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Impact of urban form on housing affordability stress in Chinese cities: Does public service efficiency matter?

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ABSTRACT

Residential housing affordability stress is an important catalyst of class solidification and the growing worldwide social divide. Based on a quantitative spatial model that considers government utility and decision-making and uses nighttime lighting data, this study utilizes *potential urban footprint* as an instrumental variable to examine the mechanisms underlying the effects of the urban form on housing affordability stress and the moderating effect of government public service expenditure efficiency. The theoretical model and empirical results indicate the following. (i) The compact urban form increases housing affordability stress through productivity and urban living amenities. (ii) The efficiency of government public service expenditures affects industrial agglomeration externalities and public service accessibility, precipitating a negative moderating effect on the relationship between urban form and housing affordability stress. (iii) Based on LandScan data, a polycentric layout was found to weaken the compact urban form's ability to reduce housing affordability stress and reduce the government spending efficiency's negative moderating effect on public services. These findings demonstrate that the positive externalities of agglomeration production and the rationalization of government public service expenditures play important roles in housing market stabilization, which is helpful in facilitating better resource factor allocations by the government in the urban sprawl process.

1. Introduction

The theme of World Habitat Day 2022 was "Mind the Gap. Leave No One and Place Behind," which focused on the growing inequalities and challenges of urban living. However, when a public health emergency occurs, such as the COVID-19 pandemic, people who are homeless or living in inadequate, informal, precarious, and overcrowded housing conditions (1.8 billion worldwide) face harsh difficulties in maintaining a simple family housing hedge against external risks. The issue of housing affordability stress has long been on the agenda of policymakers and governments because, without reasonable residential housing security, poverty, and inequality are worsened (Ben-Shahar et al., 2019). Therefore, ensuring urban residents' reasonable housing needs has become an important principle and objective of urban planning, construction, and management. Furthermore, promoting a housing supply-and-demand relationship wherein housing prices are adapted to residents' earning capacity is of practical significance and can improve the happiness index of residents in developing countries (Zhan et al., 2022) by alleviating the housing crowding-out problem for low- and middle-income individuals in superstar cities (Knoll et al., 2017).

The economic stress placed on residents by the expenses of purchasing or renting homes (i.e., housing affordability stress (Beer et al., 2007) is commonly measured using the rent-to-income ratio and house price-to-income ratio (Leung et al., 2022). That is, housing affordability stress is directly related to a resident's income and housing costs. According to the research of UN-Habitat (2020), the price-to-income ratio combines wages and house prices to provide turnkey information about the housing market. Considering the importance of housing affordability stress, several studies have explored its determinants by predominantly focusing on the effects of cities' socioeconomic development levels, labor forces, and household differentiation factors (Hsieh & Moretti, 2019; Lin et al., 2014). However, firm and individual choices are directly reflected by the spatial agglomeration of urban boundary expansion and morphological changes (Sequeira & Filippova, 2021), including walkability (Baruah et al., 2021), contiguity (Burchfield et al., 2006), and the proximity of urban footprints (Mariaflavia, 2020). With the improvements made to urban planning and the resultant changes in geography, urban form has become an increasingly important field in terms of

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measuring the effects of cities' compactness and agglomeration (Angel et al., 2020). Moreover, it is increasingly linked to demographic, social, and economic studies (Davis et al., 2019; Q. Wang et al., 2021).

Compact urban development aims to guide the economic spatial structure of cities while improving urban development and sustainability. Traditionally, urban compactness and density metrics have been measured using the ratio of built-up areas to the total area and population density (Boyko & Cooper, 2011). However, with the new availability of high-precision data (e.g., via remote sensing), the spatial attributes of a city offer more useful information about compactness than they do for density. There are three main spatial focus areas of urban form compactness metrics: the topological focus on nodes (L. Liu & Tian, 2022) and connections (Baruah et al., 2021), the shape focus on size and regularity (Boarnet et al., 2017), and the dynamical focus on growth and structural change (Miguel et al., 2016). The consensus of the academic community is that there are three specific characteristics of the non-compact urban form: low-density (Dong et al., 2019), low-efficiency (Ding & He, 2016), and unsustainability (Nazarnia et al., 2016). All of these factors lead to economic, social, and environmental problems, such as traffic congestion, air pollution, high commuting costs, inefficient land use, land encroachment, and the destruction of ecosystems.

Although urban compactness is often advocated as necessary for urban sustainability, its impact on housing affordability stress remains unclear (Taubenbock et al., 2020). First, the relationship between urban form and residential income depends predominantly on the balance between positive effects and the uneconomical costs of agglomeration. According to agglomeration economy theory, the compact urban form promotes the positive externalities of matching and sharing effects and the knowledge spillover of agglomeration activities (Pfluger & Sudekum, 2008). Thus, it drives firms to improve the quality of research, development, and production (Shima & Ahoura, 2019). That is, externalities positively impact a firm's total factor productivity (TFP), owing to the efficient matching of labor and firms (Fullerton & Villemez, 2011), the sharing of production equipment and resources (Hashiguchi & Tanaka, 2015), and the efficient linkage of industries and technologies (Guo & Minier, 2021). However, the costs of diseconomies increase due to the congestion effects of excessive development and dense economic activities as well as uncoordinated regional factor allocations (Ezeh et al., 2017; McFarlane, 2016). The negative effects include commercial and residential land constraints and excessive competition among firms, which can then lead to reduced firm productivity. In extreme cases, the positive effects of agglomeration externalities can be offset (Bartlett et al., 2014).

Second, the relationship between urban form and housing costs depends most on the accessibility of public services and infrastructure quality. At the regional level, studies have predominantly examined how density and specific factors of urban construction influence urban residential prices, indicating that denser rail transportation (Xiao et al., 2016), green environments (H. Li et al., 2021), public services (Gan et al., 2021), and infrastructure (Y. Fang & Bai, 2022) tend to elevate housing values. Recent studies conducted on single intracity mesoscopic neighborhood and microscopic building space scales have focused on the intricate interplay between architectural design and housing prices. The findings indicate that rapidly increasing urban residential prices can be predominantly driven by several factors, such as their residential floor area ratios, convenience, and accessibility (H. Li et al., 2019; Zhu et al., 2022).

The rapid urbanization of China has led to sprawling cities and rising housing prices. Owing to reforms made to the housing system in 1998 and the land supply system in 2003, China's population has grown rapidly under urbanization, and housing has become among the most attractive assets for Chinese households (J. Chen et al., 2011). By comparing the trends in house sale prices with monthly incomes across countries, housing costs in China have been found to increase rapidly since 2010, whereas incomes remained significantly lower than in other regions, such as the US, the UK, and Japan. As such, housing in China is the least affordable (Wu et al., 2022). Notably, Chinese cities tend to grow in a sprawling pattern. By 2020, the urban areas in 75 cities totaled 30,521.13 km^2, with an average of 406.95 km^2 per city. This is a 7.46× increase from the 1970s (Liu et al., 2021). China's sprawl patterns tend to move from the center outward (Dong et al., 2019), which can lead to irregular sprawls and rapid peripheral growth that exacerbate problems of unequal supply and demand in the real-estate market (Shi & He, 2022).

Amid China's accelerating urbanization, an unmistakable transition to a non-compact urban sprawl pattern is found (C. Fang & Yu, 2017). This evolution, underscored by China's unique urban developmental trajectory, where local governmental interventions are more pronounced than in other nations (Pirotte & Madre, 2011), anchors the current study's general objective to elucidate the intricate interplay between urban form and housing affordability stress while concurrently illuminating the government's pivotal role in this interrelation. More explicitly, this study pursues three specific objectives. Initially, we endeavor to decode the pathways and mechanisms through which urban form influences housing affordability stress, emphasizing the critical roles of production efficiency and living amenities. Second, we critically assess how government decisions shape the relationship between urban form and housing affordability stress. Furthermore, in light of the extensive development zones and rise of polycentric spatial structures across China (X. Chen et al., 2021), we revisit the aforementioned fundamental questions in cities hosting the construction of professional sub-centers. Therefore, the relationship between polycentricity on urban form and housing prices is another specific objective of this paper.

