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Urbanization, land conversion, and arable land in Chinese cities: The ripple effects of high-speed rail

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ABSTRACT

Since 2005, Chinese transit authorities have made substantial investments in high-speed rail (HSR) infrastructure, driven by the ambition to connect all cities with over half a million people. This study estimates the impact of HSR network expansion on agricultural land conversion using a panel dataset for 171 Chinese cities that developed HSR infrastructure between 2005 and 2012. Structural equation modeling (SEM) estimation results show that HSR contributed indirectly to arable land requisition but directly to agricultural land converted for urban uses. At the same time, real-estate investments are driving agricultural land depletion in the process of China's urbanization. In addition, HSR network expansion exhibits a geographical pattern where the effect on agricultural land conversion was considerably stronger in the western region than among eastern cities, suggesting that HSR-driven land conversion was more likely to occur in less developed places.

1. Introduction

Since 2005, high-speed rail (HSR) has become a vital government investment strategy in China to improve transportation services and economic development. A nationwide HSR network was developed systematically through the 2003–2020 Medium- and Long-Term Railway Plan (henceforth, MLTRP),[1] initiated by the former Ministry of Railways (MOR)[2] in 2004. The main objective of the 2004 plan was to build a national high-speed rail (HSR) network[3] composed of four north-south and four east-west bound corridors (Fig. 1), comprising 12,000 km of rail lines by 2020. The plan was updated in 2008 to extend the network to 16,000 km and again in 2016 to extend to 38,000 km.

With strong support from the central government and active implementation by local governments, the trunk line system was completed in 2014 (Zhao, 2016). During the period of the 12th Five-Year-Plan (2011–2015), RMB 2.33 trillion (or US$ 359.5 billion), representing 65% of total new rail transit line investment, was allocated to develop HSR lines, significantly exceeding total national railway infrastructure investment in the previous Five-Year Plan. Most of the funding came from the central government, with the rest being financed by local governments, railway bonds, and national banks (Chen & Haynes, 2015). The massive investment facilitated the HSR system's rapid development. By the end of 2020, China developed the most extensive HSR network system in the world, with a total track length of 38,000 km (The State Council, 2020). According to the most recent long-term rail plan, the HSR network will be expanded to 70,000 km by 2035, ultimately serving every city with over half a million people (NDRC, 2016).

HSR network development directly affects urban land-use change

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[1] MLTRP looks ahead at the next 15 years and is complemented by a series of Five-Year Plans. It was jointly prepared by the National Development and Reform Commission (NDRC), Ministry of Transportation (MOT), and China Railway Corporation (CRC; or their equivalents at the time) based on a detailed analytical process. Hence, it has the highest level of government authority and rarely changes once approved (Lawrence et al., 2019).

[2] In 2013, the former MOR was reformed and split into two new organizations to separate railway administration from its commercial functions. Administrative responsibilities were assigned to the National Railway Administration (NRA) affiliated with the MOT, while corporate duties were assigned to the CRC.

[3] The grid scope includes high-speed railways with a design speed of 300–350 km per hour, passenger trains at 250 km per hour, and passenger and freight railroads at 200 km per hour. Intercity railways, intercity rail transit, and metro systems are all excluded.

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(Chen et al., 2020). Indeed, several studies have found that transportation infrastructure plays a major role in shaping the spatial pattern of land use (Kasraian et al., 2016). In Chinese studies, rapid urban expansion has been attributed to local government stimulus[5] (Wu, 2019; Zhu & Roy, 2007), rural-urban migration, and urban economic development (Xie et al., 2005). However, no study has systematically examined the simultaneous impact of HSR on urbanization and agricultural land use change. At the same time, arable land in China has declined to approximately 123 million hectares (ha.), or 12.8% of its total land area, between 1996 and 2003 (Ministry of Land and Resources [MLR], Xinhua News Agency, 2004). Thus, food security for the projected 1.4 billion citizens (the Outline of the National Overall Planning on Land Use 2006–2020, The State Council, 2008) and agriculture sustainability have become a primary concern, particularly in the climate change era. Understanding the impact of HSR expansion is therefore indispensable for rural land policy and the planning of transportation infrastructure.

The transformative effects of Chinese HSR have also raised equity issues (Chen & Haynes, 2017), which often entails a tradeoff against mobility as the goal of transit-oriented planning. On the one hand, the HSR expansion has brought about job creation (Lin, 2017), appreciating property values (Chen et al., 2019), and population churn (Deng et al., 2019). On the other hand, studies show that expansion may reduce GDP and GDP per capita among households in rural areas lacking HSR access (Qin, 2017), reduce train services for less-populous counties (Qin, 2017), and increase income disparities through accelerated urbanization (Ren et al., 2020; Zheng & Kahn, 2013).

The present study is chiefly concerned with the impact of Chinese HSR expansion on agricultural land use through a process where arable land is converted for urban usage. Such conversion occurs when HSR expansion increases the intensity of rural-urban migration, urban sprawl, and urban development. Hence, the "ripple effect" refers to the indirect effect of HSR expansion on agricultural land mediated by forces of urbanization.

In contrast to previous studies, this study has several distinct features. First, it is the first to employ structural equation modelling (SEM) to evaluate the land-use effects of HSR network expansion. An equation is said to be "structural" when the available data provide sufficient evidence for the inference that one variable has a causal effect on an outcome variable (Ewing & Park, 2020). As such, SEM allows a theory of change to be expressed explicitly through path diagrams that consider causal factors and confounding variables in a single unified framework (Pearl, 2012). The structural equations make it possible for direct and indirect paths to be identified while establishing causality in the absence of a randomized controlled trial. The identification strategy provides a statistically-equivalent alternative for exploring the land use implications of a large infrastructure project using observational data. The clarification of this relationship will help in understanding the causal mechanism through which HSR exerts its impact on agricultural land.

Second, the present study is the first to disentangle the causal relationship between HSR expansion and agricultural land using a panel of 171 Chinese cities from 2005 to 2012 to consider the often-ignored initial stage of HSR development. During this period, the new Law on Land Administration (Appendix –Table A.1) provided the legal impetus for the conversion of rural land in urban construction usage. At the same time, the period witnessed the growing role of local governments as land developers (Lichtenberg & Ding, 2009) and the enactment of the city planning law that transferred the right to regulate land development from the central state to local authorities (Wu, 2019). The use of a panel dataset covering the "transition" captures the dynamics of these critical

