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Research on spatial equity and dynamic compensation mechanism of ecological element regulation under the guidance of urban-rural integration

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Article

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Abstract: Against rapid urbanization and climate change, urban and rural ecosystems show pronounced spatial inequities driven by ecological element flows. Conventional static compensation mechanisms often fail to accommodate temporal changes and may reinforce center–periphery imbalances. To address this challenge, this study develops a dual-dimensional compensation framework integrating spatial equity diagnosis with dynamic performance incentives. In the spatial equity dimension, ecosystem service value (ESV) accounting and the location quotient (LQ) model are used to identify county-level ecological "surplus" and "deficit" areas and design horizontal fiscal transfer rules. In the dynamic performance dimension, shift-share analysis (SSA) decomposes ecological element changes into "share effects" and "competitive shifts". The resulting performance differentials are converted into tradable ecological quotas, establishing a market-based incentive pathway. Taking 83 county-level administrative units in Fujian Province, China, as a case study, the results reveal significant spatial differentiation. The Gini coefficient reached 0.484, indicating "coastal consumption and inland supply". Under the static mechanism, Hui'an County was the largest payer, with 232.79 million RMB, while Taining County received 358.67 million RMB. The dynamic mechanism showed that Zhangpu County, with a national ESV deviation of +492.07 million RMB, could act as a quota seller, whereas Xiapu County, with −498.32 million RMB, would purchase quotas. A safety threshold was established for counties with negative deviations. Through the nested application of LQ and SSA, this study supports a shift from static allocation to dynamic adaptation, providing an operational approach for balancing urban–rural development and ecological conservation.

Keywords: ecological element regulation; spatial equity; dynamic compensation; location quotient; shift-share analysis

1. Introduction

With accelerating urbanization and intensifying impacts of climate change, urban-rural integration has become a central issue in achieving the Sustainable Development Goals(Guan et al., 2023). Urban and rural systems are interdependent through the flow of ecological elements, such as water resources, carbon sinks, and biodiversity. However, rapid urbanization often leads to spatial inequity in the distribution of ecological resources, thereby exacerbating regional ecological degradation and socioeconomic imbalances(Xue et al., 2025). For instance, urban agglomerations in Europe, such as those along the Rhine River basin, have been consuming ecosystem services from surrounding rural areas without adequately compensating the costs of conservation(Kleemann et al., 2020). Similarly, in rapidly urbanizing regions of Asia like the outskirts of Jakarta, cropland loss has contributed to an expanding ecological deficit (Pribadi and Pauleit, 2015). Such global phenomena underscore the urgency of spatial equity regulation. As noted in a World Bank report, ecological compensation mechanisms that lack dynamic design risk entrenching center–periphery exploitation(World Bank, 2020). Situated within this context, this study seeks to explore how innovative methodological integration can be leveraged to construct a cross-scale ecological governance framework, thereby offering theoretical support for addressing urbanization challenges while promoting regional equity.

Existing studies have laid an important foundation for the regulation of ecological elements. Internationally, Europe's Green Infrastructure initiative has promoted urban–rural ecological network connectivity through spatial planning(Mazaherylaghab, 2025), while payment for ecosystem services (PES) programs in Latin America like Costa Rica's forest compensation scheme have demonstrated the feasibility of market-based approaches(Izquierdo-Tort et al., 2025). Methodologically, scholars worldwide have introduced tools such as the location quotient (LQ) to analyze inequalities in resource allocation(Powers et al., 2024). For instance, in studies on desertification in the Sahel, scholars have employed shift-share analysis (SSA) to decompose the dynamics of ecological indicators, as seen in research on mangrove changes in Southeast Asia(Sofue et al., 2025). However, these studies are often constrained by regional specificity. Cases in Europe and the United States tend to emphasize institutional design but pay less attention to the dynamic adaptability required in rapidly urbanizing regions(Castaldo et al., 2025). Studies in developing countries, meanwhile, focus on poverty alleviation but fail to fully integrate spatial and temporal dimensions(Locatelli et al., 2025). For example, the IPCC (2022) report notes that existing ecological compensation models exhibit rigidity when responding to extreme climate events and lack the capacity to provide early warnings of nonlinear changes (IPCC, 2022). Overall, the "fragmentation" crisis evident in the global literature, characterized by a disconnection between static assessment and dynamic management as well as a separation of spatial and temporal dimensions, makes it difficult to systematically address the core tensions in the flow of urban–rural ecological elements, let alone support precise governance in a globalized context(Martin and Conway, 2025).

The central challenge confronting the current regulation of urban–rural ecological elements lies in the insufficient articulation of their inherent spatial inequity and dynamic complexity(Langemeyer et al., 2024). At the spatial level, the distribution and flow of ecological elements are highly heterogeneous. For instance, coastal urban agglomerations in Fujian Province, China, such as Xiamen and Fuzhou,, consume substantial ecosystem services provided by inland mountainous areas like Nanping and Sanming due to economic agglomeration, giving rise to a dual pattern of "ecological deficit areas" and "ecological surplus areas" (Xin et al., 2021). This inequity is reflected not only in resource appropriation but also in the distribution of governance responsibilities: surplus areas bear the costs of conservation without adequate compensation, whereas deficit areas enjoy ecological dividends without bearing corresponding costs (Su et al., 2020). At the dynamic level,

ecological elements are subject to continuous change driven by policy shifts, market forces, and natural factors of cropland loss and fluctuations in forest cover. However, traditional static assessments fail to capture such temporal evolution, resulting in compensation mechanisms that lag behind actual needs(Chen, 2025). The root of the problem lies in the fact that, during the process of urban–rural integration, institutional barriers and market failures jointly amplify the misalignment between "who protects" and "who benefits". Moreover, regional development policies often prioritize economic growth over ecological considerations, further entrenching path dependency. Existing mechanisms have not translated dynamic performance into incentive constraints. Therefore, there is an urgent need to address these challenges from the dual perspectives of spatial equity and dynamic compensation, so as to prevent the flow of ecological elements from falling into a degradation cycle(Ramírez-Mejía et al., 2025).

Existing methodologies reveal clear limitations when addressing the aforementioned challenges. First, static assessment tools, such as ecological carrying capacity models, can capture spatial differentiation at a given point in time but fail to reveal trajectories of change. For instance, while ecological carrying capacity values may indicate regional ecological self-sufficiency, they cannot explain why certain areas shift from surplus to deficit(L. He et al., 2025). Second, dynamic analytical methods, including system dynamics simulation, are capable of predicting long-term trends yet lack coupling with spatial equity indicators. This results in a disconnect between "when to compensate" and "where to compensate" (Giang et al., 2024). More importantly, current ecological compensation research often relies on qualitative descriptions or simplistic quantifications. Fiscal transfer payment models, for example, fail to account for dynamic differences in regional contributions. Similarly, market-based instruments like carbon trading platforms struggle to achieve implementation due to insufficient data granularity(Lin et al., 2025). At the technical level, methodological integration remains weak. Ecosystem service value (ESV) calculations frequently rely on uniform equivalence factors without adapting to local characteristics. Models are typically applied at the administrative unit level, overlooking the micro-level mechanisms underlying urban–rural interactions(Y. He et al., 2025). These limitations make it difficult for existing methods to support precise and adaptive compensation policies. Meanwhile, the fragmentation and rigidity of current tools leave them ill-equipped to address the nonlinear and cross-scale characteristics of urban–rural ecosystems(Spyra et al., 2025).