Within urban studies, the relationship between the urban form and housing market has been explored (Jahanmiri & Parker, 2022), but a comprehensive understanding remains elusive. Instead of relying solely on traditional basic correlations, we provide an analysis of both theoretical and practical mechanisms, exploring the relationship between urban form, its implications for productive efficiency, living amenities, and its consequent effect on housing affordability (Sun et al., 2022). Although several studies underscore the role of government in shaping urban landscapes (Carruthers & Ulfarsson, 2002; Miguel et al., 2016), our inquiry into public service expenditure efficiency provides deeper insights into the government's influence on the story of urban form and housing affordability stress. Based on prevalent perspectives that regard polycentric spatial structures simply as outcomes of metropolitan evolution (Barr & Tassier, 2016), we contend that these structures play a pivotal role in mitigating housing affordability issues and emphasize the need for the government to adjust its fiscal expenditures to the polycentric situation. Harnessing multi-dimensional remote sensing data in a long-time dimension and employing cogent instrumental variables (S. G. Yin et al., 2019), we aspire to present a holistic, distinctive, and reliable understanding of the urban form's influence on housing affordability stress.

2. Analysis of theoretical mechanisms

This section describes the spatial equilibrium of an urban system using the Rosen–Roback model (Roback, 1982; Rosen, 1979). Using a model based on the firm, consumer, and real estate sectors, we describe the Chinese government's impact on land concessions and fiscal utilization. Our model assumes that urban land elements are homogeneous to discuss the urban form's impact on housing affordability stress.

2.1. Basic model setting

For firm production, we assume that firms in the same city have the same production technology and constant returns to scale and that the market is perfectly competitive. The production function of representative firms is provided in Cobb–Douglas form (Eq. (1)), where Y represents firm output, A represents TFP, $N, K,$ and L_I represent labor, capital, and land factor, respectively, invested in production, and G_I represents government productive expenditures. Their direct output elasticities are $1-\alpha-\beta, \alpha, \beta,$ *and* γ, respectively. Assuming that the labor cost is W, the capital factor production cost is normalized to one, the production cost of the land factor production is P_I, and the maximizing profit of a producer in a perfectly competitive market is zero, thereby satisfying Eq. (2).

$$Y = A\left(K^{1-\alpha-\beta}\, N^{\alpha}\, L_I^{\beta}\right)^{1-\gamma} G_I^{\gamma}, \tag{1}$$

$$\mathrm{Max}\{\ \pi_I = Y - W\,N - P_I\,L_I - K\}; \pi_I = 0. \tag{2}$$

For consumers, the urban representative consumer utility function is the primary chi-squared type (Eq. (3)), where C and H represent the consumption of general consumer goods and housing, respectively, M represents living amenities, and δ represents the share of housing expenditures based on income. Assuming that workers' real income is entirely from wages, W, housing prices in the city are R_H, and consumer goods prices are normalized to one. In this model, intertemporal substitution and money lending are not considered, and the consumer balance constraint is satisfied by $C + R_H H = W$.

$$\mathrm{Max}\left\{\ U = M\, C^{1-\delta}\, H^{\delta}\ \right\} \text{s.t.} C + R_H\, H = W. \tag{3}$$

For competitive real-estate developers, the profit function satisfies Eq. (4), where h is the average residential building height in the city, and L_H is the total land area used for housing. Furthermore, the cost of housing construction is $CoL_H h^{\mu+1}$, where $Co > 0$, meaning that the unit area of construction cost increases monotonically with the increase in height (Liu, Qin, & Li, 2019). When real estate development and consumer housing markets are in equilibrium, $H = L_H h$. Therefore, the building height that maximizes developer profit is presented in Eq. (5).

$$\mathrm{Max}\left\{\ \pi_H = R_H L_H h - CoL_H h^{\mu+1} - P_H L_H\ \right\}; \pi_H = 0; H\,N = L_H h, \tag{4}$$

$$h = \left(\frac{Co(\mu+1)}{R_H}\right)^{-\frac{1}{\mu}}. \tag{5}$$

Productivity, migration frictions, and comfort are factors affecting the distribution of mobile and total urban populations among cities (X. Liu & Li, 2017). Ignoring migration frictions, existing studies on urban form often assume that the exogenous urban form (S) affects the equilibrium model in two main ways. That is, it affects TFP (A) through the degree of industrial agglomeration and factor circulation (Eq. (6)), whereas living amenities (M) are simultaneously affected through public services and infrastructure connectivity (Eq. (7)). A_0 and M_0 represent exogenous TFP and exogenous comfort, respectively, λ denotes the efficiency of local government spending on public services, and a larger λ implies a greater impact by government public services' fiscal spending on living amenities.

$$A = A_0 S^{\theta_A}. \tag{6}$$

$$M = M_0 S^{\theta_M}\left(\frac{G_H}{N}\right)^{\lambda}. \tag{7}$$

2.2. Model balancing analysis

Based on the maximization of producer and real-estate developer profits in a perfectly competitive market, the maximization of consumer utility under budget constraints, and the equilibrium between real-estate development and consumer housing, the spatial general equilibrium model assumes that population factors move freely between cities and that workers are incentivized to move to areas where they can obtain higher efficiency. That is, in a long-run equilibrium, representative workers retain utility $\overline{V}$ in any city.

$$\overline{V} = maxU = MC^{1-\delta}H^{\delta} = M((1-\delta)W)^{1-\delta}\left(\frac{\delta W}{R_H}\right)^{1-\delta}. \tag{8}$$

Based on Eqs. (1)–(8), the relationship between housing affordability stress and urban form can be obtained when government land use, fiscal revenues, and expenditures are fully exogenous (Mariaflavia, 2020). Considering the land finance problem in China, to simplify the operation, we do not consider intertemporal government behaviors wherein local governments influence urban development through both fiscal and land policies (Eq. (9)). On the fiscal side, φ and 1-φ represent the proportion of government fiscal expenditures allocated to production to enhance economic development and provide public services to increase resident welfare, respectively. From the land perspective, ε and 1-ε affect firms' production decisions and residents' housing statuses, respectively. Assuming that the government aims to maximize resident welfare and achieve regional economic output (W. Pan & Fan, 2019), the government utility maximization function (Eq. (10)) can be solved when portion b of the local government's fiscal revenue is determined by land rent, wherein the land use and fiscal allocation targets are determined by the utility maximization by the higher-level government (J. Yu & Shen, 2019).

$$L_I = \varepsilon L\ ;\ L_H = (1-\varepsilon)L\ ;\ G_I = \varphi G\ ;\ G_H = (1-\varphi)G, \tag{9}$$

$$\mathrm{Max}\left\{\ U_g = Y^{\delta}\, U^{1-\delta}\right\} \text{s.t.} P_I\, L_I + R_H L_H = \mathrm{G}^{b}. \tag{10}$$

Based on the maximization of the government utility function, this model endogenizes government fiscal expenditure φ and land allocation ε as an expression of the efficiency of public service expenditure λ (Eq. (11)). Thus, the government public service expenditure's efficiency is proportional to G_H/L_H, whereas the government's productive fiscal and land marginal effect is constant. Therefore, the analytical solution to housing affordability stress (R_H/W) under the spatial general equilibrium model, with the introduction of government fiscal and land constraints, is provided. Referring to an ordinary parameter selection (Duan et al., 2020; S. Pan et al., 2018), the urban form's effect on housing affordability stress in the general quantitative spatial equilibrium model based on the introduction of government finance and land decisions is as follows (Eq. (12))[1]:

$$\lambda = \frac{\delta^* dY/dG_I}{dY/dL_I}\,\frac{G_H}{L_H}\,\frac{\mu}{1+\mu} = \frac{\delta^* dY/dG_I}{dY/dL_I}\,\frac{(1-\varphi)G}{(1-\varepsilon)L}\,\frac{\mu}{1+\mu}, \tag{11}$$

$$d\left(\frac{In\left(\frac{R_H}{W}\right)}{InS}\right) = \frac{0.093\theta_M - (0.010 + 0.173\lambda)\theta_A}{0.097\lambda + 0.082}. \tag{12}$$

2.3. Theoretical hypothesis construction

When government policies are disregarded, the compact urban form directly affects housing affordability stress through two aspects: θ_A and θ_M. Compact and regular urban forms foster industrial agglomeration externalities and productivity benefits while also promoting living conveniences and amenities. Thus, when S indicates urban sprawl compactness, θ_A>0 and θ_M>0 (Hu & Zhang, 2021). According to the analytical solution of urban form effects on housing affordability stress in the theoretical model (Eq. (12)), the compact form promotes factor-flow fluidity and scale-effect externality, which further improves TFP ($\theta_A > 0$). A negative coefficient prior to θ_A in the correlation is predominantly caused by productivity improvements that drive firms to provide higher compensation in real wages (Burke et al., 2022), thereby reducing housing affordability stress. However, the compact form

[1] Parameter selection:$\alpha = 0.4687; \beta = 0.08492; \gamma = 0.8961; \delta = 0.333; \mu = 0.015; b = 0.3765; \theta_A \in (0,1); \theta_M \in (0,1)$.

directly affects the accessibility of infrastructures and public services in built-up areas, thus enhancing living amenities and satisfaction (θ_M>0). Moreover, a positive coefficient prior to θ_M in Eq. (12) predominantly indicates that residents are willing to pay higher housing costs when an area's living amenities increase (L. Liu & Tian, 2022). Thus, we hypothesize the following:

Hypothesis 1a. A compact urban form promotes productivity, thereby reducing housing affordability stress under the effect of higher real wage compensation.