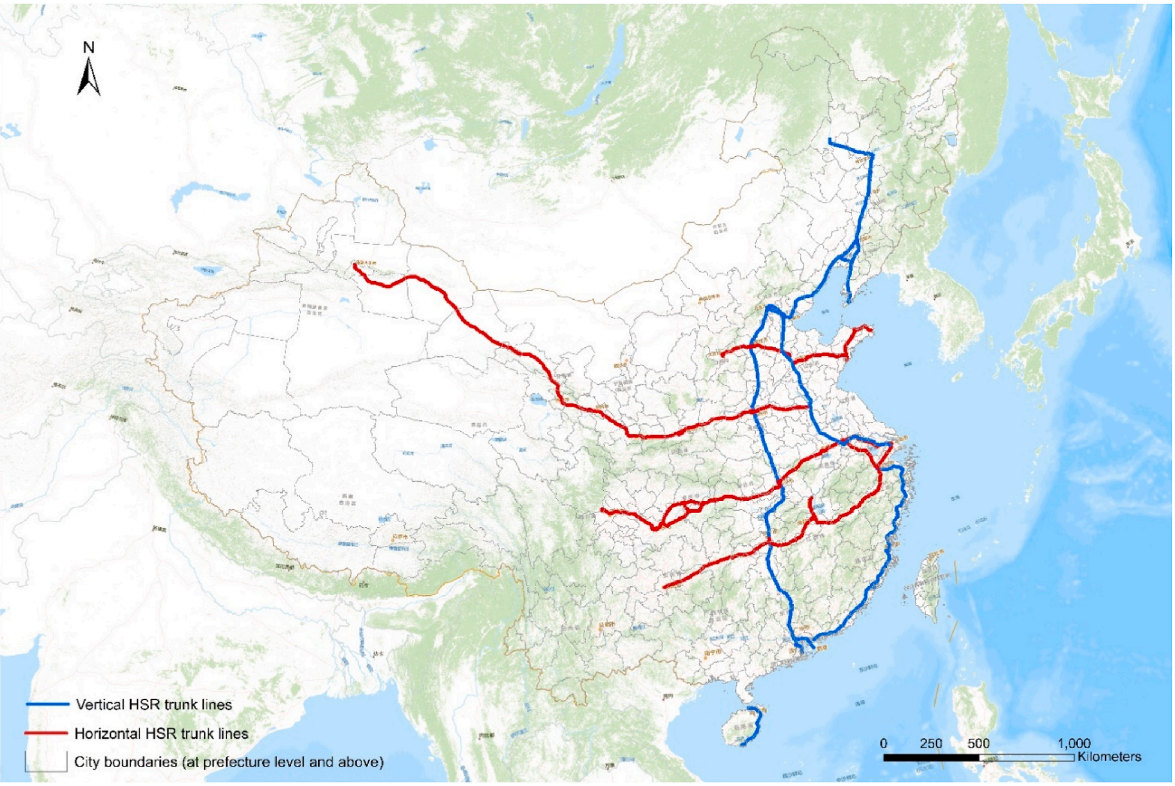

Fig. 1. The original trunk line system of China's HSR network (2003–2020)
Source: The Railway Development Plan during the 12th Five-Year Plan (2011–2015).

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[4] In general, before 2014, local governments had the right to expropriate rural collective land from farmers at a low price and transfer it to individuals or institutions at artificially high prices through bidding and auctions (Wu, 2019).

developments.

The rest of the paper is organized as follows. The following section reviews the literature pertaining to the impact of HSR networks on land use change and the mechanisms through which rural arable land is converted for urban uses. Section 2 describes the theoretical framework and the SEM estimation method. Section 3 introduces the panel data for Chinese cities. Results are reported in Section 4, and Section 5 concludes the paper.

1.1. The impact of China's HSR expansion on land use

As the 2003–2020 MLTRP describes, Chinese HSR was established to expand intercity transport capacity by providing high-speed travel at speeds greater than 200 km per hour. To meet that objective, the HSR authority upgraded about 1,035 km of existing rail lines to high-speed tracks between 2003 and 2008. Subsequent amendments to MLTRP led to an upgrade of 2,349 km of rail lines in 2009 and a further 3,804 km expansion in 2012 (MLTRP Appendix -Table A.2). China's HSR development continued to accelerate in the last decade, which saw the growth of service length by an annual average of 54%.[5]

HSR ideally links large urban centers and stops only in dense population hubs to maintain high speed. In the case of China, most newly developed HSR stations are located either in suburban or urban fringe locations to economize on land costs (Wang et al., 2013). Chen and Haynes (2015) estimated that the average distance between a Chinese HSR station and the closest urban center is over 10 km. Officially, NDRC has the legal authority to select the location of a new HSR station. In practice, local governments' active pursuit of transit-oriented development through leveraging access to HSR (Zhu, 2021) pushes HSR stations further out to the rural fringes (Garmendia et al., 2012). Consequently, new HSR stations ended up in locations far away from existing urban centers, and railway alignments passed through large tracks of previously undeveloped farmland.

How railway infrastructure development contributes to urban space expansion at the expense of agricultural land is related to two major mechanisms. The first pertains to the ability of new HSR lines to improve spatial accessibility by connecting major population centers. The second is through enhancing the economic potential of cities along the route and the stations, which stimulates population agglomeration, and leads to faster growth of urban built-up areas (Diao et al., 2017; Levinson, 2008; Zheng and Kahn, 2013). Previous studies have examined the implications of HSR network expansion on urban land structural change (Chen et al., 2020) and use intensity (Niu et al., 2021). However, it remains unclear how railroad rights-of-way, transfer stations, and new terminals outside urban cores contribute to the depletion of Chinese agricultural land already underway prior to the rise of high-speed railways. With this in mind, the paper turn to the literature on urban land supply in the next section.

1.2. Urban land supply in China

Two resources exist on the supply side to meet urban land demand in China. The first is the new land quota that the State annually allocates directly to a city upon the approval of the transportation infrastructure plan. The second and more pliant source of supply is the conversion of non-construction land (e.g., rivers or forests) and agricultural land (e.g., arable land) for urban construction. This paper focuses on the second source, namely, the conversion of arable land into urban space.

Arable land conversion for urban construction is motivated by multiple factors, including land use policy change, rural-urban migration, rural land marketization, and agricultural modernization (Creighton et al., 2016; Linkous, 2016; Semedi & Bakker, 2014; Vachadze, 2013; Ye, 2015). In the case of China, conversion policies have experienced several changes since the 1980s. Before China's reform, any market and commercial use was strictly prohibited.[6] In the early 1980s, the National People's Congress enacted the *Law on Land Administration*, allowing farmer collectives to lease rural land. Subsequently, a system of identification and registration of land ownership and usufruct rights was introduced for rural farmers in 2005. Since 2013, the separation of ownership, contractual, and operation rights among registered agricultural landowners has been fully implemented (Wang & Zhang, 2017). This study is drawn from the period between 2005 and 2012, during which the conversion of arable land was the most important source of supply for urban construction (Yang, Xu, & Long, 2016).

While the majority of China's population consists of farmers who earn considerably less from traditional farming than city dwellers, the strong demand for urban space requires arable land to be converted to support rapid industrialization and urban growth (Kong et al., 2018). Between 2001 and 2011, the annexation of agricultural land has accounted for nine-tenths of the increase in urban construction land in China, leading to the mass migration of rural labor force into cities (WorldBank and the People's Republic of China Development ResearchCenterof the State Council, 2014). The loss of rural population via agricultural land conversion frequently leads to a fall in investments. For instance, Qin (2017) showed that places bypassed by railway upgrades subsequently suffered slower per capita income growth, mainly from falling fixed-asset investments driven by population losses. Rural areas also experienced rising arable land abandonment, especially in the western provinces (Liu, Zhao, & Song, 2017), leading to further losses in the rural labor force stemming from the urban-rural income gap (Huang et al., 2015; Huang & Chan, 2018). At the same time, current policies fall short of addressing equity concerns that arise when rural migrant workers move to cities for better-paying jobs but mostly end up at the bottom of the urban informal sector.

As Hsing (2010) documented, agricultural land conversion in China has become the principal means to accommodate urban sprawl that occurred via accelerating rural-urban migration, which heightens the demand for new housing in cities (Haas & Osland, 2014; Wang et al., 2010), and this increases the rate of agricultural land conversion. In turn, the rising costs of arable land requisition placed enormous financial stress on local governments, who must compensate the displaced farmers. Previously, local officials used the revenues generated via public auction of converted arable land to offset the budget deficit caused by rising compensation costs (Kong et al., 2018). Recently, local governments increased the value of converted arable land through transit-oriented development (Shen & Wu, 2017, 2020) by leveraging the locations of the new HSR stations. Wu (2019) defines the shift in strategy from traditional land sales to an emphasis on leveraging TOD as land financialization.

1.3. Research gap

As the above review indicates, different strands of literature have examined the land-use implications of HSR development in accelerating agricultural land conversion in China. However, no study has investigated the impact of HSR infrastructure on rural land in a causal inference framework. Existing literature suggests that (i) Chinese HSR has contributed to urban space expansion and (ii) urban growth has led to arable land depletion. However, these do not consider the ripple effects of HSR expansion on rural land through the mediating mechanism of urbanization. Disaggregating the chain of causality into direct and indirect components require a systems-based approach with multiple equations and multiple dependent variables. The following section proposes the framework of SEM to capture the ripple effects of HSR

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[5] Calculated based on the data released from *Sustainable Development of Transport in China* issued by the State Council Information Office of National Bureau of Statistics of China (2020).

[6] Law on Land Administration Appendix –Table A.1.

infrastructure on agricultural land in Chinese municipalities.

2. Theory & method

2.1. SEM standard workflow

A structural equation model is a model-centered estimation method that evaluates how well a theoretical model fits the data (Grace et al., 2012). As Kline (2015) points out, a structural equation model refers to a suite of estimation procedures instead of a single statistical technique. The procedures include, first, the development of a system of equations based on current knowledge, theories, and hypotheses about the data generating processes (Grace, 2006). The validity of the structural equation model is then tested using the available information, allowing the rejection of inconsistent models. Second, a structural equation model features the ability to decompose the total impact of a predictor into the direct and indirect effects on an outcome variable (Ewing & Park, 2020). The decomposition feature is especially useful for the present study to estimate the ripple effects of HSR network expansion over all possible pathways implied by the theoretical framework.

