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Analyzing the Drivers of Multi-Scenario Urban Vitality in Luohe City, China: A Land Function Coupling Perspective

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TABLE OF CONTENTS

1. BACKGROUND AND AIMS

BACKGROUND

Since the mid-20th century, urbanization has reshaped human – land dynamics, driving rapid land use change and complex urban growth. In China, this process has transitioned from expansion to stabilization, now challenged by urban sprawl, land inefficiency, and demographic shifts. Urban vitality (UV), reflecting dynamic human activity and land-use efficiency, is key to sustainable planning but is often measured using static indicators. This study proposes a novel framework integrating mobility data, land-use functions, and spatial coupling models to evaluate UV. By focusing on the interplay between social and ecological land functions, it offers new insights into the mechanisms driving urban sustainability.

Goals

Core Research Question: How can land function coupling be optimized to enhance urban vitality and promote high-quality urban development?

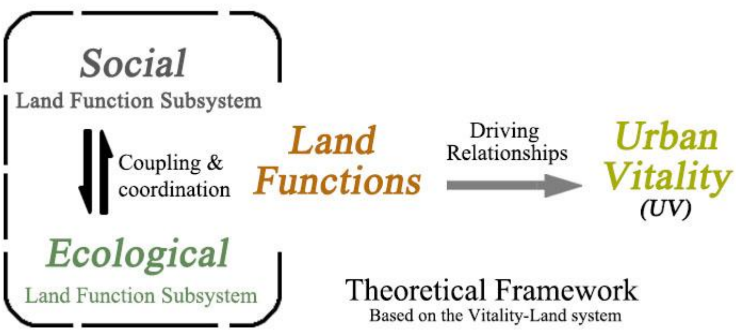

Figure 1 General Theoretical Framework.

To address this question, the study is structured around three main dimensions: Pattern, Mechanism, and Response.

1. Pattern: Understanding Urban Vitality and Land Functions

Q1: How can urban vitality be effectively measured in a multi-scenario framework?

Q2: How can land functions be comprehensively evaluated?

2. Mechanism: Exploring the Interactions Between Land and Vitality

Q3: Based on the integration of vitality and land theories, what are the factors influencing urban vitality, and what are the specific mechanisms behind this influence? This question can be further divided into:

- Q3.1: What is the impact of land coupling on UV?
- Q3.2: What is the impact of land functions on UV?
- Q3.3: What is the impact of land factors on UV?

3. Response: Developing Policy and Planning Strategies

Q4: How should land development policies be formulated to foster urban vitality? What are the corresponding planning responses?

The research provides multi-scale recommendations, ranging from citywide land-use policies to micro-scale functional adjustments, emphasizing the integration of social and ecological land uses to enhance urban resilience and sustainability while offering targeted strategies for cities facing population decline and land-use inefficiencies.

