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Heterogeneous Impacts of Intercity Railway on Land Use—A Case Study of Changzhutan

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Abstract: *This study aims to characterize the temporal evolution of land use/cover change (LUCC) around the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway, providing insights for the rational phasing of land resource development and the promotion of sustainable development in these areas. The research employs buffer analysis, intensity analysis, and geographical detector methods. The findings indicate that: (1) From 2010 to 2015, LUCC around the intercity railway stations was primarily characterized by the expansion of construction land and the decline of agricultural land; (2) The scale and intensity of LUCC around the stations were lower during the construction phase compared to the initial operational phase; (3) During the construction phase, LUCC was mainly influenced by the responsiveness of local policies, whereas in the initial operational phase, it was largely driven by local market conditions and supporting infrastructure. The study concludes that government investment and market dynamics in the areas surrounding intercity railway stations are the key factors driving LUCC and its temporal heterogeneity. To achieve sustainable development, it is essential to coordinate the roles of government and market forces in land resource development around high-speed railway stations across different phases.*

Keywords: *Intercity Railway Stations, Land Use/Cover Change, Intensity Analysis, Changsha-Zhuzhou-Xiangtan Intercity Railway*

1. Introduction

Intercity railways play a significant role in advancing regional integration and stimulating socio-economic development along their corridors. However, they also generate increased demand for land and drive land use/cover change (LUCC), particularly in the vicinity of station areas. At the initial stage of station construction, market actors often adopt a wait-and-see approach, showing limited responsiveness to policy incentives. Subsequently, the operation of intercity railway stations enhances the flow of factors, improves supporting infrastructure and accessibility, thereby raising the potential development value of surrounding land. This, in turn, attracts market entities to engage in residential, commercial, or industrial development. Against the backdrop of China's push for interconnected infrastructure and the growing phase of regional railway construction, an in-depth investigation into the temporal heterogeneity of LUCC around the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway is of great significance. It can inform the optimal sequencing of land resource utilization, guide the timing of ecological development and conservation, and help coordinate station-area development with the sustainable use of surrounding land.

Academic research has provided substantial insights into the influence of transportation stations on land use. For instance, He Donghua et al. [1] analyzed the spatial characteristics of land use along planned urban rail loop lines; Liu Shiqi et al. [2] examined land use features around typical stations after their completion; and Xiong Changsheng et al. [3] studied land use changes surrounding stations of the Hainan Island Ring High-Speed Railway. While these studies offer valuable perspectives, they primarily focus on land use analysis around high-speed rail stations or examine land use structure at a single point in time. Consequently, they do not fully capture the entire process from railway construction to operation, making it difficult to reveal the temporal heterogeneity in how intercity railways influence urban land use change. The development of an intercity railway—from inception to operation—represents a dynamic process during which both transportation infrastructure and land use undergo significant transformation. Investigating the land use characteristics around stations at different phases of intercity railway development and identifying patterns of heterogeneity can help

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clarify the spatiotemporal effects of railways on land use. Such understanding would enable more accurate predictions of land use impacts from new rail transit lines and provide quantitative support for adjusting and optimizing planning strategies.

In summary, this paper conducts a case study focused on the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway, aiming to uncover the temporal heterogeneity of Land Use/Cover Change (LUCC) around these stations. The primary rationale for selecting this case lies in the strategic role of the Changsha-Zhuzhou-Xiangtan Intercity Railway as a rapid transit artery connecting the cities of Changsha, Zhuzhou, and Xiangtan in Hunan Province, which plays a significant part in promoting the integrated development of the Changsha-Zhuzhou-Xiangtan urban agglomeration. Specifically, this paper analyzes the driving mechanisms behind LUCC around intercity railway stations, conducts spatiotemporal dynamic monitoring of LUCC around the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway, and employs an intensity analysis model to reveal variations in LUCC around high-speed rail stations across different periods. Furthermore, it aims to identify the underlying key driving factors, thereby providing a decision-making reference for the timing of land resource development and sustainable utilization around intercity railway stations.

2. Analysis of Driving Mechanisms for Land Use/Cover Change (LUCC) around Intercity Railway Stations

The driving mechanism of Land Use/Cover Change (LUCC) around the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway can be summarized as follows: improved transportation accessibility triggers interactions among multiple factors, which, combined with regional development characteristics, leads to the restructuring of land use patterns. Furthermore, this mechanism exhibits significant heterogeneity depending on the station type—whether located in urban core, suburban, or industry-oriented areas (Figure 1).