Despite these limitations, current research still provides critical clues for constructing a new framework. On the one hand, spatial analysis tools such as the LQ have proven effective in identifying ecological surplus–deficit patterns and quantifying inequalities in ecological elements (Li et al., 2023). On the other hand, dynamic methods like SSA, by decomposing share effects and competitive deviations, offer a means to quantify relative changes in regional ecological performance (Dembińska et al., 2022). This approach has been applied by the World Bank to assess performance fluctuations in forestry policies across Southeast Asia. Furthermore, cross-disciplinary integration, exemplified by the convergence of ecological economics and geographic information systems (GIS), has facilitated the application of multi-source data, including remote sensing and statistical yearbooks, in empirical research(Guan et al., 2024). These strands of evidence suggest that integrating static spatial diagnosis with dynamic temporal regulation can support the development of a "glocalized" framework. This integration includes using the LQ to identify hotspot areas and employing SSA to establish floating quotas. The European Union's Ecological Accounting System, which attempts to incorporate member states' ecological deficits into a trading platform, offers a useful reference in this regard(King et al., 2024).

This study seeks to address a globally significant challenge through methodological innovation and theoretical integration. Centered on an urban–rural coupling model, it combines the LQ with SSA to design a dual-dimensional

mechanism that integrates horizontal fiscal transfers with vertical market trading. The research objectives are twofold: first, to develop a toolkit for ecological element regulation that can be adapted to different stages of development, thereby facilitating a paradigm shift from static equity diagnosis to dynamic adaptive regulation; second, to provide an empirical foundation for resolving the issue of "spatial–temporal disconnection" in global ecological compensation. The core question this study seeks to answer is how, against the backdrop of global urbanization, the coordination of spatial equity and dynamic incentives can eliminate the center–periphery exploitation embedded in the flow of ecological elements, promote the evolution of governance systems from state-centered models toward networked equity, and provide scientific support for the 2030 Sustainable Development Agenda. This coordination involves quantifying positive and negative deviations through mechanisms such as carbon quotas.

2. Methodology

2.1 Study Area and Data Sources

As one of the countries undergoing the most rapid urban–rural transformation worldwide, China's regulation mechanism for ecological elements is directly linked to the effectiveness of its ecological civilization construction(Zhang and Wang, 2025). Fujian Province, an economically developed coastal region in southeastern China, possesses both abundant ecological resources, with a forest coverage rate of 66.8% and a densely concentrated urban agglomeration. Thus, Fujian Province was regarded a representative area for studying urban–rural ecological interactions. In recent years, Fujian has made notable progress in ecological protection; however, it still faces challenges such as the loss of ecological land due to coastal urban expansion and the lack of adequate compensation for the spillover of ecosystem services from inland mountainous areas (Wu et al., 2024). The Gini coefficient for the distribution of ecological elements across the province is 0.484, indicating a high degree of spatial imbalance. This spatial mismatch not only threatens regional ecological security but also highlights the limitations of conventional governance models in reconciling development with conservation. Fujian Province therefore serves as a typical case for investigating spatial equity and dynamic compensation mechanisms aimed at optimizing the allocation of ecological elements. In this study, townships with high construction land density and development intensity are classified as urban areas based on construction land density, while those not meeting this threshold are designated as rural areas, as illustrated in Figure 1.

The data used in this study were derived primarily from multi-source spatiotemporal datasets to ensure comprehensiveness and analytical accuracy. The study period spans from 2015 to 2020, covering 83 county-level administrative units across Fujian Province. Land use data were obtained from remote sensing interpretation results at a 30-meter resolution, including Landsat satellite imagery, and were used to identify spatial distribution changes in cropland, woodland, water bodies, and other land use types, providing foundational information for ESV calculations. ESV was quantified using the "Equivalent Value Coefficients for China's Terrestrial Ecosystem Services" proposed by Xie Gaodi and colleagues, with dynamic estimation of various ecosystem service function values based on county-level land use data. Socioeconomic data were compiled from statistical yearbooks and county-level monitoring reports. All datasets underwent spatial registration and consistency processing to ensure the reliability of multi-indicator coupling analysis.

Based on ecological element data from 83 county-level administrative units in Fujian Province for the period 2015 to 2020, this study systematically revealed the spatial differentiation pattern of ecological element allocation, the effectiveness of static compensation mechanisms, and the feasibility of market-based compensation pathways.

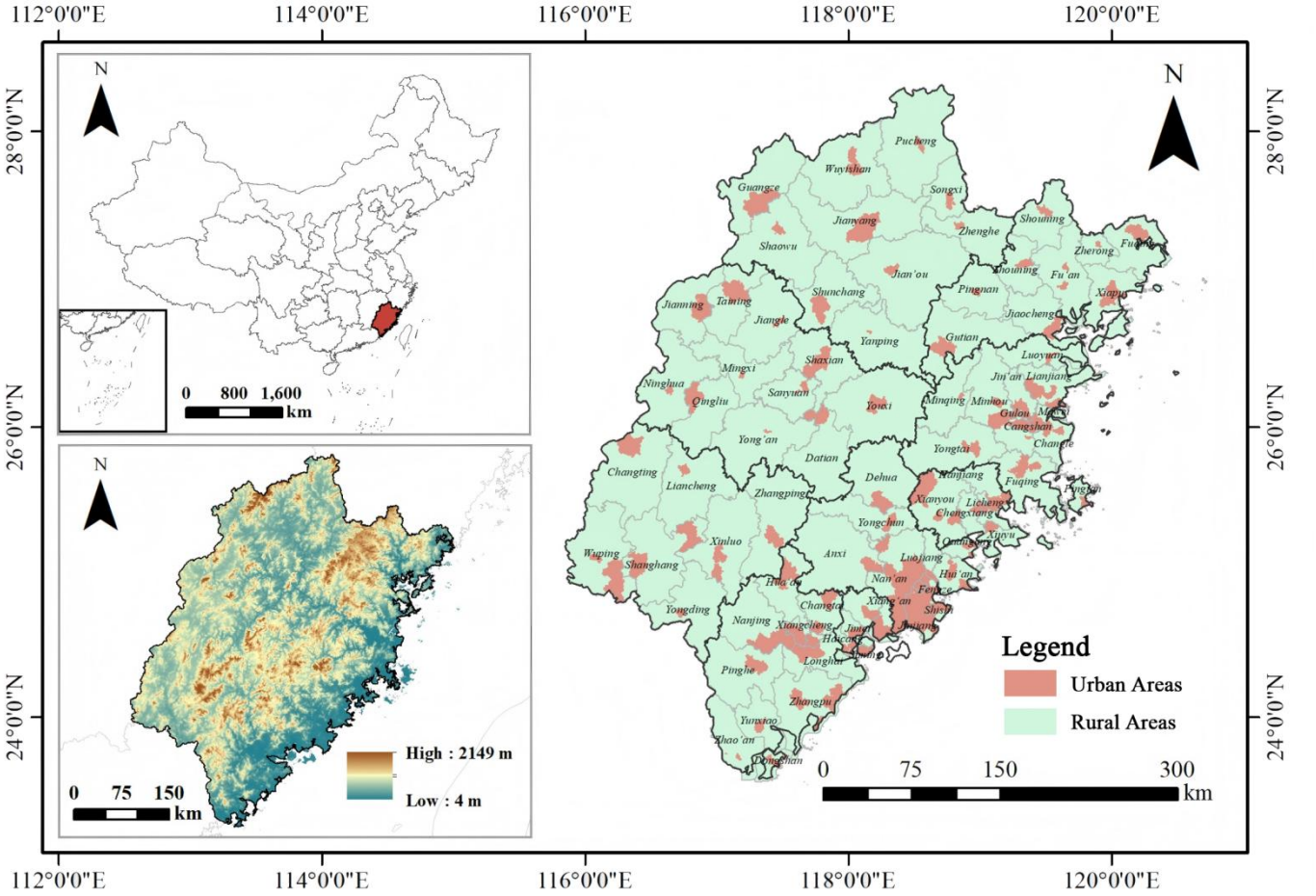


Fig. 1: Study Area

2.2 Research Framework

To systematically analyze spatial equity and dynamic compensation mechanisms in the flow of urban–rural ecological elements, this study develops a comprehensive analytical framework for ecological element regulation oriented toward urban–rural integration. The framework follows a logical sequence of "spatial equity diagnosis, dynamic performance quantification, and dual-dimensional mechanism design", as illustrated in Figure 2. Grounded in urban–rural system coupling theory, the framework integrates static spatial analysis with dynamic temporal methods, aiming to systematically address the core tensions of "spatial imbalance" and "temporal lag" in the allocation of ecological elements. The framework is structured as follows.

