Evolution Characteristics and Environmental Driving Factors of Ecological Resilience in Zhaoqing City

Haojun DENG *

School of Tourism and Historical Culture, Zhaoqing University, Zhaoqing 526061, China

Abstract This study aimed to uncover the spatiotemporal evolution and influencing factors of ecological resilience in Zhaoqing City. An evaluation index system was constructed based on data from 2000 to 2024, utilizing the comprehensive index method, obstacle degree model, and linear regression analysis. The findings revealed that the comprehensive ecological security index escalated from 0.214 3 to 0.629 0, marking an increase of 193.5%. This growth exhibited a three-stage pattern characterized by "slow rise, steady improvement, and rapid improvement". The structure of ecological security transitioned from being pressure-dominated to response-dominated, with the proportion of the pressure index decreasing from 39.7% to 26.5%, and the response index proportion increasing from 27.5% to 41.6%. The obstacle degree of solid waste utilization rate diminished from 18.2% to 11.0%, and per capita carbon emissions reduced from 15.8% to 7.0%. However, the SO_2 removal rate (16.0%) and soot removal rate (14.5%) emerged as the primary constraints, suggesting that the capacity for atmospheric pollutant removal is a critical bottleneck. Forest coverage was identified as the dominant factor regulating ecological resilience, accounting for 71% of the spatial variation. In contrast, temperature had a minimal effect, while precipitation and sunshine duration were not significant. This research provides a scientific foundation for the construction of ecological security and enhancement of resilience in Zhaoqing City and similar ecological function areas.

Key words Ecological resilience; Ecological security; Obstacle factors; Forest coverage; Zhaoqing City

DOI 10.19547/j.issn2152 – 3940.2026.04.010

Ecological resilience, a crucial indicator of ecosystem diversity, stability, and sustainability, refers to the capacity of a system to absorb disturbances and recover while preserving its fundamental functions and services[1]. This concept was initially introduced into systems ecology by Holling[2], drawing parallels with engineering principles. The development of an ecological resilience evaluation framework, the analysis of its spatiotemporal evolution, and the implementation of dynamic early warning systems are pivotal for fostering high-quality regional ecological development.

In recent years, the methodological perspectives for measuring ecological resilience have been continuously enriched and expanded, encompassing urban land use, environmental capacity, planning policies, transportation systems, climate change, institutional finance, *etc*[3]. The research content of ecological resilience mainly focuses on biodiversity conservation, green infrastructure, habitat restoration, ecosystem services, *etc*. For example, exploring the mechanism of how green space and urban forest enhance ecological resilience by promoting biodiversity and mitigating heat island effect, focusing on the dynamic relationship within the urban socio-ecological system, and emphasizing nature-based solutions and adaptive strategies[4]. The research scale covers multiple spatial levels such as national, regional, and urban agglomeration scales. From the macro level pattern, China's ecological resilience presents a distribution pattern of "high in the southeast and low in the northwest"[5]. In the Yangtze River Economic Belt, the upstream region has the highest level of resilience, followed by the midstream and downstream regions. From 2009 to 2023, the ecological resilience of this area showed a fluctuating upward trend, with the mean value increasing from 0.12 to 0.17, and an average annual growth rate of 2.31%, showing a spatial pattern of "high in the south and low in the north"[6]. The ecological resilience of Beijing – Tianjin – Hebei region decreased continuously from 2000 to 2010, but gradually recovered from 2010 to 2018. The evolution trend of Yangtze River Delta and Pearl River Delta urban agglomeration was fluctuation first and then convergence[6–8]. These differences indicate that the spatiotemporal evolution of ecological resilience is profoundly influenced by localized socio-ecological coupling processes and developmental stage transitions. Commonly employed spatiotemporal analytical methods encompass kernel density estimation, Dagum Gini coefficient, convergence models, and Markov chains. At the natural geographical level, factors such as climate and forest coverage constitute background constraints on ecological resilience[7–8]. Research demonstrates that ecological resilience exhibits negative correlations with population size and built-up area, while showing positive correlations with regional GDP, reflecting the constriction effects and cumulative pressures exerted by rapid urbanization on ecosystems. As digital economic integration and green transformation deepen, technological innovation and industrial upgrading are increasingly emerging as critical drivers for enhancing ecological resilience[9].

