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Urban Land Use Efficiency Enhancement Through Regional Economic Cooperation Network in Urban Agglomeration: Evidence From Yangtze River Delta, China

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Abstract

Understanding how regional cooperation shapes urban land use efficiency is essential for promoting sustainable development of urban agglomeration. Existing literature mainly focuses on the direct impact of regional economic cooperation on urban land use efficiency while overlooking the indirect effects transmitted through intercity network structures. This study investigates the effects of regional economic cooperation network on urban land use efficiency in the Yangtze River Delta urban

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agglomeration between 2010 and 2019. Utilizing a modified gravity model to quantify regional economic cooperation networks and a Slack-Based Measure method to evaluate urban land use efficiency, we reveal a significant and positive influence of regional economic cooperation networks on land use efficiency in the Yangtze River Delta. The findings suggest that cities leveraging economic interconnectivity networks not only enhance their land-use efficiency but also benefit from network spillover effects. These insights provide valuable implications for policymakers and urban designers seeking to promote economic development while ensuring the sustainable use of urban land resources.

Keywords
regional cooperation network, urban land use efficiency, network externalities, spatial spillover effects, Yangtze River Delta

Introduction

Land use plays a crucial role not only in driving economic development but also in shaping environmental sustainability, social equity, and patterns of urban growth and prosperity (Anguelovski et al., 2016; Deng et al. 2010; Fekade 2000; Zhang and Wang 2018; Zhang et al. 2011). Driven by the pursuit of economic growth, recent decades have witnessed rapid urban expansion and increasing concentration of social and economic activities across various countries (Ehrlich et al. 2018; Gennaio et al. 2009; Kuang et al. 2016; Millward 2006). For example, the total urban area in China reached 56,225 km^2 in 2017, nearly five times its size in 1990 (Zhang et al. 2022). The growth has come at the cost of converting substantial areas of natural and agricultural land into built-up land (Liu 2018). Such land conversion can undermine food production and the rural economy, while the destruction of natural ecosystems may lead to biodiversity loss and compromised ecosystem services (Huang et al. 2019; Yu et al. 2015; Zhang et al. 2007). Therefore, improving urban land use efficiency has become a pressing priority to balance economic development with sustainability objectives (Osman 2020; Wang et al. 2023).

With the acceleration of global urbanization, regional economic cooperation has become an increasingly prominent feature of urban development strategies (Chen and Schintler 2023; Fu et al. 2022). Within urban agglomerations, such cooperations aim to foster industrial synergies, promote intercity collaboration, and support resource sharing among geographically adjacent cities through the free flow of capital, labor, and information (Ke 2015; Li et al. 2015). To promote regional economic cooperation, governments have strengthened coordination in terms of labor markets, public services, transport infrastructure, and other essential systems (Gao et al. 2022). For instance, in China, the loosening of mobility restrictions in urban areas has been accompanied by initiatives to expand equitable access to public services. Such measures, as noted by Hong et al. (2011), not only strengthen regional economic cooperation but also reshape urban economic structures and contribute to greater economic returns (Ke 2015; Li et al. 2015). In this context, it is crucial to examine the relationship between regional economic cooperation and urban land use efficiency within an integrated analytical framework.

Network effects emerge from the interactions among interconnected urban elements, where the collective impact often exceeds the sum of individual contributors (Meijers 2005). Such effects have long been recognized across disciplines, particularly in contexts where relationships, rather than individual attributes, shape outcomes. In the past, such effects were mainly constrained to physically adjacent cities, limited by commuting challenges and underdeveloped information infrastructure. Nowadays, advances in digital technology and transportation have significantly reduced the friction of geographical distance, which enables cities to connect and collaborate more efficiently across space. In this evolving network space, urban attributes such as centrality and connectivity influence a city's ability to access shared resources, information flows, and development opportunities (Camagni and Salone 1993). Through such network externalities, even non-adjacent cities can leverage the scale, innovation, and institutional capacity of more connected peers to their development advantage.

A substantial body of literature has examined the connection between regional economic cooperation and urban land use efficiency. For example, Zhao et al. (2021) found that the influence of regional economic cooperation on urban land use efficiency is overwhelmingly beneficial in the Yangtze River Delta, China. An empirical study by Gao et al. (2020) further revealed that regional economic cooperation has an indirect effect on surrounding cities' land use efficiency in addition to directly enhancing local cities' urban land use efficiency. This suggests that urban land use efficiency is facilitated by the movement of resources and the interactions between the economic activity of the cities in the region, and the effect of regional economic cooperation on urban land use efficiency showed a spatial spillover effect, affecting neighboring areas' land use. Similar results have been found in other studies (Zhang et al. 2022). While these contributions significantly advance our understanding of how regional economic cooperation affects urban land use efficiency, relatively few studies have examined the role of network effects through the lens of network externalities in urban agglomerations.

This paper aims to address the abovementioned knowledge gap by investigating the connection between regional economic cooperation and urban land use efficiency from the perspective of network effects. We focus on 41 cities in China's Yangtze River Delta as the research area and employ a network externality framework to evaluate how the network effect of regional economic cooperation impacts urban land use efficiency. As one of China's most urbanized regions, the Yangtze River Delta has been a pioneer in implementing important land use reforms and regional cooperation procedures in recent decades. The region's economy is rapidly expanding, but the imbalance between the supply and demand for construction land is becoming increasingly pronounced. As such, the Yangtze River Delta serves as an ideal example for assessing the relationship between regional economic cooperation and urban land use efficiency. Our research mainly includes three aspects. First, we use the Slack-based Measure (SBM) method to quantify and analyze the spatiotemporal characteristics of urban land use efficiency across different stages of regional economic cooperation. Second, we apply a modified gravity model to examine the spatiotemporal changes in the regional economic cooperation network. Third, based on the urban network externality framework and spatial econometric model, we explore the network effect of regional economic cooperation on urban land use efficiency.

This paper offers two significant contributions to the existing literature. First, it extends the scope of urban network analysis to explore the linkage between intercity networks and urban land use efficiency. While existing research has largely focused on describing and explaining the structure of urban networks, insufficient attention has been given to how network externalities influence land use efficiency. This research addresses the gap by systematically examining the spatial mechanism of regional economic cooperation on urban land use efficiency using a spatial econometric model. Traditionally, spatial physical proximity metrics like the adjacency matrix and distance matrix are the main sources of the spatial weight matrix employed in spatial growth regression models. This paper, in contrast, constructs an urban network spatial weight matrix based on the urban external economic linkages among 41 cities, which, to the best of our knowledge, has been rarely adopted in the existing literature.

