Spatiotemporal Evolution of Agroecosystem Adaptability in Southern Hilly Regions under Global Change: A Case Study of the Hengyang Basin (Postprint)

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Abstract

Ecosystem adaptability has emerged as a prominent issue in global change and development studies. The evolution of ecosystem adaptability constitutes a critical manifestation of regional responses to global change. The southern hilly region of China represents a typical rice cultivation area, rendering research on agricultural ecosystem adaptability particularly significant. This article employs the Hengyang Basin as a case study, constructing an evaluation index system for agricultural ecosystem adaptability through the selection of 12 indicators across three dimensions: natural, social, and economic. Evaluation units are delineated as Hengyang urban district and its constituent counties, with the research timeframe encompassing 16 years from 1999 to 2014. The entropy weight method is utilized to determine indicator weights, thereby calculating the adaptive capacity index for the Hengyang Basin. Results demonstrate that the overall adaptability of the agricultural ecosystem in the Hengyang Basin is favorable, characterized by complex spatial differentiation: Leiyang City exhibits the highest adaptive capacity, followed by Qidong County, while Changning City displays the lowest. Temporal evolution manifests as a fluctuating ascending trajectory, with the 16-year evaluation period divisible into three distinct phases: 1999–2004 represents a low-value phase featuring minor oscillations in adaptability; 2005–2010 constitutes a phase of substantial fluctuation with an overall upward trend; and 2010–2014 marks a phase of rapid adaptive capacity enhancement. The study' s conclusions may serve as a reference for sustainable agricultural development within the study area.

Full Text

Spatio-temporal Evolution Characteristics of Agro-ecosystem Adaptability Response to Global Change in South China Hilly Regions: A Case Study of Hengyang Basin

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Abstract: Ecosystem adaptability has become a hot issue in global change and development research, with its evolution representing an important manifestation of regional responses to global change. South China' s hilly regions are typical rice-farming areas, making research on agricultural ecosystem adaptability particularly important. This study uses Hengyang Basin as a case study to construct an agricultural ecosystem adaptability evaluation index system comprising 12 indicators from natural, social, and economic dimensions. The evaluation units include Hengyang City proper and its constituent counties, covering a 16-year period from 1999 to 2014. The entropy weight method was employed to determine indicator weights and calculate the adaptability capacity index for Hengyang Basin.

The results show that the overall adaptability status of Hengyang Basin' s agricultural ecosystem is relatively good, with complex spatial differentiation. Leiyang City demonstrates the strongest adaptability capacity, followed by Qidong County, while Changning City shows the weakest. Temporal evolution exhibits a fluctuating upward trend, with the 16-year study period divided into three stages: 1999–2004 as a low-value stage with small-amplitude oscillations, 2005–2010 as a stage of significant fluctuation with overall upward trend, and 2010–2014 as a stage of rapid increase. These conclusions can provide reference for sustainable agricultural development in the study area.

Keywords: Agricultural ecosystem; Adaptability; Entropy weight method; Spatial evolution; Temporal evolution; Hengyang Basin

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1. Study Area Overview

Hengyang Basin is a typical red hilly basin in southern China, belonging to a humid, hot, erosion-prone, and degraded fragile region. The terrain slopes from high in the south to low in the north, with a composite incline from southwest to northeast, decreasing from the periphery toward the center. Geographically, Hengyang Basin spans 111°32 16 –113°16 32 E and 26°07 05 –27°28 24 N, extending 150 km from north to south and 173 km from east to west, covering an area of approximately 15,310 km^2. The basin comprises five counties under

Hengyang City' s jurisdiction (Hengyang, Hengnan, Hengshan, Hengdong, and Qidong Counties) and two county-level cities (Leiyang and Changning). The study area features a mid-subtropical humid monsoon climate with annual precipitation of 1,200–1,600 mm. Seasonal precipitation variation is substantial, with rainfall during April–June accounting for 70% of the annual total, forming a distinct rainy season that serves as the primary water source for rivers in the region. Summers are humid and hot. The area' s thermal conditions rank among the most favorable in Hunan Province, characterized by high annual average temperatures, abundant accumulated temperature, long frost-free periods, and short severe cold periods, with average annual temperatures of 17.5–18.9°C across the region. While Hunan' s average forest coverage reaches 55%, Hengyang Basin' s coverage is only 43%, with poor vegetation cover. In purple soil areas, forest coverage is merely about 10%, and soil erosion is severe.