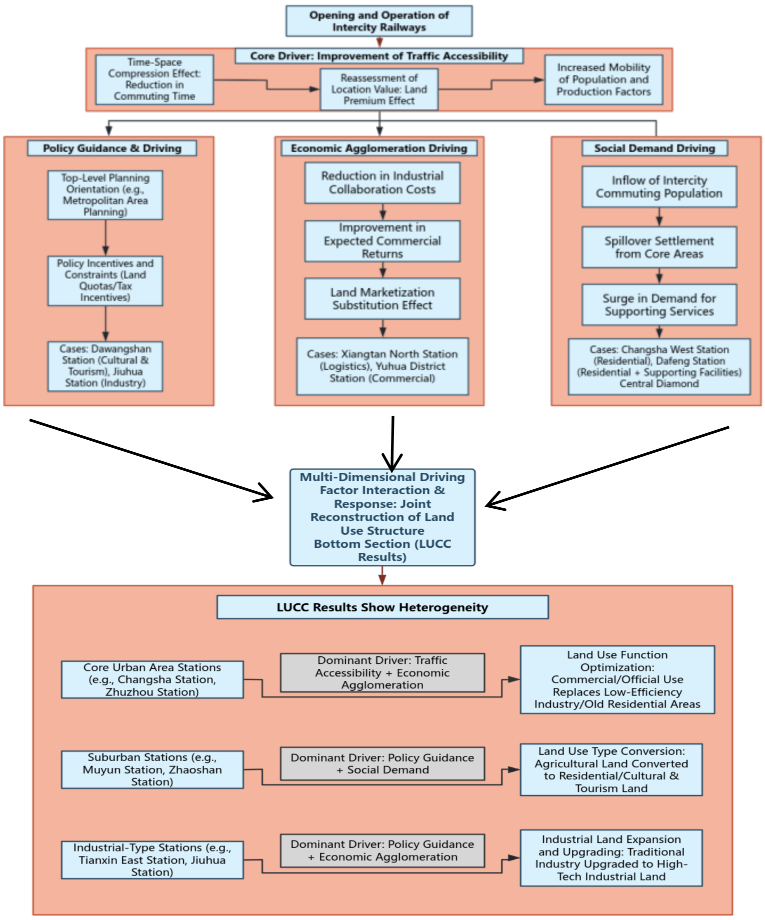

Figure 1: Analysis of Driving Mechanisms of LUCC around Intercity Railway Stations.

First, intercity railways achieve a "space-time compression" effect, directly enhancing the accessibility value of land around the stations. This drives the conversion of land from low-value to high-value uses. For example, at Changsha Muyun Station, previously dominated by agricultural land and small-scale storage facilities, the commuting advantage of "30 minutes direct to Changsha's Wuyi Square" has led to a gradual shift toward residential and community commercial uses over the past five years. The proportion of residential land increased from 12% in 2016 to 35% in 2024.

Second, national and regional planning policies explicitly define the functional orientation of land around stations, directly guiding the conversion or optimization of land use through administrative regulations or policy incentives. In line with the Changsha-Zhuzhou-Xiangtan Metropolitan Area Development Plan, Changsha Dawangshan Station has leveraged cultural tourism policies centered on the "Xiangjiang Happy City" to transform former low-efficiency industrial land into tourism-supporting land uses. At Xiangtan Jiuhua Station, guided by high-tech industry support policies, agricultural and traditional industrial land has been consolidated to make way for new industrial land for electronics and smart manufacturing, forming an industry park adjacent to the station.

Third, intercity railways effectively reduce industrial collaboration costs, attracting related enterprises to cluster around stations and promoting the expansion of industrial and storage land. Simultaneously, the concentration of passenger flows raises expectations for commercial returns, driving the optimization of commercial land. In the process of land marketization, the trend of "high-value land uses replacing low-value ones" becomes more pronounced. For instance, around Xiangtan North Station, improved logistics efficiency due to the intercity railway has attracted enterprises such as JD.com's Asia No. 1 Warehouse and SF Express's regional distribution center. The proportion of storage/logistics land increased from 8% in 2017 to 22% in 2024, replacing some idle cultivated land. At Changsha Yuhua District Station, the combined passenger flows from intercity rail and commercial districts led to the redevelopment of an old garment wholesale market into a commercial complex, with the floor area ratio of commercial land rising from 2.0 to 4.5, optimizing land use efficiency.

Fourth, intercity railways attract cross-city commuters and suburban settlers to cluster around stations, directly generating demand for residential land and driving the provision of supporting educational, medical, and daily-life facilities. For example, in the integrated demonstration zone where Changsha West Station is located—connecting Changsha, Yiyang, and Changde—about 50,000 cross-city commuters have settled in the past three years. The area of residential land expanded from 1.2 km^2 in 2020 to 2.8 km^2 in 2024, accompanied by newly allocated land for two primary schools and one community hospital. At Zhuzhou Dafeng Station, the combination of affordable housing and convenient intercity commuting has attracted first-home buyers from Changsha and Zhuzhou, transforming former vegetable plots and forestland into high-rise residential buildings and related daily-life supporting facilities.

Finally, these four driving factors do not operate in isolation but interact and respond jointly, restructuring land use patterns and functions and resulting in distinct land evolution pathways that vary by station type.

Overall, the weighting of driving mechanisms for land use/cover change (LUCC) varies significantly across different types of stations along the Changsha-Zhuzhou-Xiangtan Intercity Railway. For core urban stations, the primary drivers are "transport accessibility + economic agglomeration", with the core focus being "land use function optimization". For suburban stations, the dominant drivers are "policy guidance + social demand", centered on "land use type conversion". For industry-oriented stations, the key drivers are "policy guidance + economic agglomeration", with the main objective being "industrial land expansion".

3. Data and Methods

3.1. Overview of the Changsha-Zhuzhou-Xiangtan Intercity Railway

The Changsha-Zhuzhou-Xiangtan Intercity Railway (hereinafter referred to as the CZT Intercity Railway) is a core and backbone project within the intercity rail network of the "Middle Yangtze River Urban Agglomeration," as outlined in China's Medium and Long-Term Railway Network Plan. It serves as a backbone rapid transit link connecting the three cities of Changsha, Zhuzhou, and Xiangtan—collectively known as the Changsha-Zhuzhou-Xiangtan Urban Agglomeration, which is designated as a national comprehensive reform pilot zone for building a resource-conserving and environment-friendly society. The railway primarily fulfills the short-distance passenger transport

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functions of commuting, business travel, and tourism among these three cities. It plays a fundamental and strategic role in advancing the integrated development of the Changsha-Zhuzhou-Xiangtan Urban Agglomeration.