Theoretical Framework

Formation of Regional Economic Cooperation Network

With the advancement of regional economic cooperation within urban agglomerations, economic cooperation and connections between cities have been progressively strengthening, leading to the evolution of inter-city relationships into a complex network of regional economic cooperation. First, according to urban geography theories, the spatial distribution of industries, corporate behavior tendencies, and the evolution of industrial spatial structures follow typical geographic diffusion patterns (Berry 1964; Christaller 1966; Hasan et al. 2018; Von Thünen 1966; Weber 1929). The flow of production factors, economic activities, and industrial systems exhibit strong spatial interdependence across regions (Isard 1956). Therefore, geographic conditions are the primary factors that generate economic spatial linkages (Alonso 1964). Cities in close geographic proximity inherently engage in intensive exchange and collaboration in terms of resource sharing, infrastructure development, and market connectivity. These foundational connections constitute the critical transmission pathways of the regional economic cooperation network.

Second, driven by advances in modern transportation and communication technologies, the flow of production factors has transcended traditional spatial and environmental constraints, resulting in broader, deeper, and more intensive regional economic linkages (Castells 2011; Malecki 2002). However, due to differences in resource endowments, transportation accessibility, and levels of economic development, there exists a "potential energy difference" in economic development levels between different cities (Fujita et al. 2001). Cities with comparative advantages tend to generate spillovers that support and complement the development of less advantaged regions (Stevens 1980). During the cross-regional flow of production factors, cities realize economic exchange and cooperation, manifesting in the output and reception of economic influence among the nodes within the regional economic spatial linkage network. Such interactions result in an economic spatial linkage structure where geographically proximate channels coexist with cross-regional leapfrogging channels (Puga 2010). Consequently, economic connections among cities expand both horizontally and vertically, fostering the development of a regional economic cooperation network characterized by multiple nodes, diverse linkages, and layered hierarchical structures (Figure 1).

Effect of Regional Economic Cooperation Network on Urban Land Use Efficiency

The effect of regional economic cooperation networks on urban land use efficiency can be explained via the lens of network externality framework. Burger and Meijers (2016) define network externalities as the external economic advantages received by enterprises and households situated in agglomerations due to their connections to other agglomerations. Unlike agglomeration externalities, which rapidly attenuate with geographical distance, network externalities are not limited by geographical boundaries and diminish as the level of functional interconnections between cities decreases., with a greater emphasis on accessibility and connectivity (Boix and Trullén 2007; Meijers 2005). It includes both the direct effects brought about by economies of scale shared by horizontal cooperation between nodes, and the indirect effects brought about by the industrial division of labor formed by relying on their resource allocation capabilities.

Direct Effect of Regional Economic Cooperation Network on Urban Land Use Efficiency. From the perspective of the overall urban economic spatial linkage network,

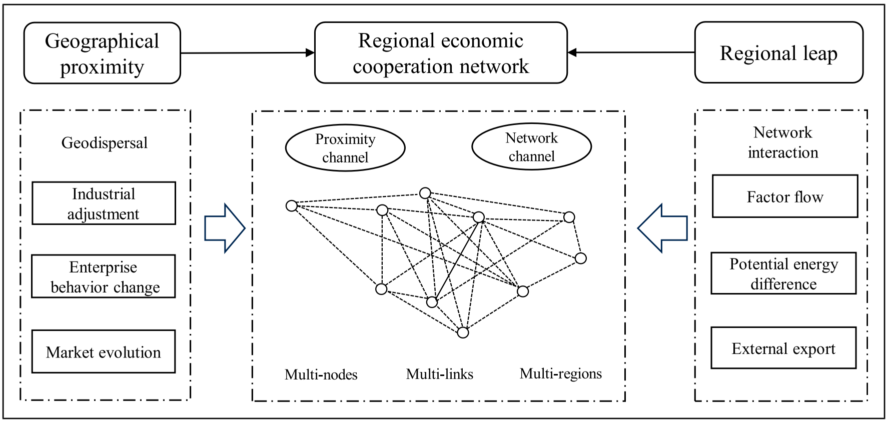

Figure 1. Formation mechanism of regional economic cooperation network.

the flow of factors, according to regional factor flow theory, serves as a significant driving force for regional economic growth and development. The urban economic spatial linkage network enhances the aggregation and diffusion of production factors through "structural spillover," "regional spillover," and "relational spillover," thereby improving factor efficiency and intensifying the effects of economic growth. This confers comparative advantages on cities in terms of industrial cooperation, specialized division of labor, and market integration (Broersma and Oosterhaven 2009; Huang and Shi 2025). Cities embedded in the network achieve regional economic cooperation through mechanisms such as employment absorption, population migration to larger cities, factor mobility, industrial structure optimization, and market integration. Economic linkages between cities represent a localized and dynamic process of collaborative evolution, facilitating formal exchanges and mutual dependencies across regions through learning and cooperation. This process promotes industrial technological innovation and increases returns, leveraging complementarity and shared resources (Xie et al. 2019), reducing industrial linkage costs through network scale effects, and unleashing the expansive effects of economic development.

Regarding the centrality of the urban economic spatial linkage network, cities embedded within the network can enhance the centrality of the economic spatial linkage network while maintaining the original number of network nodes (Derudder and Taylor 2005). This enrichment of spatial transmission pathways for industrial development amplifies the promotion effect on regional integration development and extends the geographical scope of its influence. Consequently, cities with higher centrality in the economic spatial linkage network can leverage these linkage pathways to eliminate barriers to factor flow, facilitating the bidirectional free flow of labor, capital, technology, and information within the region. This process upgrades industrial allocation and consequently impacts urban land use efficiency.

Indirect Effect of Regional Economic Cooperation Network on Urban Land Use Efficiency. According to the theory of regional economic spatial interaction, economic linkages can unlock the development potential of connected regions through collaboration, functional complementarity, and technological spillovers. Cities embedded within such networks benefit from the externalities generated by urban economic linkages, which disrupts the spatial inertia that limits economic development between "local" and "neighboring". This shift contributes to the emergence of an interconnected regional economic landscape and unleashes spillover effects on urban land use efficiency.

As economic ties among cities deepen, the network begins to generate increasing returns, with its value growing exponentially. The enhanced resilience, reduced risks, and increased specialization enabled by these spatial linkages create positive externalities that lower transaction costs, dismantle market barriers, and enhance the efficiency of resource allocation (Pan et al. 2018). These dynamics, in turn, contribute to more efficient and sustainable urban land use.

Moreover, cities leverage the spatial transmission paths of regional economies and their central positions within the network to further amplify the spillover effects of the economic network on urban land use efficiency. Through industrial integration, specialization, and clustering, the marginalization of isolated nodes is reduced, and new opportunities for "enclave cooperation" emerge. The expanded diffusion of knowledge and technology further broadens the influence of urban economies, thus reinforcing gains in land use efficiency.

