Case Study

Transportation Development, Spatiotemporal Convergence, and Urban Land Use: Study of the Opening of High-Speed Rails in the Yangtze River Delta, China

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Abstract: The rapid development of high-speed rail (HSR) has accelerated urbanization of the Yangtze River Delta (YRD). However, the impacts of HSR opening, opening time of HSR, and heterogeneity effects of HSR stations' characteristics on urban land use have not been well studied. Based on the land-use remote sensing data of YRD for 1990–2015, this study analyzes the causal effect of HSR opening on land-use change by applying the difference-in-differences model (DID). We find that the HSR opening has a significantly positive effect on the expansion of urban space and other construction land but accelerates the loss of agricultural land. Furthermore, the impact of HSR on urban land use is cumulative, and the opening time of HSR affects the speed of urban land use change. The longer the HSR opening time, the faster the change in urban land use. Moreover, the issue of the heterogeneity effects of HSR station characteristics on urban spatial expansion is also an important one. The results show that existing stations have a greater impact on urban spatial expansion. **DOI:** 10.1061/(ASCE)UP.1943-5444.0000732.
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Author keywords: High-speed rails; Urban land use; Characteristics of HSR stations; Difference-in-differences model; Yangtze River Delta.

Introduction

Along with market reform, China has been experiencing rapid urbanization since the early 1990s, which includes not only population urbanization but also land urbanization (Bai et al. 2014). Land urbanization changes the natural and social attributes of land. A prominent feature of land urbanization is the continuous expansion of nonagricultural land (Liu et al. 2014). During the economic transformation of China, a real estate boom and the development zone fever accelerated land urbanization in the edge areas of large and medium-sized cities, as well as small towns and central villages (Wei 2015). However, most urban spatial expansion is considered low-density, even urban sprawl, causing many environmental and socioeconomic problems (Zhao 2010; Li and Li 2012; Wei and Ye 2014; Li et al. 2017). For instance, urban spatial expansion generally leads to an increase in traffic jams and resource consumption and a loss of agricultural land (Seto and Kaufmann 2003; Wei and Ewing 2018). Therefore, it is critical to better understand the urbanization process in China and avoid urban sprawl by investigating land-use changes and their mechanisms.

Transportation plays an important role in land-use change (Zhang et al. 2013; Mondal et al. 2015). After the opening of Japan's Shinkansen in 1964, the world's first high-speed rail (HSR) line, other countries began to construct HSR. China's HSR is developing rapidly, and it has become the country with the longest HSR lines. The opening of HSR improves accessibility between cities (Wang and Duan 2018) and produces a *spatiotemporal convergence* effect. It promotes agglomeration of people, materials, and information in cities and develops nonagricultural industries and economies (Willigers and van Wee 2011; Dong and Zhu 2016; Donaldson 2018). The agglomeration of economic activities increases the demand for land and accelerates land transformation. In other words, HSR has multiple effects on the location of economic activities and spatial structure of cities (Preston and Wall 2008). It is evident that changes in urban land use are closely related to the construction of HSR. The land-use pattern along the HSR lines and around station areas will be affected by the opening of HSR. Therefore, the following issues need to be discussed. First, whether the opening of HSR promotes the expansion of urban space and exacerbates the loss of agricultural land should be examined. Second, do HSR stations and lines occupy a large amount of land that is converted from agricultural land? The expansion of urban space contradicts the protection of agricultural land. Blind expansion of urban space and improper planning of HSR lines may lead to inefficient land use, resulting in wastage of land. The rational and intensive use of land is a key concern for the government. Therefore, a valid understanding of the causal relationship between HSR and land use is important to improve decision making regarding future land use.

In the context of the integration of the Yangtze River Delta (YRD) and the rapid development of the HSR network, this study intends to answer the following questions. First, this study analyzes whether and how the opening of HSR affects the change in urban land use. Second, it investigates the impact of the opening time of HSR on urban land use and discusses the time effect of HSR opening. Last, the study explores the characteristics of HSR

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Note. This manuscript was submitted on May 11, 2020; approved on March 29, 2021; published online on May 26, 2021. Discussion period open until October 26, 2021; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Urban Planning and Development***, © ASCE, ISSN 0733-9488.

stations by testing the heterogeneity impacts of different HSR stations on urban land use. It has important academic and practical significance to explore the causal effect between urban land use and HSR. By analyzing the influence of HSR on urban land use and its mechanism, this study enriches the existing research on HSR and urban land use. In addition, it delineates policy implications for the government by summarizing the impact of HSR on urban land use so that the negative impact of urban spatial expansion can be avoided. In the context of China's dual land system, this study will provide a theoretical basis for the formulation of land policy and urban HSR station planning.

Literature Review and Analytical Framework

Literature Review

As a key factor influencing urban development, transportation infrastructure has been the topic of research for many urban and regional studies (Barbara et al. 2017). New economic geography theory, that emerged in the 1990s, held that the reduction of trade costs caused by the improvement of transportation infrastructure would strengthen the agglomeration of economic activities because of the local market effect (Krugman 1991; Krugman and Venables 1995) and lead to the change in the urban spatial structure. First, studies demonstrate that the construction of expressways can promote the expansion of urban space (Handy 2005) and aggravate the loss of agricultural land (Song et al. 2016). Baum-Snow (2007) finds that the construction of highways caused suburbs to expand along highway lines. In addition, many residents of the central city tend to move to the suburbs, resulting in a continuous decline in population density of the central city. Second, rail transit and railway accelerate the transformation process of land use (Kasraian et al. 2016). Mondal et al. (2015) assert that roads, railways, and metro rails affect the location of new residential areas. Zhang et al. (2013) believe that construction land is usually close to areas with convenient transportation, and railways has the most obvious impact on land use change.

As a large-scale passenger transportation infrastructure, HSR affects the development of the urban population (Verma et al. 2013; Guirao et al. 2018; Deng et al. 2019), economy (Qin 2017; Li et al. 2018), and industry (Deng et al. 2017; Lin 2017). Research on the impact of HSR on urban land use mainly focuses on urban expansion and sprawl. Long et al. (2018) argue that the opening of HSR can optimize the flow of production factors and change the urban spatial structure, thus leading to urban spatial expansion. Shen et al. (2014) find that the decrease of travel time caused by HSR has increased the area of urbanized land in the Atocha station catchment area. The opening of HSR leads to the development of surrounding areas around HSR stations and a redevelopment of the urban center (Ureña et al. 2009), hence affecting the spatial layout of the whole city. Chen et al. (2019) comprehensively analyze the impact of the HSR opening on land value, urban spatial expansion, and housing price. They emphasize the expansion direction of urban space by using Landsat data that reflect the change in land use attributes indirectly. Urban sprawl, as a special form of urban spatial expansion, is considered as the low-density expansion of population in urban space. Deng and Wang (2018) demonstrate that the opening of HSR aggravates urban sprawl. The preceding works are closely related to the study of urban land use and provide a theoretical basis for our research.