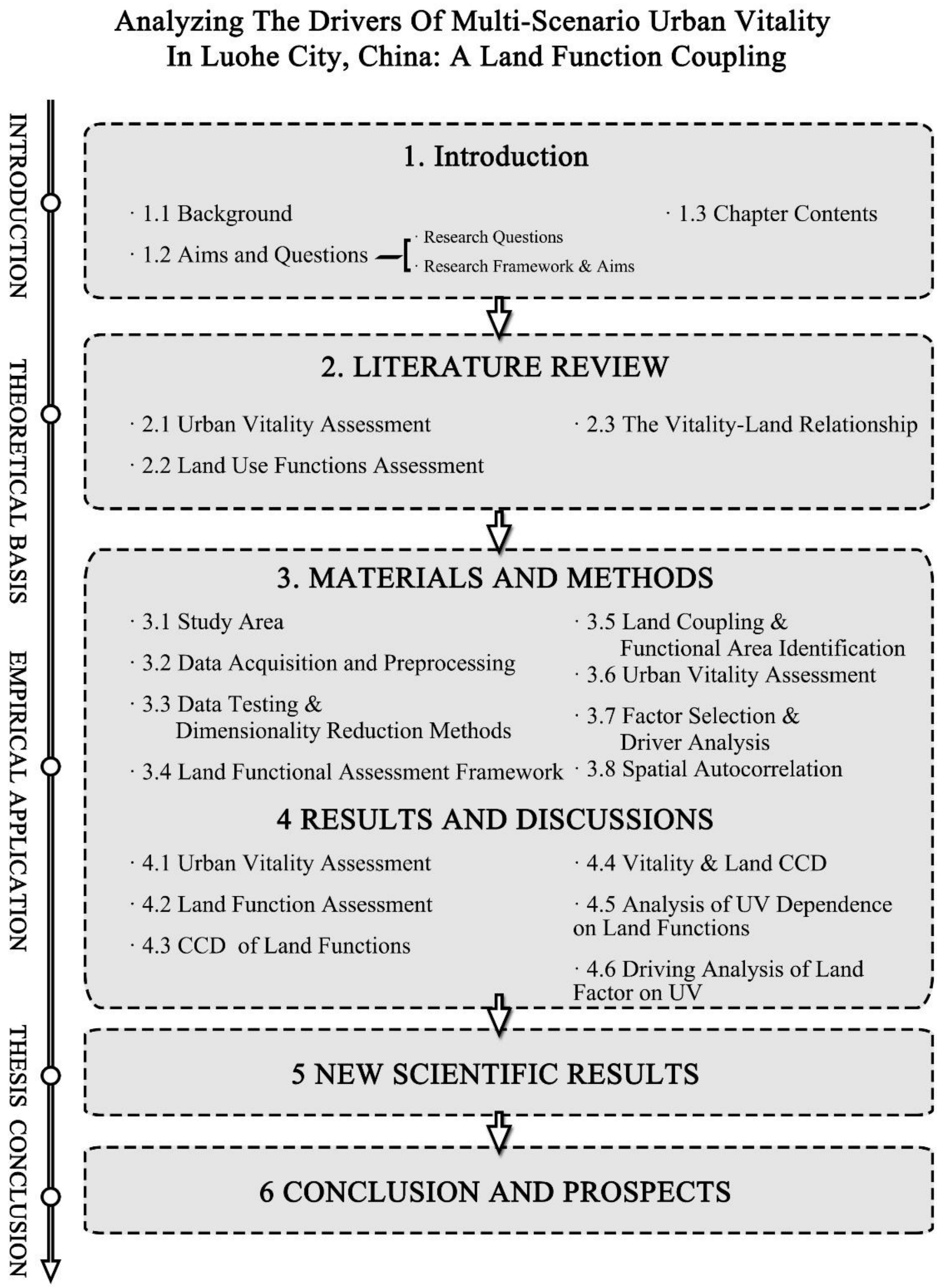

Figure 2 Contents of Individual Chapters.

2. MATERIALS AND METHODS

Study Area

Luohe City, Henan Province, exemplifies rapid urbanization, marked by artificial surface expansion, green restoration, and urban-rural imbalance. Reflecting broader Chinese trends, it serves as an ideal case to assess urban vitality (UV). Using 2023 data, this study examines UV distribution and evaluates land use strategies for enhancing urban livability and sustainable development.

Data Acquisition and Processing

The research integrates multiple datasets to assess UV and land functions.

Table 1. Data Sources and Preprocessing Methods

Data Type	Source	Usage	Processing Methods
Human Mobility Data	Baidu Heat Map	UV assessment	Self-calibration, clustering, scenario differentiation
Remote Sensing Data	MODIS, Landsat-8/9, Nighttime Light (NTL), Population and so on.	Land function Assessment	Cloud removal, normalization, index derivation
Socioeconomic Data	Urban Yearbooks, Statistical Reports		Data correction
Other Geographic Data	Road Networks, Google Maps	Accessibility and functional analysis	Spatial overlay, network analysis

Urban Vitality Assessment

UV is evaluated using a multi-scenario framework, distinguishing between workdays and weekends, as well as day-night variations. A self-organizing map (SOM) clusters activity patterns, refining the classification of UV across different urban contexts. The CRITIC method assigns weights to UV indicators, ensuring an objective representation of vitality levels.