Received: June 9, 2026 Accepted: July 31, 2026

Supported by the Zhaoqing City Science and Technology Innovation Guidance Project (250821100810410); the Zhaoqing University Quality Engineering and Teaching Reform Project (zlgc202249).

* Corresponding author.

In the Pearl River Delta, a three-dimensional "scale – density – morphology" evaluation system has revealed that as urbanization levels have increased, ecological resilience has correspondingly declined. This shift has transitioned their coupling coordination from basic balance to fundamental imbalance[7]. Zhaoqing City, which serves as a crucial ecological barrier for the Greater Bay Area, has been the subject of limited research. Most existing studies have concentrated on the importance and sensitivity of its ecological functions[10–11], while the evolutionary process of its ecological resilience and the impacts of climate change remain unexplored. Using Zhaoqing City as a case study, this research aims to construct an ecological resilience evaluation framework, analyze its evolutionary mechanism, and investigate the impacts of climate change. The findings will provide a foundation for the construction of ecological civilization and the promotion of green development.

1 Materials and methods

1.1 Study area Zhaoqing City (22°47′ – 24°24′ N, 111°21′ – 112°52′ E) is situated in the mid-western region of Guangdong Province, along the middle and lower reaches of the Xijiang River. In 2020, Zhaoqing experienced an average annual precipitation of 1 491 mm, with surface water resources totaling 127.12×10^8 m^3 and overall water resources amounting to 127.40×10^8 m^3. Zhaoqing City boasts a per capita water resource volume of 3 357.5 m^3, notably surpassing the national average of 2 100 m^3. Owing to its unique geographical location, Zhaoqing has strong ties with the Greater Bay Area. It serves as a crucial ecological barrier for the Pearl River Delta and represents a particularly sensitive area concerning the water environment. Zhaoqing City is intrinsically linked to the socio-economic progress of the Guangzhou – Foshan – Zhaoqing corridor and extends its influence to the broader Pearl River Delta region.

1.2 Methods The data used in this study were primarily sourced from various public statistical sources and scientific databases from 2000 to 2024. Socio-economic and urban development data were predominantly extracted from the *Zhaoqing Statistical Yearbook*. Environmental statistics were derived from the *China Environmental Statistical Yearbook*. Any gaps in the data for specific years or regions were addressed using interpolation techniques.

The calculation methods described below follow Zhu *et al*[12]. To eliminate differences in dimensions and units among indicators, this study employed the range standardization method to normalize the original data. Distinct formulas were utilized for positive and negative indicators, ensuring that all standardized values were confined within the [0, 1] interval. For weight determination, the entropy weight method was adopted for objective weighting. This method assigns weights based on the degree of dispersion of the indicator data—the greater the data variability, the more information it contains, and the higher the corresponding weight. By calculating the indicator proportion, information entropy, and information utility value, the entropy weight for each indicator was ultimately obtained. The ecological resilience level was assessed using the comprehensive index method. Initially, the index values for the three subsystems (pressure, state, response) were calculated separately, and then these three subsystem indices were aggregated to yield the comprehensive ecological security index. A larger comprehensive index signifies a higher level of ecological resilience. To pinpoint key factors impeding ecological resilience, the obstacle degree model was introduced. This model computes the obstacle degree percentage of each indicator to ecological resilience by simultaneously considering the standardized value and weight of the indicator. A larger obstacle degree indicates a stronger constraining effect of the indicator on ecological resilience.