The main line of the Changsha-Zhuzhou-Xiangtan Intercity Railway spans approximately 104.3 kilometers. As of 2020, it comprises 24 stations. Apart from major hubs such as Changsha West Station and Zhuzhou South Station, most stations are strategically located within the urban cores and key suburban districts of the three cities. Examples include Lugu Station and Xiangzhang Road Station in Changsha; Dafeng Station and Hetang Station in Zhuzhou; as well as Bantang Station and Zhaoshan Station in Xiangtan. The network features a primary Y-shaped structure that connects the main urban areas of Changsha, Zhuzhou, and Xiangtan. Branch lines extend into key industrial parks and densely populated districts, collectively forming a spatial layout characterized by radiating connectivity from core areas and functional linkages across multiple nodes (Figure 2).

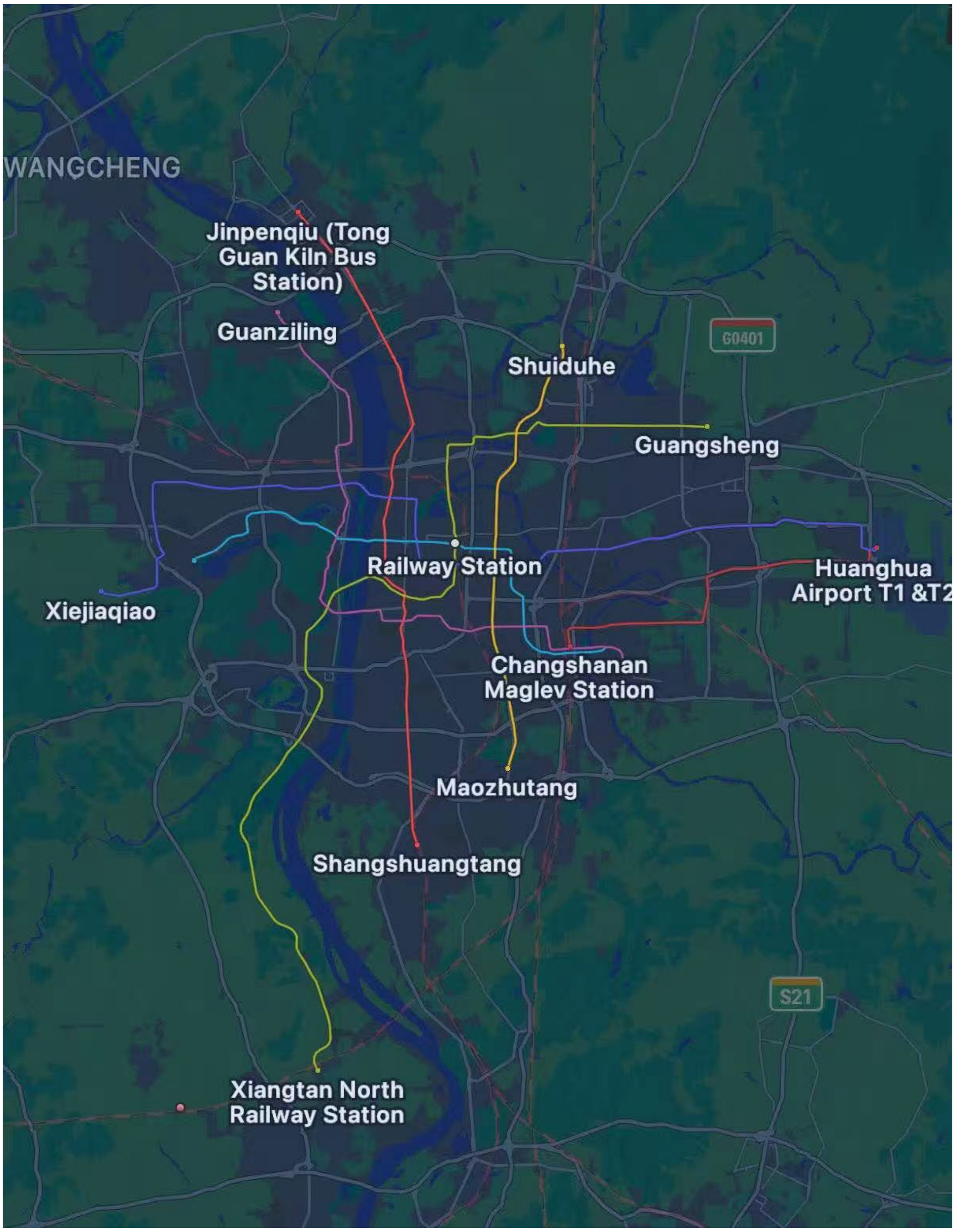

Figure 2: Location Map of Changzhutan Intercity Railway.

From the perspective of construction and operation phasing, the development of the CZT Intercity Railway progressed in distinct stages. Construction commenced in September 2010. Initial operation began in December 2016 with the opening of the sections between Changsha and Zhuzhou South, and between Changsha and Xiangtan. Full network integration was achieved in December 2017 following the inauguration of the branch line connecting Changsha West Station and Changsha Station. By 2020, the line's transport efficiency was further enhanced through optimized transfers and connectivity with major comprehensive transport hubs, including Changsha West High-Speed Railway Station and Changsha Railway Station.

Acknowledging the time-lag effect in the influence of intercity railways on surrounding land use/cover change (LUCC) [10], and aligning with the project's key milestones, the research period is segmented into two phases: the Construction Phase (2010–2016) and the Initial Operational Phase (2016–2020). The years 2010, 2016, and 2020 are selected as key temporal benchmarks. This phased approach facilitates a clearer identification of the differential impacts of the railway on LUCC across its development stages.