2.1 Concept and Connotation of Agricultural Ecosystem Adaptability

Based on the IPCC' s adaptability framework and drawing upon relevant research, we define agricultural ecosystem adaptability as the capacity of a system composed of agricultural environment, agricultural production clusters, and agricultural economy to exhibit learning ability, risk reduction potential, and system stability maintenance when responding to global change. The connotation includes the coordinated evolutionary capacity among these three components, encompassing three specific aspects: (1) Under global change, as the agricultural environment evolves, the agricultural ecosystem learns from and absorbs favorable changes to enhance the structural level of agricultural production clusters and agricultural economic development capacity, manifesting as enhanced adaptability; (2) When environmental evolution under global change becomes drastic and manifests as natural disasters, the system' s consumption and tolerance of adverse factors—its resilience; and (3) Human-driven regulation, whereby humans adjust agricultural industrial structure, develop and adopt agricultural technologies to maximize benefits and minimize harm, and improve system stability and resilience based on understanding the stress and exposure patterns of agricultural ecosystems. Self-adaptation and human-driven adaptation are coupled and interpenetrating, jointly influencing adaptability intensity and its evolution characteristics.

2.2 Construction of Agricultural Ecosystem Adaptability Evaluation Index System

Agricultural ecosystem adaptability represents a comprehensive manifestation of interactions and coupling among natural environment, society, and economy. The natural environment forms the foundation and background conditions affecting adaptability, inducing the strength and evolution direction of self-adaptation and influencing the baseline level of adaptability. Social and economic factors represent the primary means and pathways of human-driven adaptation, affecting the evolution mode and speed of adaptability. Following principles of systematicity, scientific rigor, accessibility, and expressiveness, and considering Hengyang Basin' s regional characteristics, this study constructs an adaptability evaluation index system from natural, social, and economic dimensions. Appropriate index system construction is key to objective evaluation. The system should be neither too simple nor too complex, to avoid overlooking important indicators or weakening the driving effect of primary indicators, which would affect evaluation results. Based on the research team' s experience and relevant studies, 10-15 indicators are appropriate; this study constructs 12 evaluation indicators.

2.2.1 Natural Environment Factors Abundant precipitation and ample light-heat conditions in Hengyang Basin ensure water and temperature requirements for rice farming, serving as positive indicators. However, substantial seasonal precipitation variation, with April–June rainfall exceeding half of the annual total and frequent heavy rains, increases flood risk and reduces water use efficiency. Therefore, the proportion of precipitation during April–June is a negative indicator.

Geological, geomorphological, and soil factors are profoundly influenced by tectonic movements and change over large timescales, making substantial changes unlikely within shorter time domains. Even under external forces and human activities, they remain relatively stable. This study examines adaptability evolution since the 1990s, selecting 1999-2014 as the research period—a timescale too small relative to tectonic movements to include geological, geomorphological, and soil factors in the index system. Biological factors are important natural environmental components. While species populations and community structures are profoundly affected by tectonic movements over large timescales, they are more influenced by climate and human activities within smaller time domains. Biological factors serve as indicators of natural environment, with vegetation cover status showing particularly significant indicative and driving effects. Forest coverage, as a comprehensive expression of natural environmental quality and known as a "green reservoir," plays a crucial role in maintaining agricultural ecosystem stability and is selected as a positive evaluation indicator.

2.2.2 Social Factors Agricultural ecosystem adaptability is profoundly affected by social factors. Hengyang Basin has dense population and heavy cultivated land load, with severe overexploitation. Therefore, population density (negative indicator) and per capita arable land (positive indicator) are included in the evaluation index system. Rational cropping systems can fully utilize thermal resources and enhance ecosystem adaptability. As the study area belongs to the subtropical humid monsoon climate zone, increasing late rice planting area represents an important pathway for fully utilizing climate resources. Thus, the proportion of late rice planting area to total rice planting area is included as a positive indicator.

2.2.3 Economic Factors Economic factors influence the intensity and evolution trend of adaptability. Per capita GDP and farmers' net income are positive indicators that induce adaptability enhancement, while the Engel coefficient represents poverty level as a negative indicator. Although pesticide and fertilizer use can guarantee short-term agricultural yields, they destroy soil aggregate structure, cause severe water and soil pollution, and have long-lasting effects. Therefore, fertilizer application rate per unit land and pesticide application rate per unit land are negative indicators.