First, an urban–rural coupling model is employed to analyze the spatial differentiation patterns of ecological elements and to quantify the support relationships between construction land and ecological land. This step identifies "ecological consumption areas" and "ecological supply areas" within the region, establishing a spatial baseline for equity analysis.

Subsequently, spatial equity diagnosis is conducted using ESV accounting and the LQ model. ESV is used to evaluate the ecological supply capacity of each county, while LQ identifies ecological surplus and deficit areas by comparing the density of ecological elements. Based on these results, horizontal fiscal transfer payments are designed to address the fundamental equity question of "who compensates whom and by how much", thereby forming the baseline compensation arrangement.

Following this, SSA is introduced to perform dynamic performance analysis of ecological changes. This method decomposes changes in county-level ecological elements into a "share effect", which reflects macro-level trends, and a "competitive deviation", which captures relative performance in local governance. Based on the resulting performance gaps,

tradable ecological quotas are designed to establish a market-based incentive pathway where "protectors benefit and degraders pay", thereby promoting continuous improvement.

Finally, the static responsibility mechanism based on LQ and the dynamic incentive mechanism based on SSA are integrated in a nested manner. The static component ensures spatial equity baselines, while the dynamic component provides rewards or additional compensation based on performance. A minimum guarantee mechanism for weak counties is also established to prevent adverse selection in market-based processes, ensuring the operability and effective implementation of the overall mechanism.

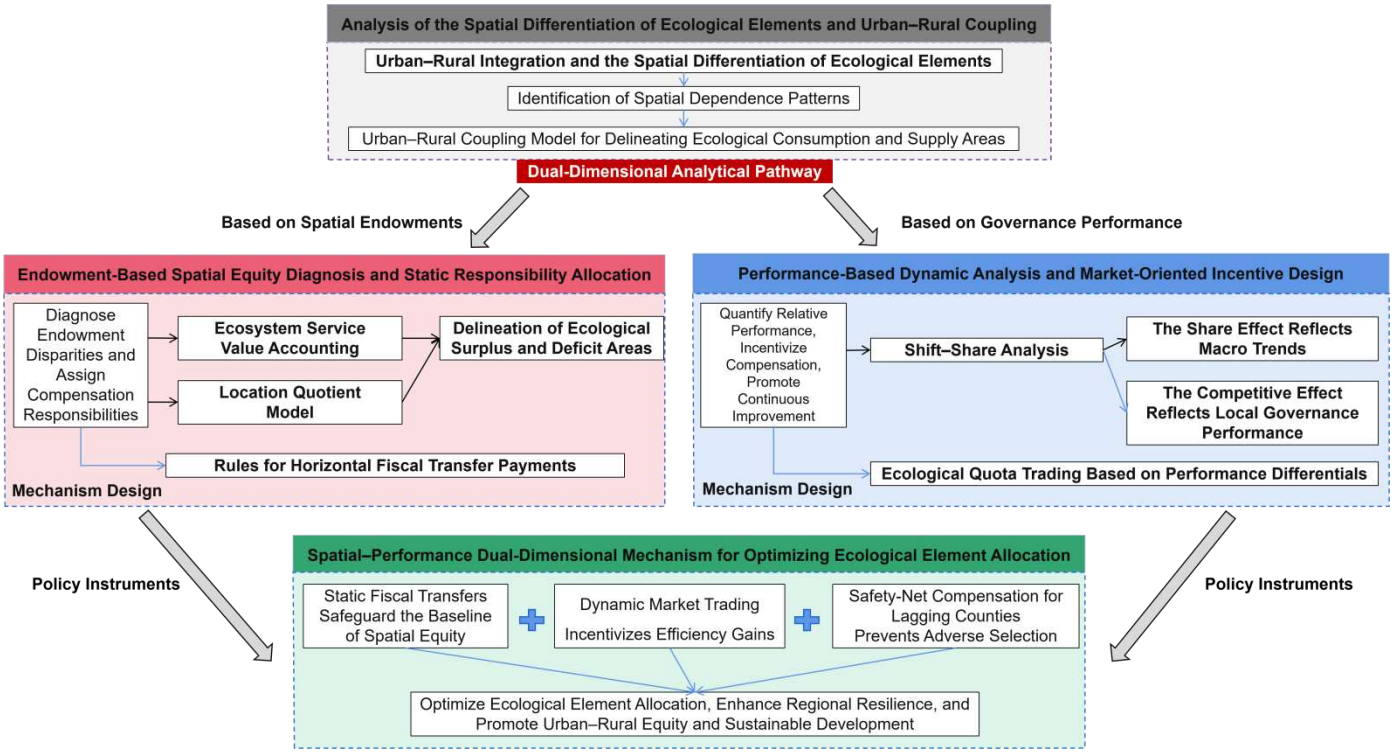


Fig. 2 Research Framework

2.3 Methods

2.3.1 Quantifying Spatial Differentiation Patterns of Ecological Elements Using the Urban–Rural Coupling Model

In this study, urban, industrial, mining, and residential land were defined as construction land, while cropland, woodland, grassland, and water bodies are defined as ecological land. The urban–rural coupling model, expressed in Equation (1), was employed to quantify the land coupling relationship between urban and rural areas. Different coupling outcomes can be used to assess the spatial differentiation of ecological elements.

$$\frac{y_{1j}}{x_{1j}}(a) \quad \frac{y_{2j}}{x_{2j}}(b) \quad \frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}}(c) \tag{1}$$

Equation (a) describes the coupling interaction between construction land and ecological land within urban areas.

Equation (b) focuses on rural areas, reflecting the interrelationship between construction land and ecological land. Equation (c) characterizes the urban–rural coupling relationship from an integrated perspective. A higher coupling value indicates a stronger degree of association between the two components. y_{1j}, y_{2j} and x_{1j}, x_{2j} represent construction land in urban and rural areas, respectively, while denotes the ESV provided by ecological land.

2.3.2 Design of a Static Compensation Mechanism Based on ESV and LQ

The static ecological compensation mechanism aimed to identify surplus and deficit areas in ecosystem service supply by quantifying the endowment differences and spatial distribution of ecological elements, thereby providing a clear and calculable rule framework for horizontal fiscal transfer payments(Ma et al., 2025). Taking the county as the basic unit, this mechanism combines ESV assessment with LQ spatial endowment analysis to construct a static compensation model centered on horizontal fiscal transfers, addressing the core issue of "who compensates whom and by how much". ESV is a monetized indicator that measures the value of products and services provided by ecosystems to human society, such as water conservation, climate regulation, and biodiversity conservation. This study employed the equivalent factor method for ESV accounting. Following the Millennium Ecosystem Assessment framework, ecosystem services are classified into four categories: provisioning services (e.g., food production), regulating services (e.g., carbon sequestration), supporting services (e.g., soil formation), and cultural services (e.g., tourism and recreation). Each service category corresponds to different land use types, including cropland, orchard land, woodland, grassland, water bodies, construction land, and unused land. Based on the "Equivalent Value Coefficients for China's Terrestrial Ecosystem Services" proposed by Xie Gaodi and colleagues, an annual value per unit area is assigned to each land use type (Table 1) (Martínez-Sastre et al., 2017; Sannigrahi et al., 2018; Zheng et al., 2019). ESV serves as a monetized measure of ecological contribution. The total ESV of each county directly reflects its ecosystem service supply capacity. The specific formula is given in Equation (2):

$$ESV = \sum A_k \times V_k \quad (2)$$

Table 1. Ecosystem service values provided by different land-use types/(yuan·hm^{-2}·a^{-1})

	Grassland	Woodland	Cropland	Water bodies	Unused land
Regulating services	3371.4	9476.8	2554.6	79719.4	35.3
Provisioning services	309.7	2389.1	569.46	415.4	8.8
Supporting services	2690	6335.5	1914.2	5830.6	318.5
Cultural services	35.4	1132.6	92.62	8610.4	8.8
Total	6406.5	19334	5130.88	94575.8	371.4

LQ is a spatial analysis tool used to measure relative advantages in regional factor endowments, enabling the classification of surplus and deficit areas (Morrissey, 2014). It can be expressed using Equation (3):

$$LQ = \frac{\mathrm{e_i}}{\mathrm{e}} / \frac{E_j}{E} \quad (3)$$

where $\mathrm{e_i}$ represents the quantity of a given ecological element (e.g., forest area) in region i, and E_j represents the total area of region i; e represents the total quantity of that element in the reference region (e.g., the entire province), and E represents the total area of the reference region. The LQ results were directly used to assign "supply–demand" roles: surplus

areas (LQ > 1) serve as ecosystem service suppliers and are potential recipients of compensation funds; deficit areas (LQ < 1) are net consumers of ecosystem services and should act as payers of compensation funds; an LQ equal to 1 indicates self-sufficiency.