Hypothesis 1b. A compact urban form enhances urban living amenities, thereby increasing housing affordability stress under the influence of higher housing costs.

The urban form's effects on housing affordability stress depend on the relationships between urban form and TFP (θ_A) and between urban form and living amenities, θ_M. Thus, the relationship between compact urban form and housing affordability stress depends on the balance between form-enhancing productivity and form-enhancing urban living amenities. The numerical simulation results are shown in Fig. 1, where $\lambda = 0.4$ based on the 2017 mean (Duan et al., 2020), indicate that compact urban sprawl morphology reduces housing affordability stress for larger absolute values of θ_A and smaller absolute values of θ_M. However, because the compact urban form exhibits a limited effect on productivity, it also exhibits a positive relationship with housing affordability stress in most cases. Thus, Hypothesis 2 is proposed based on measures of urban form within the dimensions of urban morphological connectivity, compactness, and regularity, as follows:

Hypothesis 2. Compact urban form and residential housing affordability stress are significantly correlated, and the direction of this correlation depends on the trade-off of the forces they exert on productivity and living amenities.

To better understand the trade-off between the two forces, the sensitivity test on γ shown in Fig. 1 reveals that, as the efficiency of government public service input λ increases, the range of θ_A and θ_M corresponding to the positive relationship between compact urban form and housing affordability stress becomes smaller. Eq. (7) reveals that the efficiency of government spending on public services directly acts on living amenities, and the coefficient prior to θ_M in Eq. (12) is $0.093/(0.097\lambda + 0.082)$. Thus, when the efficiency of government public service input λ is higher, the means of the compact urban form to enhance living amenities θ_M weakens. That is, when the government better guarantees the accessibility of public services for residents, the urban form's effect on public services is mitigated (Y. Fang & Bai, 2022). However, the coefficient prior to θ_A in Eq. (12) is $-(0.010 + 0.173\lambda)/(0.097\lambda + 0.082)$, where λ indirectly acts on the means of the urban form and production efficiency, strengthening the positive externality of the urban form on production accumulation θ_A. Thus, higher public service efficiency alleviates agglomeration diseconomies through infrastructure (Z. M. Liu et al., 2022) and social welfare protection (James & Richard, 1993). That is, the urban form is regulated to reduce housing affordability stress. From a larger perspective, with the introduction of government fiscal and land constraints to the spatial general equilibrium model, when other parameters are provided, the relationship between urban form and housing affordability stress (Eq. (12)) has a bias of $(-2.369\theta_A - 1.132\theta_M)/(1.184 + \lambda)^2$. The second-order bias is less than zero, indicating that the efficiency of local government inputs to public services exhibits a negative moderating effect on the relationship between urban form and housing affordability stress. Thus, we hypothesize the following:

Hypothesis 3. The local government's input efficiency for public services exhibits a negative moderating effect on the relationship between urban form and residential housing affordability stress.

In the government utility maximization model, the efficiency of local government inputs to public services is directly proportional to the amount of government fiscal expenditures on public services per unit of non-productive land (Eq. (11)). A logical diagram of the theoretical hypothesis is presented in Fig. 2. Because these models are based on the monocentric setting of a city, Section 5 expands the situation to polycentrism and reexamines the hypotheses.

3. Model, data, and identification strategy

3.1. Model design

Based on the theoretical analysis and hypotheses provided, multiple linear regression models with fixed effects were chosen for their well-documented efficacy in dealing with similar datasets and for their

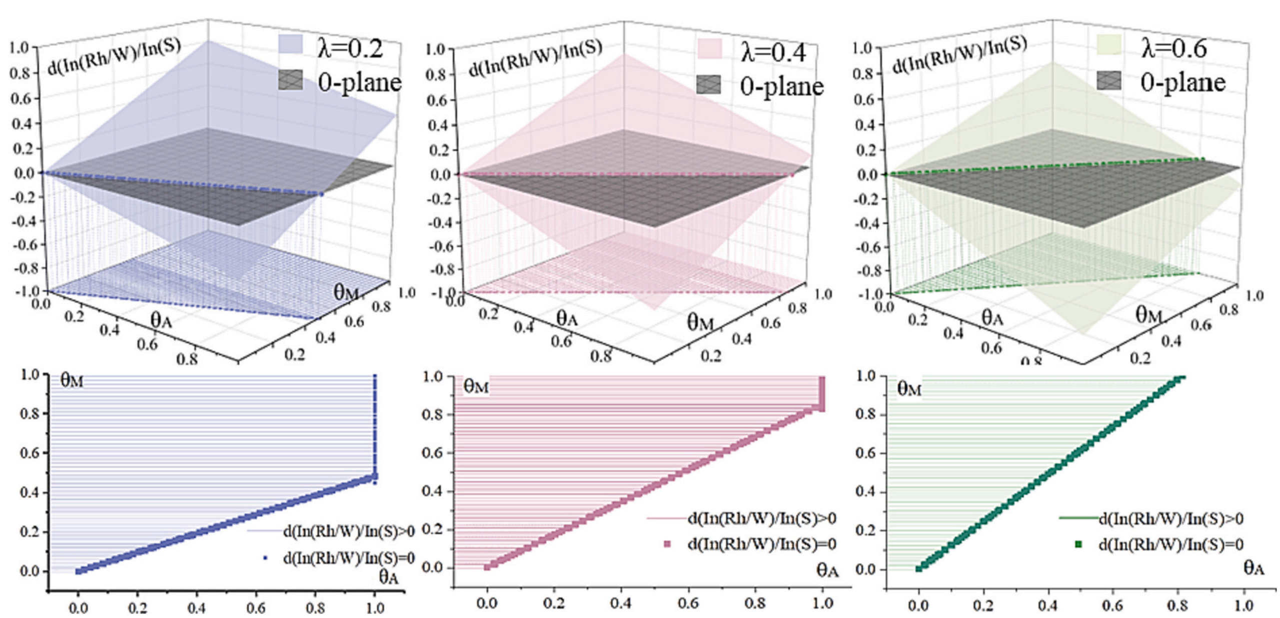

Fig. 1. Numerical simulation of $d(In(R_H/W)/In(S)$ and θ_A, θ_M (susceptibility test on γ).
Notes: The second row reflects the numerical simulation of $d(In(R_H/W)/In(S)$ and the θ_A, θ_M projection on θ_A-θ_M-*plane*.

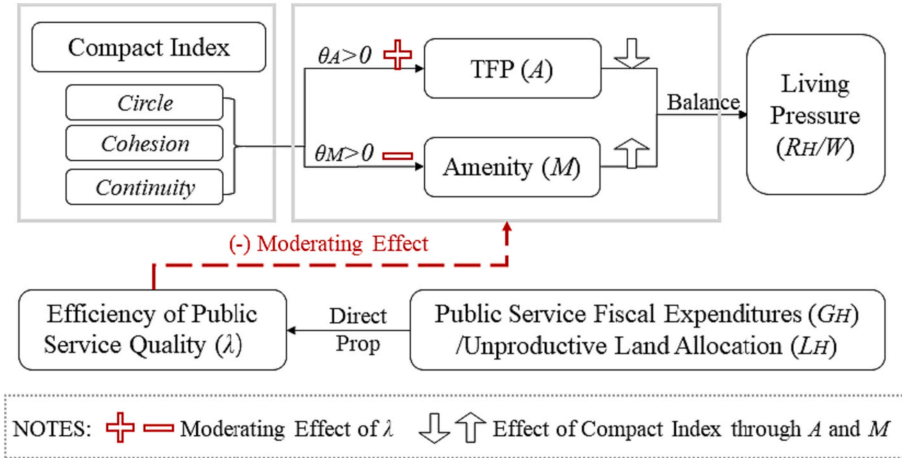

Fig. 2. Logical diagram of theoretical hypothesis.

clear interpretability (Hair et al., 2010). These models notably control for multiple covariates while providing transparency in deciphering variable relationships. They also align well with our research goals (Kline, 2010). Further, by utilizing two-stage least squares estimation model, we were able to addressing endogeneity by instrumental variables, thereby enhancing the robustness of our findings. The empirical model is shown below.