As for urban land use, previous studies mainly investigate the spatiotemporal variation (Liu et al. 2003, 2009) and influencing factors (Seto and Kaufmann 2003; Gao et al. 2014; Huang et al. 2015; Li et al. 2015; Chen et al. 2016). However, the literature pays little attention to the most important factor of urban land use: causal effects of HSR. Using data from 2005 to 2013, Zhang et al. (2019) prove that HSR has no significant effect on urban land but has a negative effect on the area of agricultural land. However, the transformation of land use is a long-term process, and changes in the short term may not be obvious. In addition, there is a lack of detailed classification data of land use in current empirical studies to measure urban land use more accurately.

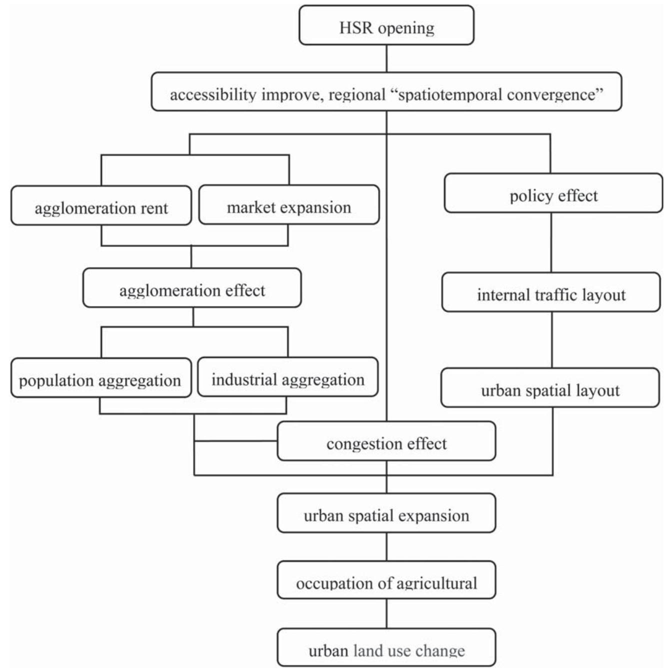

Fig. 1. Impact path of HSR opening on urban land use.

In summary, the impact of the opening of HSR on urban space and land use has gradually attracted the extensive attention of scholars. However, research on the causal relationship between HSR and urban land use is still lacking. This study aims to fill this gap: (1) Remote sensing data and rigorous econometric methods were used to empirically examine the causal relationship between the opening of HSR and urban land use. Moreover, we classified land use into urban space, agricultural land, and other construction land. (2) We analyzed the heterogeneity effect of HSR opening characteristics on land use, which deepens the research. Land use in China is largely controlled by the government. Under China's special land system, the effect of HSR on land use needs to be tested with more accurate data and more scientific statistical methods.

Analytical Framework

As a large-scale passenger transportation infrastructure, HSR improves the accessibility and strengthens the *spatiotemporal convergence* effect between cities. The opening of HSR has become an important driving force for the free flow of economic factors such as labor and information. This study constructs an analytical framework of the influence of HSR on urban land use from three aspects: agglomeration effect, congestion effect, and policy effect (Fig. 1).

Agglomeration Effect

The opening of HSR influences the agglomeration capacity of a city. First, HSR improves the accessibility between cities and

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affects the agglomeration rent. Agglomeration rent reflects the attractiveness of an area, especially in industrial cluster districts. Due to the *spatiotemporal convergence* effect, HSR cities gain the advantages of location and economic development and attract more labor and firms. Second, the HSR network expands the market size by integrating the internal and external markets in the region. It also expands the service radius of the city and brings greater market potential. This enhances the city's competitiveness and attracts more firms to form industrial clusters.

Consequently, the agglomeration generated by HSR provides more choices for firms and labors. First, the opening of HSR reduces the cost of migration and improves mobility. Laborers move from the countryside to cities for better job opportunities and higher wages (Sands 1993; Verma et al. 2013). Population agglomerates in cities increase the demand for urban land, leading to expansion of urban space. Second, firms tend to choose cities that have large markets as their production locations to save transportation costs. Moreover, the large scale of labor pool in the cities allows industries to spend less time on training employees and seeking new labor. The expanding scale and quantity of urban industries increases the demand for urban space and construction land, thereby leading to a change in urban land use.

Congestion Effect

The congestion effect caused by HSR mainly occurs in the inner-city level. The opening of HSR promotes an increase in urban enterprises and population and raises aggregation costs. Excessive concentration of enterprises in urban centers leads to competition pressure. The market congestion effect compels enterprises to choose locations with fewer competitors. Moreover, the construction cost of factories in urban suburbs is relatively low. Enterprises, especially the manufacturing industry, tend to set up production units in urban suburbs. In addition, the growing population density in urban centers increases living costs. As a result, many houses are built on the urban fringe for migrants (Yue et al. 2013), and people tend to live in suburbs where the cost of living is lower. As the population continues to urbanize in China, the size and structure of cities will change to accommodate the increasing demand for housing, industry, and commerce, causing the urban land use to change at multiple scales (Schneider and Mertes 2014).

Policy Effect

The expansion of urban space does not lead to the formation of new cities, but it occurs in existing urban areas. Therefore, the change in urban land use attributes depends on social, economic, and policy factors of the original city. HSR stations need to be integrated into the urban internal transport system and supported by the same. The location of HSR stations directly affects the planning of internal transportation channels, and, therefore, urban space expands along the main transport lines (Ma and Xu 2010). Because of the social and economic characteristics of workers and accessibility of intracity transportation, the urban form generally affects workers' commuting patterns (Zhao et al. 2010). The expansion of urban space lengthens commuting distance and creates traffic congestion. Therefore, the urban form will also affect urban transportation planning in a reverse way. Transportation infrastructure has a circular and accumulative relationship with urban spatial layout. This process causes a continuous expansion of urban space and affects urban land use. In addition, the construction of HSR stations occupies a lot of land. As the most densely populated areas in the city, HSR stations attract numerous business services, such as accommodation and catering. This also affects land use in cities.

