economic development (X_3) demonstrated a significant negative correlation with LEH, and for every unit increase, the LEH index decreased by 0.083 (Table 4). In the research time domain, though the economic aggregate of Jiangxi Province continued to grow, the economic development model, which is dominated by the secondary industry, exerted a significant inhibitory effect on LEH. A possible reason for this result is the long-term high proportion of the secondary industry in the GDP (46.6% in 2005 and 43.1% in 2020), which can weaken the self-healing ability of the land ecosystem through high-intensity resource exploitation and pollutant discharge. Although the annual fixed asset investment growth rate decreased from 28.48% to 8.2%, the initial high investment accelerated the construction land expansion. The province's per capita construction land area increased from 41.94 m^2/person to 58.71 m^2/person. The construction land expansion further occupied the ecological space, aggravated the land fragmentation, and facilitated the decline of ecological connectivity, which further reduced the carbon sink capacity and water conservation function of the urban ecosystem.

Table 4. Results of linear regression analysis of principal component factors

Variables	Coefficient	Standard deviation	T	P
Urbanization	0.048***	0.006	7.799	0.000
Social Development	0.018***	0.006	2.963	0.003
Economic Development	–0.083***	0.006	–13.495	0.000
Arable Land Security	0.039***	0.006	6.244	0.000
Environmental Governance	0.035***	0.006	5.617	0.000
Constants	0.453***	0.006	73.499	0.000

Note: *** indicate significant at 0.1 levels, respectively.

5. Discussion

5.1. Result analysis

This study found that the land ecological health of Jiangxi Province shows regional divergence and overall improvement characteristics. From 2005 to 2009, the LEH in Jiangxi Province was in the "less healthy" level, possibly because in early Jiangxi Province, environmental protection was not coordinated with economic development, and the natural environment was seriously damaged by the continuous development of incremental land for urban expansion (Lü et al., 2021). Furthermore, land use planning lacks normality and rationality, seriously threatening land ecology and resulting in a reduction in the amount of productive land available. Second, Jiangxi Province vigorously promotes industrialization. Thus, "wastewater, waste gas, and waste residue" are increasing the pollution of the land. Meanwhile, the public awareness of ecological civilization is "high recognition, low awareness, and insufficient practice." The weak awareness of land resource protection constrains the effective promotion of the construction of the social action system of ecological environmental protection (Cui & Cao, 2021), leading to deteriorated land quality and compromised ecological well-being of the land. After 2009, Jiangxi Province issued a series of policy documents, such as "Several Opinions of Jiangxi Province on Delineating and Strictly Adhering to the Ecological Protection Red Line" and "Jiangxi Province Ecological Civilization Construction Target Evaluation and Assessment Measures," firmly establishing and practicing the concept of green water and green mountains is the silver mountain of gold. The LEH moved from the "critical health" level to the "healthier" level, achieving continuous improvement and leapfrog development in LEH. However, the current socio-economic development is still intensifying the consumption of the stock of land, and further efforts are needed to bring the LEH to the "healthy" level.

Further analysis showed that the deep driving mechanism of the regional differentiation of the LEH of Jiangxi Province demonstrated significant spatial heterogeneity in the northern and central–southern regions. The differences between the eastern and western regions of Northern Jiangxi can be attributed mainly to the urbanization gradient and industrial transformation efficiency. For example, Nanchang, with an urbanization rate of 78.08% and a unit construction land GDP of 17.9254 million yuan/hectare, alleviated ecological pressure through intensive land use. In Eastern Yingtan, for a long time, the proportion of its secondary industry in its GDP was higher than 50%, and its industrial solid waste utilization rate was only 79.68%, and the cumulative effect of pollution delayed the process of ecological restoration. The north–south differentiation between Central and Southern Jiangxi is related to the intensification of agriculture and the depth of industrial governance. Ji'an, in the north, achieved nonpoint source pollution control by reducing the intensity of chemical fertilizers and pesticides. In 2020, Ji'an's unit sown area decreased by 36.30% and 70.19% compared with that in 2005. In Southern Ganzhou, the proportion of the secondary industry in the GDP decreased to 38.1%, and the industrial wastewater reuse rate increased to 48.95%. Moreover, Southern Ganzhou's ecological resilience support of 2,795.98 m^3 per capita water resources promoted the land health growth rate, which reached the highest in the province of 13.87%.