This study integrated the ESV model of land use with the spatial endowment analysis of LQ to design a horizontal fiscal transfer payment rule, namely the static compensation mechanism. The resulting allocation model for resource inputs in positive and negative ecological governance is presented in Equation (4):

$$Q_j = q_j \times \left(\frac{y_{1j}}{x_{1j}} / \frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} \right) + q_j \times \left(1 - \frac{y_{1j}}{x_{1j}} / \frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} \right) + \left| q_j \times \left(\frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} / \frac{\sum y_{ij}}{\sum x_{ij}} - 1 \right) \right| \quad (4)$$

where Q_j represents the total fiscal cost of ecological governance that county (or city) j is expected to incur, encompassing both internal governance responsibilities and external compensation or reception obligations. q_j represents the actual fiscal expenditure on ecological governance incurred by county j.

The term $q_j \times \left(\frac{y_{1j}}{x_{1j}} / \frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} \right)$ captures the division of internal responsibilities between urban and rural areas based on ecological efficiency (ESV output per unit baseline). The ratio $\frac{y_{1j}}{x_{1j}} / \frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}}$ essentially measures the relative density of ecological endowments in urban areas, determining what proportion of the actual expenditure q_j should be attributed to urban governance responsibilities. The term $q_j \times \left(1 - \frac{y_{1j}}{x_{1j}} / \frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} \right)$ serves as the complement, representing the proportion of ecological governance expenditure attributable to rural governance responsibilities. Together, these two terms complete the initial allocation of fiscal responsibilities for ecological governance between urban and rural areas within a given county.

The component $q_j \times \left(\frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} / \frac{\sum y_{ij}}{\sum x_{ij}} - 1 \right)$ is the key element enabling horizontal transfer payments within the overall model. Here, $\frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} / \frac{\sum y_{ij}}{\sum x_{ij}}$ is the ecological LQ of county j. If the value of $\left(\frac{y_{1j}+y_{2j}}{x_{1j}+x_{2j}} / \frac{\sum y_{ij}}{\sum x_{ij}} - 1 \right)$ is greater than zero, the county is considered an ecological surplus area, indicating that its ecological endowment exceeds the regional average. Such a county is entitled to receive additional compensation from the region to offset the development rights it has sacrificed for ecological protection. If the value is less than zero, the county is considered an ecological deficit area, indicating that its ecological endowment falls below the regional average. Such a county was required to pay compensation to the region for its consumption of external ecosystem services. Through Equation (4), this study translates the abstract concept of spatial equity into a concrete, quantifiable fiscal transfer amount, thereby providing an objective basis for policy formulation.

2.3.3 Design of a Market-Based Compensation Pathway Using SSA

SSA decomposed changes in regional ecological elements into a “share effect” driven by global trends and a “competitive deviation” driven by region-specific factors, thereby revealing relative ecological performance (Equation (5)) (Knudsen, 2000). Its core contribution lay in identifying the “excess component” of ecological improvement or degradation, which provided a quantitative basis for market-based compensation. This study developed a multi-scale ecological performance

evaluation system by comparing benchmarks at the national, provincial, and municipal levels, based on which quota trading mechanisms and dynamic reward–penalty mechanisms were designed.

(1) Core Principle and Mathematical Formulation of SSA

Let the change in a given ecological element (e.g., ESV, forest coverage rate) in region i over the period $[t_0, t_1]$ be $\Delta X_i = X_{i1} - X_{i0}$, where X_{i0} and X_{i1} represent the values at the beginning and end of the period, respectively Taking the nation as the benchmark region, the growth rate of the total ecological element over the same period is $g_{total} = (X_{Nationwide,1} - X_{Nationwide,0})/X_{Nationwide,0}$. ΔX_i can be decomposed as follows:$\Delta X_i = (X_{i0} \times g_{total}) + (\Delta X_i - X_{i0} \times g_{total})$. The share effect $(X_{i0} \times g_{total})$ represents the amount of change that region i would have experienced if it had developed only according to the national average growth rate, reflecting the common influence of macro-level trends. The competitive deviation $(\Delta X_i - X_{i0} \times g_{total})$ captures the relative performance differences attributable to region-specific factors, such as local policies, resource endowments, or governance effectiveness. A positive competitive deviation indicates that the region's ecological improvement exceeds the national average, whereas a negative value indicates the opposite. To capture variations in ecological performance across different spatial scales, this approach further incorporates benchmarks at the provincial and municipal levels for multi-layered decomposition.

(2) Design of a Market-Based Compensation Pathway

Based on competitive deviation values, this study transformed dynamic changes in ecological elements into a tradable quota mechanism, thereby establishing an incentive–constraint framework in which "protectors benefit and developers pay".

Areas with positive deviation (competitive deviation > 0) are eligible to sell quotas to obtain benefits, while areas with negative deviation (competitive deviation < 0) were required to purchase quotas to offset their ecological deficits. Deviation results at different spatial scales—national, provincial, and municipal—can be used to inform differentiated policy design: national deviation guides macro-level transfer payments, provincial deviation supports horizontal compensation within the province (e.g., downstream-to-upstream compensation in the Minjiang River Basin), and municipal deviation optimizes resource allocation within prefecture-level cities. This multi-scalar approach enables the market-based and dynamic operation of ecological compensation. The average of the three deviation values at the national, provincial, and municipal levels for each county is used as the county-level comprehensive performance score. The mean of these comprehensive performance scores across all counties in the province serves as the comprehensive performance benchmark, reflecting the average trend of ecological element change during the study period. The performance gap ΔPi, defined as the county-level comprehensive performance score minus the provincial comprehensive performance benchmark, serves as the core unit of measurement for market-based compensation. The performance gap, as the basis for trading, represents an idealized market share and does not account for the specific needs of impoverished mountainous counties versus economically robust coastal counties in terms of ecological compensation quotas. To avoid the adverse incentive of "weak counties being crowded out of the market", the mean performance gap of counties with negative deviation, denoted as D^-, is introduced as a safety threshold:

$$D_i = \Delta P_i - D^-$$

$$D^- = \frac{\sum_{i=1}^{n} \Delta P_i (\Delta P_i < 0)}{n} \quad (5)$$

When $\Delta P_i <$ but $R_i > 0$, the county, despite being negatively deviated, exhibits a degree of degradation that is less severe than the average of negatively deviated counties. Such a county remains eligible to receive compensation through the market, reflecting the equity principle of "penalizing the worst while supporting the vulnerable".