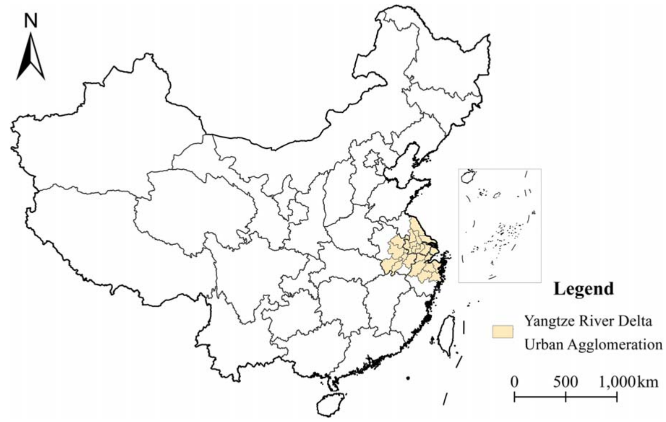

Fig. 2. Location of the Yangtze River Delta urban agglomeration in China.

Study Area and Methodology

Study Area

The YRD urban agglomeration locates in the alluvial plain on the south-eastern coast of China, with a total area of approximately 211,700 km^2 (Fig. 2). According to the 2016 Yangtze River Delta Urban Agglomeration Development Plan, the YRD urban agglomeration includes Shanghai and the other 25 cities in Jiangsu, Zhejiang, and Anhui provinces. In 2015, more than 129 million people reside in the urban agglomeration on YRD representing 9.99% of the total population of the whole country. The GDP of YRD is 13.55 trillion (yuan), 20.03% of China's total, making it one of the most economically developed regions of China. As a region with the most active economic development, the highest degree of openness, and the strongest innovation capacity, YRD plays a pivotal role in the national economy. It also has the best urbanization conditions in China. Its economic hinterland is vast and transportation infrastructure is well developed; hence, it is a comprehensive transportation network. With Shanghai being the core and Nanjing, Hangzhou, and Hefei being subcenters, YRD has formed a multilevel comprehensive transport network featuring HSR, intercity railway, expressway, and waterway.

Data Preprocessing and Methodology

Rate of Urban Spatial Expansion

The area tabulating tool in ArcGIS10.0 is used to calculate the area of different types of land use based on the land use monitoring data. According to Ma and Xu (2010), the formula for calculating the expansion rate of urban space is as follows:

$$\mathrm{USES} = \frac{U_{t_1} - U_{t_0}}{t_1 - t_0} \tag{1}$$

where U_{t1} and U_{t0} = urban space in t_1 and t_0, respectively; and $t_1 - t_0$ = time span between two phases. This is how the annual growth of urban space is obtained.

Difference-in-Differences Model

In the early stage of research on the influence of HSR, two methods are generally used. One is a comparison between cities with HSR and those without and the other is comparing the differences in a city before and after the opening of HSR. However, there are inherent differences between cities with and without HSR, so the first comparison may be biased. Moreover, changes in explanatory

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Table 1. Variable definitions and descriptive statistics

Categories	Variables	Definition	Obs.	Mean	Std. Dev.	Min.	Max.
Explained variables	ln ulu	The logarithm value of urban space area (km^2)	104	4.917	0.992	2.757	6.924
	ln farm	The logarithm value of agricultural land area (km^2)	104	8.115	0.746	5.793	9.402
	ln built	The logarithm value of construction land area (km^2)	104	3.491	1.411	0.194	6.595
Main explanatory variables	HSR	The opening of high-speed railway	104	0.298	0.460	0	1
	HSR_{2000}	The opening of high-speed railway in 2000	104	0.106	0.309	0	1
	HSR_{2010}	The opening of high-speed railway in 2010	104	0.106	0.309	0	1
	HSR_{2015}	The opening of high-speed railway in 2015	104	0.192	0.396	0	1
HSR station characteristics	time	The opening time of HSR	104	1.029	2.097	0	8
	new	New station or existing station	104	0.538	0.501	0	1
Mediation variables	ln M1	The logarithm value of employees	104	3.821	0.975	1.466	6.525
	ln M2	The logarithm value of local fiscal expenditure	104	13.087	2.259	8.683	17.941
Control variables	ln pd	The logarithm value of population density	104	6.402	0.491	5.225	7.730
	multi	Urban special structure index	104	0.503	0.254	0.100	1
	ln FDI	The logarithm value of foreign direct investment (10 thousand dollar)	104	9.455	3.075	0	14.428
	indus	Share of nonagricultural industries in GDP	104	0.869	0.112	0.503	0.996
	ln tra	The logarithm value of urban road area (10,000 m^2)	104	6.715	1.364	3.555	9.564
	integ	Degree of integration	104	0.510	0.502	0	1

variables may not be caused by the opening of HSR but by some other factors that change over time. Therefore, these two methods misestimate the impact of HSR opening. This study uses the difference-in-differences (DID) model to examine the effect of HSR opening on urban land use. The DID model has been widely used in policy assessment, especially in HSR research (Albalate and Fageda 2016; Long et al. 2018). The DID model fully considers the difference between cities and the difference in time and calculates the net effect of the opening of HSR on urban land use.

The basic principle of the DID model is as follows. First, the samples are divided into treatment group and control group. $H_i = 1$ means that city i belongs to the treatment group affected by the policy. $H_i = 0$ means that city i is in the control group not affected by the policy. T_t is the time variable: T_1 indicates the time after the opening of HSR and T_0 is time before the opening of HSR. Second, the net effect of HSR on land use is obtained by calculating two differences. The first difference is between the treatment group and the control group, and the second difference is calculated before and after the opening of the HSR.

$$\beta = \Delta\overline{Y_1} - \Delta\overline{Y_0} = (\overline{Y_{1,t1}} - \overline{Y_{1,t0}}) - (\overline{Y_{0,t1}} - \overline{Y_{0,t0}}) \quad (2)$$

The basic estimation model is as follows:

$$Y_{it} = \alpha + \delta H_i + \gamma T_t + \beta(H_i \times T_t) + \varepsilon_{it} \quad (3)$$

Model (3) assumes that the policy occurs in the same year, and the coefficient of cross-term β represents the net effect of the policy. This study adopts the multi-DID model, because HSR in YRD has been opened gradually. When $HSR_{it} = 1$, the sample belongs to the treatment group. When $HSR_{it} = 0$, the sample belongs to the control group. The influence of HSR on urban land use is accurately estimated by controlling time and individual effect. The estimation model is as follows:

$$\ln y_{it} = \alpha + \beta\,HSR_{it} + \gamma_1 \ln pd_{it} + \gamma_2\,\text{multi}_{it} + \gamma_3 \ln \text{FDI}_{it} + \gamma_4\,\text{indus}_{it} + \gamma_5 \ln \text{tra}_{it} + \gamma_6\,\text{integ}_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (4)$$

where y_{it} = explained variable, representing the area of urban space, agricultural land, and other construction land of city i in year t; α = constant term; HSR_{it} = main explanatory variable, which reflects whether city i opens the HSR in year t; and HSR_{it} = dummy variable. If city i opened HSR in year t, then $HSR_{it} = 1$; otherwise, $HSR_{it} = 0$. Stata 16.0 is used for estimation. β = coefficient of HSR_{it}, reflecting the net effect of HSR on the explained variables. When β is positive and statistically significant, it indicates that the opening of HSR promotes change in urban land use. When β is negative and statistically significant, it indicates that the opening of HSR has an inhibitory effect on the change in urban land use. When β is not statistically significant, it indicates that the effect of HSR opening on urban land use is not obvious. μ_i = individual fixed effect; ν_t = time fixed effect; ε_{it} = random disturbance term; and γ_1–γ_6 = coefficients of the control variables.