(i) Regression models of urban form on productivity and living amenities

$$TFP_{it} = \alpha_0 + \alpha_1{*}Shape_{it} + \beta_1{*}Control_{it} + i.Pro + i.Year + \mu_{it}, \quad (13)$$

$$Living_{it} = \alpha_0 + \alpha_1{*}Shape_{it} + \beta_1{*}Control_{it} + i.Pro + i.Year + \mu_{it}. \quad (14)$$

(ii) Regression model of urban form on housing affordability stress

$$Rhw_{it} = \alpha_0 + \alpha_1{*}Shape_{it} + \beta_1{*}Control_{it} + i.Pro + i.Year + \mu_{it}. \quad (15)$$

(iii) Regression model of the moderating effects on government public service input efficiency

$$Rhw_{it} = \alpha_0 + \alpha_1{*}Shape_{it} + \alpha_2{*}Shape_{it}{*}govserv_{it} + \beta_1{*}Control_{it} + i.Pro + i.Year + \mu_{it}. \quad (16)$$

In the regression model of urban form affecting productivity and living amenities, TFP_{it} represents the proxy variable of production efficiency, and $Living_{it}$ represents the proxy variable of living amenities on the left side. On the right side, $Shape_{it}$ is the urban form index, $Control_{it}$ is the city-level control variable, and μ_{it} is the residual term of each city at time t, where i is a sample of 260 cities after data treatment, and t represents the 2005–2020 period. In the regression model of urban form affecting housing affordability stress, Rhw_{it} is the housing affordability stress index. In the regression model of the moderating effects, $govserv_{it}$ is the moderating variable of fiscal expenditures on public services per unit of unproductive land. Additionally, considering the significant variation in urban form across cities and the small changes over time for a given city, we controlled for province- and time-fixed effects in the least-squares dummy variable model (Charles et al., 1999). Furthermore, city-level non-time-varying variables at the geographic level (e.g., slope, elevation, and number of streets) were controlled.

The decision to center our empirical model analysis on China is both relevant and crucial, considering its unmatched and rapid trajectory toward urbanization, which is driven by significant government regulation. China's urban metamorphosis prominently features widespread urban sprawl, which leads to pronounced spatial disparities and striking irregularities within real estate sectors. Moreover, such dynamics have positioned housing as a paramount asset for Chinese families, highlighting its singularity on the global stage. Further amplifying China's unique urban tale is the influential role of its local governments with regard to urban progressions, which is less prominent in other countries. This confluence of aspects accentuates the urgency of delving deeply into the impact of urban form on housing affordability stress, drawing upon data from China. To rigorously tackle our research inquiries, we employ the methodological framework depicted in Fig. 3, ensuring alignment between our theoretical orientations and the chosen research methodologies.

3.2. Description of basic indicators

For urban housing affordability stress Rhw_{it}, we used the ratio of sales of commercial residence per area and total wages per number of employees to measure housing affordability stress (S. Yin et al., 2020). This indicator is often used to measure housing affordability based on house prices to wages: the more residents who cannot afford homes, the more stress on housing (Mattingly & Morrissey, 2014). Considering the effects of public accumulation funds for urban housing in China, the corrected housing prices for public accumulation funds were used as the explanatory variable for robustness testing (Y. P. Wang & Murie, 2011). The data were obtained from the China Stock Market and Accounting Research (CSMAR) database.

Regarding urban form $Shape_{it}$, urban form is a spatial system comprising structures, shapes, and interrelationships that externally reflect urban elements' spatial distributions and activities (Chiaradia, 2019). Although the primary emphases of some studies were on the distribution of morphological elements at the meso-block and micro-building scales, their scopes remained constrained to singular cities over one-year durations owing to data availability constraints (Zhou et al., 2022). To conduct a comprehensive assessment of the urban form's impact over a prolonged period in China, our research prioritizes the city-level analysis, primarily due to the extensive range and granularity of available indicators (L. Liu & Tian, 2022). Furthermore, morphological indicators at the urban level can primarily examine agglomerated plots that include density-based (e.g., population density, built-up areas, and housing saturation) and shape-based (e.g., peripheral urban footprint and perimeter-to-area ratio) metrics (Boarnet et al., 2017).

To better measure urban form's compactness in terms of the relationships among geographic parcels, we primarily considered morphology-based indicators of inner urban structure at the following three levels: near-circularity index (*Circle*), cohesion index of patches (*Cohesion*), and neighborhood agglomeration index (*Continuity*) (Angel et al., 2020). *Circle* is expressed as the ratio of area-weighted patch area to the area of its largest outer circle and measures the degree of regularity of urban form. *Cohesion* increases with the proportion of

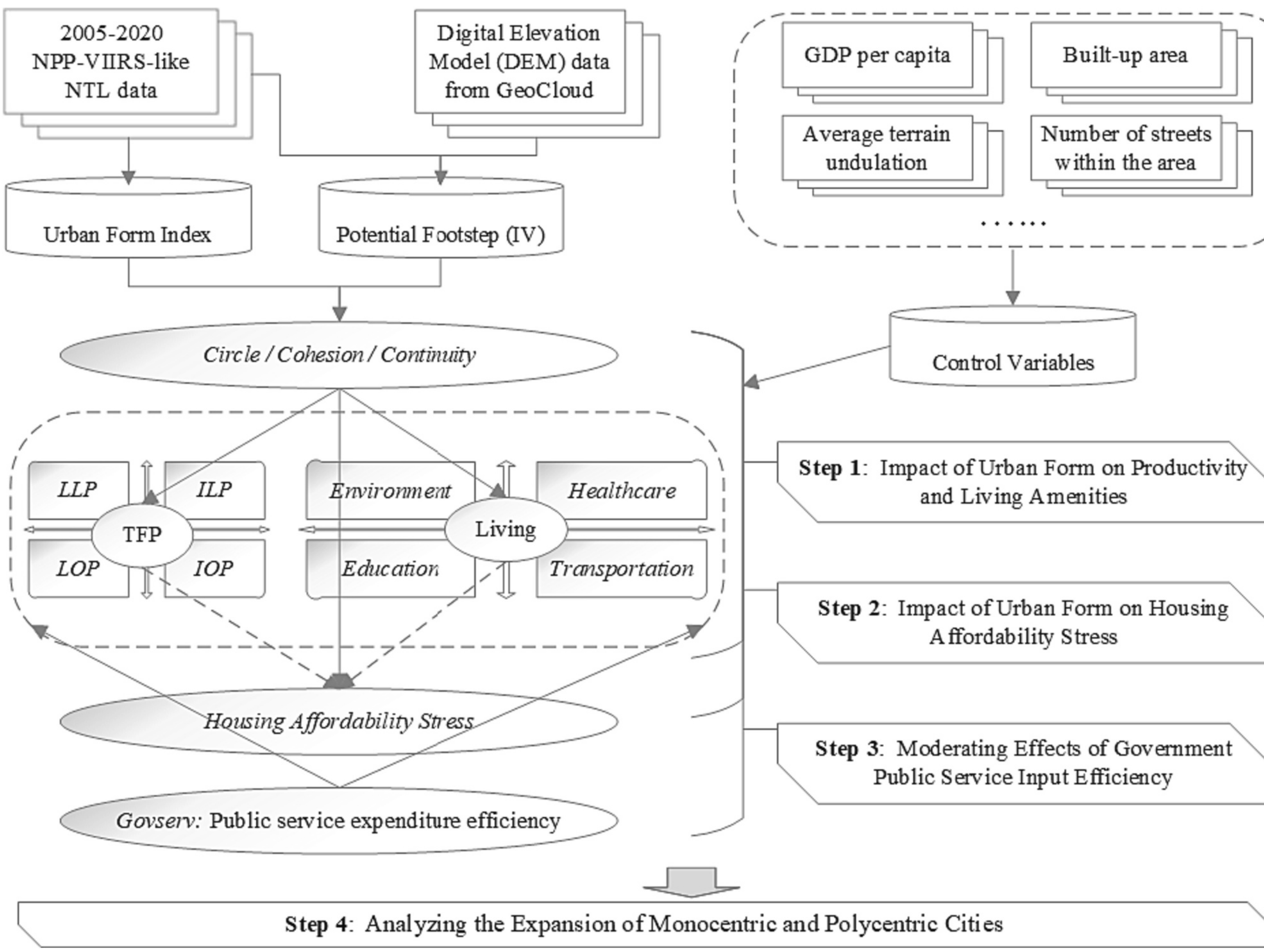

Fig. 3. Overview of the methodological framework.