Land Function and Coupling Assessment

Land functions are classified into social (LSF) and ecological (LEF) components using a quantity-quality-structure framework. Quantity: Proportion of land allocated to each function. Quality: Indicators include NTL, population, accessibility (LSF factors), and vegetation quality, RSEI (LEF factors). Structure: Landscape pattern indices evaluate spatial configuration. The Coupling Coordination Degree (CCD) model assesses inter-group interactions, while the Minimum Spanning Tree (MST) model analyzes intra-group functional relationships.

Statistical and Spatial Analysis

To further explore the driving factors of UV, the study integrates multiple analytical approaches. OLS Regression & Spatial Correlation Analysis: Establish baseline relationships between UV and land functions. Multi-scale Geographically Weighted Regression (MGWR): Identifies localized effects of land-use factors on UV across different spatial scales. Geographical Detector (OPGD): Uncovers nonlinear interactions and synergies between land-use variables affecting UV.

3. RESULTS AND DISCUSSION

(1) Urban vitality and land functions exhibit significant spatial spillover effects within the built-up areas.

Urban vitality (UV) in Luohe City shows strong spatial spillovers, with high UV in central zones. Although both land social function (LSF) and land ecological function (LEF) concentrate in the built-up zone, their distributions are not aligned. Moran's I confirms significant spatial autocorrelation between UV and these functions, indicating that high-vitality zones boost nearby areas while low-vitality zones depress them.

(2) LSF and LEF exhibit optimal coupling at the 3000m scale.

Coupling coordination analysis shows that LSF and LEF integrate best at about 3000 meters, closely matching their aggregation ranges (LSF: 2650m; LEF: 2950m), which reflect the scale of Luohe's urban function clusters. Urban interventions should align with natural clustering distances.

(3) Inter-group coupling of LSF-LEF contributes more to urban vitality than intra-group coupling of single functions.

The joint interaction between LSF and LEF has a stronger effect on UV than either function alone. While individual distance-based CCD show no significant correlation with the Urban Vitality Index (UVI), the combined CCD consistently correlates around 0.7. UV peaks when CCD ranges from 0.7 to 1.0, though historical declines in coupling warn of potential vitality loss.

(4) LSF has a stronger influence and priority over LEF in affecting UV.

LSF consistently has a greater impact on UV than LEF. Social functions form the foundation for UV, while ecological functions provide enhancements only when social infrastructure is robust. Urban planning should thus prioritize social systems, with ecological benefits complementing rather than replacing them.

(5) The MGWR and OPGD analysis identifies ASR and LERNCI as the main drivers of urban vitality, with weekend human activity increasing demand for GIR and VQ.

MGWR highlights that Artificial Surface Ratio (ASR) and LERNCI are key UV drivers. Increased weekend activity raises demand for Green Infrastructure Rate (GIR) and Vegetation Quality (VQ). Other factors, including RSEI, GIR, ASR, and ALSI, show variable spatial effects. Furthermore, the OPGD reveals that interactions between factors—such as LERNCI ∩ ASR and LERNCI ∩ VQ—can mitigate localized low-vitality risks.

Summary

Urban vitality in Luohe is shaped by spatial spillovers and scale-sensitive integration of socio-ecological land functions. The 3000m coupling scale underscores the need for balanced social and ecological components. These quantitative insights into spatial autocorrelation, coupling coordination, and vitality drivers provide a solid basis for sustainable urban planning and policy optimization. These results offer guidance for strategic urban development in the context of evolving socio-ecological dynamics for future planning.

4. CONCLUSION AND RECOMMENDATIONS

This study provides a comprehensive framework for understanding the relationship between UV and land functions through a multi-scale and multi-scenario perspective. The findings confirm that urban vitality is strongly influenced by the spatial interplay between social and ecological land functions, with significant spatial spillover effects. The optimal coupling of these functions occurs at a scale of approximately 3000 meters, aligning with observed urban functional clusters and living circle dimensions. The research also highlights the dominant role of LSF in shaping urban vitality, while LEF enhances vitality only when sufficient social function infrastructure is in place.