Regarding the delineation of the research scope, with reference to the typical impact radius of high-speed rail stations on surrounding LUCC [3, 31] and considering the characteristics of the Changsha-Zhuzhou-Xiangtan Intercity Railway—primarily serving short-distance commuting with relatively short average station spacing (approximately 4.3 km)—a 2-kilometer buffer zone was generated outward from the boundary of each station as the study area. This range is selected to adequately cover the land development zones directly influenced by improved transportation accessibility around the stations, while minimizing potential analytical interference caused by overlapping buffer zones of adjacent stations, thereby ensuring the precision of the study.

As the core component of the "half-hour commuting circle" within the Changsha-Zhuzhou-Xiangtan urban agglomeration, the opening of the CZT Intercity Railway has significantly reduced the spatial-temporal separation between the three cities (the fastest commuting times from Changsha to the main urban areas of Zhuzhou and Xiangtan have been shortened to 30 and 25 minutes, respectively). This has not only facilitated the cross-regional flow of key factors such as population, industry, and capital but has also stimulated demand for the development of construction land—including residential, commercial, and logistics uses—around its stations. Consequently, it provides a representative case for examining the temporal characteristics and driving mechanisms of LUCC surrounding intercity railway stations.

3.2. Full-text Data Foundation

The study's Data Foundation comprises two main components:

Land Use/Cover Data: Primarily sourced from the China Annual Land Cover Dataset (CLCD) [1].

Multi-source Spatial Data, including:

· Station Operation & Statistics: Data on train frequency, station area size, and related metrics for each intercity railway station.

· Geospatial Data for Changsha: Landsat imagery (30m resolution)[4], Digital Elevation Model (DEM), and road network data.

· Regional Socio-economic Statistics: County/city-level statistical data for the years 2010, 2015, and 2020, corresponding to the locations of the stations.

· Point of Interest (POI) Data: Georeferenced data for features such as tourist attractions and administrative centers within the station areas.

The above datasets were primarily obtained from platforms including Professor Huang Xin's research team at Wuhan University, the National Geomatics Center of China, OpenStreetMap, Baidu Maps, and the Hunan Provincial Bureau of Statistics.

The data underwent necessary preprocessing procedures. Initially, relevant imagery was processed through steps including projection transformation, geometric correction, and data fusion, and was then projected into a unified spatial coordinate system. Subsequently, the Random Forest algorithm was employed to extract feature information from the corresponding annual Landsat images, followed by corrections to the land use/cover data surrounding each station. The corrected land use/cover data for the study area achieved an overall accuracy exceeding 85%, which is generally considered reliable and

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meets the precision requirements of this study.

3.3. Intensity Analysis

To gain a deeper understanding of the temporal characteristics of land use/cover change (LUCC) around high-speed railway stations[5], this study focuses on two key time intervals: 2010–2015 and 2015–2020. An intensity analysis model[6] is applied at the interval level to examine the average annual intensity of LUCC around each station during these specific periods, as well as over the entire study duration. This approach allows for an assessment of whether the observed changes occurred at a relatively slow or rapid pace. For instance:

$$S_t = \frac{\sum_{j=1}^{J}(\sum_{i=1}^{J} c_{tij} - c_{tii}) / \sum_{j=1}^{J}\sum_{i=1}^{J} c_{tij}}{Y_{t+1} - Y_t} \times 100\% \tag{1}$$

$$U = \frac{\sum_{t=1}^{T-1}\sum_{j=1}^{J}(\sum_{i=1}^{J} c_{tij} - c_{tii}) / \sum_{j=1}^{J}\sum_{i=1}^{J} c_{tij}}{Y_T - Y_1} \times 100\% \tag{2}$$

In Equations (1) and (2):

· St represents the average intensity of change over the study interval[Yt，Yt+1].

· U denotes the average intensity of change across the entire study period, which serves as the uniform line value for the intensity analysis.

· J indicates the number of land use/cover categories.

· i refers to a specific land category at the initial time point of the interval.

· j refers to a specific land category at the final time point of the interval.

· T represents the total number of time points.

· Yt is the calendar year corresponding to time point t.

· Ctij is the quantity of elements that transitioned from land category i to land category j during the interval[Yt，Yt+1], i.e., the gain in category j.

· Ctii is the quantity of elements that remained unchanged in land category i throughout the interval[Yt，Yt+1].

4. Results and Analysis

4.1. Analysis of LUCC around the Intercity Railway

From 2010 to 2020, land use/cover change (LUCC) in the areas surrounding the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway was highly pronounced (Table 1). The dominant pattern was characterized by a substantial expansion of construction land (impervious surface) alongside a significant loss of cultivated land, with other land cover categories exhibiting complex and dynamic rebalancing. These trends are intrinsically linked to the region's role as the core growth pole of the Changsha-Zhuzhou-Xiangtan urban agglomeration, subject to the dual drivers of major transportation infrastructure development and rapid urbanization[7].

Notably, the intensity of LUCC varied significantly both across different stations and between temporal phases. For instance, at Muyun Station—a key interchange hub—the LUCC intensity during the 2015–2020 period was approximately three times higher than during 2010–2015. In contrast, Changsha Station, having reached a stage of early development saturation, exhibited a stabilized and much lower change intensity in the later period.

The Construction and Initial Operational Phase (2010–2015)

This phase, covering the railway's construction and early operations, witnessed LUCC of unprecedented intensity and scale around the stations.