agglomeration patches in the overall sample and reflects the differentiated state of aggregation and dispersion of the urban form from the perspective of intra-plate compactness. *Continuity* is expressed as the ratio of actual neighboring patches to accessible neighboring patches. In the equations below, A_i represents the area of patch I, $A_{circle\ i}$ is the area of the smallest outer circle, P_i is the perimeter of the patch, n is the overall number of patches in the city, $M_{real\ i}$ is the number of real neighboring patches of patch I, and $M_{access\ i}$ is the number of neighboring patches accessible to patch i. More detailed definitions are provided in Appendix A.

$$Circle = \frac{A_i}{A_{circle\ i}} * \frac{A_i}{\sum_{i=1}^{n} A_i}, \tag{17a}$$

$$Cohesion = \left[1 - \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} P_i \sqrt{A_i}}\right]\left[1 - \frac{1}{\sqrt{n}}\right]^{-1}, \tag{17b}$$

$$\text{Continuity} = \frac{M_{real\ i}}{M_{access\ i}}. \tag{17c}$$

Using remote sensing data, the measurement and analysis of specific urban spatial morphological indicators were based on the ArcGIS platform. Because DMSP-OLS and NPP-VIIRS nighttime light remote-sensing data are incompatible, the available time-series lengths were obscured. Hence, we used a self-encoder-based cross-sensor nighttime light data correction scheme with global NPP-VIIRS-like NTL data with a 500-m city-scale resolution scale accuracy and an R^2 of 0.95 during the 2005–2020 period. Regarding the specific data processing and index calculation activities, the interception threshold of the annual nighttime light data was corrected using the built-up area of Beijing (Yang et al., 2020), and the raster of the built-up areas of each prefecture-level city was obtained from the nighttime light raster using the threshold extraction method of auxiliary data comparison. Additionally, the *Circle*, *Cohesion*, and *Continuity* indicators were used to calculate the degree of the urban form (Miguel et al., 2016). Fig. 4 presents the data processing and index calculation methods using Beijing as an example.

3.3. Endogeneity and instrumental variables

The correlation between urban form and housing affordability stress exhibits an endogeneity problem. That is, a two-way causal problem exists for the relationship between urban form and housing affordability stress, because housing affordability stress can promote the expansion of urban residential construction cores to the periphery of new development areas, creating a decentralized polycentric residential development pattern. However, an endogenous determinant of the urban form is within the local governments' capacity. With all things equal, cities with

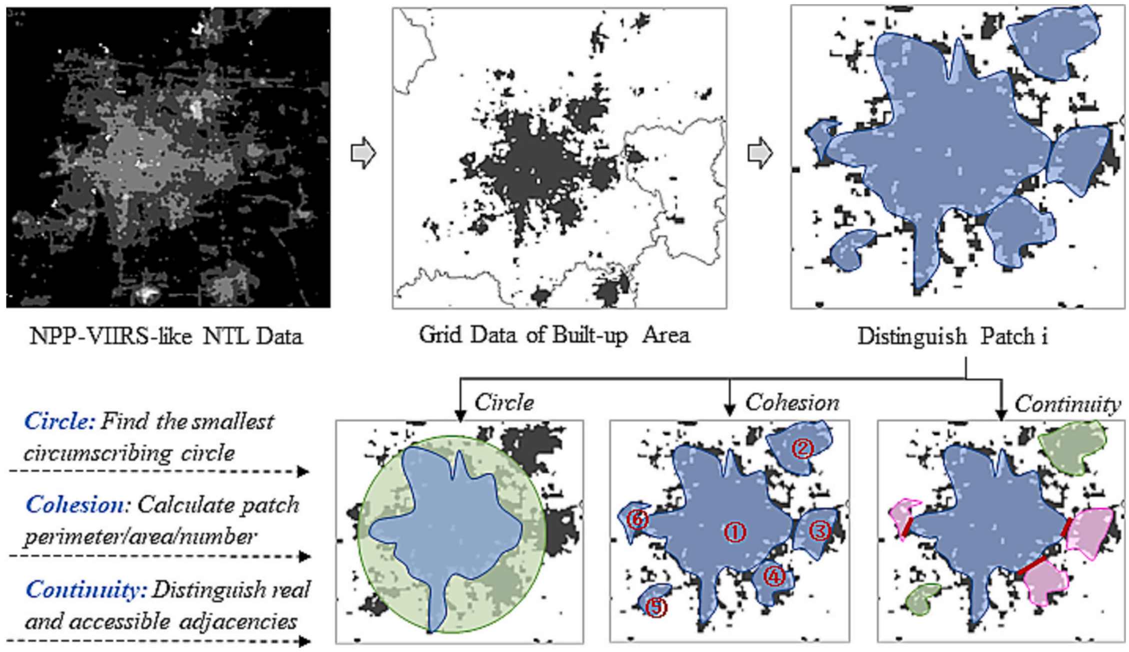

Fig. 4. Urban form recognition process using Beijing in 2020 as an example.

a greater government capacity tend to exhibit better urban planning and sprawl boundary controls and are likelier to be compact. Furthermore, cities with greater institutional capacity and a well-functioning local government tend to be better at relieving housing affordability stress. Although the number of streets in a region can partially control for the effects of local government promotion incentives (Y. Yu et al., 2020), the omitted variables still present a problem. Therefore, this study considered cities' *potential footprint* as an instrumental variable for the urban form. This variable is only related to urban form and not to other interfering terms in the regression exercise. Therefore, the potential footprint can distinguish the unrelated parts of the urban form from the interfering terms and estimate the correct coefficients.

When examining the relationship between urban form and housing affordability stress, the hurdle of endogeneity is strikingly significant. Historical research methodologies have utilized patterns of past urban developments as instrumental variables, suggesting that modern city configurations are deeply anchored in their historical origins (Baum-Snow, 2007). Another perspective emerges from research that underscores the constraining effects of natural geographic barriers, such as rivers or mountains, on urban expansion (Saiz, 2010). Although these instrumental variables provide valuable insights into potential development locations, they often fall short of capturing the complex dynamics of urban evolution. Our study introduces the concept of the "potential footprint" as a novel instrumental variable. Distinct from traditional instrumental variables that are static over time, the potential footprint represents a dynamic variable that accounts for the evolving nature of a city influenced by technological advancements, governance shifts, and urban planning strategies (Mariaflavia, 2020).

We defined the proportion of continuous developable land areas in the urban sprawl process as the potential footprint, which is the ratio of the largest continuously developable land area to the total area within the radius of each urban activity (i.e., buffer zone). First, based on guidance from China Natural Resources Office Document No. 127, the terrain slope was calculated using the Digital Elevation Model (DEM) data (of the whole area, and a $\leq 3^\circ$, 3–8°, 8–15°, 15–25°, and $> 25^\circ$ slope-grading map was generated. Finally, urban construction land resources were classified into five slope levels with elevation and terrain undulation correction, as follows: lower, low, medium, high, and higher, respectively.[2] The "higher" and "high" slope ranges refer to undevelopable urban construction land.[3] Second, based on the nighttime lighting raster and the range of developable land for urban construction in each prefecture-level city, the ratio of the developable area to the total buffer area was considered based on a 500-m buffer, and the ratio of the developable area within the 300-m buffer area was used for exogeneity verification. The 500- and 300-m buffer radii were based on the historical annual urban spread radius (Shlomo Angel et al., 2005; F. Liu et al., 2021; Qureshi et al., 2021). We referred to the sprawl urban built-up area from 1990 to 2000, in which the urban sprawl radius of developing countries was about 681.23 m. In East Asia and the Pacific region, this radius is about 523.49 m. In countries with a city population > 4,180,000, the urban sprawl radius was about 331.95 m. Fig. 5 presents the instrumental variable's identification boundaries using Beijing as an example. This instrumental variable varies at the city–year level and incorporates the fact that cities encounter different topographic barriers at different stages of their development.

The potential footprint indicator was constructed based on the buffer zone's exogenous mechanical urban extension vector rather than the actual urban sprawl vector. Therefore, it is not directly related to the production of housing construction and enterprises within cities. Thus, on their own, Ratio05 and Ratio03 do not directly affect enterprise

[2] Elevation corrections include the following: For areas with an elevation of ≥5000 m, the land resource grade is directly taken as the lowest; if the elevation is 3500–5000 m, the slope grade will be reduced by one level as the land resource grade. The correction of terrain undulation includes the following: For areas with a terrain undulation degree >200 m, the preliminary evaluation result is lowered by two levels; if the terrain undulation degree is 100–200 m, the preliminary evaluation result is reduced by one level as the urban land resource level.