SEM is the statistical foundation of the “causal revolution” (Pearl & Mackenzie, 2018), which seeks mechanism-based explanations of a social phenomenon, and thus represents a fundamental departure from correlational methods of statistical analysis (Halpern & Pearl, 2005). Central to the SEM approach is directional associations that specify which explanatory variables have a causal effect on an outcome variable (Golob, 2003). This study follows the six basic steps (Fig. 2) Kline (2015) recommended to facilitate causal interpretation. The following sections 2.2-2.4 illustrate Step I, namely, the model’s specification to articulate the theoretical relationships between multiple explanatory and multiple outcome variables using equations (Hur, Han, Yoo, & Moon, 2015). Section 2.5 explains Step II, namely, model identification to determine whether the SEM parameters can be estimated (“identified”) based on the available information.[7]

2.2. Impact of HSR network expansion on arable land

This section begins with the conceptualization of arable land requisition as a response to demand pressures arising from HSR network expansion, the growing urban fringe, and real estate investments:

$$arableLand_{i,t} = f\left(\overbrace{\Delta HSR_{i,t-1}}^{+}, \overbrace{\Delta urbArea_{i,t}}^{+}, \overbrace{realEstInv_{i,t-1}}^{+}\right), \tag{1}$$

where $i = 1, \ldots, N$ is the set of municipalities,[8] and t is the year index. According to Equation (1), the construction of new HSR tracks in municipality i at time t-1 ($\Delta HSR_{i,t-1}$) leads to the increased requisition of arable land in the same municipality i at time t ($arableLand_{i,t}$). Embedded in this relationship is the intuitive hypothesis that part of arable land losses is directly attributable to an increase in HSR track length, urban space expansion ($\Delta urbArea_{i,t}$), and land financialization through real-estate investments ($realEstInv_{i,t-1}$) as discussed in Section 1. To empirically operationalize Equation (1), we specify the following regression equation:[9]

$$arableLand_{i,t} = \beta_0 + \beta_1\, \Delta HSR_{i,t-1} + \beta_2\, \Delta urbArea_{i,t} + \beta_3 realEstInv_{i,t-1} + \varepsilon_{1i,t}\,, \tag{1.1}$$

where the slope coefficient β_1 is the key parameter of interest quantifying the direct effect of new HSR construction, $\Delta HSR_{i,t-1} \rightarrow arableLand_{i,t}$. Note that HSR expansion here is associated with a higher rate of land appropriation. Therefore, β_1 is expected to enter with a positive sign. At the same time, the increment in urban areas and private investments in the city’s real estate development are two control variables that directly contribute to arable land requisition, suggesting a positive sign for β_2 and β_3, respectively. Finally, the residual $\varepsilon_{1i,t}$ is a random disturbance term.

Requisitioned arable land is subsequently converted into urban construction use, which provides the other indicator of HSR impact on agricultural land. The two indicators, arable and urban construction land, are complementary as they capture different aspects of agricultural land depletion. The former belongs to rural collectives, while the latter belongs to the state, which has the authority to direct converted land for urban use. Owing to their complementary nature, an alternative specification replaces the dependent variable in (1.1) with land newly converted for urban construction use in prefecture i at time t ($constructLand_{i,t}$), with everything else remaining the same as follows:[10]

$$constructLand_{i,t} = \beta_0^{'} + \beta_1^{'}\, \Delta HSR_{i,t-1} + \beta_2^{'}\, \Delta urbArea_{i,t} + \beta_3^{'} realEstInv_{i,t-1} + \varepsilon_{1i,t}^{'}\,, \tag{1.1’}$$

2.3. City growth and urbanization under transit catalyst

Urbanization in China could be classified into two types. The first type is manifested by the growth of cities via urban economic development and population clustering (Long et al., 2007). Hence, territorial expansion at the peri-urban edge is an endogenous variable driven by the growing urban population ($\Delta urbHH_{t-1}$). The second type occurs through financialization (Wu, 2019), where land is collateral for real-estate investments ($realEstInv_{t-1}$) driven by local governments’ large-scale infrastructure and mega-urban projects (Shen & Wu, 2017). Equation (2) reflects the above arguments:

$$\Delta urbArea_{i,t} = f\left(\overbrace{\Delta urbHH_{i,t-1}}^{+}, \overbrace{realEstInv_{i,t-1}}^{+}\right), \tag{2}$$

where the directions of the hypothesized effects are indicated by the positive signs. The idea is that urban sprawl occurs as individuals and households who migrated to the cities end up in the outskirts to take advantage of cheaper housing (Brueckner, 2000). The following linearization operationalizes this idea:

$$\Delta urbArea_{i,t} = \delta_0 + \delta_1 \Delta urbHH_{i,t-1} + \ \delta_2\ realEstInv_{i,t-1} + \ \varepsilon_{2i,t} \tag{2.1}$$

The next equation specifies how the population of urban households as an endogenous variable that responds to transit mobility improvement and the urban-rural living standards gap ($urbStd_{t-1}$):

$$\Delta urbHH_{i,t} = f\left(\overbrace{HSR_{i,t-1}}^{+}, \overbrace{urbStd_{i,t-1}}^{+}\right) \tag{3}$$

The specification is inspired by the influential model of the new economic geography (Fujita et al., 1999), which views improved accessibility as the primary mechanism through which transport infrastructure catalyzes the growing size of cities. To maintain a high speed,

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[7] SEM approach’s ability to quantify an unobserved variable using measurable indicators based on the procedure of confirmatory factor analysis should also be noted, while the present study does not include a measurement component because all the variables considered for the SEM analysis are observed variables.

[8] The vector of controls ideally should include other transportation modes. However, conventional railroads had remained unchanged before the HSR network began its rapid ascent and thus cannot be a confounding factor affecting agricultural land use.

[9] An urban area can only expand either by arable land requisition or newly-converted land for construction use in the same period t.

[10] The prime “’” marker is used to differentiate the coefficients from those in Equation (1.1).

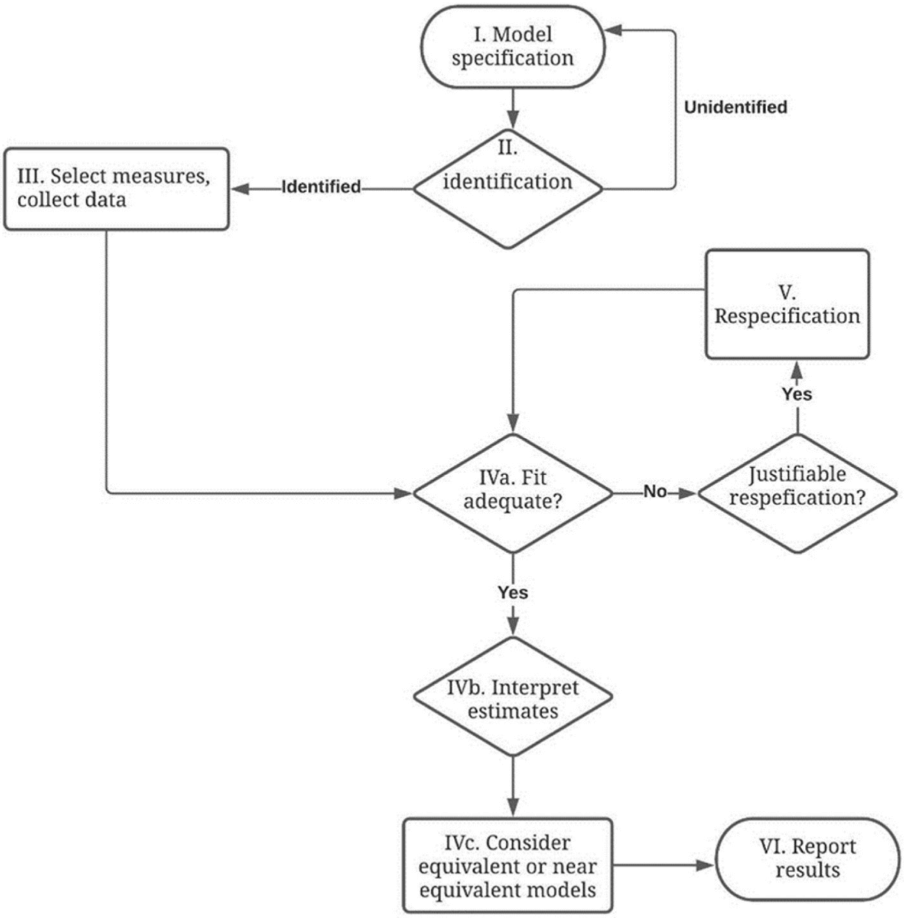

Fig. 2. SEM flowchart. Adapted from Kline (2015).