This study selects 12 evaluation indicators from natural, social, and economic factors that exert obvious driving effects on agricultural ecosystem adaptability, establishing the adaptability evaluation index system (Table 1).

2.3 Evaluation Units and Data Sources

The selected evaluation units include Hengyang City proper and its constituent counties. Hengyang Basin comprises seven counties and Hengyang City proper. Among them, Leiyang and Changning are county-level cities, while the remaining five are counties. For convenience, they are collectively referred to as counties in this paper. Although Hengyang City proper' s agricultural ecosystem differs substantially from the counties, it is included to maintain study area completeness. To analyze temporal evolution of the entire basin' s agricultural ecosystem, the overall situation of Hengyang City (including seven counties and the city proper) was also calculated, with Hengyang City representing Hengyang Basin.

Data sources: Annual mean temperature, annual average precipitation, proportion of precipitation during April–June, and proportion of late rice planting area were obtained from the *Hengyang Statistical Yearbook* for corresponding years. Per capita arable land, population density, per capita GDP, farmers' net income, farmers' Engel coefficient, fertilizer application rate per unit land, and pesticide application rate per unit land were obtained from the *Hunan Rural Statistical Yearbook* for corresponding years.

2.4.1 Data Standardization

Evaluation indicators are classified as positive or negative. Positive indicators mean larger values indicate stronger adaptability, and vice versa. Data standardization methods are as follows:

Positive indicators:
Negative indicators:

Where ijx represents the original value of indicator j in region i, and ijx represents the standardized value (i = 1, 2, ···, 8; j = 1, 2, ···, 12).

2.4.2 Determination of Indicator Weights

Various methods exist for determining indicator weights, including principal component analysis, analytic hierarchy process, fuzzy comprehensive evaluation, and entropy weight method. The analytic hierarchy process is highly subjective, while principal component analysis objectively determines weights and is effective for complex index systems. The entropy weight method is another objective approach that derives weights from a judgment matrix composed of evaluation indicator values (standardized values). For numerical indicators with complete sample data, the entropy weight method can reflect the utility value of indicator information entropy, making it suitable for determining evaluation indicator weights with high credibility and reduced uncertainty from uncontrollable factors. This study employs the entropy weight method:

1) Calculate the entropy value of indicator j:
   (formula with $k > 0$, $k = 1/\ln(n)$)
2) Calculate the difference coefficient for indicator j. For indicator j, larger differences in indicator values among samples have greater impact on scheme evaluation and smaller entropy values. The difference coefficient is defined as:
   $g\_j = 1$ - e_j (where m is the number of indicators)
3) Calculate the weight value (w_j):
   $w\_j = g\_j$ / Σg_j ($0 \leq w\_j \leq 1$, $\Sigma w\_j = 1$)

2.5 Agricultural Ecosystem Adaptability Capacity Calculation

Agricultural ecosystem adaptability capacity is calculated using the multi-indicator linear weighted function method:

$P\_n = \Sigma(w\_j \times ijx\,)$

Where P_n represents the agricultural ecosystem adaptability capacity index for year n, ijx represents the standardized value of indicator j in region i for year n, and w_j represents the weight of indicator j.

Based on Hengyang Basin' s actual conditions and calculation results, and drawing upon existing research, the study area' s agricultural ecosystem adaptability capacity is classified into four levels: low (0.2800-0.3800), medium (0.3800-0.4800), relatively high (0.4800-0.5800), and high (0.5800-0.6800).

3.1 Spatial Differentiation Characteristics of Adaptability in Hengyang Basin

Figure 1 [Figure 1: see original paper] reveals complex spatial differentiation in agricultural ecosystem adaptability across Hengyang Basin, with substantial variation in relative adaptability strength, evolution speed, and direction among counties in different years.