The main factors driving land-use change are development factors, economic factors, and other factors. Based on the relevant literature and a mechanism review, population density ($\ln pd_{it}$), urban spatial structure (multi_{it}), foreign direct investment ($\ln \text{FDI}_{it}$), nonagricultural industry (indus_{it}), urban transportation ($\ln \text{tra}_{it}$), and integration degree (integ_{it}) are selected as control variables. The description of each variable is provided in Table 1. The indexes of multi_{it} and integ_{it} need to be introduced in detail. First, following Sun and Li (2016), a virtual city is constructed by treating the municipal district and county area as a continuous geographical area. Urban spatial structure is measured by the ratio of the GDP of a municipal district to that of the whole city (Liu et al. 2017). The larger the index of the urban spatial structure, the more prosperous the economy of the municipal district, and the greater the economic gap between the county and the municipal district. Second, the integration degree is measured by dummy variables. To promote the development of cities, the YRD urban agglomeration has undergone a long-term and steady expansion process, eventually forming the current agglomeration stage. Therefore, some cities in the study sample may not belong to the YRD urban agglomeration of the early stage and lack the policy advantages of integration. Therefore, this study controls for the influence of the urban agglomeration characteristics of YRD at different stages. When the city is located in the YRD urban agglomeration, the integration degree index is 1; otherwise, it is 0.

On the DID model, the opening time of HSR is calculated to replace the dummy variable. There are two main purposes: the first is to explain the time cumulative effect of HSR. We aim to explore whether the longer the HSR is open, the greater the impact on urban land use. Second, the test of the variable of HSR opening time can be used as the robustness test to prove the accuracy of the estimated results.

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Parallel Trend Test

The requirement of the DID model is that the treatment group and the control group should have the same trends before the opening of HSR. In other words, the estimator obtained from the DID model is unbiased only if the treatment group and control group meet the parallel trend assumption. This study uses the counterfactual method to test this assumption. This study assumes that the opening time of HSR is 10 years ahead of initial schedule, that is, HSR had opened in 2000. Three dummy variables (HSR_{i2000}, HSR_{i2010}, and HSR_{i2015}) are added in the model and set as follows. If the city i opened HSR in 2000, then $HSR_{i2000} = 1$; otherwise, $HSR_{i2000} = 0$. The same applies for HSR_{i2010} and HSR_{i2015}

$$\begin{aligned}\ln y_{it} = \alpha + \beta_1\, HSR_{i2000} + \beta_2\, HSR_{i2010} + \beta_3\, HSR_{i2015} \\ + \gamma_1 \ln pop_{it} + \gamma_2 multi_{it} + \gamma_3 \ln FDI_{it} + \gamma_4\, indus_{it} \\ + \gamma_5 \ln tra_{it} + \gamma_6\, integ_{it} + \mu_i + \nu_t + \varepsilon_{it}\end{aligned} \tag{5}$$

The coefficients of HSR_{i2000}, HSR_{i2010}, and HSR_{i2015} in the model represent the impact of HSR opening on urban land use in 2000, 2010, and 2015. HSR_{i2000} is the counterfactual variable. If the coefficient of HSR_{i2000} is not significant, it indicates that the opening of HSR in 2000 does not have an impact on urban land use. In other words, there is no significant difference in urban land use between the treatment group and the control group before the opening of HSR. This indicates that the model meets the requirement of parallel trend assumption. Other variables have the same meaning as in model (4).

Heterogeneous Impact of HSR Stations on Urban Land Use

The HSR stations are divided into new stations and existing stations. If a station exists before the opening of HSR, it is considered as an existing HSR station, and then, $new_i = 0$. If the station is operated in the same year as HSR opening, it is considered as a newly built station, then $new_i = 1$. The heterogeneity influence of HSR stations on urban land use is tested by adding a cross term of HSR station characteristics and HSR opening. The estimated model is as follows:

$$\begin{aligned}\ln y_{it} = \alpha + \beta_1\, HSR_{it} + \beta_2\, new_i + \beta_3\, HSR_{it} \times new_i \\ + \gamma_1 \ln pop_{it} + \gamma_2\, multi_{it} + \gamma_3 \ln FDI_{it} + \gamma_4\, indus_{it} \\ + \gamma_5 \ln tra_{it} + \gamma_6\, integ_{it} + \mu_i + \nu_t + \varepsilon_{it}\end{aligned} \tag{6}$$

β_3 = heterogeneity impact of HSR stations on urban land use. When β_3 is greater than 0 and significant, it indicates that the new HSR stations have a greater impact on urban land use. When β_3 is less than 0 and significant, it indicates that the existing stations have a greater impact on urban land use. When β_3 is not significant, it indicates that there is no difference in the impact of the new stations and existing stations on urban land use. α, γ_i, μ_i, ν_t, and ε_{it} have the same meaning as in model (4).

Data Resource

Because the data of urban built-up areas in the statistical yearbooks is relatively rough, this study uses land-use monitoring data to calculate the change in urban land use. The data set is provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC). Data from 1990, 2000, 2010, and 2015 are used, because the transformation of land attributes is a long-term process. The remote sensing data make up a raster of 30 m × 30 m, which has the advantages of high precision and fine classification. The data of HSR opening come from the train schedules of each year and can be obtained according to the opening routes. The location data of HSR stations are obtained from the Baidu map, and the initial operation time of each station is taken from the internet. The control variables are derived from the China City Statistical Yearbook of 1990, 2000, 2010, and 2015. In 1994, the State Council abolished the county-level cities of Taizhou, Huangyan, and Jiaojiang and established Taizhou as a prefecture-level city. For consistency of statistical caliber, the data of Taizhou in 1990 are taken as the total data of Jiaojiang, Linhai, and Huangyan. The integration degree data are compiled from the 2010 Yangtze River Delta Regional Plan, Yangtze River Delta City Economic Coordination Commission (2010), and 2016 Yangtze River Delta urban agglomeration Development Plan (Liu and Wu 2017). Table 1 shows the descriptive statistics of the variables.