2 Results

2.1 Evolution characteristics of ecological resilience in Zhaoqing City (2000 – 2024) From 2000 to 2024, the ecological resilience index of Zhaoqing City increased from 0.214 3 to 0.629 0, with a cumulative increase of 0.414 7 (193.5%). Based on the trend, this period can be divided into three stages (Fig. 1). The first stage (2000 – 2007) was characterized by a slow rise in the index, increasing from 0.214 3 to 0.294 1, with an average annual growth rate of approximately 0.010 0. The second stage (2008 – 2019) represented a steady improvement, with the index rising from 0.307 8 to 0.495 9, at an average annual rate of about 0.015 7. The third stage (2020 – 2024) marked a rapid improvement, wherein the index increased from 0.519 4 to 0.629 0, with an average annual growth rate of approximately 0.027 4.

The pressure index rose from 0.085 0 in 2000 to 0.166 7 in 2024, although its growth rate gradually decelerated over time. In contrast, the state index increased from 0.070 4 to 0.200 5, exhibiting significantly accelerated growth during the later years. The response index demonstrated the most substantial increase, rising from 0.058 9 to 0.261 8 while maintaining an accelerating growth trajectory throughout the period.

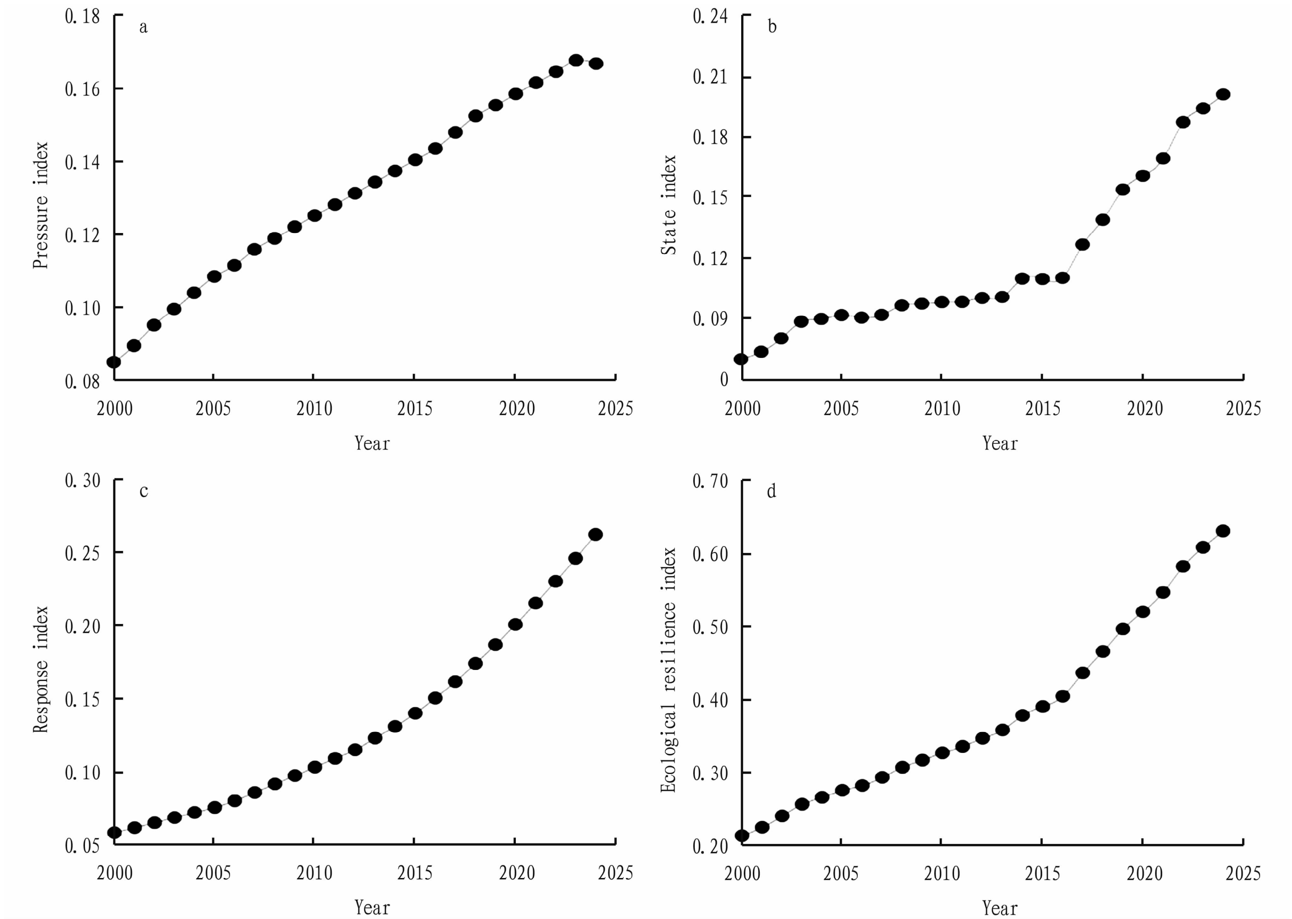
In terms of proportional contributions to the ecological resilience index, the pressure index decreased from 39.7% to 26.5% (a reduction of 13.2 percentage points). The proportion of the state index remained relatively stable, fluctuating between 30% and 33%. Conversely, the response index showed significant proportional growth, increasing from 27.5% to 41.6% (an increase of 14.1 percentage points). Notably, the response index surpassed the state index for the first time in 2010, equaled the pressure index by 2015, and became the largest contributor by 2020. By 2024, the response index accounted for 41.6% of the ecological resilience index.