In addition, the research results of this study on LEH align with those of the literature and highlight the regional particularity. The results are consistent with the macro judgement of Bai's (Bai et al., 2018) on the overall improvement of urban eco-efficiency in China, but Jiangxi Province's LEH improvement rate increased substantially after it became a national ecological civilization pilot area, that is, an average annual growth rate of 5.82%. This policy-driven acceleration effect was rarely quantified in the literature. In terms of the spatial differentiation, the "north high, south low; east high, west low" pattern of Jiangxi Province contrasts that of the "core-edge" gradient model proposed by Li et al. (2021) in Chongqing. Northern Jiangxi relies on its high urbanization rate and intensive land use to achieve ecological optimization, but Central Jiangxi achieved an LEH index that surpassed that of Northern Jiangxi in 2020 by adopting technical measures, such as improving its solid waste utilization rate, which indicated that less developed areas can quickly improve their ecological health through policy intervention. In terms of the urbanization effect, the urbanization of Jiangxi Province exerted a significant promoting effect on its ecological health, which is in stark contrast with the results of Wang and Pan (Pan et al., 2021; Wang et al., 2024) from their examination of Qingdao and the middle reaches of the Yangtze River Economic Belt. The differences in the results can be attributed to Jiangxi Province's strict control of construction land expansion and strengthening of its industrial pollution control technology, which can effectively reduce the potential ecological risks of urbanization. The finding is consistent with that of Yu (2021) on the "new urbanization" pollution reduction and efficiency path, but the present study clarifies the effectiveness of the policy tools through the use of empirical data. With regard to the impact of industrialization, the inhibitory effect of the proportion of the secondary industry in the GDP clashes with the findings of the research on technological innovation-driven economic transformation by Shang et al. (2018). The data showed that, though Jiangxi Province's industrial solid waste utilization rate increased to 44.98%, it remained significantly lower than that of the new urbanization area, which indicated that offsetting the ecological cost of the technological lag by relying simply on the adjustment of the industrial proportion would be difficult, which challenges the hypothesis that an increase in the proportion of the tertiary industry in the GDP can improve the ecology and reveals the core position of the quality of industrialization.

5.2. Policy recommendations

This study presents several policy recommendations based on the analysis of the spatial and temporal evolution and the factors that can influence the LEH of Jiangxi Province between 2005 and 2020.

(1) The land use structure should be optimized, and incremental development and agricultural pollution should be strictly controlled. Construction land total control should be implemented, the revitalization of land resource stock should be prioritized, and the ecological restoration and redevelopment of inefficient industrial land and abandoned industrial and mining land should be promoted. For example, Nanchang City replaced its industrial land with green spaces through its "retreat two into three" policy. Moreover, soil testing and formula fertilization should be promoted. The use of organic fertilizers, instead of chemical fertilizers, and other technologies of Central and Southern Jiangxi decreased their chemical fertilizer and pesticide use intensity by 24.51% and 39.98%, respectively. Thus, regional agricultural nonpoint source pollution prevention measures should be taken, control demonstration areas should be established, and land transfer mechanisms should be improved to encourage the large-scale operation of high-quality farmland.

(2) The green transformation of the industrial structure should be promoted, and the expansion of high-energy-consuming industries should be restricted. In view of the significant inhibitory effect of the proportion of the secondary industry in the GDP on LEH, a negative industry access list should be formulated to limit the expansion of high-pollution industries. The transformation path of Ganzhou City, wherein the proportion of the secondary industry in the GDP dropped to 38.1%, should be examined to realize traditional industrial upgrading through the carbon trading mechanism. At the same time, urbanization and ecological protection and the "multiregulation" experience of Nanchang City should be promoted, ecological corridors and green space systems should be incorporated into urban planning, the per capita public green space area

should be guaranteed to be no smaller than 8 m^2, and construction land expansion should be restricted.

(3) Regional differentiated governance should be implemented, and ecological compensation coordination mechanisms should be strengthened by taking intensive land use promotion as the core, strengthening the control of the ecological protection red line in Poyang Lake Basin, and promoting the intensive mode of increasing the GDP per unit construction land in Nanchang by 146.95%. In the central and southern regions of Jiangxi Province, priority is given to the restoration of high-risk soil erosion areas, the implementation of the Grain for Green Project, the development of water-saving agriculture based on the advantages of their per capita water resources of 4,248.32 m^3, and the establishment of special funds for cross-city ecological compensation to give financial transfer payments to ecological contribution areas.

(4) A smart monitoring system should be developed to promote the ecological participation of the entire population. Remote sensing and geographic information system technologies should be integrated; a dynamic LEH monitoring platform should be constructed to monitor key indicators in real time, such as pesticide use intensity and industrial wastewater discharge; and monitoring stations should be added in areas with weak data, such as Yingtan City. Furthermore, "land health community" pilot projects should be conducted, ecological health data should be provided on digital platforms, public participation in pollution supervision and governance decision making should be encouraged, and policy transparency and implementation efficiency should be improved.