Therefore, the networked development of regional economic cooperation shapes the land-use efficiency of urban agglomerations not only through direct local effects but also through indirect network spatial spillover effects. The theoretical framework is illustrated in Figure 2.

Methods

Study Area

The study area chosen is the Yangtze River Delta in China, which includes 41 cities situated in Shanghai, Jiangsu, Zhejiang, and Anhui (Figure 3). Despite its relatively small size (less than 4 percent of the country's total area), the Yangtze River Delta plays a crucial role in contributing a substantial share to the economic production of the country, accounting for close to one-quarter of the total. The Yangtze River Delta has undergone sustained integration and rapid economic growth in recent decades. The Yangtze River Delta has seen outstanding urbanization to support rapid economic growth, leading to the conversion of a considerable amount of farmland for non-agricultural uses. Meanwhile, the scarcity of urban construction land resources imposes constraints on urban economic expansion. Moreover, the growing tension between rapid economic expansion and the scarcity of available urban land has become a major constraint on the long-term socio-economic development of cities in the region.

To boost economic growth and enhance operational effectiveness, the central Chinese government has been actively investigating approaches to dismantle administrative barriers and foster intercity collaboration. The Regional Plan for the Yangtze River Delta Region was released in 2010, marking the official start of the

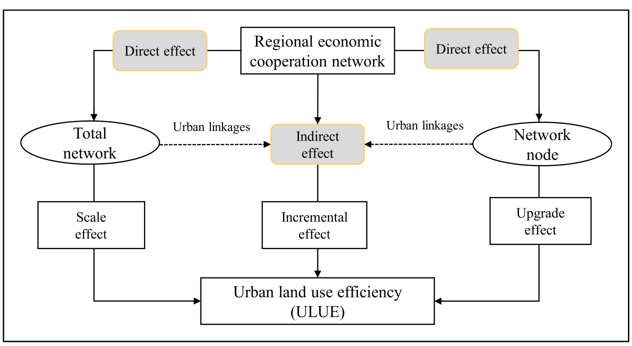

Figure 2. Theoretical framework.

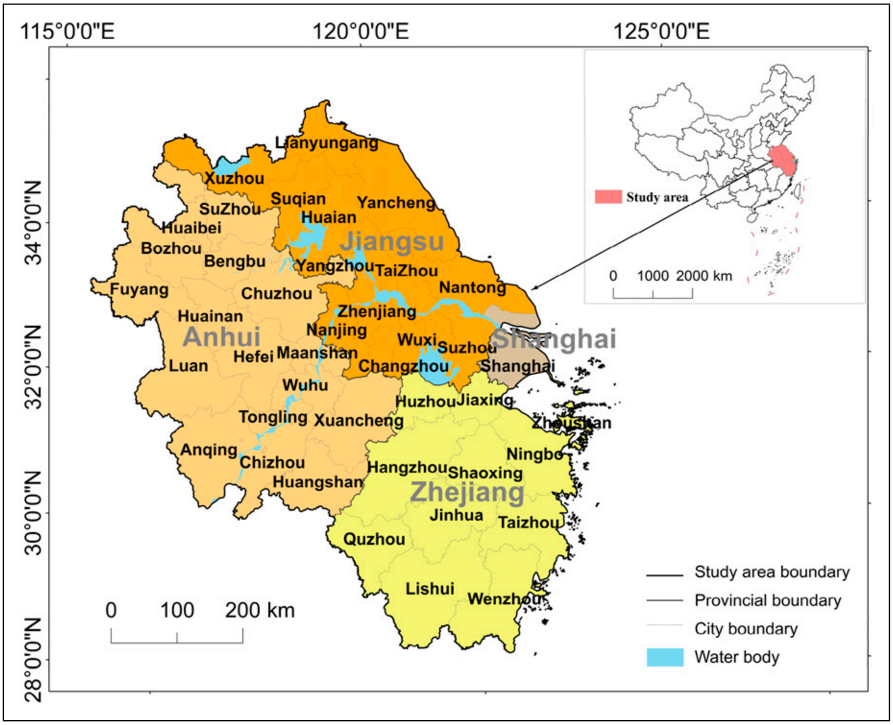

Figure 3. The study area in the Yangtze River Delta region, including Shanghai, Jiangsu, Zhejiang, and Anhui.

regional integration strategy's execution for the Yangtze River Delta region. Following this, the government implemented a series of regional integration initiatives for the Yangtze River Delta region in 2016, 2018, and 2019. By 2019, the scope of regional integration in the Yangtze River Delta has progressively broadened from the central area to include all cities in the three provinces and Shanghai. The Yangtze River Delta urban agglomeration is a prime example of China's regional integration plan. In recent decades, it has moved from traditional, physically close economic ties to a wider regional economic circle development model. Consequently, we selected the Yangtze River Delta as the focus of our study.

Since the government's official regional integration policy began in 2010, and the global COVID-19 outbreak in 2020 disrupted the normal economic order, we chose 2010–2019 as the study period for this paper. In the following analysis, we employ triennial intervals to examine the spatial and temporal fluctuations in regional economic cooperation and urban land use efficiency.

Methodology

Model Settings. This research employs a spatial econometric model to describe the network effect of regional economic cooperation on urban land use efficiency. The formula is as follows:

$$Y_{it} = \beta X_{it} + \rho \sum_{j=1}^{N} W_{ij} Y_{jt} + \varphi \sum_{j=1}^{N} W_{ij} X_{jt} + \mu_i + v_t + \varepsilon_{it} \tag{1}$$

where Y_{it} indicates the response variable, X_{it} shows the explanatory variables, W_{ij} represents the spatial weights, β is the coefficient of explanatory variables, ρ and φ are the coefficients of spatial lag terms of response variable and explanatory variables, respectively, and ε_{it} represents the error term, μ_i and v_t are the coefficients of spatial effect and time effect, respectively.

We construct an economic network spatial weight matrix (W_{net}) based on the urban external economic linkages to explore how cities in the region can bring about network effects on urban land use efficiency through network links (Huang et al. 2020). In the existing literature, either administrative boundary adjacency spatial weight matrix (W_{adj}) or geographical distance spatial weight matrix (W_{dis}) was generally used in similar studies, and we do a comparative analysis using each of the three spatial weights in Section 5. The formulas are as follows:

(1) Economic network spatial weight matrix

$$W_{net} = \left[\frac{1}{\left| \overline{E_j} - \overline{E_i} + 1 \right|} \right] \times e^{-d_{ij}} \tag{2}$$

where W_{net} represents economic network spatial weight matrix; $\overline{E_i}$ and $\overline{E_j}$ are the mean values of the economic linkages of cities i and j from 2010 to 2019, respectively; d_{ij} denotes the geographical distance between cities i and cities j.