2.2 Obstacle factors of ecological resilience in Zhaoqing City (2000 – 2024) According to the phased obstacle degree calculation results, the main obstacle factors for the three periods were identified and are presented in Table 1.

Phase 1 (2000 – 2007): the top five obstacle factors are comprehensive utilization rate of industrial solid waste (16.3% – 18.2%), per capita carbon emissions (14.9% – 15.8%), centralized sewage treatment rate (11.0% – 13.8%), industrial SO_2 removal rate (10.5% – 13.0%) and per capita park green space area (5.3% – 8.2%).

Phase 2 (2008 – 2019): the top five obstacle factors are comprehensive utilization rate of industrial solid waste (12.0% – 16.2%), industrial SO_2 removal rate (13.2% – 16.0%), industrial soot removal rate (9.5% – 14.2%), per capita carbon emissions (9.8% – 14.8%) and per capita built-up land area (4.4% – 8.5%).

Phase 3 (2020 – 2024): the top five obstacle factors are industrial SO_2 removal rate (16.0%), industrial soot removal rate (14.3% – 14.5%), comprehensive utilization rate of industrial solid waste (11.0% – 11.8%), per capita built-up land area (9.0% – 10.0%) and per capita carbon emissions (7.0% – 8.5%). The obstacle degrees of solid waste utilization and per capita carbon emissions continue to decrease. In contrast, the obstacle degrees of SO_2 and soot removal rates increase and become the main limiting factors in the latest stage.