3.1.1 Overall Good Adaptability Status in Hengyang Basin The adaptability capacity of Hengyang Basin' s eight counties (including the city proper) ranges from 0.2498 to 0.6794, predominantly above 0.3800, indicating mainly medium or higher adaptability levels. This correlates closely with the basin' s favorable natural environment and long-standing agricultural culture. Hengyang Basin enjoys abundant light-heat resources, plentiful rainfall, and concurrent rainfall-heat conditions beneficial for rice farming. The basin' s long history of rice cultivation has yielded rich experience in intercropping and rotation, with widely circulated agricultural proverbs demonstrating farmers' profound capacity to predict meteorological disasters, providing foundational conditions for reducing agricultural risks and enhancing ecosystem resilience. Additionally, Hengyang Basin's agricultural ecosystem exhibits rich crop diversity: grain crops include rice, wheat, corn, sorghum, barley, and other cereals, while rice cultivation encompasses early, middle, single-season, and late rice, each occupying important shares in planting area and yield. This cropping system and farming method can maximize benefits and minimize harm according to seasonal distribution of light, heat, and water resources, demonstrating good adaptability.

3.1.2 Leiyang City Shows Strongest Adaptability, Changning City the Weakest Figure 1 demonstrates complex regional differences in adaptability across Hengyang Basin. Overall, Leiyang City exhibits the strongest adaptability, followed by Qidong County, while Changning City shows the weakest agricultural ecosystem adaptability. Hengdong County ranks second to last.

Leiyang City, located on Hengyang Basin' s southeastern margin, features medium-low mountains (300–500 m) in its eastern and southern parts with good bamboo and oil tea forest coverage, resulting in minimal soil erosion and landslide risk. The central and northwestern low hills and plains (60–150 m) serve as planting areas for rice, wheat, sorghum, tobacco, and peanuts, while peripheral medium-low mountains provide natural barriers for agricultural production. Leiyang City is rich in water resources, with the Xiang River system forming a dense network of 79 tributaries exceeding 5 km in length and totaling 1,203.94 km. The water conservancy infrastructure is well-developed, including one large reservoir (Ouyanghai Irrigation District), three medium reservoirs, 271 small reservoirs, 27,900 mountain ponds, 2,947 water channels spanning 4,654 km, and 426 aqueducts totaling 53,612 m. The total water storage, diversion, and lifting capacity reaches 442 million m^3 (327 million m^3 storage, 48 million m^3 diversion, 67 million m^3 lifting), providing effective irrigation for 39,000 ha (78.1% of total cultivated land) and drought-flood ensured area of 33,000 ha (64.58% of total cultivated land). This irrigation system, combining reservoirs as the backbone with ponds as the foundation and integrating storage, diversion, and lifting at large, medium, and small scales, provides convenient irrigation water for agricultural production and strong drought-flood resistance, with drought risk being the lowest in Hengyang Basin. As the southern gateway of Hunan' s economic strategic focus "five districts and one corridor" and a frontier for undertaking industrial transfer from the Pearl River Delta, Leiyang City' s comprehensive economic strength consistently ranks first in Hengyang City. The coupling of favorable natural environment and economic conditions results in strong agricultural ecosystem adaptability.

Changning City, located on Hengyang Basin' s southwestern margin, features towering mountains in the south, with 16 peaks exceeding 1,000 m and 63 peaks at 800–1,000 m, making its southern mountainous area unsuitable for farming. Changning has a mid-subtropical humid monsoon climate with complex terrain, showing high variability in seasonal and interannual changes of precipitation, temperature, and sunshine, indicating strong climatic environmental fragility. Once economically supported by abundant mineral resources, long-term mining has transformed Changning into a resource-exhausted city, with extensive groundwater funnels severely hindering agricultural development and creating high natural environment sensitivity. Changning' s distance from Hengyang City proper and lack of railway transportation have constrained economic development to some extent. Examination of annual *Hengyang Statistical Yearbooks* reveals that Changning' s farmers' net income lags behind other counties, with a high Engel coefficient. High natural environment sensitivity combined with relatively backward economy and transportation results in weak agricultural ecosystem adaptability.

3.1.3 Changning Shows Largest Fluctuation, Hengnan the Smallest, Leiyang Shows Clear Upward Fluctuation The coefficient of variation (CV) expresses the degree of variation or dispersion in geographic data, reflecting system resilience and stability. Calculated CVs for each county are shown in Table 2 .