A key implication of this study is the need for strategic urban planning that fosters both growth poles and polycentric structures to enhance urban vitality. The research suggests prioritizing the establishment of localized vitality hubs in areas with strong LSF influence, ensuring their sustained growth through mixed-function land use. Additionally, coupling coordination between LSF and LEF should be optimized at different scales to avoid inefficient land allocation and mitigate the risks of functional decoupling, which could lead to declining urban vitality.

Beyond spatial patterns, the study emphasizes the role of key driving factors, such as the artificial surface ratio (ASR) and the LST and EVI regulated night-time light city index (LERNCI), in shaping UV. The MGWR analysis confirms the varying spatial influence of these factors, particularly the enhanced role of vegetation quality (VQ) and green infrastructure rate (GIR) on weekends, reflecting shifts in human activity patterns. The interactions between these factors exhibit nonlinear enhancement effects, indicating that urban vitality is not merely an outcome of individual land functions but rather a product of their complex interplay.

From a planning perspective, this study advocates for a balanced integration of social and ecological functions through function-dependent coupling strategies. Policymakers should avoid over-reliance on single-function developments and instead implement land-use configurations that maximize the synergistic benefits of mixed-use areas. Additionally, functional clustering should be adapted to specific urban contexts, ensuring that different regions within a city receive tailored interventions based on their vitality levels and dominant land functions.

Future research should further refine vitality assessment models by incorporating real-time human activity data, demographic segmentation, and machine-learning approaches to enhance predictive capabilities. Additionally, integrating multi-source data—such as point-of-interest (POI) distributions, mobility traces, and urban environmental metrics—will improve the understanding of how land-use policies shape long-term vitality trends. By addressing these research gaps, urban planning can move towards more sustainable, adaptable, and vitality-enhancing frameworks, ensuring resilient and livable urban environments.

5. NEW SCIENTIFIC RESULTS

Thesis 1: A self-calibrating urban vitality (UV) assessment method and a multi-source data-based land function evaluation framework are proposed.

Current Situation: Many studies rely on static indicators or single data sources, failing to capture the dynamic spatiotemporal fluctuations in urban human activities. Existing UV assessments overlook variations between workdays and weekends, while conventional land function evaluations —predominantly one-dimensional— do not fully reflect the multifunctional and interrelated nature of urban land.

Innovation: This study integrates high-temporal-resolution human mobility data from Baidu LBS with the SOM algorithm to self-calibrate UV assessments, effectively distinguishing workday and weekend activity patterns. Simultaneously, this study leverages multi-source satellite data (Landsat, MODIS, and VIIRS) to develop a comprehensive evaluation framework for land functions, spanning quantitative, qualitative, and structural dimensions. Moreover, a novel method is introduced to capture spatial heterogeneity and the intricate interactions among land functions. Collectively, these innovations overcome the limitations of static, one-dimensional approaches and provide a robust, data-driven framework that simultaneously advances urban vitality assessment and land function evaluation for sustainable urban planning.

Related Results: Result (1) shows significant spatial spillover and distinct workday/weekend UV patterns. High-temporal Baidu LBS and multi-source satellite data capture dynamic urban activity and land functions, validating our integrated assessment framework.

Thesis 2: Revealing the multi-scale dependence between urban vitality and land social/ecological functions.

Current Situation: Although studies increasingly recognize the role of land social functions (LSF) in enhancing UV, the role of ecological functions (LEF) is often overlooked. Furthermore, many studies focus on single-scale analyses, which miss the variability and stability of these relationships across spatial scales.

Innovation: This study evaluates the robustness of the relationship between LSF/LEF and UV across multiple spatial scales, uncovering a multi-scale dependence. The findings highlight that LSF is a stronger driver of UV across scales, and the research quantifies UV's dependence on both LSF and LEF across these scales.

Related Results: Result (2) reveals optimal LSF/LEF coupling at 3000 m and scale-dependent UV sensitivity. LSF exerts stronger influence than LEF, confirming multi-scale dependence of land functions on urban vitality.

Thesis 3: Quantifying the correlation between urban vitality and land function CCD.