[3] Natural Resources Office Documents [2020] No. 127: "Guidelines for the Assessment of the Carrying Capacity of Resources and Environment and the Suitability of Land and Space Development (Trial)" Appendix B.2: Land Resources Evaluation.

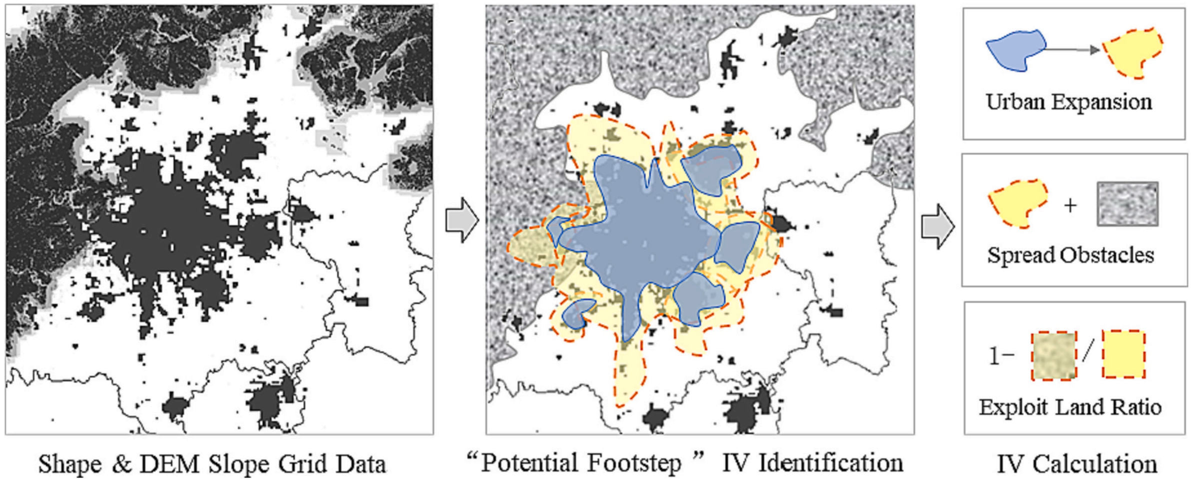

Fig. 5. Instrument variable recognition path using Beijing in 2020 as an example.

productivity or the residential housing situation, which satisfies the exogenous premise (Mariaflavia, 2020). Furthermore, cities exhibit different rates of sprawl between developable and undevelopable land. Therefore, when the proportion of developable land in a buffer zone is higher, urban space is likelier to expand uniformly outward in all directions, making urban form more regular and compact. Accordingly, Ratio03 and Ratio05 predominantly affect wage incomes and housing prices by influencing urban spatial rules and agglomeration characteristics, thereby satisfying the correlation premise.

3.4. Description of mechanism and moderating indicators

Based on the mechanism hypothesis and model design of Eq. 13, TFP is mainly used as the production-side proxy variable (Fullerton & Villemez, 2011). Considering that TFP at the macro-data level can be influenced by variations in data calculation standards across regional yearbooks, we chose the micro-firm-level TFP, weighted appropriately, as our explanatory variable. Relying on the database of CSMAR-listed companies and the China Industrial Enterprise database, we used market capitalization-weighted TFPs of listed and industrial firms under the LP and OP algorithms[4] for the 2005–2013 period.

In Eq. (14), $Living_{it}$ represents the proxy variable of living amenities. Residents' willingness to settle is highly correlated with available living amenities, as providing infrastructure and public services is the main channel through which urban form affects living amenities in China. To explore how the urban form affects access to public resources and commuting behaviors, we selected four indicators (i.e., *Environment*, *Healthcare*, *Education*, and *Transportation* (Liu, Chen, & Cao, 2019) that residents care about deeply. The urban *Environment* indicator consists of the comprehensive utilization rate of industrial smoke (dust) and solid waste (industry waste, *IW*) and the centralized treatment rate of sewage (dirty water, *DW*); *Healthcare* consists of urban workers' basic medical insurance participation rates (medical insurance, *MI*) and occupational/assistant physicians ratio (hospital doctor, *HD*); *Education* consists of the number of teachers in middle schools per student (middle-school teachers, *MT*) and the number of teachers in higher education per student (university teachers, *UT*); and *Transportation* consists of area of transportation roads per capita (road area, *RA*) and road length per capita (road length, *RL*).

Based on Hypothesis 3 and the model design in Eq. (16), the moderating variable is the *proportion of fiscal expenditures on public services per unit of unproductive land*. Measures of productive land were derived from the sum of the areas of industrial, storage, and external transportation lands[5] from the China Urban Construction Statistical Yearbook of the corresponding year (Duan et al., 2020). Public service expenditures include social security and medical and health expenditures. The control variables are *city category*, *undulation*, *elevation*, *number of streets*, per capita *gross regional product*, *proportion of fixed assets*, *built-up area*, *dependence on government funding*, and the *logarithm of the resident population*. The source of the control variables was also the China Urban Statistical Yearbook, the China Urban Construction Statistical Yearbook, the Geospatial Data Cloud, and the EPS database. After variable matching, linear interpolation of missing values, and extreme value processing, the total sample size was fixed at 4160 samples from 260 cities in 2005–2020. The definitions of the main variables are listed in Table 1, and further descriptive statistics are given in Appendix B.

4. Analysis of empirical results

Based on past theories and hypotheses, this section presents our investigation into the direct role of urban form based on TFP and urban living amenities. Through these two channels, the urban form is shown to affect housing affordability stress, and the vector (i.e., magnitude and direction) depends on their scales. After clarifying the underlying correlations, we seek to further understand the government's role in the relationship between urban morphology and housing affordability stress by estimating the efficiency of government fiscal public service expenditures in regulating the morphology and housing affordability stress. Hence, we arrive at a breakthrough point for governments in developing countries for measurably improved urban planning.

4.1. Impact of urban form on productivity and living amenities

4.1.1. Impact of urban form on productivity

The TFP measure directly corresponds to *A* in the theoretical model, and regressing the urban form and regional TFP effectively identifies the influence vector of θ_A. However, regional productivity developments affect the location of enterprises (An & Yang, 2020), causing a two-way causality problem. Therefore, we considered a two-stage least-squares regression using the instrumental variables from the model of urban

[4] LP method according to Levinsohn and Petrin (2003) and Petrin et al. (2004); OP method according to Olley and Pakes (1996).

[5] According to the subject adjustment of the *China Urban Construction Statistical Yearbook*, before 2011, it was external transportation land, and in 2012 and later, it was land used for road transportation facilities; these data were smoothly adjusted based on the node in 2011.

Table 1
Variable definitions.

Variable	Name		Definition
Explained variable	*Rhw*		Housing affordability stress index (sales of commercial housing per unit area/gross wages per unit of employees × 100) (person/m^2)
Explanatory variables $Shape_{it}$	*Circle*		Near-circularity index
	Cohesion		Cohesion index of patches
	Continuity		Proximity agglomeration index
Tool variables $Instru_{it}$	*Ratio05*		Developable area/total area in the 500 m buffer
	Ratio03		Developable area/total area in a 300 m buffer
Production mechanism variables: TFP_{it}	*LLP*		TFP measured by the LP method of listed companies
	LOP		TFP measured by the OP method of listed companies
	ILP		TFP measured by the LP method of industrial enterprises
	IOP		TFP measured by the OP method of industrial enterprises
Resident mechanism variables: $Living_{it}$	*Environment*	*IW*	Industry waste: Comprehensive utilization rate of industrial smoke (powder) dust and solid waste (%)
		DW	Dirty water: Centralized treatment rate of sewage (%)
	Healthcare	*MI*	Medical insurance: Participation rate of basic medical insurance for urban employees (%)
		HD	Hospital doctor: Occupational/ assistant physicians per capita
	Education	*MT*	Middle-school teachers: Number of teachers in middle schools per student
		UT	University teachers: Number of teachers in higher education per student
	Transportation	*RA*	Road area: road area per capita (km^2/10,000 people)
		RL	Road length: Road length per capita (km/10,000 people)
Moderating variables	*Govserv*		Public service expenditure per unit of unproductive land
Control variables: $Control_{it}$	*Bigcity*		City category, 5–1 represents megalopolises, megacities, large cities, medium cities, and small cities
	Terrain		Average terrain undulation
	Elevat		Altitude
	Street		Number of streets within the area
	Agdp		GDP per capita
	Invest		Regional fixed asset investment/ gross domestic product
	Area		Built-up area
	Chur		Land transfer transaction price/ revenue from local budget
	People		Logarithmic number of the resident population

Notes: Cities with a permanent urban population of <500,000 are small cities; cities with a permanent urban population of >500,000 and <1 million are medium cities; cities with a permanent urban population of >1 million and <5 million are large cities; cities with a permanent urban population of >5 million and <10 million are megacities; and cities with a permanent urban population of >10 million are megalopolises (National Development [2014] No. 51).

form affecting productivity and living amenities. Per the results of a one-stage regression of these instrumental variables (Appendix C), coefficients in the one-stage regression of urban form and potential footprint indicators were significant at the 1 % level, which passes the unidentifiable (UI) and weak identification (WI) tests, thereby satisfying the exogeneity and correlation requirements.