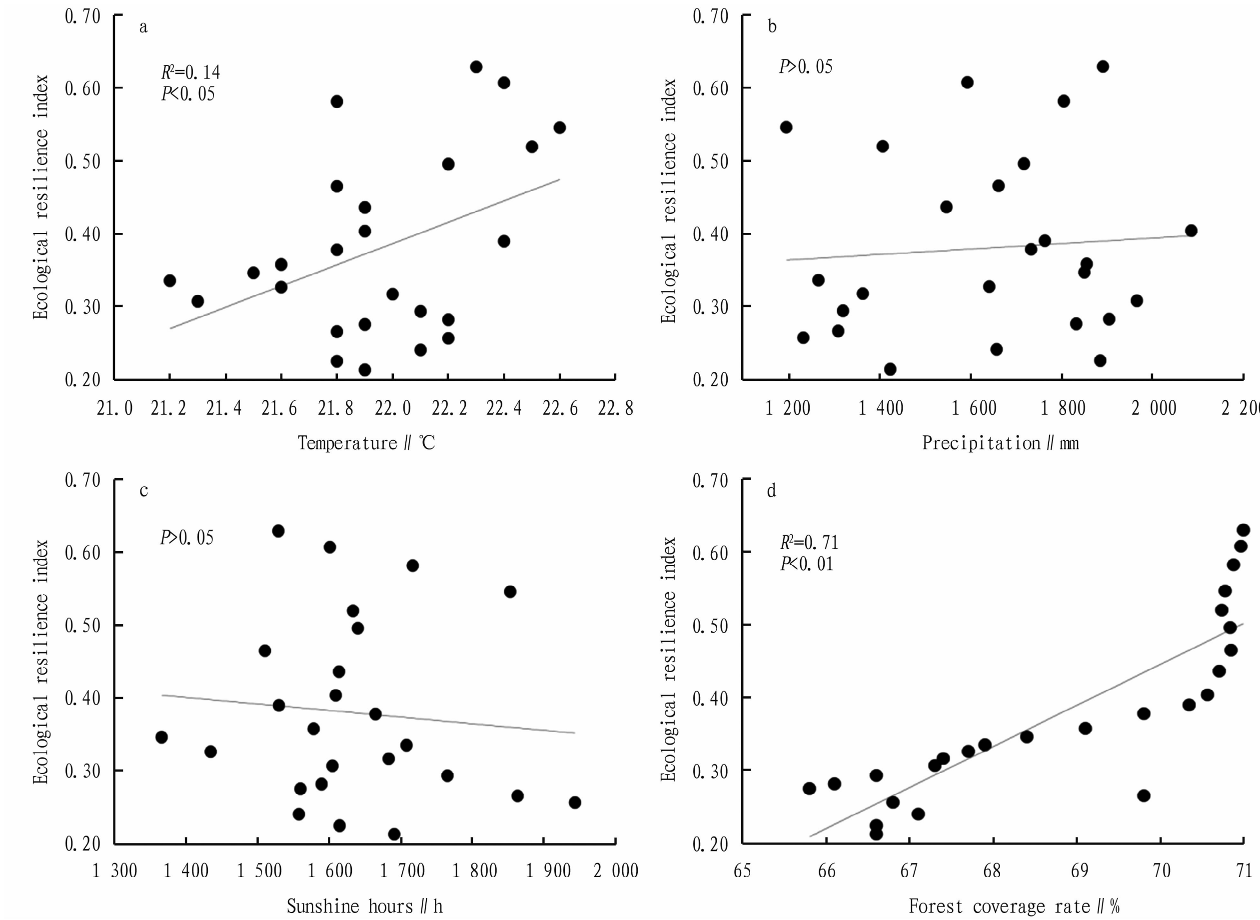
Note: a. Pressure index; b. State index; c. Response index; d. Ecological resilience index.

Fig. 1 Evolution characteristics of ecological resilience and each indicator element in Zhaoqing City from 2000 to 2024

Table 1 Analysis of main obstacle factors in Zhaoqing City across three phases (2000 – 2024)

Rank	Phase 1 (2000 – 2007)	Phase 2 (2008 – 2019)	Phase 3 (2020 – 2024)
1^{st}	Solid waste utilization rate (16.3% – 18.2%)	Solid waste utilization rate (12.0% – 16.2%)	SO_2 removal rate (16.0%)
2^{nd}	Per capita carbon emissions (14.9% – 15.8%)	SO_2 removal rate (13.2% – 16.0%)	Soot removal rate (14.3% – 14.5%)
3^{rd}	Sewage treatment rate (11.0% – 13.8%)	Soot removal rate (9.5% – 14.2%)	Solid waste utilization rate (11.0% – 11.8%)
4^{th}	SO_2 removal rate (10.5% – 13.0%)	Per capita carbon emissions (9.8% – 14.8%)	Per capita built-up area (9.0% – 10.0%)
5^{th}	Per capita park green space (5.3% – 8.2%)	Per capita built-up area (4.4% – 8.5%)	Per capita carbon emissions (7.0% – 8.5%)

2.3 Analysis of factors influencing ecological resilience in Zhaoqing City This study analyzed the correlation between four environmental factors (temperature, precipitation, sunshine duration and forest coverage rate) and ecological resilience index (Fig. 2). The linear fitting results showed significant differences in the strength and significance of effects. Temperature had a weak but significant positive correlation ($R^2 = 0.14$, $P < 0.05$), explaining only 14% of the variation in ecological resilience. Precipitation and sunshine duration did not show statistically significant correlations ($P > 0.05$). In contrast, forest coverage rate was the core dominant factor with a highly significant positive correlation ($R^2 = 0.71$, $P < 0.01$), explaining 71% of the variation in ecological resilience index.