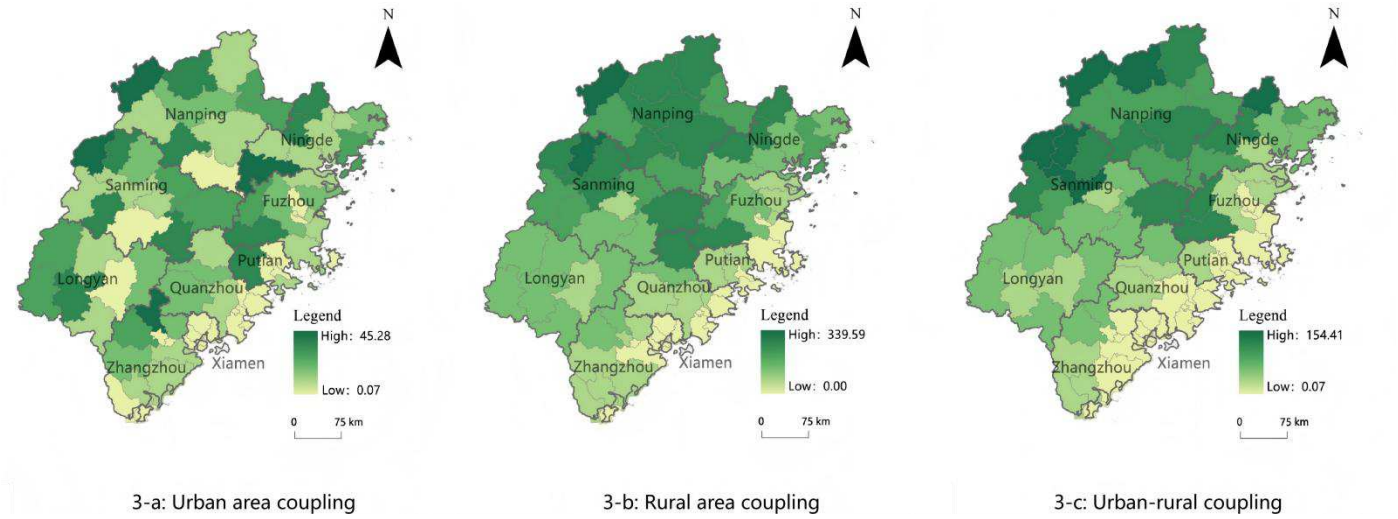
This study integrated the spatial equity mechanism (based on LQ) with the market efficiency mechanism (based on

performance) to quantify the allocation of ecological governance costs. The LQ mechanism identifies differences in ecological supply and demand, establishing a foundational responsibility framework that serves as the baseline obligation. The shift-share mechanism provides dynamic incentives through performance gaps, with quota adjustments balancing equity and efficiency.

3. Results

3.1 Spatial Differentiation Pattern of Ecological Elements

The spatial distribution of ecological elements in Fujian Province exhibited a pronounced "coastal–inland" differentiation pattern, which was quantified through the urban–rural land-use coupling relationship and spatial imbalance measurement. The urban–rural coupling model revealed that the overall coupling score for Fujian Province was 39.13 (Figure 3; Table S1), indicating that one hectare of construction land required, on average, 39.13 hectares of ecological land for support. However, substantial variation exists across counties. For instance, the urban area of Taijiang District in Fuzhou had a coupling score of only 0.07, reflecting the scarcity of ecological land resulting from its high degree of urbanization. In contrast, Jianning County in Sanming exhibited a coupling score of 45.28, highlighting its abundance of ecological land. Spatially, coastal counties—such as Xiamen and the core area of Fuzhou—generally had lower coupling scores compared to inland mountainous areas like Nanping and Sanming, forming a dual structure characterized by "coastal consumption and inland supply". The Gini coefficient for the distribution of ecological elements was calculated to be 0.484, exceeding the international alert threshold of 0.4 and confirming a high degree of inequality in ecological element allocation. This spatial differentiation is negatively correlated with the level of economic development: highly urbanized areas experience greater ecological pressure, whereas mountainous counties possessed clear ecological advantages. The overall pattern of ecological element flows indicated that coastal urban agglomerations intensify the ecological burden on inland areas through resource consumption, providing a spatial basis for the static compensation mechanism.



3-a: Urban area coupling 3-b: Rural area coupling 3-c: Urban-rural coupling

Fig. 3 Spatial differentiation of urban-rural land use coupling at the county level in Fujian Province

3.2 Analysis of Static Compensation Results Based on ESV and LQ

The static compensation mechanism, centered on ESV and LQ, balances regional ecological surpluses and deficits through horizontal fiscal transfer payments. ESV quantification (Table S2) showed that the total ESV in Fujian Province changed by –0.22%, with significant variation across counties (Table S3). Zhangpu County recorded the highest increase in ESV (+539.2171 million RMB), while Xiapu County experienced the largest decrease (–453.5275 million RMB). In terms of spatial distribution, inland counties such as Guangze County in Nanping and Taining County in Sanming maintained high

ESV values, whereas coastal counties such as Pingtan County in Fuzhou saw substantial declines. LQ analysis was used to assign compensation responsibilities. Surplus areas (LQ > 1), such as Guangze County with an ESV LQ of 1.54, were eligible to receive compensation, whereas deficit areas (LQ < 1), such as Xiang'an District in Xiamen with an ESV LQ of 0.89, were required to make payments. Based on the static compensation model derived from Equation (3), horizontal fiscal transfer amounts were calculated for each county (Figure 4; Table S4). For example, Hui'an County, as a deficit area, is required to pay the highest compensation amount (approximately 232.7934 million RMB), whereas Taining County, as a surplus area, is eligible to receive a net inflow (approximately 358.6740 million RMB). The direction of compensation fund flows clearly reflects the principle of "deficit areas compensating surplus areas", with coastal counties (e.g., Fuzhou and Quanzhou) transferring funds to inland counties (e.g., Nanping and Sanming). While the static mechanism ensures a baseline level of spatial equity, it does not account for dynamic changes and may therefore lag behind actual needs. The combined application of ESV and LQ provides a quantifiable benchmark for ecological compensation, yet integration with dynamic performance is necessary to enhance efficiency.

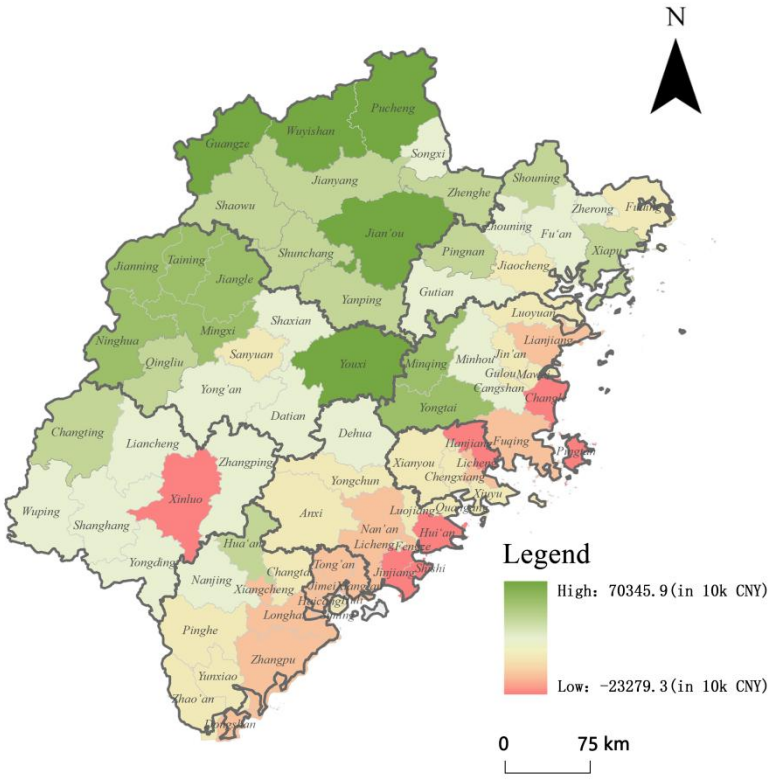
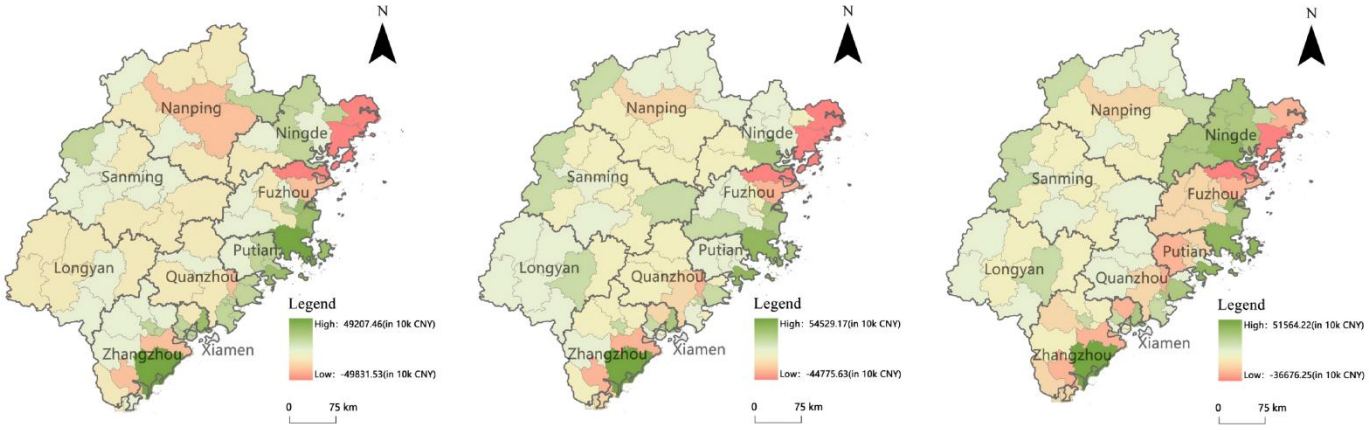