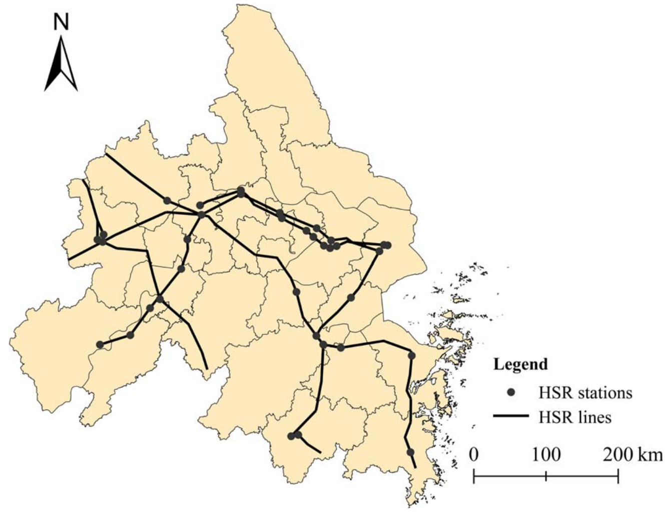

Fig. 3. Distribution of the HSR network in the Yangtze River Delta.

Development of the HSR Network and Urban Spatial Expansion in the Yangtze River Delta

Development of the HSR Network in the Yangtze River Delta

As shown in Fig. 3, HSR lines cover almost all cities in YRD, forming the densest HSR network in China. Since the opening of the Nanjing–Hefei Railway on April 28, 2008, the HSR network in YRD developed rapidly. By the end of 2015, Nanjing–Chengdu Railway, Hangzhou–Shenzhen Railway, Shanghai–Kunming HSR, Shanghai–Nanjing HSR, Beijing–Shanghai HSR, Hefei–Bengbu HSR, Nanjing–Hangzhou HSR, Jinhua–Wenzhou Railway, Nanjing–Anqing HSR, and Hefei–Fuzhou HSR had opened.

There are 26 prefecture-level cities in YRD. By the end of 2015, 21 cities had opened HSR, including 76 HSR stations. There are 20 cities whose municipal districts have HSR stations. Out of the 20 cities, 11 had opened HSR by the end of 2010 and 9 opened HSR between 2011 and 2015. Moreover, 32 HSR stations are located in municipal districts, including 14 new stations and 18 existing stations.

Land use Change in the Yangtze River Delta

Fig. 4 shows land use change in YRD from 1990 to 2015. It can be seen from Fig. 4 that the land use has undergone great changes between 1990 and 2015, especially agricultural land and urban space. Agricultural land decreased from 114,979 km^2 in 1990 to 102,692 km^2 in 2015, a decrease of 12,287 km^2 in 25 years. On the contrary, urban space has expanded rapidly. It increased from

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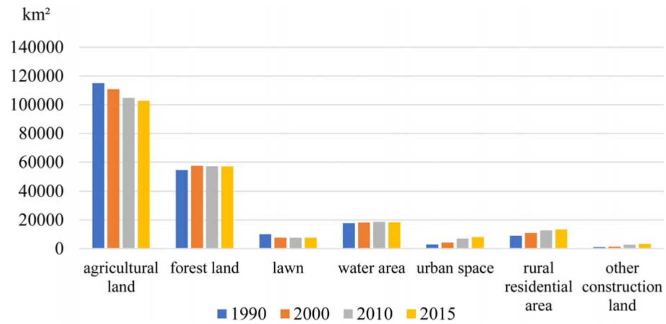

Fig. 4. Land-use change in the Yangtze River Delta, 1990–2015.

2,886 km^2 in 1990 to 8,022 km^2 in 2015, a nearly 2.78-fold increase. At the same time, rural residential areas and other construction land have also increased. Other construction land refers to the land used for factories and mines, large industrial zones, oil fields, salt fields, quarries, roads, airports, and so on. Other types of land have not changed much. Therefore, under the condition that the total urban area was unchanged, we understand that the increase in urban space, rural residential area, and construction land have all been the result of the transformation of agricultural land.

Urban Spatial Expansion in the Yangtze River Delta

Fig. 5 shows the average annual growth of urban space and the opening of HSR in each city during the three stages of 1990–2000, 2000–2010, and 2010–2015. It shows the expansion speed of urban space clearly. In the first stage, urban space in each city expanded differently between 1990 and 2000. Shanghai, Wuxi, and Suzhou have the fastest growth in urban space. The latter two cities are close to the central city of Shanghai. At this stage, the urban spatial expansion of most cities is relatively slow, and urban land use mainly depends on urban development and government policies. In the second stage, urban spatial expansion began to accelerate between 2000 and 2010. The superposition map of HSR opening and urban spatial expansion show that cities that have undergone rapid urban spatial expansion all have HSR. They had opened HSR by the end of 2010, causing an *HSR-corridor* effect. In the third stage, most cities opened HSR between 2010 and 2015, and those with HSR had rapid urban spatial expansion. Zhoushan continues to have the lowest rate of urban spatial expansion due to its special geographical location and urban function positioning in YRD.

Impact of HSR Development on Urban Land Use

Results of Parallel Trend Test

Parallel trend assumption should be tested before using the DID model. The method of counterfactual test is adopted for estimation in this study. The estimation results are shown in Table 2.

It can be seen from the results that the coefficients of HSR_{i2000} in the three models are not significant, indicating that the opening of HSR in 2000 has no significant impact on urban land use. In other words, there is no difference in the explained variables between the treatment group and the control group in 2000, proving that these groups have the same trend in these variables. The coefficients of HSR_{i2010} and HSR_{i2015} are significant in the three models, indicating that the opening of HSR in 2010 and 2015 creates differences between the explained variables of the treatment group and the control group. This proves that the opening of HSR in 2010 and 2015 has an impact on urban land use.