(2) Administrative boundary adjacency spatial weight matrix

$$W_{adj} = \begin{cases} 1 \ (\text{Adjacency}) \\ 0 \ (\text{0therwise}) \end{cases} \tag{3}$$

where W_{adj} represents the geographical queen adjacency spatial weight matrix; if the administrative boundaries of cities i and j are adjacent, W_{adj} is recorded as 1; otherwise, W_{adj} is recorded as 0.

(3) Geographical distance spatial weight matrix

$$W_{dis} = \frac{1}{d_{ij}} \tag{4}$$

$$d_{ij} = \text{arcos}\left[\left(\sin\phi_i \times \sin\phi_j\right) + \left(\cos\phi_i \times \cos\phi_j \times \cos(\Delta\Gamma)\right)\right] \times \mathcal{R} \tag{5}$$

where W_{dis} represents the geographical distance spatial weight matrix;d_{ij} is the geographical distance between two cities calculated based on their latitudes and longitudes; ϕ_i and ϕ_j denote the latitudes and longitudes of cities i and j, respectively; $\Delta\Gamma$ is the difference in longitude between cities i and j; $\mathcal{R}$ is the Earth's radius.

Variables

Response Variable. This paper takes urban land use efficiency (*ULUE*) as the response variable. In this paper, *ULUE* is defined as a city's ability to maximize expected outputs, such as economic growth, based on a given input of land resources, capital, and labor, while simultaneously minimizing undesirable outputs. Improving *ULUE* means that a city can achieve higher economic benefits with the same or fewer inputs of land, capital, and labor, while also reducing the negative environmental impacts, such as pollution. This balance between economic growth and environmental protection is essential for sustainable urban development.

The super-efficiency SBM model is employed to measure urban land use efficiency. As one of the most widely adopted models in the measurement of land use efficiency, the super-efficiency SBM model is particularly well-suited for urban contexts, where input-output imbalances and environmental constraints are common. By accounting simultaneously for input slack, output deficiencies, and environmental burdens, the model provides a refined assessment of urban land use performance. Unlike conventional Data Envelopment Analysis (DEA) approaches, the SBM model explicitly considers the excess use of inputs, the shortfall in desirable outputs, and the excessive generation of undesirable outputs, thereby offering a more accurate and comprehensive efficiency evaluation. In this study, cities are treated as decision-making units (DMUs), and the SBM model assesses urban land use efficiency across the economic, social, and environmental dimensions. The model is applied to a pooled panel dataset covering multiple years, which enables all DMUs to be evaluated against a common efficiency frontier. This approach ensures comparability of efficiency scores both across cities and over time. The specific model construction is presented as follows:

$$\theta^* = \min_{\lambda, s^-, s^+} \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{io}^t}}{1 - \frac{1}{q+h}\left(\sum_{r=1}^{q} \frac{s_r^+}{y_{ro}^t} + \sum_{k=1}^{h} \frac{s_k^-}{b_{ko}^t}\right)}$$

$$\begin{aligned} s.t.\quad & x_{io}^t \geq \sum_{t=1}^{T}\sum_{j=1, j\neq o}^{n} \lambda_j^t x_{ij}^t - s_i^-, \quad i = 1,2,\cdots,m; \\ & y_{ro}^t \geq \sum_{t=1}^{T}\sum_{j=1, j\neq o}^{n} \lambda_j^t y_{rj}^t + s_r^+, \quad r = 1,2,\cdots,q; \\ & b_{ko}^t \geq \sum_{t=1}^{T}\sum_{j=1, j\neq o}^{n} \lambda_j^t b_{kj}^t - s_k^-, \quad k = 1,2,\cdots,h; \\ & \lambda_j^t \geq 0(\forall j), s_i^- \geq 0(\forall i), s_r^+ \geq 0(\forall r), s_k^- \geq 0(\forall k) \end{aligned} \tag{6}$$

where suppose there are n DMUs, each consisting of the following components: i represents the number of input variables, ranging from 1 to m; q denotes the desirable output, and h denotes the undesirable output. The slack variable s_i^- represents the excess use of inputs, such as land, labor and capital input elements, indicating potential inefficiencies in resource allocation. The slack variable s_r^+ captures the shortfall in desirable outputs, implying underperformance. The slack variable s_k^- measures the excess amounts of undesirable outputs, suggesting that environmental performance could be improved. The elements $x_{i_o}^t$, $y_{r_o}^t$, $b_{k_o}^t$ correspond to the input matrix, desirable output matrix, and undesirable output matrix, respectively. The efficiency value θ represents urban land green use efficiency. When $\theta \geq 1$, it indicates that the DMU is efficient; when $0 \leq \theta < 1$, it indicates that the DMU is in a state of low efficiency or inefficiency, suggesting room for efficiency improvement.

Drawing from existing literature, the following indicators are selected to measure urban land use efficiency.

(1) Input Indicators: Land, capital, and labor are the three input variables for the urban land use system. Specifically, the area of urban built-up regions represents land input, urban fixed asset investment represents capital input, and employment in the secondary and tertiary industries represents labor input.
(2) Desirable Output Indicators: Indicators that align with economic benefits are chosen as desirable output indicators. Specifically, the added value of the secondary and tertiary industries represents economic benefits.
(3) Undesirable Output Indicators: Urban land use system's undesirable outputs include major urban pollutants. Specifically, industrial sulfur dioxide emissions, industrial wastewater discharge, and industrial smoke and dust emissions are selected as undesirable output indicators.

Explanatory Variable. The core explanatory variable in this study is the ability of regional economic cooperation (*Cooperation*). The ability of regional economic cooperation intuitively reflects the closeness of economic ties between cities within the urban economic spatial linkage network. It can examine the hub position of nodes in the network and their access to resources.

We begin by employing a modified gravity model to quantify the intensity of economic linkages among cities within an urban cluster and assess the degree of regional economic cooperation. A set of socio-economic data is used to measure economic linkages. Specifically, the year-end data on the population and Gross Domestic Product (GDP) of cities are employed as proxies for the mass of the cities, thereby reformulating the mass parameter in the gravity model. The modified gravity model is utilized to quantify the extent of economic linkages among cities in the urban agglomeration of the Yangtze River Delta (Wen et al. 2021). The modified gravity model is presented as follows:

$$Linkage_{ij} = \frac{\sqrt[2]{E_i} \times \sqrt[2]{E_j}}{D_{ij}^2}, E_i = G_i P_i, E_j = G_j P_j \tag{7}$$

where $Linkage_{ij}$ represents the economic linage strength between city i and city j; G_i and G_j represent the total Gross Domestic Product (GDP) of city i and city j, respectively. P_i and P_j represent the total population of city i and city j, respectively. E_i and E_j are the comprehensive economic scales of the cities, defined as the GDP and population size. D_{ij} represents the geographical distance between city i and city j. This model optimizes the traditional gravity model by incorporating population size as a key factor and adjusting the impact of city size on linkage strength to more accurately measure the level of regional economic integration.