HSR stops only in dense urban areas with sufficient demand for travel, in contrast to small towns and rural areas. In a climate of intense intercity competition, the impact of HSR on urban population growth is consistent with place-based strategies in which Chinese cities boost their image using mega-government infrastructure projects to attract footloose capital and new residents (Wu, 2019). Hence, urban-biased resource allocation, such as HSR investment, may play a role in the rapid growth of the Chinese urban population in the past few decades (Kanbur & Zhang, 2005; Xu, 2011). The resulting rural-urban migration is reinforced by the differential urban and rural living standards (Young, 2013). Equation (3.1) below operationalizes these causal statements:

$$\Delta urbHH_{i,t} = \gamma_0 + \gamma_1 HSR_{i,t-1} + \gamma_2 urbStd_{i,t-1} + \varepsilon_{3i,t}, \tag{3.1}$$

Equations (1)–(3) together imply the mediated path, $HSR_i \rightarrow \Delta urbHH_i \rightarrow \Delta urbArea_i \rightarrow arableLand_i$, through which HSR expansion indirectly affects arable-land requisition or newly-converted urban construction land use (as the alternative measure in Equation (1.1')). Thus, given the linear counterpart Equations (1.1), (2.1) and (3.1), the product of the individual coefficients, $\gamma_1 \Delta\delta_1 \Delta\beta_2$, measures the indirect effect on arable-land requisition of a unit change in HSR alignment (while $\gamma_1 \Delta\delta_1 \Delta\beta_2^{'}$ measures the indirect impact on newly-converted urban construction land).

2.4. From annual increase of HSR expansion to the cumulative total

What distinguishes SEM from other estimation procedures is the ability to discriminate between alternative mechanisms by examining variables simultaneously in a single system of equations. Thus, the arrow diagram of Fig. 3 depicts the baseline distinct causal pathways articulated by Equations (1.1) - (3.1). The two remaining causal paths are explained next. The first is the arrow pointing from other investments ($othInv_{t-1}$) to HSR expansion. As described in Equation (4) below, coefficient θ_1 captures the degree to which HSR expansion is dependent on public funding in the same period, which is included in $othInv_{t-1}$. The second is the arrow pointing from previous HSR development ($\Delta HSR_{i,t-1}$) to the total length of the Chinese HSR network in the current period. This causal relationship is captured in Equation (5), which links annual increments of HSR expansion to the cumulative total alignment ($HSR_{i,t}$).

$$\Delta HSR_{i,t-1} = \theta_0 + \theta_1 othInv_{t-1} + \varepsilon_{4i,t}, \tag{4}$$

$$HSR_{i,t} = \rho_0 + \rho_1 \Delta HSR_{i,t-1} + \varepsilon_{5i,t} \tag{5}$$

2.5. Model identification

The specified equations for Model A (Fig. 3) consider eight variables, namely $arableLand_{i,t}$, $\Delta HSR_{i,t-1}$, $HSR_{i,t-1}$, $\Delta urbArea_{i,t}$, $realEstInv_{i,t-1}$, $\Delta urbHH_{i,t-1}$, $urbStd_{i,t-1}$, and $othInv_{t-1}$. Model B in Fig. 3 also considers eight variables, albeit with arable-land requisition replaced by $constructLand_{i,t}$. This section examines whether the system of equations is identified, or whether it is possible to estimate the path coefficients using the available data. A necessary condition for model identification is the number of correlations between the variables exceeding or equaling the number of the unknown parameters (Kenny, 1979; Kline, 2015). Nine unknown path coefficients (β_1, β_2, β_3, δ_1, δ_2, γ_1, γ_2, θ_1, and ρ_1) need to be estimated in the model for arable land (Model A). With n = 8 variables, there are n (n-1)/2 = 28 unique correlations, which is greater in number than the unknowns (28 > 9). Therefore, the SEM for

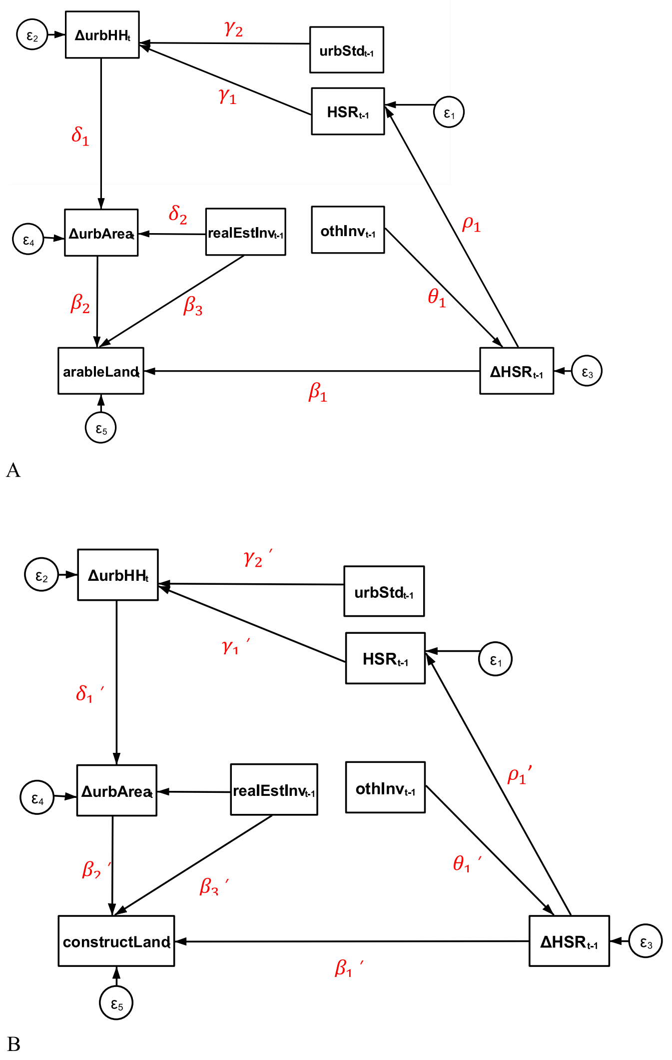

Fig. 3. Path diagram of SEM causal links between the exogenous and endogenous variables.

arable-land requisition meets the identification requirement. Model B for urban construction land is similarly identified.

3. Materials

This study considers the dataset for 171 Chinese cities comprising the four special municipalities directly under the central government, namely Beijing, Tianjin, Shanghai, and Chongqing, provincial capitals, and prefectures passed through by an HSR line. These 171 cities anchor the Chinese HSR system through at least one HSR line passing through them by 2012, marking the end of this study's focus period. During the same period, local governments from coastal regions to inner land aggressively converted agricultural land into urban space, especially in economically-developed cities experiencing a large influx of rural workers. The result was the intensifying conflict between agricultural land regulations and urban development, with arable land transferred for urban construction use at the center of the controversies. The following sections, 3.1–3.4, discuss the variables collected for this study (see Table 1 for variable description, basic statistics, and key symbols).

3.1. HSR network data

HSR alignment dataset (for the variables $HSR_{i,t}$ and $\Delta HSR_{i,t-1}$) was obtained from the Urban Research Center at Tsinghua University's School of Architecture, accessible through the Beijing City Lab website. The dataset reveals a mean HSR alignment of 4.8 km for the 171 cities in 2005 that rose to 101.9 km in 2012, indicating an average annual increase rate of 29% (Table 2). There is also a great deal of track-length variability as prefectures connected to regional hubs or the four special municipalities experienced much more rapid expansion of the HSR network than other prefectures with similar population size or travel demand. For example, the small city Lu'an experienced the fastest growth early on, adding at least 37 km of HSR tracks in 2006 because it is on the *Hurong* line, which links the regional hub Nanjing to a provincial capital Hefei. In the same year, 133 cities that were not part of the primary grid did not see any HSR track expansion. Similarly, Chongqing and Mudanjiang saw the most significant increase in 2012, each adding over 73 km of HSR tracks to the previous total. Chongqing is one of the four municipalities and a terminal on the *Hurong line*. Despite being a peripheral city, Mudanjiang is on the *Jingha* line that connects Beijing to Harbin.