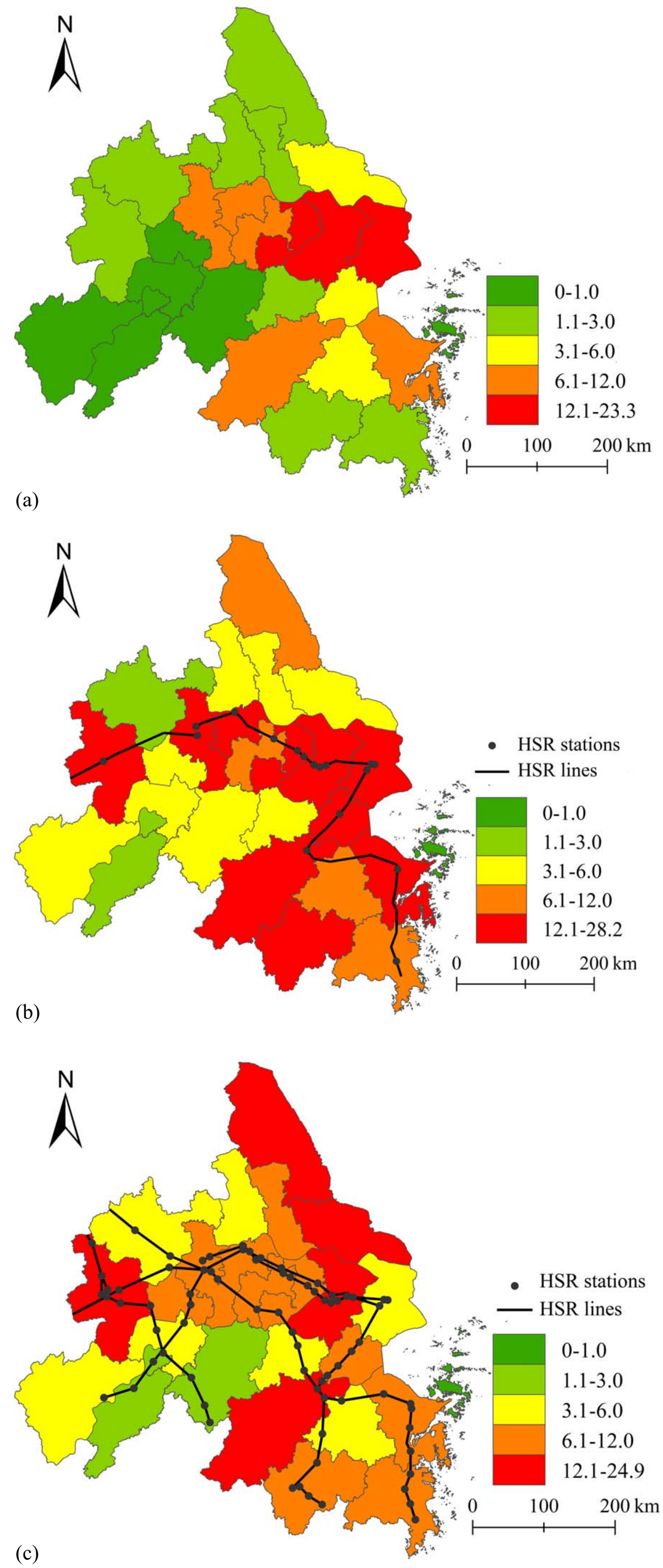

Fig. 5. Average annual growth of urban space from (a) 1990–2000 (km^2); (b) 2000–2010 (km^2); and (c) 2010–2015 (km^2).

Impact of HSR Opening on Urban Land Use

Based on the parallel trend of the treatment group and control group, this study uses the DID model to examine the net effect of the HSR opening on urban land use. We calculate the variance inflation factor (VIF) of the variables for the multicollinearity test

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first. The results show that the VIF of each variable is less than 10, so there is no serious multicollinearity problem. Following this, clustered robust standard estimation is used to avoid possible heteroscedasticity problems. The estimated results are shown in Table 3.

First, we only use HSR to make a univariate regression for urban spatial expansion. The estimated result shows that the coefficient is positive and significant at the 1% level. To avoid the bias caused by missing variables, a series of control variables are added. Although the estimated coefficient decreases, it is still significant at 1% level. This shows the robustness of the estimated results. The coefficient of HSR illustrates that the opening of HSR increases the urban space by 14.9%. Among the control variables, ln FDI and integ are significantly positive. It indicates that the increase of FDI and the integration of YRD can expand the urban space.

Then we test the net effect of the opening of HSR on agricultural land. The results show that the coefficients of HSR are all negative, indicating that the HSR opening intensifies the reduction of agricultural land, decreasing it by 4.46%. There are two main reasons. First, the construction of HSR stations and lines need a lot of land, which is obtained through government expropriation of agricultural land. Second, urban spatial expansion requires a large amount of agricultural land for construction, resulting in the reduction of agricultural land (López et al. 2001; Xie et al. 2005; Thapa and Murayama 2009; Pandey and Seto 2015; Shi et al. 2016). When the explained variables are ln built, the coefficients of HSR are significantly positive, indicating that the opening of HSR promotes an increase in other construction land by 40.7%. Other construction land includes the land for HSR stations and HSR lines, so the opening of HSR directly increases the scale of other construction land.

Table 2. Parallel trend test

Explained variables	ln uln	ln farm	ln built
HSR_{i2000}	0.090 (1.36)	0.0001 (0.01)	0.216 (1.35)
HSR_{i2010}	0.187*** (2.98)	−0.048*** (−2.98)	0.439** (2.38)
HSR_{i2015}	0.179*** (3.53)	−0.0376 (−1.62)	0.590*** (2.88)
Control variables	Yes	Yes	Yes
Time Fe	Yes	Yes	Yes
City Fe	Yes	Yes	Yes
Observations	104	104	104
R-squared	0.930	0.810	0.880
Number of groups	26	26	26

Note: The *t*-statistics for the coefficients are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Impact of HSR Opening Time on Urban Land Use

Because of the time span of the data, this study further tests the impact of the opening time of HSR on urban land use. It illustrates the long-term impact of HSR opening on urban land use. The estimated results are shown in Table 4.

First of all, the coefficients of the opening time of HSR are significantly positive at the level of 1% when the explained variables are ln unu, indicating that when the opening time of HSR increases

Table 3. Impact of HSR opening on urban land use

Explained variables	ln uln	ln uln	ln farm	ln farm	ln built	ln built
HSR	0.179*** (2.98)	0.149** (2.70)	−0.072*** (−4.38)	−0.0446*** (−2.84)	0.253 (1.21)	0.407** (2.44)
ln pd	—	0.275 (1.40)	—	−0.0104 (−0.18)	—	−0.575 (−1.58)
multi	—	−0.0675 (−0.39)	—	−0.0814 (−1.47)	—	−0.366 (−1.07)
ln FDI	—	0.0571** (2.27)	—	0.00467 (0.70)	—	0.113 (1.38)
indus	—	0.194 (0.50)	—	0.310** (2.55)	—	−1.045 (−0.82)
ln tra	—	0.0469 (0.71)	—	0.00803 (0.44)	—	0.248* (2.02)
integ	—	0.151** (2.64)	—	−0.0173 (−1.19)	—	−0.179 (−1.29)
Constant	4.370*** (153.40)	1.951 (1.32)	8.190*** (859.54)	8.002*** (20.69)	2.584*** (34.07)	5.328** (2.16)
Time Fe	Yes	Yes	Yes	Yes	Yes	Yes
City Fe	Yes	Yes	Yes	Yes	Yes	Yes
Observations	104	104	104	104	104	104
R-squared	0.912	0.929	0.729	0.810	0.840	0.877
Number of groups	26	26	26	26	26	26

Note: The *t*-statistics for the coefficients are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 4. Impact of HSR opening time on urban land use