Table 2 reports on the urban form's impact on TFP according to the key explanatory variables (i.e., *Circle*, *Cohesion*, and *Continuity*) based on 2005–2020 indices. Columns (Alesina & Zhuravskaya, 2011; An & Yang, 2020) of Table 2 present the urban form with market capitalization-weighted TFPs of listed firms under the LP and OP algorithms (*LLP* & *LOP*), and Columns (Angel et al., 2005; Angel et al., 2020) supplement the results with market capitalization-weighted TFPs of industrial firms for the 2005–2013 period (*ILP* & *IOP*). The results indicate that the regression coefficients of the urban form on the TFPs of listed companies are all significantly positive, showing that cities generate productivity premiums as they develop into increasingly compact forms. From a production perspective, the compact urban form promotes productivity improvements through the agglomeration of positive externalities and the increased circulation of certain factors. Thus, compact urban forms effectively take advantage of spatial agglomerations and industrial synergies to enhance the degree of the positive externalities of innovation and knowledge synergy. On the other hand, the compact urban form also reduces the additional costs of physical factor circulation, improves the quality of road and network usage in the region, and enhances the efficiency of factor outputs. Additionally, as shown in Appendix D-1, increased productivity can generate higher real wages while lowering housing affordability stress under the effects of real wage compensation. Therefore, Hypothesis 1a is supported.

Table 2
Regression results of urban form on productivity.

TFP	(1)	(2)	(3)	(4)
	LLP	*LOP*	*ILP*	*IOP*
Circle	0.432**	0.355**	0.152	0.150
	(2.195)	(2.051)	(1.542)	(1.599)
UI test	16.65***	16.65***	18.02***	18.02***
WI test	11.08***	11.08***	12.17***	12.17***
Cohesion	0.389***	0.307**	0.135*	0.128*
	(2.749)	(2.529)	(1.785)	(1.805)
UI test	47.67***	47.67***	35.09***	35.09***
WI test	23.93***	23.93***	19.81***	19.81***
Continuity	0.297***	0.248***	0.240**	0.231**
	(3.105)	(2.706)	(2.573)	(2.573)
UI test	60.99***	60.99***	34.88***	34.88***
WI test	25.47***	25.47***	14.53***	14.53***
Observations	4160	4160	2340	2340
Year	YES	YES	YES	YES
Province	YES	YES	YES	YES
Control	YES	YES	YES	YES

Notes: The *t*-value under the cluster robust standard error is in parentheses. The instrumental variables are Ratio05 and Ratio03, the unidentifiable test is the result of the Kleibergen–Paap rk LM statistic, and the weak instrumental variable test is the result of the Cragg–Donald Wald F statistic. The variables in the model containing the TFP and living amenities mechanisms were normalized, but the remaining model variables were not standardized. *, **, and *** indicate significance levels of 10, 5, and 1 %, respectively. The tables that follow have the same indicators.

4.1.2. Impact of urban form on living amenities

Columns (Alesina & Zhuravskaya, 2011; An & Yang, 2020; Angel et al., 2005; Angel et al., 2020; Barr & Tassier, 2016; Bartlett et al., 2014) in Table 3 present the effects of urban shape on access to public resources, including urban environment, healthcare, education, and transportation, and the results show that compact urban form's coefficients on access to public resources are positive at the 10 % significance level across *Circle*, *Cohesion*, and *Continuity*. These results show that an increase in urban shape compactness leads to a decrease in the cost of public service provision and that the likelihood of residents' access to public infrastructure is improved. This naturally leads to population inflow and an increase in housing demand in compact urban forms. Columns (Baruah et al., 2021; Baum-Snow, 2007) in Table 3 present the effects of urban form on residents' commuting efficiency. Controlling for the local economic development level, the regression coefficients of *Cohesion* and *Continuity* are significantly positive, indicating that the internal agglomeration and external connectivity of the urban form promote urban accessibility and reduce potential

Table 3
Regression results of urban form on living amenities.

Living	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Environment		*Healthcare*		*Education*		*Transportation*	
	IW	*DW*	*MI*	*HD*	*MT*	*UT*	*RA*	*RL*
Circle	0.466**	0.482***	0.324**	0.258**	0.535***	0.357**	0.10	0.20
	(2.52)	(3.30)	(2.39)	(2.15)	(3.20)	(2.23)	(1.01)	(1.64)
UI test	15.99***	15.99***	15.99***	15.99***	15.99***	15.99***	15.99***	15.99***
WI test	14.81***	14.81***	14.81***	14.81***	14.81***	14.81***	14.81***	14.81***
Cohesion	0.493***	0.341***	0.299***	0.212***	0.237***	0.286***	0.112*	0.175**
	(4.17)	(4.09)	(3.62)	(2.92)	(3.18)	(2.95)	(1.83)	(2.49)
UI test	30.12***	30.12***	30.12***	30.12***	30.12***	30.12***	30.12***	30.12***
WI test	23.49***	23.49***	23.49***	23.49***	23.49***	23.49***	23.49***	23.49***
Continuity	0.586***	0.196**	0.302***	0.177***	0.126**	0.224**	0.136***	0.161**
	(4.65)	(2.53)	(3.35)	(2.82)	(2.11)	(2.44)	(2.69)	(2.51)
UI test	65.20***	65.20***	65.20***	65.20***	65.20***	65.20***	65.20***	65.20***
WI test	39.91***	39.91***	39.91***	39.91***	39.91***	39.91***	39.91***	39.91***
Observations	4160	4160	4160	4160	4160	4160	4160	4160
Control	YES	YES	YES	YES	YES	YES	YES	YES
Year/Prov	YES	YES	YES	YES	YES	YES	YES	YES

Notes: *IW*, *DW*, *MI*, *HD*, *MT*, *UT*, *RA*, and *RL* indicate industry waste, dirty water, medical insurance, hospital doctor, middle school teacher, university teachers, road area, and road length, respectively.

commuting costs, thereby enhancing urban living amenities. Additionally, as shown in Appendix D-2, increased urban living amenities in terms of environment, healthcare, education, and transportation can bring about higher housing prices, which enhances housing affordability stress. Therefore, Hypothesis 1b is supported. However, urban shape regularity exhibits a limited effect on transportation in this study's sample.

4.2. Impact of urban form on housing affordability stress

Section 4.1 reveals opposite vectors representing the effects of the compact urban form on housing affordability stress, including real wage increases that reduce housing affordability stress. It also increases living amenities, thereby increasing housing affordability stress. Table 4 reports the effects of the urban form on housing affordability stress across *Circle*, *Cohesion*, and *Continuity*. The explanatory variable in this instance is the urban housing affordability stress index. Columns (Alesina & Zhuravskaya, 2011; An & Yang, 2020; Angel et al., 2005; Angel et al., 2020; Barr & Tassier, 2016; Bartlett et al., 2014) present the results of ordinary and two-stage least-squares regressions, with *potential footprint* as the instrumental variable. From the base model's regression results, the coefficients of *Circle*, *Cohesion*, and *Continuity* are all significantly positive, indicating that the compact urban form's effect on improved living amenities is dominant. Specifically, the compact urban form increases residents' welfare and wages, which precipitates a faster population flow into compact cities and an increase in demand and prices in the housing market. Eventually, under spatial equilibrium, rent growth is greater than positive productivity externality under compact urban form, which increases housing affordability stress. Overall, the degrees of both urban form regularity and spatial compactness within and between built-up areas of cities increase housing affordability stress on urban residents.