3.2. Arable land data

The main outcome variable of interest is arable-land requisition ($arableLand_{i,t}$), available at the prefectural level and obtained from the *Urban Construction Statistical Yearbook*. In China, appropriated arable land is primarily used for non-farm uses. As described in the *State Land Resource Yearbook*, it is generally obtained from state allocation,[11] granting, or leasing after a transfer of property rights to the government through an administrative mechanism. This flow variable measures agricultural land previously owned by farmer collectives and reserved for urban development after conversion.

Following a requisition, arable land is added to local government's land quota, which represents the amount of land that can be allocated for various urban uses. In the case of transportation projects such as HSR infrastructure intended for the public, the local government has the responsibility to offer land for HSR stations and rights-of-way for HSR passenger services from the available land quota. More generally, requisition is an acquisition process that reserves arable land for future use but does not make it immediately available for urban construction activities (Du & Peiser, 2014) that will be discussed next.

3.3. Urban construction land data

After transfer of property rights, farmland can be developed for residential, commercial, industrial, transit infrastructure, green space, municipal utilities, and other public service use. In China, all these development activities take place on urban construction land, defined as land quota, which consists of two types. The first type corresponds to land reserved and eventually allocated for future public development projects after conversion (*nongzhuanjian*), while the second to land sold in market to generate revenues for local government (*churang*). The latter type distinguishes the variable urban construction land ($constructLand_{i,t}$) from arable-land requisition in terms of government's ability to generate revenues through market mechanism. The data collected from *Urban Construction Statistical Yearbook* indicate that newly-added urban construction land enables nearly all HSR cities to expand their urban areas every year between 2005 and 2012.

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[11] The allocation of state-owned land is much more rigid than that through conversion methods. It is not a significant source of variations in either arable land requisition or land converted for urban construction.

Table 1a
List of variables used in the structural equation models.

Variable	Description	Type	Obs.	Mean	Std. Dev.	Min	Max
arableLand	Arable land requisition (sq km)	Endogenous	1365	2.542	7.318	0	131.8
constructLand	Land newly converted for urban construction use (sq km)	Endogenous	1326	6.368	7.9	0	82.369
HSR	Cumulative HSR track (km)	Endogenous	1366	47.462	64.821	0	762.772
Δ *HSR*	Incremental HSR track (km)	Exogenous	1193	13.872	17.362	0	144.294
Δ *urbArea*	Change in urban area (sq km)	Endogenous	1114	10.445	99.012	−973.81	1083
Δ *urbHH*	Change in urban household population (10,000 ppl)	Endogenous	1193	3.972	27.605	−521.23	524.37
urbStd	Urban living standard relative to rural	Exogenous	1309	2.727	0.619	0	6.456
realEstInv	Real estate investments (100 million yuan)	Exogenous	1362	186.95	336.237	1.31	3153.45
othInv	Other investments (100 million yuan)	Exogenous	1362	696.48	770.52	21.59	8121.6
balance	The land use structure change index at city level nationwide	Endogenous	1001	0.656	0.113	0.129	0.891
roadArea	Size of the road area (million sq m)	Exogenous	1001	17.640	24.201	0	268.13

Note: each numerical cell records a summary statistic for the 171 HSR cities from 2005 to 2012.

Table 1b
Table of unique pairwise correlation coefficients.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) $arableLand_t$	1.0000										
(2) $constructLand_t$	0.2879	1.0000									
(3) HSR_{t-1}	0.2139	0.4436	1.0000								
(4) $\Delta\ HSR_{t-1}$	0.1638	0.4034	0.6708	1.0000							
(5) $\Delta\ urbArea_t$	0.1466	0.1776	0.1154	0.0591	1.0000						
(6) $\Delta\ urbHH_t$	0.1745	0.1962	0.3322	0.2873	0.1280	1.0000					
(7) $urbStd_{t-1}$	−0.0598	−0.2175	−0.1652	−0.1022	−0.0322	0.0376	1.0000				
(8) $realEstInv_{t-1}$	0.3518	0.5538	0.4825	0.3393	0.1667	0.2405	−0.2110	1.0000			
(9) $othInv_{t-1}$	0.3549	0.7105	0.5826	0.4532	0.1785	0.2973	−0.2163	0.8143	1.0000		
(10) $balance_{t-1}$	0.1480	0.2692	0.2817	0.1805	0.0885	0.0648	−0.0295	0.3004	0.3191	1.0000	
(11) $roadArea_{t-1}$	0.3531	0.5212	0.4082	0.2763	0.1597	0.2103	−0.1359	0.7927	0.7452	0.2844	1.0000

Note: each cell records the correlation coefficient between the column variable and the row variable for the 171 HSR cities from 2005 to 2012.

Table 1c
Table of key symbols.

Symbol	Description	Equation
$\beta_1\ (\beta_1^{'})$	Coefficient on $\Delta HSR_{i,t-1}$	1.1 (1.1′)
$\beta_2\ (\beta_2^{'})$	Coefficient on $\Delta urbArea_{i,t}$	1.1 (1.1′)
$\beta_3\ (\beta_3^{'})$	Coefficient on $realEstInv_{i,t-1}$	1.1 (1.1′)
δ_1	Coefficient on $\Delta urbHH_{i,t-1}$	2.1
δ_2	Coefficient on $realEstInv_{i,t-1}$	2.1
γ_1	Coefficient on $HSR_{i,t-1}$	3.1
γ_2	Coefficient on $urbStd_{i,t-1}$	3.1
θ_1	Coefficient on $othInv_{t-1}$	4
ρ_1	Coefficient on $\Delta HSR_{i,t-1}$	5

3.4. Other land-use and economic data

Urban household population data $(urbHH_{i,t})$ were collected from the *China Statistical Yearbook for Regional Economy* for every HSR city between 2005 and 2012.[12] Economic indicators include private real estate investments $(realEstInv_{i,t})$ and total fixed assets investments; the latter contain investments in HSR infrastructure and private construction projects $(othInv_{i,t})$ for a particular year.

This study also controls for the consumption expenditures ratio between urban and rural households $(urbStd_{i,t})$ to capture the degree of income disparities between rural and urban residents. The ratio is partly driven by the urban-rural price differentials (including land/housing prices) and partly by the income gap between urban and rural areas. On

Table 2
The mean values of arable-land requisition ($arableLand_{i,\ t}$), land converted for urban construction usage ($constructLand_{i,\ t}$), and cumulative HSR length ($HSR_{i,t}$). The last two columns record the annual contemporaneous correlations between these variables.

Year	Mean $HSR_{i,t}$ (km)	Mean $arableLand_{i,t}$ (sq.km)	Mean $constructLand_{i,t}$ (sq. km)	Correlation $r_{HSR,\ arableLand}$	Correlation $r_{HSR,\ constructLand}$
2005	4.80	2.35	3.54	−0.01	0.18
2006	9.60	2.48	5.48	0.15	0.19
2007	17.53	1.58	5.34	0.28	0.30
2008	33.20	2.54	4.09	0.07	0.29
2009	53.51	2.00	7.94	0.22	0.45
2010	71.81	2.76	6.44	0.36	0.37
2011	88.15	2.93	10.37	0.45	0.57
2012	101.86	3.70	7.64	0.20	0.57

Note: $t = 2005,\ 2006, \ldots, 2012$ represents the time index; $i = 1, 2, \ldots,\ 171$ represents the index for the Chinese cities analyzed in this study.

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[12] Residents with the so-called Hukou—a legal record that determines where a resident can live. Therefore, the population data exclude the migrant population and include registered residents relocated elsewhere.

average, urban households have earned an income 2.7 times that of their rural counterparts since China's economic reform (National Bureau of Statistics of China [NBSC], 2020).