Fig. 4: Spatial Distribution of Ecological Governance Costs in the External System

3.3 Analysis of Market-Based Compensation Results Based on SSA

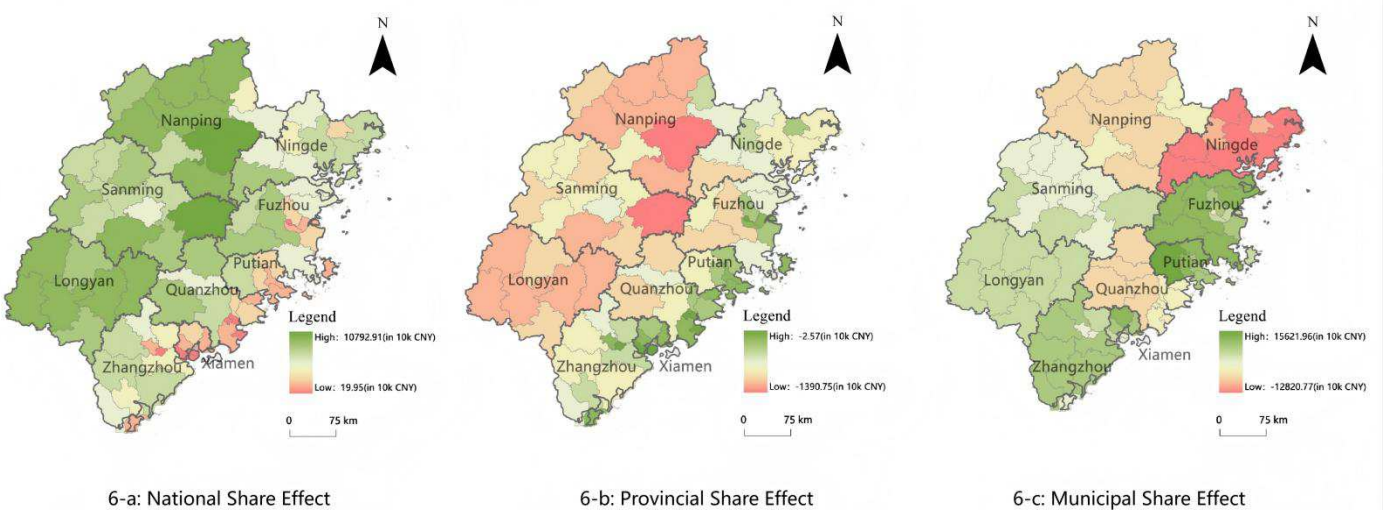
SSA revealed dynamic performance by decomposing changes in ecological elements into a "share effect" (global trends) and a "competitive deviation" (regional specificity), thereby providing a basis for market-based compensation. The analysis covered six indicators: ESV, grassland ESV, woodland ESV, cropland ESV, total annual residential water consumption, and unused land ESV. National-level deviation results (Figure 5-a) showed that only approximately 35% of the 83 counties in Fujian Province achieved positive deviation, indicating performance above the national average. Zhangpu County, for example, recorded a national deviation in ESV of +492.0746 million RMB. The majority of counties (65%) exhibited negative

deviation, with Xiapu County showing a national deviation of –498.3153 million RMB. Provincial and municipal-level deviations further highlight internal disparities (Figure 5-b, c). At the provincial level, 60 counties showed positive deviation (e.g., Zhangpu County with a provincial deviation of +545.2917 million RMB), while 22 counties showed negative deviation. At the municipal level, the distribution was more balanced, with 39 counties showing positive deviation and 44 showing negative deviation. The spatial pattern of dynamic performance revealed that (Figure 6) inland counties, such as those in Nanping and Sanming, exhibited prominent positive deviation, indicating ecological improvement exceeding the average. Coastal counties, including parts of Ningde and Zhangzhou, showed significant negative deviation, reflecting accelerated ecological degradation. The market-based compensation pathway uses performance gaps as trading units (Table S5). Counties with positive deviation, such as Shishi City with a comprehensive performance score of 16, were eligible to sell ecological quotas for profit, whereas counties with negative deviation, such as Longhai District with a comprehensive performance score of 5, were required to purchase quotas. The coupling of SSA results with the static LQ mechanism forms a dual-dimensional framework that integrates horizontal fiscal transfers with vertical market trading. This framework ensures spatial equity while providing incentives for continuous improvement. The quantification of dynamic performance establishes a data foundation for an ecological quota trading platform, enabling compensation mechanisms to evolve from static allocation toward adaptive regulation.



5-a: National Deviation 5-b: Provincial Deviation 5-c: Municipal Deviation

Fig. 5 Spatial differentiation of the ESV change deviation at the county level in Fujian Province



6-a: National Share Effect 6-b: Provincial Share Effect 6-c: Municipal Share Effect

Fig. 6 Spatial differentiation of the ESV change share effect at the county level in Fujian Province

3.4 **Analysis of Dynamic Trading Mechanisms Based on Performance Gaps and Minimum Guarantee Compensation for Weak Counties**

Building on the SSA framework, this study quantifies performance gaps in county-level ESV changes to establish a dynamic trading mechanism and a minimum guarantee compensation rule for weak counties. These mechanisms aim to address temporal lags in ecological compensation and ensure regional equity. Performance gaps were directly mapped to tradable ecological quota quantities: counties with positive deviation, such as Zhangpu County and Fuqing City, were eligible to sell quotas for profit, whereas counties with negative deviation, such as Xiapu County and Yunxiao County, are required to purchase quotas to offset their ecological deficits. As shown in Table 2, only 31.3% of the 83 counties exhibited positive performance gaps. These are primarily concentrated in economically developed coastal areas, such as Zhangpu County (526.9123 million RMB) and Fuqing City (336.4952 million RMB), where ecological improvement has been significant, positioning them as quota suppliers. The performance gap value corresponds directly to the amount of quota available for sale. The remaining 68.7% of counties showed negative performance gaps. These are predominantly inland mountainous areas or ecologically vulnerable regions, such as Xiapu County (-428.3687 million RMB) and Yunxiao County (-202.5274 million RMB), which were required to fulfill their responsibilities by purchasing quotas. The performance gap value corresponds directly to the amount of quota that must be purchased. The minimum guarantee compensation mechanism for weak counties established a threshold based on the mean performance gap of counties with negative deviation ($D^- = -51.2030$ million RMB), thereby identifying economically weak counties with relatively mild degradation for targeted compensation. This mechanism covers 19 counties where $D_i > 0$, such as Yongchun County and Zherong County, effectively safeguarding their basic governance capacity. For instance, Yongchun County has a performance gap of –1.2600 million RMB and a D_i value of +49.9431 million RMB, making it eligible for minimum guarantee support. In contrast, Tong'an County, with a D_i of –44.4956 million RMB, is required to bear a higher compensation responsibility. This design reflects the equity principle of "penalizing poor performers while assisting weaker regions", preventing underfunded weak counties from falling into a degradation cycle. Regional differentiation reveals a clear coastal–inland gradient. Coastal counties exhibited concentrated positive deviation but with significant internal variation, while inland counties have a higher proportion of negative deviation yet benefit from broader coverage under the minimum guarantee mechanism. These patterns confirm the overall trend of "coastal ecological deficits and inland ecological surpluses".