Table 2 reveals that Changning City exhibits the largest fluctuation in agricultural ecosystem adaptability capacity (CV = 0.2277), followed by Hengdong County (0.2162), while Hengnan County shows the smallest fluctuation (0.1329). Qidong County' s CV is only slightly larger than Hengnan' s at 0.1511. Changning' s largest fluctuation indicates minimal system stability and strongest sensitivity and fragility, resulting in the weakest agricultural ecosystem adaptability. Hengnan County' s adaptability index ranks at a medium level overall, but its minimal fluctuation suggests relatively stable agricultural ecological environment with slow evolution. Hengnan' s agricultural limiting factors are difficult to improve, particularly the water retention and afforestation challenges of widely distributed purple soil, requiring long-term planning and measures to significantly enhance agricultural ecosystem adaptability. Leiyang City has the highest overall adaptability level, ranking fourth in fluctuation, but this fluctuation represents a rapid upward positive trend related to vigorous industrial structure adjustment since the late 20th century. Since 2005, Leiyang has vigorously adjusted its industrial structure to improve agricultural comparative benefits, forming a new pattern with grain production as the foundation and comprehensive development of forestry, animal husbandry, sideline production, and fisheries. Large-scale national premium hybrid rice seed production bases, Hunan' s advantageous flue-cured tobacco production bases, and herbivorous animal bases have been established successively, with rural secondary and tertiary industries centered on township enterprises developing rapidly, boosting the rural economy and substantially improving adaptability. Leiyang' s agricultural ecosystem adaptability demonstrates good development potential and prospects.

3.2 Temporal Evolution Characteristics of Adaptability

3.2.1 Overall Upward Trend in Adaptability Over Time To summarize the overall characteristics of adaptability evolution in Hengyang Basin, this study uses Hengyang City's overall values to represent the basin. Figure 1 shows that although changes in each evaluation unit are complex, adaptability capacity in each county generally exhibits a fluctuating upward trend, transitioning from low and medium to relatively high and high adaptability levels. This is closely related to the region' s natural resources, economic development, and agricultural infrastructure improvements. Hengyang Basin's high crop maturity, suitable annual average temperature, abundant annual precipitation, gradually improving agricultural irrigation facilities, and steadily increasing farmers' net income have enhanced agricultural ecosystem resilience and improved adaptability capacity.

3.2.2 Large Temporal Fluctuations with Amplification Effect Hengyang Basin' s agricultural ecosystem adaptability shows large fluctuations with an amplification effect across evaluation units. The amplification effect can be understood as: when adaptability indices of evaluation units are at low levels, the basin' s overall adaptability falls below the mean of evaluation units; when indices are at high levels, the basin's adaptability exceeds the county-level mean. Analysis of Figure 1 and Table 3 reveals that 2001–2006 was a low adaptability stage, with the basin' s overall capacity below individual counties; 2010–2014 was a high adaptability stage, with basin capacity exceeding all counties. Temporal fluctuation analysis (Table 2) shows Hengyang Basin' s CV of 0.2312 exceeds all individual counties' values, demonstrating a clear amplification effect closely related to climate fluctuations. The average drought frequency during 2001–2013 was the highest in the recent 33-year period (1980–2013), indicating high drought risk.

Based on evolution characteristics and trends, the 16-year study period can be divided into three stages:

1) Low-value stage with small-amplitude oscillation (1999–2004)
During 1999–2004, Hengyang Basin' s agricultural ecosystem adaptability was dominated by medium and low levels with small oscillations. Hengyang City proper, Hengyang County, and Hengshan County showed minimal variation and low overall adaptability. Farmers' net income was ¥3,480, with an annual increase of ¥190. While per capita GDP and Engel coefficient changed slightly,

unstable natural environmental factors such as water-heat coordination and frequent flood-drought disasters resulted in low agricultural ecosystem stability, preventing full utilization of water-heat resources provided by the ecological environment and causing misalignment between agricultural industry and resources, leading to low adaptability.

2) Stage of significant fluctuation with overall upward trend (2005-2010)

During 2005–2010, adaptability fluctuated substantially but showed an upward trend, with the index rising from 0.3180 in 2005 to 0.4851 in 2010—a 49% overall increase. Fluctuation patterns varied among units: Hengnan, Hengshan, Hengdong, Qidong, Changning, and Leiyang showed upward trends, while Hengyang City proper and Hengyang County declined during 2007–2009. Agricultural and socioeconomic systems are closely related. Beginning in 2005, the complete abolition of agricultural taxes and implementation of rural road access projects, combined with Hengyang City' s 11th Five-Year Agricultural Development Plan prioritizing agricultural ecological environment protection, produced initial results of agricultural support policies. Regional per capita GDP increased from ¥8,800 to ¥20,419 (56% growth) during 2005–2010, with socioeconomic progress facilitating increased agricultural investment and improved adaptability. However, Hengyang Basin lies in Hunan' s driest Heng-Shao drought corridor, with frequent droughts occurring in 2003, 2005, 2007, 2009, and 2011, causing severe losses to agricultural ecosystems. The unprecedented ice disaster in southern China in 2008 also dealt heavy blows to agricultural facilities and winter-spring production. These periodic meteorological disasters caused strong sensitivity and exposure in agricultural ecosystems, resulting in significant adaptability fluctuations.