Then, building upon the economic linkage computed through the modified gravity model, the study calculates the aggregate gravitational pull exerted by each city externally, representing the degree of each city's regional economic cooperation. The formula is as follows:

$$Cooperation_i = \sum_{j=1}^{n} Linkage_{ij} \tag{8}$$

where $Cooperation_i$ is the level of the regional economic cooperation ability of the city i, $Linkage_{ij}$ is the strength of economic linkage from city i to city j.

Control Variables. To mitigate potential estimation bias resulting from omitted variables, this study controls for the following variables.

(1) Industrial Structure (*IS*): The land output of the tertiary sector is higher than that of the secondary sector. Therefore, reasonably increasing the proportion of the tertiary sector helps to improve land use efficiency.
(2) Government Investment Intensity (*Gover*): Government investment plays a crucial role in shaping urban spatial structure and guiding land use patterns. A higher level of investment intensity may promote infrastructure development and improve land efficiency. In this study, we use the ratio of fixed asset

investment to local general public budget expenditure to represent government investment intensity.

(3) Innovation Capacity (*Innov*): Innovation drives technological progress and industrial upgrading, which in turn promotes intensive land use and green transformation. A higher level of innovation is expected to enhance land use efficiency through increased productivity and reduced environmental impact. In this study, the number of granted patents is used as a proxy for innovation capacity.

(4) Marketization Level (*Market*): A higher degree of marketization improves the efficiency of resource allocation. Market-oriented cities are more likely to optimize land use patterns based on price signals and demand, thereby enhancing land use efficiency. In this study, the ratio of employment in private and self-employed sectors to total urban employment is used to approximate the level of marketization.

Data Source

This study utilizes annual citywide socio-economic data from 41 cities in the Yangtze River Delta urban agglomeration in China, spanning from 2010 to 2019. The data were sourced from the EPS Data Retrieval and Forecast Platform (EPS 2024). To ensure temporal comparability, all GDP-related indicators were adjusted to constant prices using the official GDP deflator published by China's national statistical authorities.

Results

Changes in Regional Cooperation Network and Urban Land Use Efficiency

The time variation trends of the regional economic cooperation network and urban land use efficiency in the Yangtze River Delta urban agglomeration from 2010 to 2019 are shown in Figure 4. During the 2010–2019 period, the level of regional economic cooperation ability in the Yangtze River Delta generally showed an upward trend, with the average level increasing from 788.18 to 2,273.70, an average annual growth rate of 18.85 percent. Meanwhile, the urban land use efficiency in this region also exhibited a similar trend, with the average level rising from 0.62 to 0.83, reflecting an average annual growth rate of 3.39 percent.

Spatially, Figure 5 illustrates the spatial distribution characteristics of the regional economic cooperation network development and urban land use efficiency in the Yangtze River Delta urban agglomeration for the years 2010, 2013, 2016, and 2019. In the early stages of the Yangtze River Delta regional integration strategy proposed by the Chinese government in 2010, there were significant regional differences in the development of the regional economic cooperation network. Central cities such as Shanghai, Suzhou, Wuxi, and Hangzhou were connected to surrounding cities like Nantong, Zhenjiang, Jiaxing, and Huzhou, while Yangzhou connected to Nanjing, Zhenjiang, and Taizhou, forming dense economic networks in the eastern and central

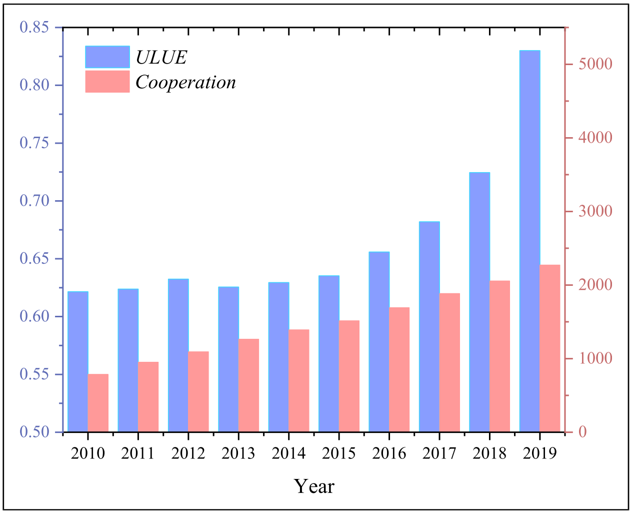

Figure 4. Time trends of regional economic cooperation and urban land use efficiency in the Yangtze River Delta urban agglomeration.

regions. Subsequently, the economic linkages between cities in the Yangtze River Delta improved significantly. By 2019, a multi-level, multi-center network structure had formed, centered around cities such as Shanghai, Suzhou, Wuxi, Nanjing, Hangzhou, and Hefei. Strong radiation capabilities within the regional economic cooperation network are possessed by regions that have a high level of regional economic co-operation. These cities possess greater political authority, sophisticated economies, and infrastructure, and exert substantial effect on economic development and overall re-gional urban and economic growth.

Urban land use efficiency initially displayed spatial distribution characteristics consistent with the regional cooperation network, with overall low efficiency across the Yangtze River Delta. By 2019, the overall urban land use efficiency had improved compared to 2010, with high-efficiency areas primarily located in central cities such as Shanghai, Suzhou, Wuxi, Nanjing, and Hefei. This trend mirrors the development of the regional economic cooperation network, suggesting a possible causal relationship between the two on a macro scale.

The Effect of Regional Economic Cooperation Network on Urban Land Use Efficiency

Model Diagnostics. Before estimating the Spatial Durbin Model (SDM), we performed a comprehensive set of diagnostic tests to ensure the appropriateness and robustness of the model. The first step was a spatial autocorrelation test. The Moran's I index for urban land use efficiency (ULUE) was computed for the years 2010, 2013, 2016, and 2019 using spatial weights based on network contiguity (Figure 6). In all 4 years,