Current Situation: Although early studies (e.g., Jacobs) recognized a link between mixed land functions and urban vitality, quantitative research on their coordinated integration remains limited. Most studies focus on physical mixing, overlooking the significance of balanced integration in enhancing urban vitality.

Innovation: This study extends traditional mixing approaches (e.g., land use and POI integration) by employing OLS regression, which confirms a positive correlation between conventional functional mixing and urban vitality (coefficient = 0.458, R^2 = 0.715). Crucially, to quantify the intricate relationship between CCD and urban vitality, both the traditional CCD model and an enhanced d-CCD model—integrating Gaussian decay functions and Minimum Spanning Tree networks—are utilized. The findings reveal a nonlinear, threshold-driven relationship, demonstrating that balanced functional integration significantly amplifies urban vitality and providing specific thresholds to inform high-efficiency urban development strategies.

Related Results: Result (3) finds CCD peaks at 3000 m with a stable correlation (~0.7) and nonlinear threshold effects, confirming the importance of balanced functional integration for UV.

Thesis 4: Analyzing the driving effects and bandwidths of land function factors on urban vitality in different scenarios in Luohe.

Current Situation: Traditional studies often overlook the variation in urban vitality across different temporal scenarios and the specific roles and influence ranges of various land function factors within these scenarios.

Innovation: This study employs the MGWR model to analyze the driving effects and bandwidths of land function factors on UV under different scenarios in Luohe. The research highlights how land factors exert significant driving forces on UV across different temporal contexts, such as workdays and weekends. Moreover, the study reveals variations in the bandwidths of each factor's influence on UV across different scenarios, demonstrating the diversity of land function factor impacts. This multi-scenario analysis offers insights into the varied influence of land function factors.

Related Results: Results (4 & 5) show that LSF has a consistently stronger influence on UV, while MGWR analysis detects key drivers (e.g., ASR, LERNCI) with variable influence ranges across scenarios.

Thesis 5: Uncovering the nonlinear enhancement effects among land function factors.

Current Situation: Most current research focuses on the single linear effects of factors on UV. However, urban vitality is the ultimate geographic outcome of a city as a complex system. The complex interactions among factors in geographic processes and the potential compound effects they generate should not be overlooked.

Innovation: Through OPGD analysis, this study uncovers the complex interactions among land function factors and their bilinear/nonlinear enhancement effects when combined. For example, the combinations of LERNCI (+) and ASR (+), as well as LERNCI (+) and VQ (-), demonstrate significant nonlinear enhancement effects in specific scenarios. These findings suggest that urban planning and land use optimization should fully consider the interactions between factors to achieve more effective improvements in urban vitality. Furthermore, the continuous intensification of single factors may suppress vitality. As a complex system, enhancing urban vitality should begin with the coupling of social and ecological functions at both the factor and functional levels, taking into account the coordinated development of multiple factors. This study offers a new scientific perspective for understanding the interactions between land function factors and their overall impact on urban vitality.

Related Results: Result (5) shows significant nonlinear enhancement among land function factors. OPGD confirms that combinations (e.g., LERNCI∩ASR, LERNCI∩VQ) amplify UV, emphasizing coordinated integration.

6. LIST OF PUBLICATIONS

6.1 Journal Publication (First Author, or Co-first Author)

[1] **Wang, X**., Bai, T., Yang, Y., Wang, G., Tian, G., & Kollányi, L. (2024). A Multi-Scenario Analysis of Urban Vitality Driven by Socio-Ecological Land Functions in Luohe, China. Land, 13(8), 1330.

[2] **Wang, X**., Yao, X., Shao, H., Bai, T., Xu, Y., Tian, G., ... & Kollányi, L. (2023). Land Use Quality Assessment and Exploration of the Driving Forces Based on Location: A Case Study in Luohe City, China. Land, 12(1), 257.

[3] **Wang, X**., Wu, Y., ... & Bai, T. (2025). Spatio-Temporal Dynamics of Water Quality and Land Use in the Lake Dianchi (China) System: A Multi-Source Data-driven Approach. Journal of Hydrology: Regional Studies, Accept.