· Rapid Expansion of Construction Land: Impervious surface area increased dramatically by 71.96 km², marking it as the category with the most vigorous change. This surge was primarily driven by targeted public infrastructure investment and strategic planning interventions by local governments. By developing integrated transport hubs, road networks, and municipal utilities, authorities created

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favorable preconditions for development. Simultaneously, the planning of new urban districts attracted market actors to undertake large-scale real estate, commercial, and industrial projects, leading to the rapid outward spread of construction land.

· Significant Loss of Cultivated Land: Serving as the primary source for new construction, cultivated land area decreased by 59.72 km². This indicates that early-stage development was concentrated on the conversion of farmland at the urban-rural fringe, representing a rapid structural shift from agricultural to urban land uses.

· Pressure on Ecological Land: Forest area decreased by 11.14 km², and water bodies shrank by 1.03 km². These losses resulted partly from direct conversion to construction land and potentially from agricultural reclamation activities aimed at compensating for the loss of primary cultivated land, reflecting the complex pressures on the ecological matrix during this transformative phase.

The Mature Operational Phase (2015–2020)

In this later phase, the overall intensity of LUCC around stations noticeably weakened, and the structure of change exhibited new characteristics.

· Slowed Expansion of Construction Land: Although impervious surface area continued to grow, the increase of 41.75 km² represented a slowdown of approximately 42% compared to the previous period. This suggests that the peak phase of large-scale infrastructure and greenfield development had passed, transitioning into a more normalized and refined stage of land development[8].

· Sharply Reduced Loss of Cultivated Land: The decrease in cultivated land area narrowed significantly to 4.73 km², a reduction of over 92%. This trend can be attributed to both the dwindling stock of readily convertible, high-quality farmland and the likely strengthening effect of cultivated land protection policies.

· Signs of Ecological Land Recovery: A notable positive change was the net increase in forest area by 7.63 km². This recovery may stem from ecological restoration projects, policies promoting the return of farmland to forest, or the natural regeneration of vegetation as intensive development activities eased. However, water bodies continued to decline by 1.68 km², indicating ongoing pressures on aquatic ecosystems. The primary driving forces during this stage gradually shifted towards market-driven mechanisms. While improved accessibility and agglomeration effects from station operations continued to attract investment, development became more contingent on actual regional market demand, leading to altered patterns and reduced intensity compared to the earlier government-led construction phase.

Synthesis: A Trajectory of Temporal Heterogeneity

In summary, LUCC around the Changsha-Zhuzhou-Xiangtan Intercity Railway stations from 2010 to 2020 displayed clear temporal heterogeneity[9]. During the construction and initial operational phase (2010–2015), under the dominance of government-led investment, LUCC intensity was high, manifested as the rapid expansion of construction land and the swift loss of cultivated and forest land. In the mature operational phase (2015–2020), guided by market-driven forces and augmented by environmental policy interventions, LUCC intensity diminished significantly. The expansion of construction land decelerated, the loss of cultivated land was effectively curbed, and active recovery of forest ecosystems emerged. This evolutionary trajectory profoundly reveals the differential impact of major transportation infrastructure on surrounding land resource utilization across distinct stages, from initial "construction-driven" transformation to subsequent "service-oriented" optimization (see Table 1).

Table1: Status of Land-Use and Land-Cover Change around Changzhutan Intercity Railway Stations During 2010–2020(km2)

land type	Status of Land-Use and Land-Cover Change Around Changzhutan Intercity Railway Stations	
	2010—2015	2015—2020
Agriculture	-59.71706042	-4.72508551
Forests	-11.14184592	7.628202264
Grass	-0.055610797	-0.4760105
Water	-1.032883131	-1.683156304
Barren lands	-0.011700003	0.028776595
Impervious land	71.95910027	41.75299346

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4.2. Temporal Heterogeneity in LUCC Intensity around Intercity Railway Stations

Based on the intensity analysis results, the average intensity of Land Use/Cover Change (LUCC) around the 24 stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway was significantly higher during the construction phase compared to the initial operational phase (Figure 3). This clearly indicates that the railway stations induced more intense LUCC in their vicinities before full operations commenced than after. This pattern can be attributed to the combined influence of several factors: the progressive realization of transportation functionality, the rhythm of market and policy responses, and the pace of supporting infrastructure development. Specifically, a key objective of constructing the railway network was to support the expansion needs of the provincial capital. During the construction phase, government-led, large-scale development in core areas around major infrastructure nodes drove drastic changes. This development aimed to leverage improved transportation to stimulate population mobility, promote urban and tourism industries, and meet the daily commuting demands within the metropolitan area. In contrast, despite active market forces during the initial operational phase, the magnitude of change moderated due to diminishing available land reserves and increased policy constraints.

Notably, the change was particularly pronounced at interchange hub stations such as Muyun Station (C17) and Xiangtan Station (C18). At Muyun Station, a key transfer hub connecting the three cities, the LUCC intensity during 2015–2020 was approximately three times that of 2010–2015. This is visually represented by the substantially taller green bar compared to the orange bar in Figure 3, directly illustrating the powerful agglomeration effect of a major transport node on industry and population. In stark contrast, Changsha Station (C5), which experienced substantial early development, showed the opposite trend: higher intensity in 2010–2015, followed by a stabilization in 2015–2020. This reflects growth stagnation as development in the core urban area approached saturation.