3) Stage of rapid increase (2010-2014)

During 2010–2014, adaptability reached relatively high and high levels with rapid and stable upward trends, increasing from 0.4851 in 2010 to 0.6794 in 2014. This stage saw Hengyang City promote agricultural "one transfer and five services," replacing scattered extensive management with intensive operations, implementing agricultural technology extension, and rapidly improving fertilizer and pesticide use efficiency. The direct grain subsidy policy of "whoever plants grain benefits, however much planted gets subsidized" significantly increased farmers' enthusiasm, controlling farmland abandonment. Agricultural ecosystem adaptability developed elastically with a sustained upward trend. Hengyang County and Hengnan County showed smaller adaptability indices with fluctuating declines in 2013, related to two drought disturbances in these counties that year.

4. Discussion and Conclusion

Ecosystem adaptability is a research hotspot in global change and regional response studies. Research on agricultural ecosystem responses to global change from an adaptability perspective constitutes core content in this field. This study explores spatio-temporal evolution characteristics, particularly temporal evolution, representing a novel attempt under the global change framework. Adaptability evolution speed and trends vary across stages, with strong intervention from human socioeconomic activities, making enhanced adaptability management crucial for improvement. Quantitative research on ecosystem adaptability remains in an exploratory stage without standardized evaluation methods. Strengthening empirical studies is necessary to enrich theoretical and methodological foundations. Constructing reasonable evaluation index systems and research models is key to quantitative research.

Agricultural ecosystem adaptability research must consider agricultural industry characteristics. Agriculture is extremely affected by natural environment, with climate change causing major changes in production conditions that threaten agricultural production. Social and economic factors influence adaptability evolution direction and speed. Our team' s previous research on driving forces of agricultural ecosystem adaptability in Hengyang Basin identified socioeconomic factors as the primary driver, which aligns with temporal evolution causes in this study. Agricultural laborers' scientific and cultural quality affects adaptability, but this factor was not included because, with deepening rural land transfer, scaled intensive agriculture is forming where some rural household registrants work outside agriculture while some agricultural college graduates work as technicians without rural household registration, making such data difficult to obtain —also related to limited research funding. Future studies should strengthen field investigations, extensively collect data, enhance coupling research among various influencing factors in index system construction, and incorporate important micro-indicators, agricultural practitioners' quality and quantity, agricultural activity willingness, and agricultural support policy implementation to ensure more objective and reliable evaluations for guiding agricultural economic activities.

This study selected 12 indicators from natural, economic, and social dimensions to establish an agricultural ecosystem adaptability evaluation index system, used the entropy weight method to determine indicator weights, and calculated adaptability capacity indices for each county and Hengyang City proper during 1999–2014. The index system and evaluation model are objective, scientific, reasonable, and generalizable. Most existing research on agricultural ecosystem adaptability presents static spatial studies using single-year examples; this study' s spatio-temporal dynamic evolution research on Hengyang Basin represents a new attempt and exploration without comparable existing conclusions. The results show that Hengyang Basin' s agricultural ecosystem adaptability is generally good with a fluctuating upward trend, which aligns well with actual conditions and demonstrates high credibility.

Main conclusions: 1) **Spatial differentiation characteristics:** Hengyang Basin' s adaptability is generally good but spatially complex. Leiyang City shows the strongest adaptability with clear upward fluctuation; Qidong County ranks second with small interannual fluctuation; Changning City shows the weakest adaptability with the largest interannual fluctuation; Hengdong County' s adaptability is only better than Changning' s, with fluctuation second only to Changning.

2) **Temporal evolution characteristics:** The evolution shows a fluctuating upward trend, with the 16-year study period divided into three stages: 1999–2004 as a low-value stage with small-amplitude oscillation, 2005–2010 as a stage of significant fluctuation with overall upward trend, and 2010–2014 as a stage of rapid increase.

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Note: Figure translations are in progress. See original paper for figures.