Table 2. Estimated results of county-level ESV performance gaps and minimum compensation gaps for negatively deviating counties in Fujian Province (unit: 10,000 CNY)

Administrative unit	ESV Performance Score	Performance Benchmark	Performance Gap	Avg. Gap (Negative)	Min. Compensation Gap
Zhangpu County	51766.95	-924.27	52691.23	-5120.30	-
Fuqing City	32725.25	-924.27	33649.52	-5120.30	-
Xiuyu District	24834.95	-924.27	25759.22	-5120.30	-
Mawei District	19541.04	-924.27	20465.31	-5120.30	-
Pingtan County	15150.44	-924.27	16074.71	-5120.30	-
Changle District	11794.06	-924.27	12718.33	-5120.30	-
Xiang'an District	9815.86	-924.27	10740.13	-5120.30	-
Jiaocheng District	9744.91	-924.27	10669.18	-5120.30	-
Fengze District	5725.28	-924.27	6649.55	-5120.30	-
Hui'an County	5422.86	-924.27	6347.13	-5120.30	-
Jimei District	3769.36	-924.27	4693.63	-5120.30	-
Xiangcheng District	2945.14	-924.27	3869.41	-5120.30	-
Shouning County	2914.72	-924.27	3838.99	-5120.30	-
Zhouning County	2331.18	-924.27	3255.45	-5120.30	-
Fu'an City	2319.61	-924.27	3243.88	-5120.30	-
Jinjiang City	1548.44	-924.27	2472.71	-5120.30	-
Gutian County	1471.62	-924.27	2395.89	-5120.30	-
Licheng District	1328.27	-924.27	2252.55	-5120.30	-
Jianning County	1259.86	-924.27	2184.13	-5120.30	-
Haicang District	1215.27	-924.27	2139.54	-5120.30	-
Siming District	752.01	-924.27	1676.28	-5120.30	-
Pingnan County	609.27	-924.27	1533.54	-5120.30	-
Zhenghe County	548.65	-924.27	1472.92	-5120.30	-
Shishi City	463.98	-924.27	1388.25	-5120.30	-
Zherong County	400.39	-924.27	1324.66	-5120.30	-
Guangze County	179.76	-924.27	1104.03	-5120.30	-
Cangshan District	46.45	-924.27	970.72	-5120.30	-
Taijiang District	-59.11	-924.27	865.17	-5120.30	-
Licheng District	-102.42	-924.27	821.85	-5120.30	-
Quangang District	-143.92	-924.27	780.35	-5120.30	-
Ninghua County	-242.52	-924.27	681.75	-5120.30	-
Songxi County	-263.74	-924.27	660.53	-5120.30	-
Xinluo District	-301.56	-924.27	622.71	-5120.30	-
Gulou District	-454.83	-924.27	469.44	-5120.30	-
Wuping County	-831.67	-924.27	92.60	-5120.30	-

Chengxiang District	-845.26	-924.27	79.01	-5120.30	-
Yongchun County	-1050.27	-924.27	-126.00	-5120.30	4994.31
Huli District	-1054.42	-924.27	-130.15	-5120.30	4990.16
Changtai District	-1135.66	-924.27	-211.39	-5120.30	4908.92
Sanyuan District	-1138.10	-924.27	-213.83	-5120.30	4906.48
Longwen District	-1146.53	-924.27	-222.26	-5120.30	4898.04
Youxi County	-1209.37	-924.27	-285.10	-5120.30	4835.21
Mingxi County	-1356.14	-924.27	-431.87	-5120.30	4688.43
Hanjiang District	-1412.44	-924.27	-488.17	-5120.30	4632.14
Taining County	-1514.71	-924.27	-590.44	-5120.30	4529.87
Yongding District	-1567.30	-924.27	-643.03	-5120.30	4477.28
Changting County	-1625.84	-924.27	-701.57	-5120.30	4418.73
Yong'an City	-1692.12	-924.27	-767.85	-5120.30	4352.45
Qingliu County	-1701.60	-924.27	-777.33	-5120.30	4342.98
Pinghe County	-1750.97	-924.27	-826.70	-5120.30	4293.61
Wuyishan City	-1752.64	-924.27	-828.37	-5120.30	4291.94
Yongtai County	-1781.68	-924.27	-857.41	-5120.30	4262.89
Shaxian District	-1804.05	-924.27	-879.78	-5120.30	4240.52
Shunchang County	-1821.87	-924.27	-897.60	-5120.30	4222.71
Minqing County	-1936.34	-924.27	-1012.07	-5120.30	4108.23
Hua'an County	-2034.02	-924.27	-1109.74	-5120.30	4010.56
Pucheng County	-2089.40	-924.27	-1165.13	-5120.30	3955.17
Dehua County	-2183.03	-924.27	-1258.76	-5120.30	3861.54
Liancheng County	-2340.29	-924.27	-1416.02	-5120.30	3704.29
Jin'an District	-2400.64	-924.27	-1476.37	-5120.30	3643.94
Jiangle County	-2446.45	-924.27	-1522.18	-5120.30	3598.13
Anxi County	-2582.22	-924.27	-1657.95	-5120.30	3462.35
Shanghang County	-2685.64	-924.27	-1761.37	-5120.30	3358.93
Nanjing County	-2757.46	-924.27	-1833.18	-5120.30	3287.12
Datian County	-2817.92	-924.27	-1893.65	-5120.30	3226.65
Zhangping City	-3084.88	-924.27	-2160.61	-5120.30	2959.69
Yanping District	-3194.90	-924.27	-2270.63	-5120.30	2849.67
Shaowu City	-3520.79	-924.27	-2596.52	-5120.30	2523.79
Minhou County	-3902.83	-924.27	-2978.56	-5120.30	2141.74
Zhao'an County	-4257.57	-924.27	-3333.29	-5120.30	1787.01
Jian'ou City	-4563.86	-924.27	-3639.59	-5120.30	1480.72
Dongshan County	-4954.69	-924.27	-4030.42	-5120.30	1089.88

Nan'an City	-5268.72	-924.27	-4344.45	-5120.30	775.85
Xianyou County	-6071.44	-924.27	-5147.17	-5120.30	-26.86
Jianyang District	-6258.20	-924.27	-5333.93	-5120.30	-213.62
Tong'an District	-10494.14	-924.27	-9569.86	-5120.30	-4449.56
Luojiang District	-11944.56	-924.27	-11020.29	-5120.30	-5899.99
Longhai District	-14206.60	-924.27	-13282.33	-5120.30	-8162.03
Yunxiao County	-21177.01	-924.27	-20252.74	-5120.30	-15132.44
Lianjiang County	-21508.36	-924.27	-20584.09	-5120.30	-15463.79
Fuding City	-29573.72	-924.27	-28649.44	-5120.30	-23529.14
Luoyuan County	-33562.50	-924.27	-32638.23	-5120.30	-27517.92
Xiapu County	-43761.14	-924.27	-42836.87	-5120.30	-37716.56

4. Discussion

Urban and rural systems are interdependent through the flow of ecological elements such as water resources, carbon sinks, and biodiversity. However, rapid urbanization often leads to spatial inequity in the distribution of ecological resources, exacerbating regional ecological degradation and socioeconomic imbalances. Taking Fujian Province as a case study, this study constructed a “static responsibility–dynamic performance” compensation mechanism for ecological elements, providing a scientific basis for ecological governance oriented toward urban–rural integration.