Furthermore, some stations exhibited a temporal reversal in the direction of change. Taking Xiangtan Station (C18) as an example, the negative value of the orange bar for 2010–2015 indicates a net decrease in construction land during that period, possibly due to urban renewal or industrial relocation. The shift to a positive green bar in 2015–2020 signifies the recommencement of development around the station following the railway's opening, with an increase in new residential or commercial facilities. This directional shift is directly linked to the activating effect of improved transportation on the land market. As commuting efficiency increased, previously declining areas regained attractiveness due to enhanced accessibility, leading to positive land use conversions.

From a spatial differentiation perspective, high-intensity change during 2010–2015 was primarily concentrated in central Changsha (e.g., C5). By 2015–2020, it had diffused to inter-city transfer stations (e.g., C17) and peripheral stations in Xiangtan and Zhuzhou (e.g., C22). This shift follows the pattern of "transport network extension driving peripheral development." Changsha, leveraging its provincial capital advantage, completed core-area development early, leading to natural growth deceleration later. Transfer stations like Muyun, connecting all three cities, emerged as new growth poles, effectively attracting industrial and population agglomeration. Suburban stations in Xiangtan and Zhuzhou began to accelerate development by accommodating demand spillovered from Changsha. This spatial diffusion not only narrowed the development gap among the three cities but also effectively promoted regional integration.

In conclusion, the land expansion patterns around the 24 stations varied significantly. LUCC intensity was jointly influenced by terrain and policy. Integrating land use data with analyzes of associated transportation and ecological factors, three typical models are summarized:

(1) Concentric Expansion (2010-2016): Stations like Changsha Station and Xinjiang Road Station, driven by government leadership and mechanisms like "bulk land banking and phased leasing," exhibited a concentric expansion pattern, with high initial growth rates that stabilized later.

(2) Axial Infill (2014-2018): Stations such as Mun Station and Deafening Station, leveraging the construction of nearby arterial roads and driven by both government and market forces, developed through axial infill along transportation corridors. Their growth rates in the initial operational phase exceeded those during the construction phase.

(3) Cluster Development (2016-2020): Stations like Xiangtan North Station and Zhaoshan Station, constrained by ecological conservation policies, adopted a government-guided, market-driven cluster development model, balancing growth with ecological preservation.

Evidently, the spatial expansion of stations is co-determined by policy, terrain, and market forces.

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The synergy among these three factors explains the developmental disparities observed across different stations.

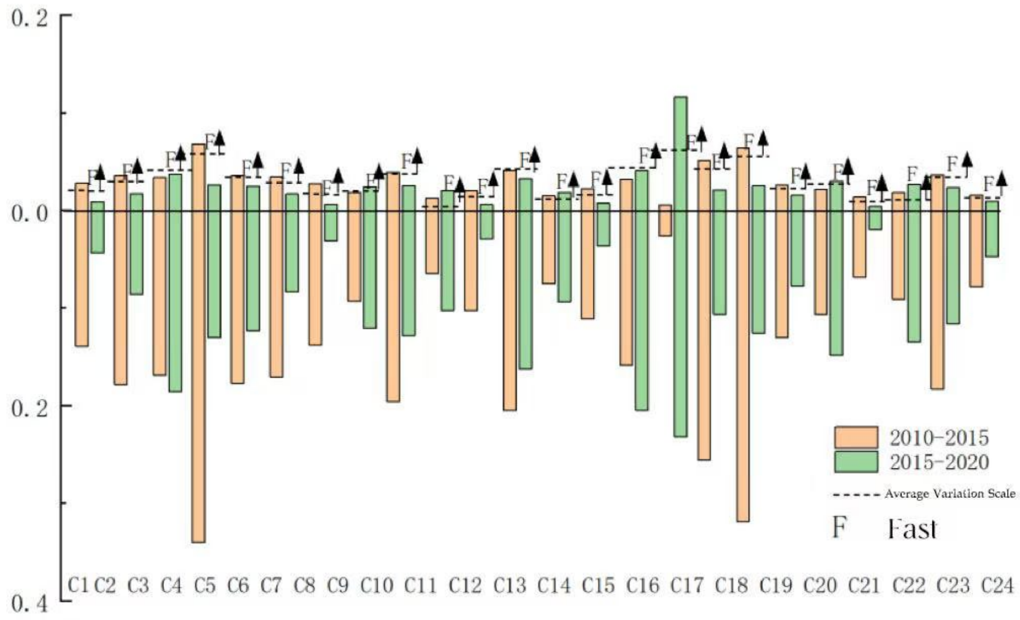

Figure 3: Change Intensity of Land Types around Changzhutan Intercity Railway Stations during 2010–2020.

4.3. Analysis of Driving Factors Underlying the Temporal Heterogeneity in LUCC Intensity around Intercity Railway Stations

Factor detection analysis was conducted on LUCC around stations in the Changsha, Zhuzhou, and Xiangtan sections of the Changsha-Zhuzhou-Xiangtan Intercity Railway across different time periods. The results reveal temporal heterogeneity in the driving factors influencing LUCC across the different urban sections of the railway. Furthermore, within the same time period, the dominant driving factors also varied among the different city sections.