3.5. Descriptive statistics

In 2005, the first year in the dataset, 104 cities converted an average of 400 ha of arable land into urban construction uses. However, there was virtually no correlation with HSR reach ($HSR_{i,t}$) at that time (Table 2), suggesting a spatial stagger between where the requisition of arable land took place and where HSR infrastructure was initially developed. Most of the HSR infrastructure development took place in major eastern coastal cities, while requisition took place elsewhere, resulting in the lack of correlation.

This study's dataset reveals that as the average annual increments of a city's area rose from 3.5 sq km in 2005 to over 7.5 sq km just seven years later, the correlation between HSR alignment length and urban construction land more than tripled from 0.19 to 0.58 during the same period (Table 2). The rapidly-rising correlations suggest that the metropolitan area expansion that occurred in Chinese cities via land conversion, in part, can be attributed to new transit infrastructure. Correlations do not imply causality, which motivates the SEM analysis in the next section.

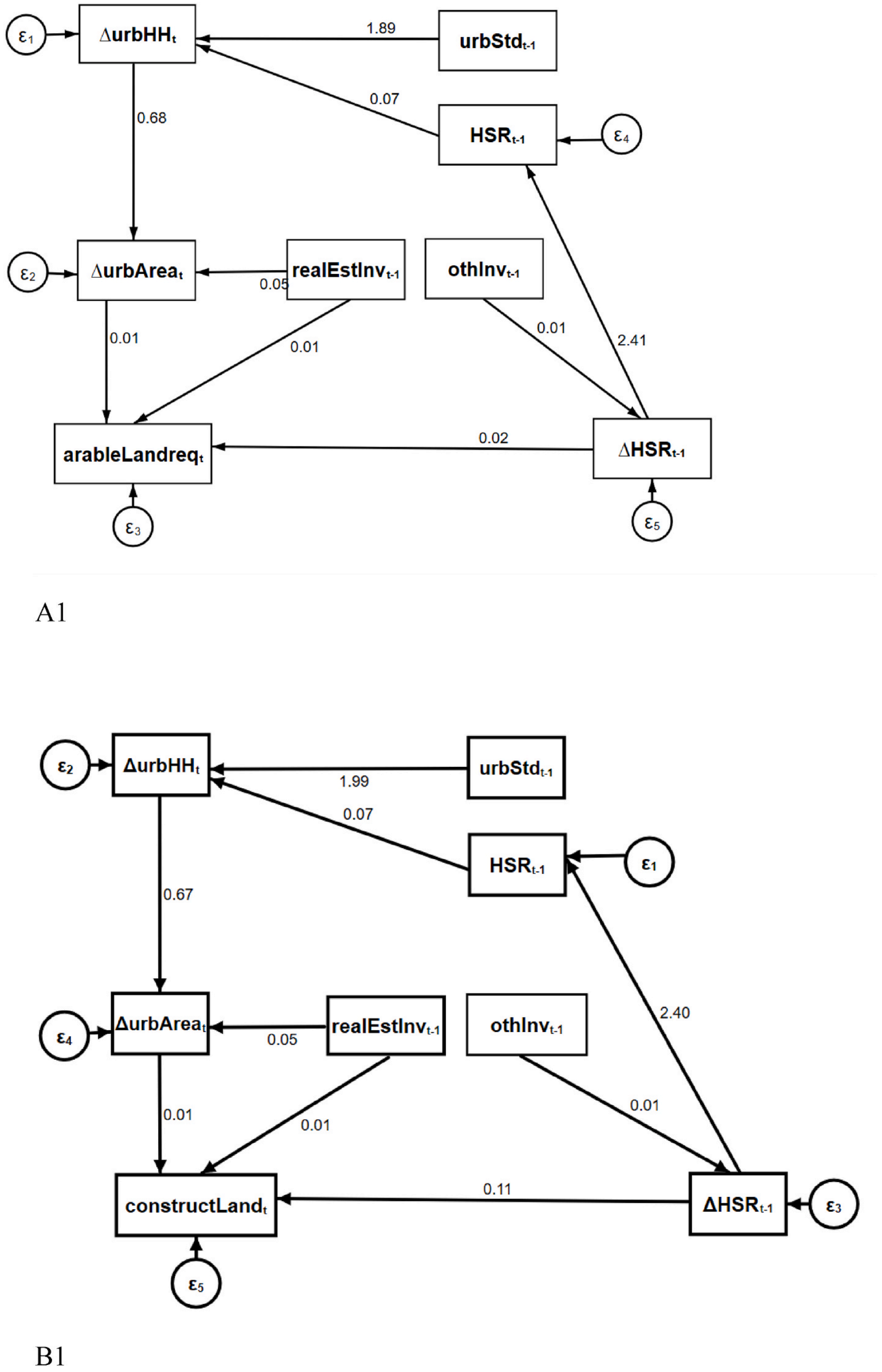

Fig. 4. SEM path diagrams for the baseline models.

4. Results

Following steps IV through VI of the SEM workflow (Fig. 2), this section presents results from the estimation of Model A and Model B (see the path diagrams in Fig. 3). Step IV evaluates the models' fit to the data using the coefficient of determination, chi-square (χ^2), RMSEA, CFI, and SRMR. Step V entails model re-specification based on the justifiable modification indices as the guiding mechanism, while Step VI reports the results. Lastly, spatial impact of HSR expansion is explained.

4.1. HSR impact on arable and urban construction land

This section considers the fit statistics (the coefficient of determination, χ^2, RMSEA, CFI, and SRMR) for the SEM described by equations (1.1), (1).1′), (2.1), (3.1), (4), and (5), which we refer to collectively as the baseline models. Assessing the model's fit to the data is Step IV in the SEM workflow (Fig. 2). The subsequent Step V adds additional causal paths or correlated error terms to the baseline model, a process that is called respecification. The result is a set of modified models with improved overall fit to the data relative to the baseline models. Specifically, a smaller χ^2, RMSEA, and SRMR and a larger coefficient of determination and CFI indicate an improvement in the model fit (see Appendix Table A.3 for details).

4.1.1. Baseline models

Estimates of the baseline models for arable land (Model A1) and urban construction land Model B1 are shown in Fig. 4 and reported in Appendix -Table A.4. The results suggest that while the direct effect of HSR expansion on arable land requisition is not significant, the direct impact on urban construction land use is statistically significant. At the same time, the ripple effect of HSR on arable land, i.e., the indirect path $HSR_i \rightarrow \Delta urbHH_i \rightarrow \Delta urbArea_i \rightarrow arableLand_i$ in Model A1, is statistically significant at the 10%. According to the fit statistics, however, the base models fit is inadequate (see the lower panel of Model A1 and Model B1 in Appendix –Table A.4). Therefore, the models modified next following step IV-A of the SEM workflow.

4.1.2. The modified models

The base models were subsequently modified using modification indices (MI)[13] to improve the models' fit to the data (Kline, 2015). The modified models are shown in Fig. 5, while the estimates are reported in Appendix –Table A.5. The path diagram for Model A2 indicates that the arable-land model's fit to the data is improved by allowing a non-zero covariance between (i) the error terms for urban area and arable-land requisition and (ii) the error terms for incremental and cumulative HSR alignment. In contrast, the modifications of the construction land model (Model B2 in Fig. 5) allow non-HSR investments ($othInv_{i,t}$) to influence land conversion for urban construction and contribute to HSR network expansion while allowing the residual terms between cumulative and incremental HSR alignment to be correlated.

The estimated structural equation for the urban household population ($\Delta urbHH_t$) in Models A2 and B2 shows that each city experiencing a one-unit increase in the urban-rural ratio of living standards will attract a migration of 18,900–19,900 rural households to the urban area. The impact of every additional kilometer of HSR tracks is of particular interest here, which, according to the estimates of Equation (3.1), will attract 696-701 additional households to the city, controlling for the living standards ratio.

In Equation (2.1), urban population growth and real estate investments are the hypothesized causal factors responsible for the territorial expansion of the peri-urban edge ($\Delta urbArea_t$). Consistent with the monocentric urban model for most cities in China (Deng et al., 2008), the estimated coefficients have the expected positive signs and are statistically significant at the 1% and 5%, respectively. Specifically, an HSR city's urban area is projected to expand by 6.7–6.8 sq km for every 100,000 households migrating to the city. In contrast, every additional RMB 10 billion (US$ 1.5 billion) of real-estate investments is estimated to stretch the frontiers of the urban fringe by 4.7–4.8 sq km.