Note: a. Temperature; b. Precipitation; c. Sunshine hours; d. Forest coverage rate.

Fig. 2 Analysis of factors influencing annual ecological resilience in Zhaoqing City

3 Discussion

The ecological resilience index of Zhaoqing City increased from 0.214 3 to 0.629 0 during 2000 – 2024, with a fundamental structural change occurring as it transitioned from a "pressure-dominated" security state to a "response-dominated" one, following the logistic "S"-curve law observed in Huainan City by Zhu *et al*[12]. This pattern is consistent with that of the Yangtze River Economic Belt, where ecological resilience exhibited an upward trend with fluctuations[6], and differs from the decline-then-recovery pattern in Beijing – Tianjin – Hebei and the convergence pattern in the Yangtze River Delta and Pearl River Delta[6–8]. The obstacle factor analysis revealed a shift in the main constraints. Although solid waste utilization and per capita carbon emissions improved significantly, SO_2 and soot removal rates became the primary obstacles. This contrasts with the findings for Huainan City, where land reclamation rate and total afforestation area were more significant factors[12], indicating that these constraints are highly context-dependent.

The dominant effect of forest coverage on ecological resilience is the most important finding. Its highly significant correlation ($R^2 = 0.71$) is consistent with Cheng and Zhang[13], who identified forest cover as a key regulator in Southwest China, and with the fact that Zhaoqing City plays an important role as an ecological barrier for Guangdong Province by virtue of its forest coverage being well above the provincial average[14]. High forest coverage enhances water conservation, soil retention and carbon sequestration[13] and contributes to "size resilience" through constraining urban sprawl and to morphological resilience through creating balanced sink landscapes[7]. Furthermore, Zhaoqing's relatively low level of urbanization intensity compared to core Pearl River Delta cities[15] has probably allowed more natural development of its forest ecosystems. The weak effect of temperature ($R^2 = 0.14$), and non-significant effects of precipitation and sunshine hours suggest that baseline climatic conditions are less limiting than forest cover in Zhaoqing's humid subtropical climate[13]. These findings highlight that continued protection and restoration of forest resources, integrated with air pollution control measures, while strictly enfor-

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cing ecological redlines and managing the intensity of urban development, is the core pathway to enhancing ecological resilience in Zhaoqing so as to maintain its function as an ecological barrier for the Greater Bay Area.

4 Conclusion

Between 2000 and 2024, Zhaoqing City's ecological resilience index surged from 0.214 3 to 0.629 0, marking an increase of 193.5%. This growth manifested in three distinct stages. Concurrently, Zhaoqing City's ecological security framework transitioned from being predominantly pressure-driven to response-oriented. Specifically, the proportion attributed to the pressure index declined from 39.7% to 26.5%, whereas the response index's share escalated from 27.5% to 41.6%. An analysis of obstacle factors revealed that although there were notable improvements in solid waste utilization and per capita carbon emissions, the SO_2 removal rate (16.0%) and soot removal rate (14.5%) emerged as primary constraints. This underscores that atmospheric pollutant removal capacity is a critical bottleneck. Further environmental factor analysis pinpointed forest coverage as the paramount determinant influencing the ecological resilience index ($R^2 = 0.71$, $P < 0.01$), accounting for 71% of its spatial variation. In contrast, temperature exerted a marginal influence ($R^2 = 0.14$, $P < 0.05$), while precipitation and sunshine duration were statistically insignificant. To bolster Zhaoqing City's ecological resilience index, it is imperative to prioritize forest protection and stringent air pollution control measures.

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