Changsha Section (Core Growth Pole): As the core growth pole of the metropolitan area, the driving mechanism for LUCC around stations in the Changsha section exhibited distinct phased. During the Construction Phase (2009-2016), LUCC was primarily influenced by government investment and locational advantages. The Changsha municipal government promoted "station-city integration," utilizing fixed-asset investment to enhance transport connections at core stations like Changsha South Railway Station and Lugu Station (e.g., subway links, road network densification). Stations located in new urban districts, near administrative centers, or industrial parks leveraged their locational advantages to drive construction land expansion, with significant conversion of forest and cultivated land. In the Operational Phase (2016-2025), the dominant drivers shifted to market conditions and station-specific attributes. Post-opening, a surge in passenger flow (exceeding 8 million in 2023) and the consequent agglomeration of population and factors stimulated demand for commercial and residential land. The influence of indicators like the share of secondary/tertiary industries and the growth rate of total retail sales increased by over 38% compared to the construction phase. The expansion of major stations like Changsha South Railway Station in terms of scale and train frequency spurred the development of commercial complexes and corporate headquarters parks, making market forces the core driver. The influence of government investment significantly decreased (dropping to a q-statistic of 0.23). In Figure 4, the variations in LUCC intensity (represented by orange and green bars) for Changsha-section stations (C-series codes) between 2010-2015 and 2015-2020, along with their deviation from the average change line and the "Fast" markers, visually reflect the differences in land use conversion intensity under different driving factors, clearly demonstrating the shift from the construction to the operational phase.

Zhuzhou Section (Industrial Hub): As the industrial powerhouse of the metropolitan area, the LUCC driving mechanism around stations in the Zhuzhou section was characterized by "government guidance-industrial linkage." During the Construction Phase (2009-2016), LUCC was mainly driven by government investment and the industrial base. The Zhuzhou municipal government leveraged stations like Zhuzhou West Station and Dafeng Station to advance the "rail transit industry corridor," using local general public budget expenditure to develop supporting infrastructure for industrial parks (e.g., Zhuzhou Rail Transit Equipment Industrial Park), promoting the conversion of cultivated land to construction land. Zhuzhou West Station, due to its proximity to tourist attractions, also saw coordinated planning of tourism facilities, accelerating the loss of forest and cultivated land. In the Operational Phase (2016-2025), the dominant drivers transformed into market conditions and locational advantages. After the railway opened, the commute between Zhuzhou and Changsha was shortened to within 30 minutes, stimulating real estate and airport-adjacent economic development around stations. The influence of the total retail sales growth rate increased by 32.5% compared to the construction phase. The riverside location of stations along the Xiangjiang River attracted market-driven waterfront project development. Government investment shifted toward policy support (e.g., industrial subsidies, planning regulations), with the q-statistic for fixed-asset investment decreasing from 0.72 to 0.28. In Figure 4, the data for Zhuzhou-section stations (C-series codes) show corresponding differences in LUCC intensity between 2010-2015 and 2015-2020, aligning with the shift from a government-led construction phase to a market-led operational phase. The relationship between bar heights and the "Fast" markers across periods further illustrates the practical manifestation of land use conversion under this shift in driving factors.

Xiangtan Section (Focus on Education and Port Economy): As a key area for education and the port-based economy within the metropolitan area, the LUCC driving mechanism around stations in the Xiangtan section exhibited a "government-led, market-followed" progressive feature. During the Construction Phase (2009-2016), LUCC was primarily influenced by government investment and the natural environment. The Xiangtan municipal government focused on stations like Xiangtan North Station and Xiangtan Station to promote the "Northern New City" and "Port Economic Zone," utilizing fixed-asset investment to build station-port connecting lines and new university campuses (e.g., Hunan University of Science and Technology's new campus). The predominantly flat terrain around the stations kept land development costs low, facilitating government-led conversion of cultivated and forest land to construction land. In the Operational Phase (2016-2025), the dominant driving factor gradually transitioned towards market conditions, though government investment retained significant influence. After the railway opened, industrial collaboration between Xiangtan and Changsha/Zhuzhou strengthened, attracting supporting industries like automotive parts and electronics to areas around stations (e.g., the Xiangtan North Station area), increasing the influence of the secondary/tertiary industry share growth rate. However, due to slower population agglomeration (2023 passenger volume was only one-third of Changsha's section) and insufficient market vitality, the government continued to guide development through subsidies and investment promotion policies, creating a "government supplementation-market driving" pattern.

In summary, the underlying logic for the temporal heterogeneity in LUCC around the Changsha-Zhuzhou-Xiangtan Intercity Railway stations is "government investment dominance during the construction phase, transitioning to market condition dominance during the operational phase." However, due to differences in economic foundations and industrial positioning among the city sections, nuanced distinctions exist in the dominant factors: the Changsha section, leveraging its core city advantage, saw a rapid market takeover of LUCC driving forces; the Zhuzhou section utilized its industrial base, making industrial linkage the key conduit for market-driven changes; the Xiangtan section, due to weaker market vitality, required continued government investment supplementation even during the operational phase. This analysis provides a critical basis for the differentiated development and temporal regulation of land resources around the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway.

5. Discussion

The railway network within the Changsha-Zhuzhou-Xiangtan region comprises both high-speed rail (HSR) stations and intercity railway stations, each exhibiting distinct land use characteristics. Intensity analysis of HSR stations reveals significant fluctuations in the average annual rate of change during the study period, with different stations following varying temporal rhythms of change. Initial development around these stations was predominantly influenced by transport accessibility, while later phases saw development trajectories shift in response to adjustments in municipal master planning and industrial policy, reflecting the evolving urban development stage. In contrast, intercity stations, serving internal commuting and short-distance connections within the urban agglomeration, are numerous and widely

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distributed. Consequently, land use change patterns differ markedly among these stations. From 2010 to 2020, the average annual change rate for all intercity stations showed considerable volatility, indicating that surrounding lands experienced LUCC of varying degrees, more susceptible to localized influencing factors and presenting a more diversified spectrum of development models. This underscores how the functional orientation introduced by different types of transport nodes shapes the spatial patterns of land use and development within a region. For instance, HSR stations tend to foster a "regional-radial" development pattern, whereas intercity rail nodes contribute to an "urban-network" development model.