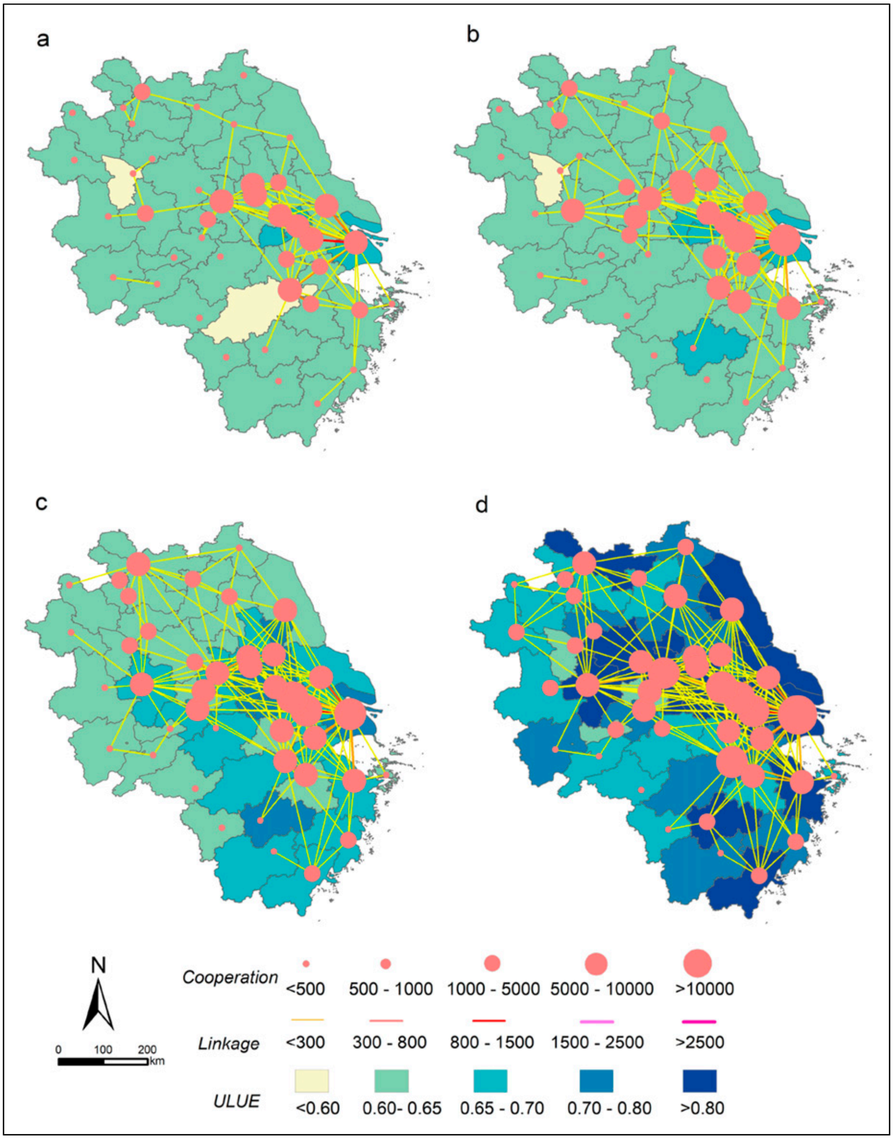

Figure 5. The spatial distribution of regional economic cooperation for 2010 (a), 2013 (b), 2016 (c), and 2019 (d).

Moran's I was significantly positive at the 1 percent level, indicating a strong spatial clustering of ULUE. This finding suggests that, with the advancement of the Yangtze River Delta integration strategy, intercity economic linkages have been strengthened and the industrial division of labor has deepened, thereby intensifying the spillover

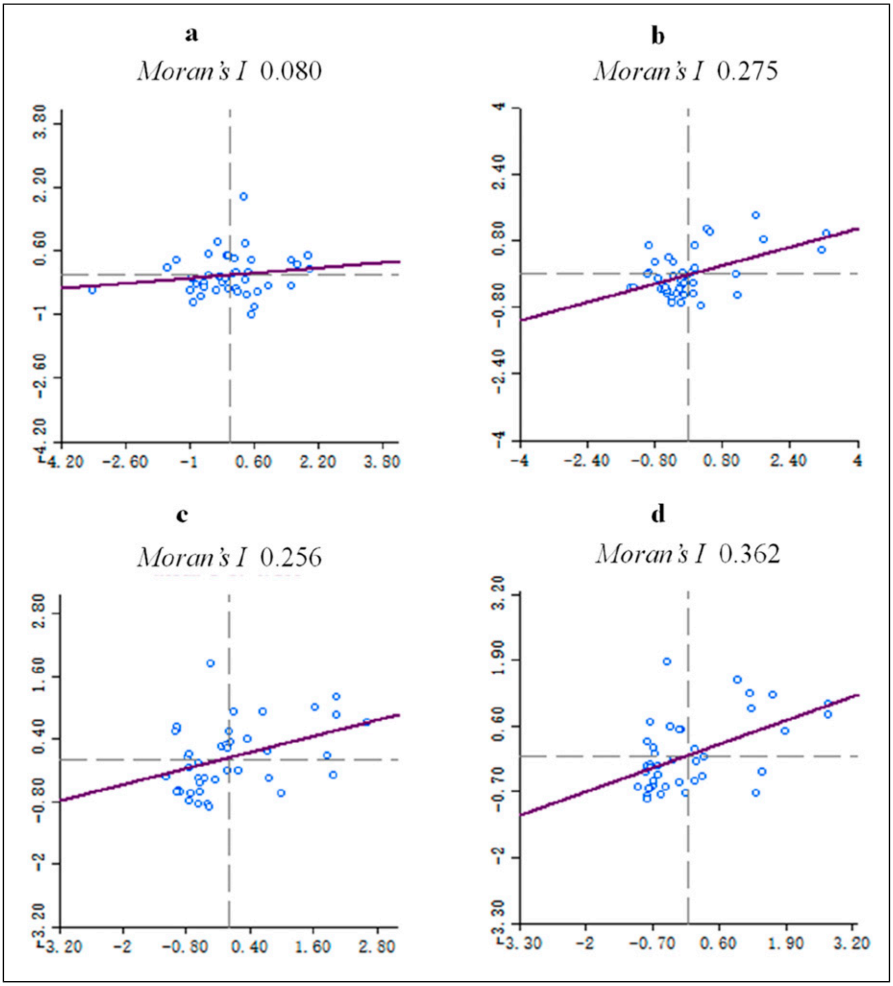

Figure 6. Moran's *I* of *ULUE* for 2010 (a), 2013 (b), 2016 (c), and 2019 (d).

effects from high-efficiency cities to low-efficiency cities and promoting the gradual convergence of ULUE among neighboring cities. This underscores the importance of incorporating spatial effects when examining the combined effects of urban land use efficiency within a network context.

Following this, spatial dependence in the OLS residuals was examined using Lagrange Multiplier (LM) tests, including LM-Lag, robust LM-Lag, LM-Error, and robust LM-Error. All tests rejected the null hypothesis at the 1 percent level, confirming the presence of both spatial lag and spatial error dependence (Table 1). Based on these results, three alternative spatial econometric models—Spatial Lag Model (SLM), Spatial Error Model (SEM), and Spatial Durbin Model (SDM)—were estimated.