Explained variables	ln uln	ln uln	ln farm	ln farm	ln built	ln built
time	0.140*** (12.95)	0.0391*** (3.98)	−0.024*** (−8.17)	−0.0101*** (−3.73)	0.254*** (10.02)	0.0882*** (3.12)
ln pd	—	0.274* (1.81)	—	−0.0523 (−1.08)	—	−0.520 (−1.28)
multi	—	0.0004 (0.00)	—	−0.0760 (−1.47)	—	−0.206 (−0.53)
ln FDI	—	0.0678*** (3.38)	—	−0.0124* (−1.91)	—	0.135* (2.01)
indus	—	0.0659 (0.18)	—	0.256* (1.87)	—	−1.493 (−1.07)
ln tra	—	0.160*** (4.38)	—	−0.0196 (−1.46)	—	0.506*** (4.52)
integ	—	0.0595 (1.01)	—	−0.0306*** (−2.99)	—	−0.376** (−2.46)
Constant	4.773*** (428.71)	1.319 (1.38)	8.140*** (2,643.36)	8.540*** (26.77)	3.230*** (123.96)	3.652 (1.49)
City Fe	Yes	Yes	Yes	Yes	Yes	Yes
Observations	104	104	104	104	104	104
R-squared	0.363	0.888	0.449	0.759	0.315	0.813
Number of groups	26	26	26	26	26	26

Note: The *t*-statistics for the coefficients are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

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Table 5. Heterogeneity impact of HSR stations on urban land use

Explained variables	ln uln	ln uln	ln farm	ln farm	ln built	ln built
HSR	0.904*** (20.17)	0.401*** (7.80)	−0.121*** (−4.01)	−0.0541** (−2.52)	1.422*** (6.36)	0.645*** (3.12)
HSR × new	−0.145* (−1.93)	−0.151* (−1.87)	−0.00644 (−0.18)	0.00130 (0.05)	0.119 (0.49)	0.150 (0.58)
ln pd	—	0.228* (1.77)	—	−0.0551 (−1.10)	—	−0.838* (−2.04)
multi	—	−0.0864 (−0.63)	—	−0.0635 (−1.26)	—	−0.283 (−0.82)
ln FDI	—	0.0509** (2.69)	—	−0.00955 (−1.46)	—	0.0977 (1.63)
indus	—	0.292 (0.93)	—	0.222 (1.64)	—	−0.579 (−0.48)
ln tra	—	0.149*** (3.87)	—	−0.0198 (−1.50)	—	0.441*** (3.75)
integ	—	0.0493 (0.79)	—	−0.0295** (−2.44)	—	−0.449*** (−3.37)
Constant	4.678*** (350.92)	1.653** (2.08)	8.153*** (1,582.47)	8.561*** (25.27)	3.042*** (104.99)	5.618** (2.10)
City Fe	Yes	Yes	Yes	Yes	Yes	Yes
Observations	104	104	104	104	104	104
R-squared	0.586	0.913	0.579	0.761	0.544	0.852
Number of groups	26	26	26	26	26	26

Note: The *t*-statistics for the coefficients are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

by 1 year, urban space expands by 3.91%. In other words, the opening of HSR has a long-term effect on urban spatial expansion. Second, when the explained variables are ln farm, the coefficients of HSR's opening time are significantly negative, indicating that HSR's opening time inhibits the expansion of agricultural land. Each additional year of HSR's opening results in a 1.01% decrease in agricultural land. Finally, the results are the same as those of urban space when explained variables are ln built, that is, the opening time of HSR expands the scale of other construction land. This is because HSR accelerates the flow of labor, capital, and information and causes their agglomeration in HSR cities, ultimately expanding the market scale of cities. The expansion of urban markets attracts more enterprises and population, forming a circular and cumulative causal relationship. This process takes time. Under the influence of markets, local governments have had to expropriate more agricultural land and convert it into urban space and construction land.

Heterogeneity Impact of HSR Stations on Urban Land Use

HSR stations have different characteristics. Most HSR lines in China are newly constructed. However, because of the influence of urban planning, HSR stations may be either newly built or upgraded from existing stations. This section further analyzes the heterogeneity impact of HSR stations on urban land use by adding a cross term (HSR × new). The coefficients of HSR × new represent the heterogeneous impact of different types of HSR stations on urban land use. The regression results are shown in Table 5.

The coefficients of the cross term are significantly negative at 10% level when the explained variables are ln unu. This indicates that the impact of the new HSR stations on urban spatial expansion is 15.1% lesser than that of existing stations. To reduce construction costs and achieve multicenter urban development, local governments have built many new stations on the outskirts of cities. There is no doubt that the new HSR stations can promote the transformation of land attributes. However, many areas around the HSR stations have not developed well. The existing stations are upgraded from railway stations, mostly located in urban centers. Its impact on transformation of land use attributes is not obvious immediately. However, after the opening of HSR in the existing railway stations, the transport capacity of economic factors has greatly improved. Moreover, because of its location advantages in the city center, the agglomeration and congestion effect are more effective. In addition, the existing stations have serviced before the upgrade. The impact will be greater after the opening of HSR. Through a heterogeneity test of the newly built stations and existing stations, we gain a deeper understanding of the effect of HSR on urban land use.

The estimated results also confirm the previous conclusion that the longer the opening time of HSR, the greater the impact on urban spatial expansion. When agricultural land and other construction land are the explained variables, the cross-term coefficients are not significant. This indicates that the influence of the new stations on agricultural land and other construction land is not different from that of existing stations when other factors are unchanged.

Impact Path of HSR Opening on Urban Land Use

According to the preceding analytical framework, the opening of HSR mainly affects urban land use through the agglomeration effect, congestion effect, and policy effect. This study adopts the step-by-step mediation model to examine the impact path of HSR opening on urban land use (Baron and Kenny 1986). In Fig. 1, we can see that the agglomeration effect and congestion effect may exist simultaneously. The number of employees (M_1) is used to represent the agglomeration effect and congestion effect. The policy effect is represented by local fiscal expenditure (M_2). It represents government intervention in urban planning. M_1 and M_2 are mediation variables. Because of the conclusions in section "Policy Implications," the mediating paths can be directly tested in this section. The examination results of the mediation model are given in Table 6.

First, the explained variable is $\ln M_1$, and the coefficient of HSR opening is significantly positive at 1% level. This indicates that the opening of HSR promotes the increasing of urban labor force. It proves that the opening of HSR produces the agglomeration and congestion effects in cities. Second, the explained variables are urban land use, and the HSR and $\ln M_1$ are added as explanatory variables in the estimation models. The results show that the coefficients of HSR and $\ln M_1$ are all statistically significant at 5% level, indicating that the agglomeration and congestion effects can lead to an increase in urban space and other construction land but in a shrinkage of agricultural land. It proves that the opening of HSR changes the urban land use through the agglomeration and congestion effects. Moreover, as the coefficients of HSR are also significant, the agglomeration and congestion effects play a partial mediating role.