Over time, both station types have exhibited analogous spatial phenomena, demonstrating that the direction and intensity of development can alter according to developmental needs within a given period. For example, the growth rate around HSR stations from 2015 to 2020 differed from previous periods, indicating that land development along railway corridors is not necessarily linear or consistently progressive. As the Changsha-Zhuzhou-Xiangtan urban agglomeration evolved, certain areas around stations experienced "deceleration," "slowdown," or even a "reversal" in development momentum. The changes observed across the two study periods consistently reflect an overarching urban land-cover transformation: a persistent decline in cultivated land coupled with a rapid expansion of urban construction land. Throughout 2010–2020, cultivated land was continuously replaced by other land types. This was most pronounced during the peak HSR construction phase from 2010 to 2015, when the loss of cultivated land around stations amounted to 12.98% of the regional total. This loss intensified in the subsequent period (2015–2020), reaching 16.11%. Concurrently, impervious surfaces (construction land) expanded rapidly. For example, the net increase in construction land around Changsha HSR Station alone surpassed the cumulative growth of previous decades. The rate of this transformative trend reached 16.77% in the period after 2010–2015, escalating dramatically to an increase of 71.96 km² in the later interval.

Changes in ecological land categories such as forest, grassland, and water bodies were less drastic compared to the shifts between cultivated and impervious land, yet they were still notable. A positive shift occurred in the forest area around Changsha HSR Station, which increased by 1.56% from 2015 to 2020. Similarly, forest area around the intercity railway stations saw a net gain of 7.63 km² during the same period. This suggests that transport corridor development does not necessarily proceed at the complete expense of the ecological environment. Several factors contribute to this:

(1) Ecological Compensation: Urban planning mechanisms incorporate "ecological compensation" to offset environmental losses from economic activities, mandating green spaces within developments or the restoration of degraded woodlands.

(2) Amenity-led Development: Creating high-quality ecological landscapes[11] around stations serves as an amenity to attract talent and industry, leveraging the transport node's agglomeration effect on human and economic flows.

(3) Passive Restoration: Some underutilized lands with ecological value may experience natural improvement or assisted regeneration.

While some grassland and water bodies near the regional HSR system showed positive changes, the overall reduction in cultivated land area—driven by population mobility and regional expansion—remains substantial. This indicates a need for continuous improvement and fine-tuning of the ecological land structure in station areas. However, these positive adjustments are often insufficient to fully counterbalance the adverse ecosystem impacts stemming from rapid regional construction and sprawl. Therefore, future development must more closely integrate the management of these ecological land types with the development process itself, aiming to formulate sustainable transportation corridor planning strategies.

6. Conclusions and Implications

This study synthesizes the driving mechanisms of Land Use/Cover Change (LUCC) around high-speed railway stations and applies this framework to an investigation of the Changsha-Zhuzhou-Xiangtan Intercity Railway. The research identifies the characteristic temporal heterogeneity of LUCC around its stations and elucidates the underlying driving factors. The key findings are as follows: (1) During the study period, LUCC around the stations of the Changsha-Zhuzhou-Xiangtan Intercity Railway was predominantly characterized by the expansion of construction land and the reduction of forested area. (2) From the construction phase to the initial

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operational phase, both the scale and intensity of LUCC around the stations continuously increased, demonstrating clear temporal heterogeneity. (3) This temporal heterogeneity is primarily linked to the varying influence of governmental and market forces across different periods. During the construction phase, LUCC was predominantly government-investment-driven, accelerated by local government funding, the development of supporting infrastructure, and associated land speculation. In contrast, the operational phase has been chiefly influenced by local market conditions. However, as the operation of the Changsha-Zhuzhou-Xiangtan Intercity Railway has not yet delivered a pronounced boost to regional economic development in some segments, it has failed to effectively attract sustained market participation in surrounding land development, leading to a decline in LUCC intensity around certain stations in later stages.

To promote the rational development, utilization, and protection of land resources around intercity railway stations, the following policy recommendations are proposed based on the above findings. First, it is essential to foster synergistic collaboration between government and market forces in land resource development around stations, leveraging their respective strengths at different stages. During the construction phase, government investment should lead in establishing infrastructure and guiding land use orientation. In the initial operational phase, the market should play a decisive role in resource allocation to drive efficient land use. Second, differentiated land resource development strategies should be formulated according to the economic foundation, industrial positioning, and developmental stage of each urban section. The Changsha section could focus on high-end services and headquarters economy; the Zhuzhou section on advanced manufacturing and airport-adjacent economy; and the Xiangtan section on education-scientific research industries and port-based economy. Third, the land development process must prioritize ecological and environmental protection, aiming for a coordinated balance among economic, social, and ecological benefits. Mechanisms such as ecological compensation and landscape enhancement should be employed to offset environmental losses from economic activities, thereby constructing a sustainable model for transport corridor development.

This study has certain limitations. First, it relies on 30-meter resolution remote sensing imagery and statistical data, which may not capture fine-grained details of land use transitions at a micro scale. Second, the research period concludes in 2020 and thus does not capture the land use responses during the middle and later stages of railway operation, particularly the impact of post-pandemic commuting pattern shifts on land use structure. Finally, as the case study is focused on the Changsha-Zhuzhou-Xiangtan region, the generalizability of its conclusions to intercity railway projects in other regions or of different types requires further validation.

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