The modified Equations (1.1) and (1).1′) depicted by the causal diagrams for Model A2 and Model B2, respectively, anticipate a depletion in agricultural land due to either an urban area expansion, a boost in real estate investments, or an increase in the HSR network reach. Estimation results from Model A2 suggest that every additional RMB 10 billion of real estate investments would lead to 4.7 sq km of arable land requisition. The same amount of other physical asset investments would lead to increased land conversion for urban construction uses by 7.5 sq km according to Model B2. Moreover, every 1,000 sq km increase in urban area is associated with the requisition of 81.3 sq km of arable land (Model A2) and the conversion of 3.8 sq km agriculture for urban construction uses (Model B2).

The key finding is the effect of HSR infrastructural expansion on agricultural land losses. Specifically, the SEM estimate of Model B2 reveals a statistically significant impact of 4.63 sq km of land converted for urban construction use for every 100 km increase in HSR track length, controlling for fixed-asset investments. The direct effect of HSR on urban construction land is statistically significant at the 1% level. However, the direct influence of HSR expansion on arable-land requisition remains statistically insignificant in Model A2. Therefore, the results suggest that real estate investments are the key variable driving the expansion of urban areas and the Chinese HSR network. Once real estate investments are controlled for in the SEM estimation, the correlation between HSR and arable-land requisition disappears. Nonetheless, the ripple effect of HSR on arable through the indirect pathway $HSR_i \rightarrow \Delta urbHH_i \rightarrow \Delta urbArea_i \rightarrow arableLand_i$ is statistically significant at the 1% level. This finding highlights the advantage of a causal framework like SEM over a simple correlational analysis.

Additional modifications may improve the models' fit to the data further. However, the improved fit will come at the cost of adding causal paths that do not make sense from the substantive point of view and likely lead to misspecification error, thereby causing severe bias in the causal path estimates.

4.2. Robustness checks

A model is robust if the estimated coefficients are unaffected by a change in the estimation methods, a small number of influential observations, or similar models with additional control variables (Kennedy, 2008). Robustness checks are essential because they determine whether causal inferences based on the SEMs are sensitive to outliers in the data or tied to a particular specification. Accordingly, this section reports estimation results using alternative estimation methods, different subsets of the data, and equivalent models to demonstrate the robustness of the estimates for Model A and Model B. The first type of robustness check employs the alternative method of maximum likelihood with missing values (MLMV), which addresses the pitfalls associated with the normality assumption of a maximum likelihood estimator. The MLMV results (Appendix-Fig. A.1) indicate that the main conclusion remains robust. In particular, the direct effect of HSR on arable-land requisitions is statistically insignificant, but the indirect impact persists in Model A2. Similarly, for Model B2, the MLMV method confirms the statistically significant direct and indirect effects of the HSR network on urban construction land (Appendix- Fig. A.4).

The second robustness check employs a subset of the data that excludes the four special municipalities. The key findings remain intact even after Beijing, Chongqing, Shanghai, and Tianjin are dropped from the data. Models A1 and B2 estimation results still hold (Appendix-

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[13] MI is an index that measures how much the χ^2 fit statistic can be reduced by estimating a parameter (i.e., a path coefficient or an error covariance term) that was previously constraint to zero. Thus, a higher value of MI indicates better improvement in the model's fit to the data if that path is added.

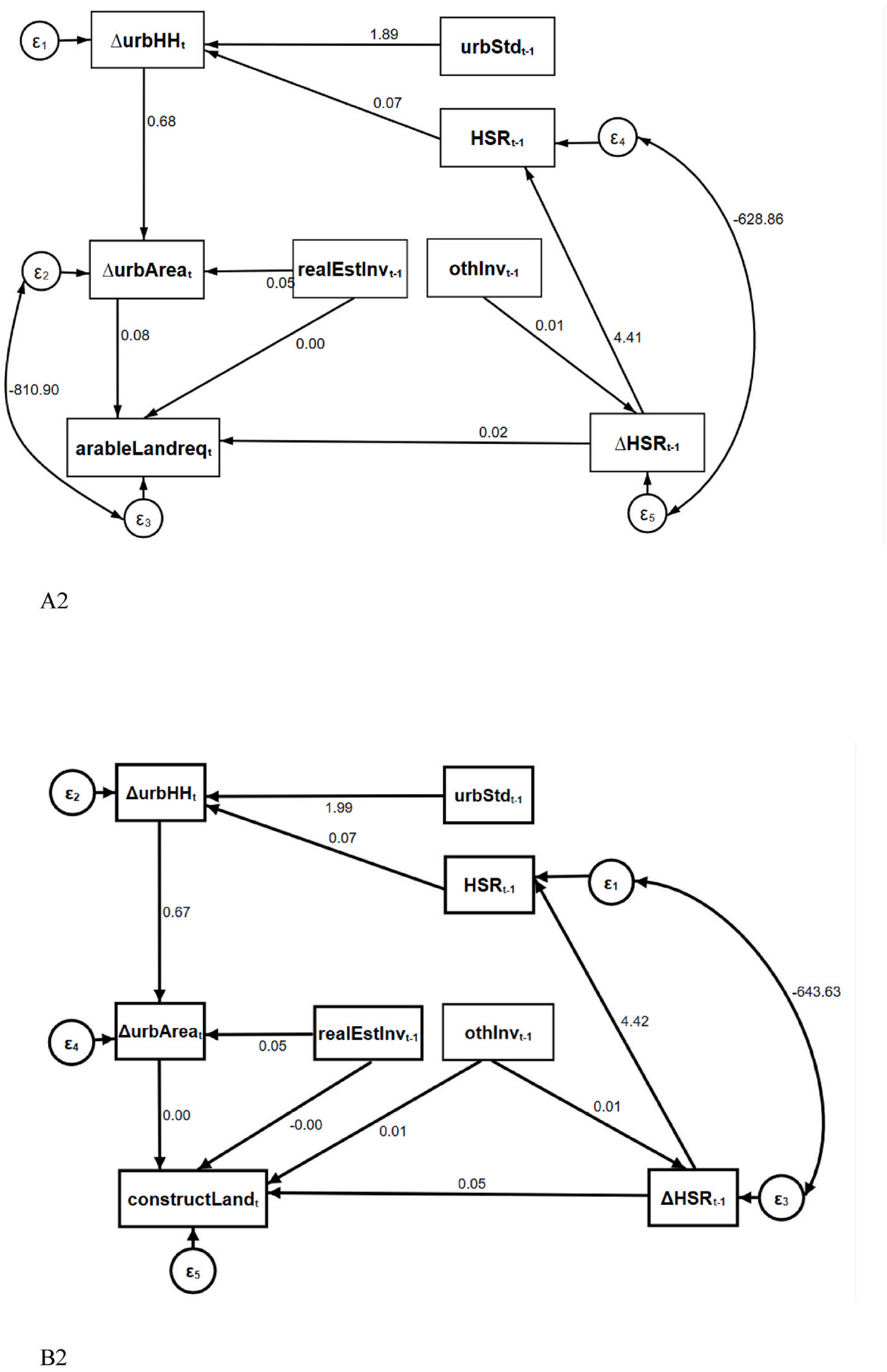

Fig. 5. SEM path diagrams for the improved models.

Fig. A.2 and Fig. A.5), showing that the SEM results are robust and not driven by the dynamics of the four municipalities.

For the third type of robustness check, similar models with additional control variables are considered to determine whether the results are tied to a particular specification. The idea is to show that the results are insensitive (that is, robust) to different specifications with additional control variables. Accordingly, an equivalent model is specified to consider the variable "balance index" (Chen et al., 2020), which represents the built environment in terms of the land-use structural change at the city level. A higher value of the index variable corresponds to a more mixed land use structure. Appendix-Fig. A.3 displays the model diagram that extends Model A1 with the path where HSR infrastructure affects arable land through the variable balance index. The results affirm the statistical significance of the ripple effect of HSR expansion on arable-land requisition in the equivalent model that considers changes in the physical characteristics of a city in terms of land-use structure.