Table 1. Results of spatial dependence tests

Test type	LM statistic	P-value
LM-lag test	845.821	.000
Robust LM-lag test	240.553	.000
LM-error test	704.856	.000
Robust LM-error test	99.588	.000

Hausman tests supported random effects for SLM and SEM but indicated fixed effects for the SDM. Among the three models, the SDM demonstrated the best fit, as evidenced by the lowest residual variance and highest R^2. Moreover, Likelihood Ratio (LR) tests confirmed that the SDM could not be simplified into SLM or SEM (Table 2).

Accordingly, the fixed-effects SDM was selected for subsequent analysis of the impact of the Yangtze River Delta regional economic cooperation network on ULUE. These diagnostics confirm the suitability of the model specification and ensure the robustness of the empirical results.

Baseline Regression Estimate Results. According to the estimation results of the SDM in Table 2, the coefficient of regional economic cooperation is positive and statistically significant at the 1 percent level, indicating that a higher level of regional economic cooperation within a city is associated with higher urban land use efficiency. The spatial lag term of regional economic cooperation is also positive and significant at the 1 percent level, suggesting that regional cooperation exhibits a strong spatial effect, namely, the cooperation level in one city can positively influence the land use efficiency of other cities through network-based spillovers. Specifically, the direct effect of ln*Cooperation* on urban land use efficiency is 0.071, and the indirect effect is 0.408; both are statistically significant at the 1 percent level. This implies that regional economic cooperation networks exert both direct and indirect (spatial spillover) effects on urban land use efficiency through intercity economic linkages. The strengthening of urban networks not only enhances the efficiency of local land use but also significantly influences the land use patterns of other interconnected cities. As the flow of resources and economic activities among cities intensifies, urban land tends to be used more intensively and efficiently (Batten 1995). Through network connections, cities can access and integrate the resource advantages of other cities to improve their land use efficiency. Such spatial spillovers can overcome the traditional constraints of geographic proximity or spatial distance. Therefore, by actively integrating into regional economic cooperation networks and leveraging network externalities, cities have great potential to enhance the efficiency of land use on a broader regional scale.

Among the control variables, Industrial Structure (Indus) and Innovation Capacity (Innov) exhibit opposite effects on ULUE. Specifically, a 1 percent increase in Indus directly improves ULUE by 0.025 percent, while a 1 percent increase in Innov directly reduces ULUE by 0.074 percent. This suggests that cities with a higher share of the tertiary sector tend to achieve more efficient land use, whereas innovation investment,

Table 2. Results of spatial regression estimation

	Model 1	Model 2	Model 3	Model 4
	OLS	SLM	SEM	SDM
Main				
ln*Cooperation*	0.176***	0.058***	0.040***	0.071***
	[0.016]	[0.013]	[0.009]	[0.013]
ln*Indus*	0.052***	0.020*	0.032***	0.025**
	[0.018]	[0.011]	[0.010]	[0.011]
ln*Gover*	−0.023**	−0.003	0.003	0.003
	[0.010]	[0.008]	[0.008]	[0.008]
ln*Innov*	−0.104***	−0.060***	−0.068***	−0.074***
	[0.012]	[0.011]	[0.009]	[0.010]
ln*Market*	0.013	0.022**	0.008	−0.014
	[0.017]	[0.010]	[0.010]	[0.012]
$W_{net} \times x$				
ln*Cooperation*				0.408***
				[0.099]
ln*Indus*				−0.354***
				[0.103]
ln*Gover*				−0.036
				[0.028]
ln*Innov*				0.136***
				[0.037]
ln*Market*				−0.443***
				[0.114]
Constant	−0.292***	0.159*	0.125	2.036***
	[0.096]	[0.084]	[0.107]	[0.566]
Spatial		0.800***		0.719***
Rho		[0.035]		[0.051]
Lambda			0.888***	
			[0.021]	
LR test		63.58***	57.60***	
R^2	0.633	0.731	0.745	0.848
N	410	410	410	410

Note. The t-values are indicated within brackets, whereas ***, **, and * represent statistical significance at the 1 percent, 5 percent, and 10 percent levels.

in the short term, may not effectively translate into land use efficiency gains, possibly due to long R&D cycles or inefficiencies in innovation output transformation. However, their spatial lag effects present an opposite pattern. A 1 percent increase in Indus in network-associated cities significantly reduces the local city's ULUE by 0.345 percent, indicating that excessive agglomeration of service-oriented industries in surrounding cities may cause competitive crowding-out effects. In contrast, a 1 percent increase in

Innov in neighboring cities significantly increases local ULUE by 0.136 percent, reflecting the positive spatial spillover of regional innovation—where innovation capacity in one city can benefit land use efficiency in adjacent areas through knowledge diffusion and collaborative networks. In addition, Marketization Level (Market) has a significant negative effect on ULUE, with the indirect effect being statistically significant at the 1 percent level.

Spatial Effect Decomposition. Furthermore, a partial differential technique was built using the LeSage and Pace (2009) model, in which the consequences were evaluated using both direct and indirect effects. The influence of independent factors on the dependent variable is referred to as the direct effects. Indirect effects, or spatial spillover effects, show how independent factors affect the dependent variable. The regional spillover impact is illustrated in detail in Table 3. The coefficients of ln*Cooperation* were 0.302, 0.063, and 0.239, respectively, with $p < 0.01$, indicating that the development of the regional economic cooperation network had a significant positive impact on urban land use efficiency. In particular, with a 1 percent increase in ln*Cooperation* using W_{net}, the urban land use efficiency in the Yangtze River Delta region will increase by 0.302 percent, which includes a direct increase of 0.063 percent and an indirect decrease of 0.239 percent (in net-related areas), suggesting a positive network synergy effect.

Table 2 also shows the sensitivity analysis results of SDM using W_{adj} and W_{dis} as the spatial weight matrices. The two weight matrices show that ln*Cooperation* has statistically significant and positively associated direct and indirect impacts on urban land use efficiency. The evidence indicates that regional economic cooperation has a considerable impact on both the local region's land-use efficiency and the land usage of neighboring cities, which is consistent with earlier research findings (Gao et al. 2020). The influence of regional cooperation on resource efficiency and urban land use is not only based on distance or proximity but also on the economic ties that bind metropolitan regions together.

Table 3. Direct and indirect effects of SDM according to three spatial weights

	W_{net}	W_{adj}	W_{dis}
Variables	ln*ULUE*	ln*ULUE*	ln*ULUE*
Total effect	0.302***	0.133***	0.099***
	[0.086]	[0.039]	[0.025]
Direct effect	0.063***	0.050***	0.037***
	[0.014]	[0.015]	[0.009]
Indirect effect	0.239***	0.083***	0.062***
	[0.076]	[0.025]	[0.016]

Note. The t-values are indicated within brackets, whereas ***, **, and * represent statistical significance at the 1 percent, 5 percent, and 10 percent levels.