[4] **Wang, X**., Shi, Z., Kollányi, L., Yang, Y., Liu, M., & Zhang, X. (2023). Exploration of Urban Subsystem Coupling Coordination Based on Resilience in Luohe City. 4D Journal of Landscape Architecture and Garden Art, 22–29.

[5] Wu, Y., **Wang, X**., Kollányi, L., Zhang, J., & Bai, T. (2024). Analyzing and Forecasting Water–Land Dynamics for Sustainable Urban Developments: A Multi-Source Case Study of Lake Dianchi’s Environmental Challenges (China). Ecological Indicators, 166, 112335.

[6] Bai, T., **Wang, X**., Cushman, S. A., Yang, J., Wang, G., László, K., ... & Wu, Y. (2023). A Neglected Phenomenon: The Spatiotemporal Evolution of Rivers in the City of Luohe, China. Ecological Indicators, 158, 111323.

6.2 Journal Publication (Other Author)

[7] Shi, Z., **Wang, X**., Liu, M., Zhang, X., & Kovács, K. F. (2024). Identification and Landscape Pattern Analysis of Peri-Urban Areas: A Case Study of Budapest, Hungary. Journal of Environmental Geography, 17(1–4), 112–118.

[8] Tao, Y., Wang, Y., **Wang, X**., Tian, G., & Zhang, S. (2022). Measuring the Correlation Between Human Activity Density and Streetscape Perceptions: An Analysis Based on Baidu Street View Images in Zhengzhou, China. Land, 11(3), 400.

[9] Shi, Z., Liu, M., **Wang, X**., & Kovács, K. F. (2024). Morphological Spatial Pattern of Peri-Urban Green Infrastructure: A Case Study of Zhengzhou City, China. 4D Journal of Landscape Architecture and Garden Art, 74, 64–71.

[10] Li, D., Yang, J., Hu, T., Wang, G., Cushman, S. A., **Wang, X**., ... & Bai, T. (2023). The Seeds of Ecological Recovery in Urbanization – Spatiotemporal Evolution of Ecological Resiliency of Dianchi Lake Basin, China. Ecological Indicators, 153, 110431.

[11] Liu, M., Kollányi, L., **Wang, X**., & Shi, Z. (2023). Habitat Quality Assessment Based on InVEST Model: Zhengzhou, China. 4D Tájépítészeti és Kertművészeti Folyóirat, 44–55.

[12] Yang, Y., He, R., Tian, G., Shi, Z., **Wang, X**., & Fekete, A. (2022). Equity Study on Urban Park Accessibility Based on Improved 2SFCA Method in Zhengzhou, China. Land, 11(11), 2045.

[13] Huang, J., Song, P., Liu, X., Li, A., **Wang, X**., Liu, B., & Feng, Y. (2024). Carbon Sequestration and Landscape Influences in Urban Greenspace Coverage Variability: A High-Resolution Remote Sensing Study in Luohe, China. Forests, 15(11), 1849.

6.3 Conference Publication

[14] **Wang, X**., Kollányi, L., Shi, Z., Liu, M., & Yang, Y. (2022). Study on Land Use Aggregation Pattern of Luohe City Based on Spatial Heterogeneity. In Proceedings of the Fábos Conference on Landscape and Greenway Planning (Budapest, Hungary).

[15] Shi, Z., Kovács, K. F., Liu, M., & **Wang, X**. (2022). Evaluation of Ecological Supply-Demand Synergy of Park Green Space in the Main Urban Region of Zhengzhou City. In Proceedings of the Fábos Conference on Landscape and Greenway Planning (Vol. 7, No. 1). University of Massachusetts Amherst Libraries.

[16] Kollányi, L., Weiperth, A., Tar, G., Staszny, Á., Csőszi, M., Török, K., Liu, M., **Wang, X**., & Kovács, K. F. (2022). Modelling Structural Connectivity to Identify Areas of Conflicts Between Ecological and Transportation Networks in Hungary. In IENE 2022 International Conference: "Connecting People, Connecting Landscapes" (September 19–23). Abstract Book.