The study also examines the possibility of a third variable confounding the relationship between HSR infrastructure and urban construction land. An additional variable, "*roadArea*" (Chen et al., 2020) was introduced to control for another aspect of the physical environment, namely the road transportation network. The SEM results establish the statistical significance of the direct and indirect effects of HSR expansion on urban construction land in the alternative specification that simultaneously considers the variable balance index and the road system (Appendix-Fig. A.6 and Fig. A.7). Therefore, this study concludes that the SEM estimates of China's HSR impact on agricultural land depletion still hold across the three types of robustness checks.

4.3. The spatial aspect of HSR impact

Since HSR follows the plan stipulated in MLTRP, cities are connected to HSR lines "on purpose" instead of being "quasi-randomly" assigned (Qin, 2017). Thus, the degree to which HSR influences land use varies significantly across regions, administrative levels, and stages of economic development (Jiang et al., 2015). For example, the first three HSR trunk lines that went into operation between 2003 and 2008 are in the coastal regions primarily due to population density and travel demand considerations (Appendix -Table A.2). Consequently, major cities in the eastern seaboard were linked to the HSR network ahead of cities in other regions, potentially experiencing land-use changes earlier. Therefore, the estimation of average nationwide effects may not reflect on how the dynamics of agricultural land conversion would vary across locations in response to HSR expansion. This section addresses whether the impact of HSR network expansion on land conversion was asymmetrically distributed across Chinese regions.

Accordingly, HSR cities are grouped into three separate regions associated with the eastern, central, and western provinces in this section.[14] Within each regional group, cities are likely to share similar geographical characteristics, and are expected to exhibit a similar pattern of responses to changes in the explanatory variables. Thus, specifying a model identical to Model B2 allowing the coefficients to vary across regions provides an approach to capture the differentiating effects of geography.

Table 3

Geographic differentiation of HSR impact on land converted for urban construction usage.

Dependent variable is *constructLand*$_t$				
	Step 1: All 171 HSR cities		Step 2: Eastern & western cities	
Explanatory variables	Central (1)	Non-central (2)	Eastern (3)	Western (4)<
			(with Central region as a control)	
ΔHSR_{t-1}	.0196	.0528	.0345	.1763
	(.0163)	(.0156)***	(.0184)*	(.0329)***
$\Delta urbArea_t$	−.0014	.0052	.0060	−.0250
	(.0024)	(.0023)**	(.0025)**	(.0097)***
$othInvest_{t-1}$	.0041	.0078	.0079	.0028
	(.0010)***	(.0006)***	(.0006)***	(.0020)
$realEstInvest_{t-1}$	.0074	−.0020	−.0024	.0071
	(.0027)***	(.0011)*	(.0013)*	(.0045)
Indirect effect of ΔHSR_{t-1}	.0000	.0015	−.0000	−.0259
	(.0010)	(.0010)	(.0001)	(.0108)**
Number obs.	304	588	446	142
CD	.598		.535	739
χ^2	86.711		102.71	62.454
df	28		28	28

Note: Column (1) reports the unstandardized regression coefficients for the control group of central cities. Column (2) shows the coefficients on the dummy for non-central (i.e., eastern and western) cities. Similarly, central region is the control group for columns (3) and (4). Standard errors appear in parentheses. The rest of the estimates are omitted because the highlight here is how the effect of HSR on urban construction land varies between different regions.

As shown in Table 3, the core estimates suggest that the total effects of HSR on land converted for urban construction use by region are statistically insignificant. However, comparison between cities in central region and those in the rest of China allows statistically significant regional direct effects to be detected. As Table 3 shows, every 100 km of additional HSR alignment leads to an average of 5.28 sq km of land converted for urban construction uses in non-central cities. The regional effect is statistically significant with $p < 0.01$.

Next, non-central cities are disaggregated into eastern and western cities and the results are compared with those for central cities (as a control). Table 3 shows that eastern cities exhibit an average increase of about 3.45 sq km in urban construction land conversion for every 100 km of HSR tracks. Western cities show the greatest impact with 17.63 sq km of urban construction land added via conversion per 100 km of HSR tracks. Furthermore, urban area growth reduces agricultural land conversion for urban uses in western cities. The direct impact of 0.025 sq km reduction in urban construction land for every sq km of urban area growth in western cities is statistically significant at the 1% level. The effect is small but significant evidence of the contribution of HSR expansion to a more rapid economic growth in the western region that did not depend on land conversion during the study period. This supports Zhu's (2021) finding that local governments in the western region with relatively lower economic status and greater dependence on land-based fiscal revenues possess a weaker negotiating power regarding HSR station location. Therefore, unlike in the eastern cities, HSR-oriented development does not lead to increased land conversion for urban uses in the western cities.

5. Conclusions

This study examines the ripple effects of China's HSR on arable-land requisition and conversion to meet the demand of Chinese urbanization. Using the causality modeling framework of the SEM approach, this study assesses the direct and indirect effects of HSR expansion on agricultural land depletion. The main findings are summarized below.

- Our assessment shows that every 100 km expansion of the HSR network led to 4.63 sq km of agricultural land converted for urban uses annually between 2005 and 2012. In particular, 37% of the effect was transmitted through the indirect (ripple) effect, which was mainly driven by an increased urban housing demand resulting from the development of new HSR stations in peripheral areas.
- The effect of HSR on agricultural land conversion was found five times stronger in the western region than in eastern cities (Table 3), suggesting that land conversion driven by HSR expansion is more likely to occur in less populated areas in less developed cities.

The expansion of China's HSR network is expected to continuously generate social benefits, such as travel time savings and reconfiguring the distribution of economic opportunities. It is also likely to further promote an increase in productivity, thereby contributing to higher living standards (Chen & Vickerman, 2017).

Overall, this study provides the following implications for planning and policymaking to domestic and international audiences.

1. Since HSR development is found to have significant direct and indirect effects on agricultural land depletion, future HSR planning and expansion should be conducted carefully to avoid unnecessary waste of arable land. Policymakers may address this issue via stricter land regulations to guide private real-estate investments and manage urban expansion during HSR infrastructure development.
2. The modeling results suggest that HSR is not a panacea to solve contemporary urban growth problems. The scenario in China indicates that the adverse effect of HSR development on arable land is considerable, and it may also increase the potential risk of a food

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[14] Eastern: Guangdong, Guangxi, Hainan, Fujian, Jiangsu, Zhejiang, Hebei, Liaoning, Shandong, Beijing, Tianjin, Shanghai; Central: Hunan, Hubei, Jiangxi, Shanxi, Anhui, Heilongjiang, Jilin; Western: Yunnan, Guizhou, Sichuan, Gansu, and Shaanxi.

supply chain disruption due to the reduction of arable land. Hence, planners should carefully evaluate the socioeconomic impact of HSR. These lessons are critical for the future HSR planning and development in China and other countries, such as the UK, the US, India, and Malaysia, where HSR development is currently underway.

The above interpretation of the SEM estimation results is subject to several caveats, one of which is the panel data required for the causal inferences to be valid. Since cause must chronologically precede effect, a cross-sectional research design would not be appropriate. In addition, the theory-driven aspect of SEM requires the researcher to have a clear idea about the hypothesis before collecting data. Instead of an experimental research design, the researcher must carefully consider which variables to include in every structure equation before testing hypotheses.

The present study has several limitations that future research can address. First, the results only capture the land-use impact during the early stage of HSR development in China. Since many HSR lines did not begin operation until the later years between 2014 and 2020, a follow-up study should extend the panel dataset for a more comprehensive assessment. Second, as China's rural land policy adapts to the changing economic environment, the mechanism through which HSR affects arable land may change. Therefore, future research should examine how the nature of HSR's ripple effects on agricultural land use evolved.

Finally, a follow-up study can also explore the use of satellite-based land-use data to assess the validity of the SEM results presented in this study.

Data availability statement

The dataset of this study is available for replication purposes.

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Credit author statement

Meng Yu: Conceptualization, Data curation, Formal analysis, Resources, Writing- Original Draft, Review & Editing, Investigation, Visualization. Zhenhua Chen: Resources, Writing- Review & Editing, and Supervision. Ying Long: Resources, Data Curation. Yuri Mansury: Methodology, Formal analysis, Resources, Writing- Reviewing and Editing, and Supervision.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2022.102756.

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