Then we test the impact path of the policy effect. The opening of HSR promotes an increase in the local fiscal expenditure ($\ln M_2$). Also, the local fiscal expenditure ($\ln M_2$) changes the urban land use, indicating that the opening of HSR affects urban land use by increasing the local fiscal expenditure (policy effect).

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Table 6. Impact path of HSR opening on urban land use

Explained variables	Agglomeration and congestion effect				Policy effect			
	ln M_1	ln uln	ln farm	ln built	ln M_2	ln uln	ln farm	ln built
HSR	0.529*** (5.07)	0.217*** (3.67)	−0.034** (−2.55)	0.572*** (3.63)	1.038*** (6.34)	0.181*** (3.71)	−0.039** (−2.58)	0.478*** (2.83)
ln M_1	—	0.158*** (2.98)	−0.037*** (−4.05)	0.324** (2.38)	—	—	—	—
ln M_2	—	—	—	—	—	0.116*** (4.35)	−0.013** (−2.07)	0.256*** (4.13)
ln pd	−0.368 (−0.77)	0.242* (1.87)	−0.068 (−1.25)	−0.675* (−1.79)	−0.503 (−0.65)	0.242 (1.62)	−0.0615 (−1.21)	−0.665*** (−1.78)
multi	−0.796** (−2.66)	0.077 (0.48)	−0.093* (−1.89)	−0.061 (−0.20)	−1.018 (−1.67)	0.069 (0.41)	−0.078 (−1.46)	−0.059 (−0.19)
ln FDI	−0.075 (−1.60)	0.064*** (3.42)	−0.012** (−2.25)	0.121** (2.29)	0.182 (1.66)	0.031 (1.69)	−0.007 (−1.10)	0.050 (0.78)
indus	1.221 (1.08)	0.186 (0.50)	0.266** (2.19)	−1.061 (−0.94)	0.912 (0.47)	0.273 (0.72)	0.233* (1.92)	−0.898 (−0.74)
ln tra	0.146 (1.25)	0.118*** (3.81)	−0.014 (−1.30)	0.402*** (4.12)	1.227*** (5.29)	−0.001 (−0.02)	−0.003 (−0.21)	0.135 (1.30)
integ	−0.166 (−1.33)	0.064 (1.09)	−0.036*** (−2.87)	−0.384*** (−2.98)	−0.556* (−1.83)	0.102* (2.03)	−0.037*** (−2.88)	−0.295** (−2.30)
Constant	5.164 (1.70)	1.072 (1.30)	8.750*** (23.45)	3.711 (1.41)	6.038 (1.28)	1.189 (1.25)	8.640*** (25.18)	3.841 (1.59)
City Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	104	104	104	104	104	104	104	104
R-squared	0.388	0.920	0.785	0.863	0.928	0.930	0.773	0.879
Number of groups	26	26	26	26	26	26	26	26

Note: The t-statistics for the coefficients are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Conclusions and Policy Implications

Conclusions

For more than the last three decades, development in Chinese cities has been characterized by strong urbanization. Land use is changing agricultural land to urban land. This is what is called the land urbanization process. Meanwhile, the *spatiotemporal convergence* effect of HSR promotes the agglomeration of population and industry, which affects the urban spatial distribution and land use. Based on the land use monitoring data of YRD in 1990, 2000, 2010, and 2015, this study uses the DID model to test the causal effect of HSR opening on urban land use.

We find that the land use of YRD has changed greatly from 1990 to 2015. With the expansion of urban space, agricultural land continuously decreases. Furthermore, we built an analytical framework to illustrate that the opening of HSR affects urban land use through the agglomeration effect, congestion effect, and policy effect. The empirical results suggest that the change in urban land use, as an inevitable result of urbanization, is deeply affected by HSR. The opening of HSR increases urban space by 14.9% and other construction land by 40.7% but reduces agricultural land by 7.2%.

In addition, this study adopts the opening time of HSR instead of dummy variables to further test the impact of the opening time of HSR on urban land use. The estimated result is significantly positive, which proves the time effect of HSR. For each additional year of HSR service in the city, urban space will expand by 3.91% and other construction land will expand by 8.82%, but agricultural land will shrink by 1.01%. This suggests that there is a cumulative effect of HSR opening on urban land use. China's HSR stations are divided into new HSR stations and existing stations upgraded from the original railway stations. Through the heterogeneity test, the estimation results show that HSR stations' characteristics have a significant heterogeneity impact on urban land use. The impact of the existing stations on urban spatial expansion is 15.1% greater than that of new stations. With continuous in-depth research, this study not only proves the time effect and heterogeneity impact of HSR but also reflects the robustness of the empirical results.

Policy Implications

In the context of the integration of YRD and the rapid development of HSR, the conclusions of this study accurately reveal the important role of HSR in the changing process of urban land use. This provides theoretical support for the government and relevant departments to carry out scientific urban planning and avoid the negative impact of blind expansion.

First, urbanization is an inevitable trend under the development of HSR. The opening of HSR will lead to an increase in population in cities and HSR station areas, thereby promoting the expansion of urban space. Therefore, it is necessary to balance the increase in urban population and the expansion of urban space reasonably to avoid the disorderly sprawl of cities. In the construction and planning of cities and HSR stations, the scale and boundary should be determined first based on the scale of urban population and industry. At the same time, local governments should optimize the spatial structure and the distribution of population and industry around HSR station areas. It should also be forward-looking to avoid planning while building and aim to promote the positive interaction between HSR opening and urban development.

Second, in the process of urban spatial expansion, it is necessary to avoid enclave construction caused by the construction of HSR stations and avoid urban sprawl caused by blind expansion. The reconstruction of the old town and the construction around the built-up area should be the main ways to realize the urban spatial expansion. The government should adhere to the strictest possible systems for protecting agricultural land and saving land when expanding urban space and building HSR stations.

Third, the government should plan the location of HSR stations rationally. The newly built HSR lines should reduce the division of cities as far as possible. The location of new stations should be close to the urban center or built-up areas. HSR stations' location and scale should be reasonably determined to promote the integrated development of stations and cities. These approaches will enable HSR stations to serve the city better.

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Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The data include Chinese land use remote sensing data (30 m × 30 m) from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC); the data of HSR opening from the Website of National Railway Administration; and other socioeconomic data from the China City Statistical Yearbook of 1990, 2000, 2010, and 2015.

Acknowledgments

This work was supported by the Ministry of Education (MOE) of the People's Republic of China) Project of Humanities and Social Sciences (Project No. 17YJC790021), the China Scholarship Council fund (File No. 201906480004), and the National Natural Science Foundation of China (NNSFC) (No. 41871169).

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