The allocation of ecological governance costs cannot be accomplished through a single logic; rather, it requires the interconnection and nesting of a government-led spatial equity mechanism and a market-driven performance efficiency mechanism. This study developed a composite operational system that balances “baseline protection” and “dynamic incentives”, representing the first integration of the LQ model with SSA to form a dual-layer framework of “spatial equity diagnosis–dynamic performance quantification”. This framework addresses the disconnection between static assessment and temporal dynamics inherent in traditional ecological compensation approaches(Clifton and Mánez, 2025). Within this system, the LQ mechanism and the shift-share mechanism operate in a nested logic of “equity first, efficiency second”. The LQ mechanism first identifies structural differences in ecological supply and demand across counties, where $LQ > 1$ indicates ecological surplus areas and $LQ < 1$ indicates deficit areas, thereby establishing a responsibility framework based on ecological endowments. This defines the baseline of ecological compensation and clarifies the direction of horizontal fiscal transfer payments (from deficit areas to surplus areas), ensuring the baseline of spatial equity. SSA then decomposes changes in ecological elements into share effects and competitive deviations, capturing the above-trend components of ecological change (such as performance gaps) and laying the foundation for market-based quota trading. For instance, static ecological surplus areas that continue to improve (positive deviation) can profit through market transactions, while static deficit areas that experience accelerated degradation (negative deviation) were required to pay higher compensation, providing ongoing incentives for improvement across regions. This coupling overcomes the limitation of single tools such as ESV calculations, which can only capture stock conditions without revealing relative performance, and enables refined quantification of ecological improvement “contributions” through multi-level comparisons (national, provincial, and municipal levels).

The synergy of this dual-dimensional mechanism lies not in simply adding LQ and SSA together, but in achieving a nested operation of “equity first, efficiency second”. Specifically, LQ first defines the basic responsibility structure at the

governmental level (identifying suppliers, demanders, and baseline bearers), while SSA subsequently provides dynamic calibration of governance performance (identifying entities with greater improvement or more severe degradation). This design ensures the baseline of spatial equity while enhancing efficiency through market incentives. In the Fujian case, for example, coastal deficit areas such as Xiang'an District in Xiamen were required to pay horizontal compensation to inland surplus areas such as Guangze County in Nanping, while the shift-share mechanism quantifies the "excess contributions" of different areas through performance gaps, driving continuous improvement. Building on this dual-dimensional mechanism, this study innovatively introduced a minimum guarantee compensation mechanism for weak counties, designed to prevent the adverse selection of economically weak counties in market-based processes and ensure substantive equity in ecological compensation.

Compared with existing studies, this research achieved important breakthroughs in both theoretical framework and empirical dimensions. Internationally, initiatives such as Europe's Green Infrastructure emphasize spatial planning but are often confined to static ecological network construction(Bellil et al., 2025). PES programs in Latin America, such as Costa Rica's forest compensation scheme, have introduced market-based approaches yet lacked dynamic adaptability(World Bank, 2020). Domestically, studies have often focused on a single scale, such as the provincial or municipal level, without integrating multi-level deviation analysis across national, provincial, and municipal benchmarks (Ren et al., 2023). For instance, compared with traditional ecological carrying capacity models, this framework not only diagnoses the coastal–inland differentiation in Fujian, evidenced by a Gini coefficient of 0.484, but also provides early warnings of degradation risks in areas such as Xiapu County through performance gaps (negative deviation in ESV of –498.3153 million RMB), addressing the limitations of system dynamics simulations in capturing spatial equity (Wang and Bao, 2021). In comparison with similar studies in regions such as Southeast Asian mangroves, the application of SSA in this study places greater emphasis on policy operability, such as directly translating performance gaps into quota trading units, thereby offering a replicable quantitative template for ecological compensation(Croci et al., 2025).

The theoretical contribution of this study lies in establishing a "spatial–temporal synergistic" paradigm for ecological governance, offering new insights for sustainable development in urban–rural integration regions worldwide. First, the methodological framework developed here can be adapted to regions at different levels of development. For example, by adjusting ESV weights in Southeast Asian mangrove conservation areas or strengthening the minimum guarantee mechanism in the Sahel region of Africa, this framework facilitates the transformation of ecological compensation from "regional experience" to "global tool". Second, through its dual-dimensional design of "spatial equity diagnosis and dynamic incentives", the practical innovation demonstrated in China's ecological civilization efforts provides a new pathway for developing countries to balance economic growth with ecological protection, serving as an important reference for global environmental governance.

This study has certain limitations. First, socioeconomic dimensions such as resident livelihoods and community participation are not fully incorporated, leaving the compensation mechanism relatively focused on ecological indicators and potentially overlooking social equity. Second, the case study is confined to Fujian Province, which, although representative, requires further validation across additional regions to establish the generalizability of the findings. Future research could address these limitations through the integration of multi-source data, combining remote sensing with social surveys, and through comparative analyses across multiple cases.

5. Conclusions

Guided by the flow of ecological elements and targeting the spatial inequity and dynamic complexity inherent in ecological element regulation, this study constructed a dual-dimensional compensation mechanism that integrates spatial equity diagnosis with dynamic performance incentives. Through empirical analysis of 83 county-level administrative units in Fujian Province, the study validated the feasibility and effectiveness of this mechanism in addressing center–periphery exploitation and optimizing the allocation of ecological resources. The research not only provides a quantitative tool for resolving imbalances between ecological deficits and surpluses but also offers a replicable paradigm for sustainable governance in analogous regions worldwide.

Empirical results revealed a pronounced coastal–inland differentiation pattern in the distribution of ecological elements across Fujian Province, with a Gini coefficient of 0.484 that underscores a high degree of inequity in resource allocation. The static compensation mechanism, through the coupling of ESV and LQ, clearly defined the fiscal responsibilities of ecological deficit areas, such as Xiang'an District in Xiamen, and surplus areas, such as Guangze County in Nanping, establishing a horizontal transfer payment framework in which deficits compensate surpluses. The dynamic compensation mechanism quantified the relative changes in regional ecological performance through competitive deviation values, such as Zhangpu County with a national ESV deviation of +492.0746 million RMB, and converted these values into tradable quotas. This approach thereby realized a market-based incentive structure in which "protectors benefit and developers pay". The minimum guarantee mechanism for weak counties further identified economically weak counties, such as Yongchun County, through a performance gap threshold (D^{-} = –51.2030 million RMB), preventing adverse selection and ensuring equity in compensation. These results are closely interconnected through their underlying logic: the static mechanism establishes the baseline for spatial equity, the dynamic mechanism drives continuous improvement through performance gaps, and the minimum guarantee design addresses market failures, together forming a collaborative governance chain of "baseline protection, dynamic optimization, and support for the vulnerable".

The essence of urban–rural ecological interactions lies in the coupled balance between spatial endowments and temporal evolution. By integrating the LQ and SSA methods, this study facilitated a paradigm shift in ecological compensation from static allocation to dynamic adaptation. This approach simultaneously addresses the equity question of "who compensates whom" and the efficiency requirement of "how to incentivize". The resulting framework provides a quantifiable and operational template for ecological governance in similar regions worldwide and offers a viable approach to ecological compensation in support of the 2030 Agenda for Sustainable Development.

Competing interests

The authors declare no competing interests.

Ethical statements

Ethical approval was not required for this study because it did not involve human participants, human data, or human biological material. The study was based on publicly available spatial and statistical data.

Data availability

The data used in this study are available from the public sources described in the manuscript. The processed data generated during the study are included in the article and Supplementary Material.

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