Robustness Test

Robustness analysis was conducted by substituting the response variable. Non-agricultural output per unit of land input is commonly used as an indicator for calculating urban land use efficiency. Referring to existing studies, the industrial added value per square kilometer of the secondary and tertiary industries was used as the indicator for land use efficiency. The land use efficiency of 41 cities in the Yangtze River Delta urban agglomeration from 2010 to 2019 was recalculated and used as the response variable for re-estimation. Empirical tests show that the sign and significance levels of the regression coefficients (Table 4) are consistent with the results of the baseline regression analysis. The research conclusions remain consistent with previous findings, confirming the robustness of the study results.

Discussion

The relationship between urban land use efficiency and regional economic cooperation has become an increasingly prominent focus in the field of sustainable urban development. The research proposes a theoretical framework to investigate this relationship through the lens of network externalities. By employing SDM models and panel data from 41 Chinese cities located in the Yangtze River Delta between 2010 and 2019, our study reveals the dynamics of network effects in shaping land use outcomes.

Our study offers important policy insights into land use planning and urban agglomeration strategies at different stages of regional development, which supports the broader goal of sustainable urbanization. The results demonstrate that the Yangtze River Delta urban agglomeration significantly benefits from regional economic cooperation in terms of both network synergy and land use efficiency. Along with a direct impact on the area's efficiency in land use, improving the network's status has a major indirect

Table 4. Results of the robustness test

	Model 1	Model 2	Model 3	Model 4
	OLS	SLM	SEM	SDM
ln*Cooperation*	0.548***	0.472***	0.488***	0.491***
	[0.036]	[0.045]	[0.036]	[0.047]
W_{net} × ln*Cooperation*				0.634**
				[0.314]
Control variables	Yes	Yes	Yes	Yes
Constant	7.033***	6.337***	6.714***	10.946***
	[0.215]	[0.481]	[0.225]	[2.259]
R^2	0.898	0.898	0.898	0.901
N	410	410	410	410

Note. The t-values are indicated within brackets, whereas ***, **, and * represent statistical significance at the 1 percent, 5 percent, and 10 percent levels.

impact on the land use of connected cities within the network (Meijers 2005). This suggests that cities can improve land use efficiency by actively leveraging network externalities and embedding themselves more deeply within economic interconnectivity networks. Ultimately, urban land use efficiency across the agglomeration can be collectively improved through strengthened network linkages and intercity cooperation, a finding consistent with previous studies on intercity collaboration and spatial efficiency gains (Boarnet 1998; Capello 2000; Rodríguez-Pose and Crescenzi 2008) and aligned with our initial expectation regarding the positive role of network externalities.

Furthermore, utilizing the partial differentiation technique established by LeSage and Pace (2009), which employs direct and indirect effects to assess outcomes, this study compares the results under three spatial weight matrices: economic network, administrative boundary adjacency, and geographical distance. The findings indicate that the synergistic improvement of land use efficiency within urban agglomerations can occur simultaneously under conditions of network connectivity, administrative boundary adjacency, and geographical proximity. Existing literature primarily focused on the mechanisms behind the latter two scenarios, emphasizing the theory of agglomeration externalities. This theory suggests that economic actors benefit from being located in the same area, although the acquisition of these benefits is often constrained by the scale of spatial agglomeration (Duranton and Overman 2005). However, our findings highlight the benefits derived from intercity connections, grounded in the theory of urban network externalities. This indicates that under certain conditions, network externalities can complement the limitations of agglomeration externalities.

In line with China's growth of regional policies, regional cooperation is crucial for improving the overall efficiency of urban land use. The beneficial effects of urban network externalities are reflected in the coordinated enhancement of land use efficiency within urban agglomerations. Regional economic cooperation, through the circulation of production factors, facilitates the expansion of product markets and the liberation of factor markets, thereby supporting more sustainable land use in metropolitan areas. Thus, it is imperative for policymakers to persist in viewing regional economic integration as a strategic objective, work toward creating interactive trade platforms for diverse industries, enhance collaboration and communication between cities, and encourage superior land use development. This shift should be considered in urban planning as well, with an increased emphasis on the structural placement and links within urban networks. By completely integrating into national and even global supply chains and markets, cities can enhance the efficiency of land use.

While this study focuses on the Yangtze River Delta, the mechanisms identified, particularly the complementary roles of network and agglomeration externalities, may have broader applicability to other rapidly urbanizing regions worldwide. Similar urban agglomerations in Southeast Asia, Africa, and Latin America face comparable challenges of land scarcity, rapid economic growth, and the need for coordinated planning (Arfanuzzaman and Dahiya 2019; Cervero 2013; Deininger and Byerlee 2012). The findings suggest that fostering intercity economic linkages, promoting integrated land use strategies, and embedding local economies into larger regional and global networks can enhance land use efficiency beyond the Chinese context. However, the external validity of these conclusions depends on the presence of enabling institutional frameworks, adequate infrastructure, and policy coordination mechanisms, which may vary significantly across countries and regions.

Nevertheless, several limitations warrant further investigation. First, while regional economic cooperation networks are among the most representative urban networks, they capture only a single dimension of the complex web of intercity interactions. A more systematic and comprehensive comprehension of urban network externalities could be achieved by integrating diverse data sources, such as population migration, social interactions, and transportation flows, to construct a more holistic representation of urban connectivity. Second, this research focuses exclusively on the Yangtze River Delta city cluster in China as a single case study. Further research could extend the analysis to urban agglomerations across nations and regions, which could enable comparative assessments and the classification of diverse urban network models. Such insights could help policymakers and planners identify land use strategies that are best aligned with the specific characteristics and development needs of their communities.

Conclusion

This study uses a panel dataset on 41 cities in the Yangtze River Delta region of China, covering the period from 2010 to 2019. By applying multiple spatial models, this study seeks to investigate the connection between urban land use efficiency and regional economic cooperation networks. The findings indicate that the regional economic cooperation network has led to an increase in urban land use efficiency and contributed to the promotion of sustainable urban expansion. Our investigation has revealed two major findings. During the study period, there was a consistent upward trend and a significant rise in urban land use efficiency. The main factor contributing to this growth was the regional economic cooperation network. Furthermore, the integration of regional economies within urban agglomerations can provide network synergistic impacts on urban land use efficiency by capitalizing on network externalities. Intercity economic links can improve land use efficiency not only within individual metropolitan areas but also across cities embedded in the broader urban network. Urban regions can optimize land use by incorporating it into economic networks and leveraging network externalities. We recommend that policymakers continue to leverage regional economic integration as a strategic tool to enhance urban prosperity and promote the expansion of the urban economic network.

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