5.3. Shortcomings and prospects

(1) This paper combines the highly recognized PSR model and EES basic theory to construct an index system, which can provide a good characterization of the LEH. However, the "3S" technology and the prediction model are not fully utilized to dynamically monitor the study area. The richness of the statistical data information and the spatial visualization must be improved, and the application of remote sensing information should be enhanced in subsequent studies.

(2) This paper focuses on the study of land ecological health in Jiangxi Province, but in China, three other provinces belong to the NPZ for Ecological Conservation, including Fujian, Guizhou. and Haina. Subsequent studies should be conducted under the comparative perspective of the four provinces horizontally and other regions vertically to form a highly comprehensive ecological civilization construction program and expand the path of sustainable development of land ecological resources.

(3) This study did not divide the impact of the economic structure on LEH. The empirical data showed that the decrease in the proportion of the secondary industry in the GDP and the increase in the proportion of the tertiary industry in the GDP may have heterogeneous effects. For example, the industrial wastewater reuse rate of Nanchang City (with a highly developed service industry) reached 84.87%, whereas that of Ganzhou City (with a high proportion of the traditional industry in its GDP) was 48.95% during the same period, which indicated that industrial upgrading may reduce the land load. Future research can examine indicators such as the proportion of the tertiary industry in the GDP and green industry investment and analyze the ecological benefits of economic restructuring.

(4) Although the data used this study covered 2020, they encompassed the key stage after the implementation of China's ecological civilization pilot area policy (2016–2020). The results showed that the average annual growth rate of the comprehensive LEH index of Jiangxi Province increased to 5.82% after 2016, and the entire region improved from being at the "less healthy" level to being at the "healthier" level. The trend indicated that policy interventions substantially improved the LEH of the province in the short term. If the current urbanization optimization, industrial solid waste utilization rate increased by 65.98% and fertilizer use intensity decreased by 28.65% and other measures continue to deepen, it is expected that the land ecological health index will steadily approach the "health" level. Therefore, the existing data can provide a robust empirical basis for policy effect evaluation and an extensible analysis framework for continuous future monitoring. In the future, continuous policy iteration tracking and data updating and improving the dynamic LEH evaluation system will be necessary.

(5) Although the current indicator system indirectly reflects the impact of technological upgrading and climate fluctuations on LEH to a certain extent through indicators such as the industrial solid waste/wastewater utilization rate in the response layer and the per capita water resources in the state layer, the depth of the analysis of this research was insufficient. To evaluate the impact of the factors comprehensively, future research should systematically integrate relevant driving factors and indicators such as the proportion of agricultural science and technology investment in the total investment and the number of days of extreme precipitation, which can directly reflect technological progress and climate change. At the same time, future studies should employ remote sensing data and high-resolution climate models to enhance their spatial heterogeneity analysis. Furthermore, through multimodel comparisons, future studies should compare the model results before and after the addition of other factors and further explore the influence of technological progress and climate change on LEH to improve the robustness and scientificity of this study and the research results.

6. Conclusions

This paper takes Jiangxi Province, which is one of the first NPZ for ecological civilization in China, as the research object. By measuring the LEH from 2005 to 2020 using the composite index method, the spatial and temporal evolution characteristics of 11 cities were analyzed. The factors influencing LEH were subjected to principal component analysis. This study provides a reference for the construction of ecological civilization in China. On the basis of empirical analysis, the following conclusions were drawn.

Analysis was performed based on the PSR-EES model. Overall, the LEH index in Jiangxi Province presents a fluctuating growth trend. In the early stages of a study, the ecological health of land in Jiangxi cities was poor. The spatial variation in ecological health of land among the cities showed an overall improvement trend "from west to east, from north to south" year by year. However, the entire region must enter the "healthy" level, focus should be given on the coordinated development of socio-economic and land resources, and the consumption of natural resources must be reduced.

In terms of influencing factors, urbanization, as characterized by the urbanization level, the common green space per capita, and the construction land area per capita, has the strongest effect on promoting land ecological health. Economic development, which is characterized by the annual growth rate of fixed asset investment and the share of the secondary industry in GDP, has a significant inhibitory effect on the LEH. In general, it should start from the key influencing factors to achieve a positive interaction and mutual promotion. On the basis of maintaining the existing achievements in land ecological construction in Jiangxi Province, the ecological health of the land should be improved.

Author contributions

Zhenggen Fan: Conceptualization, supervision, validation, writing – original draft; Binghua Liu: Data curation, writing – original draft; Peng Zhong: Writing – review and editing.

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