To further analyze the identification tradeoff between the two vectors, we identified their mechanisms by comparing changes in the coefficients of key explanatory variables after controlling for mechanism variables (Alesina & Zhuravskaya, 2011). Table 5 presents the model regression results after standardizing the variables, and Columns (An & Yang, 2020; Angel et al., 2005) control for the production mechanism variables' effects on the base regression's results. Columns (Angel et al., 2020; Barr & Tassier, 2016; Bartlett et al., 2014; Baruah et al., 2021) control for the living amenity mechanism variables. The regression results indicate that the production mechanism plays an intermediate masking utility role in the relationship between compact urban form and housing affordability stress. Thus, before incorporating the TFP variable, the compact urban form impacts housing affordability stress, including the negative impact of this stress through TFP. Therefore, controlling for the production mechanism variable enhances the positive relationship between compact urban form and housing affordability stress. By contrast, their coefficients decrease significantly when controlling for the living amenity mechanism variables of urban environment, healthcare, education, and transportation, indicating that the dimensions of suitability for urban living act as positive mechanistic variables in the relationship between compact urban form and housing affordability stress. Thus, the compact urban form increases housing affordability stress by improving amenities for urban living. The model passes the Sober test after standardizing the variables, in which the trade-off

Table 4
Regression results of urban form on housing affordability stress.

Rhw	*Circle*		*Cohesion*		*Continuity*	
	(1)	(2)	(3)	(4)	(5)	(6)
Methods	OLS	IV	OLS	IV	OLS	IV
Shape	1.535**	23.518***	2.878***	30.251***	1.876***	27.839***
	(2.079)	(3.097)	(3.313)	(4.861)	(3.206)	(5.414)
Constant	17.780***	15.291***	17.669***	14.783***	17.668***	13.290***
	(28.065)	(15.450)	(27.903)	(18.572)	(27.967)	(14.416)
Observations	4160	4160	4160	4160	4160	4160
R^2	0.613	–	0.614	–	0.614	–
Control	YES	YES	YES	YES	YES	YES
Year/Province	YES	YES	YES	YES	YES	YES
UI test		6.25**		23.10***		15.04***
WI test		6.32***		24.21***		15.17***

Table 5
Additional verification of the basic model's influencing mechanisms.

Rhw	Basic	Control *TFP*		Control *Living*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mediator	*None*	*LLP*	*ILP*	*IW*	*MI*	*MT*	*RA*
Circle	0.386***	0.460***	0.496***	0.346***	0.361***	0.354***	0.385***
	(2.791)	(3.164)	(3.646)	(2.616)	(2.716)	(2.602)	(2.881)
Producing/Living		−0.078***	−0.042**	0.045**	0.126***	0.003	0.178***
		(−5.391)	(−2.554)	(2.481)	(5.817)	(0.123)	(6.112)
UI test	15.96***	16.55***	17.84***	15.95***	16.09***	15.81***	16.41***
WI test	14.76***	14.94***	16.15***	14.82***	14.87***	14.57***	15.14***
Cohesion	0.362***	0.465***	0.376***	0.340***	0.336***	0.357***	0.346***
	(4.145)	(4.848)	(4.419)	(3.913)	(4.053)	(4.082)	(4.182)
Producing/Living		−0.075***	−0.034**	0.022	0.132***	0.007	0.178***
		(−5.483)	(−2.385)	(1.182)	(6.285)	(0.357)	(6.669)
UI test	30.04***	30.38***	25.89***	30.03***	30.33***	31.15***	30.86***
WI test	23.36***	23.91***	22.19***	23.53***	23.63***	24.00***	24.13***
Continuity	0.373***	0.614***	0.527***	0.347***	0.352***	0.368***	0.355***
	(4.137)	(5.350)	(4.168)	(3.835)	(4.030)	(4.038)	(4.014)
Producing/Living		−0.045***	−0.028*	0.042**	0.121***	0.011	0.124***
		(−2.751)	(−1.772)	(2.275)	(5.626)	(0.587)	(4.588)
UI test	65.24***	59.13***	32.07***	63.21***	65.06***	65.23***	64.64***
WI test	39.95***	35.69***	19.07***	38.17***	39.80***	40.09***	39.73***

Notes: *LLP*, *ILP*, *IW*, *MI*, *MT*, and *RA* indicate the TFP measured by the LP method of listed companies, the TFP measured by the OP method, industry waste, medical insurance, middle school teacher, and road area, respectively.

between the vectors of production and amenity mechanisms exhibits a combined effect on the correlation between urban form and housing affordability stress.

4.3. Moderating effects of government public service input efficiency

Although the compact city form generally increases housing affordability stress, the vectors of the urban form based on productivity and living amenities in relation to housing affordability stress are also influenced by government decisions in China, where public services are predominantly regulated by local governments. To maximize the total fiscal revenue and regional economic growth, local governments must rationalize the land elements between industrial and residential uses to balance the tax contributions of industrial and residential areas, as well as to allocate further expenditures based on land fiscal revenues. Our theoretical model, which considers government lands and fiscal allocations, reveals the impact of efficient public service expenditures on the relationship between urban form and housing affordability stress, indicating that the housing market is subject to the moderating effect of government resource allocation behaviors.

The moderating effect model's regression results further demonstrate how the government influences the vector equilibrium through the regulation of the efficiency of public service fiscal expenditures, indicating that the relationship between urban form and housing affordability stress may shift under different states of regulation for government land and fiscal decisions. According to the theoretical model, public service expenditure per unit of unproductive land can be used as a proxy variable for assessing the efficiency of public service fiscal spending. Table 6 presents the regression results of the regulating model, in which the proportion of social security and healthcare expenditures per unit of unproductive land reflects the government's policy preferences for improving living amenities. The regression results reveal that when a local government improves its public service expenditure efficiency, the coefficient of the positive effect of the compact urban form on housing affordability stress decreases, indicating that the efficiency of government public service expenditures exhibits a negative moderating effect on the relationship between urban form and housing affordability stress. When the government's public service fiscal expenditure efficiency increases, it has a crowding-out effect on the compact urban form's influence vector for enhancing living amenities and increasing housing affordability stress. However, by empowering production externalities, the efficiency of the government's public service fiscal expenditures indirectly enhances the influence vector of the compact urban form, which enhances enterprise production efficiency to reduce housing affordability stress. Overall, the efficiency of public service inputs weakens the positive influence vector and strengthens the negative vector of the compact urban form as it relates to housing affordability stress. That is, it negatively moderates the basic relationship.

Table 6
Regression results for moderating effects of public service fiscal expenditure efficiency.

Rhw	(1)	(2)	(3)
	Circle	*Cohesion*	*Continuity*
Shape	20.554***	16.746***	19.307***
	(3.223)	(3.520)	(5.776)
c.Shape # c.Govserv	−26.317***	−17.947***	−7.938***
	(−5.196)	(−4.574)	(−3.003)
Observations	4160	4160	4160
Control	Y	Y	Y
Year/Province	Y	Y	Y
UI test	22.32***	52.18***	60.24***
WI test	8.62**	12.78***	12.71***

4.4. Robustness tests

Robustness tests were conducted as described below.

(i) We replaced the explanatory variables: Considering the effects of public accumulation funds for urban housing in China, the corrected housing prices for public accumulation funds in 43 large- and medium-sized cities from 2010 to 2020 were used as the explanatory variable for robustness testing. This variable is defined as the ratio of house price to income after correcting the housing provident fund. This is the average transaction price of residential buildings multiplied by the building area of residential buildings per capita divided by the product of disposable income per capita and the correction coefficient of the housing provident fund. The correction coefficient of the housing accumulation fund is the housing accumulation fund deposit amount plus disposable income per capita multiplied by the urban population divided by the product of the disposable income per capita and the urban population. The data were obtained from the Wind database.

(ii) We substituted the urban form explanatory variables. First, the landscape shape index (Eq. (18a)) without area weighting was considered as a proxy variable for the robustness of *Circle* when the landscape has only one circular patch, $Lsi = 0$. The near-circularity index's value decreases when the patch shape in the landscape is irregular or deviates from circularity. Second, *Diver* and *Polo*, alternative indicators of *Cohesion* and *Continuity*, represent the degrees of urban polycentricity and inter-center accumulation identified using LandScan remote sensing data. *Diver* represents the importance of subcenters in the city relative to the main center and is defined as presented in Eq. (18b), where P_{centre} is the population of each subcenter in the city, and P_{total} is the population of all population centers. The larger the *Diver* index value, the higher the importance of subcenters and the higher the degree of equal concentration of each center in the city. *Polo* is presented in Eq. (18c), where n represents the number of identified centers, d_i is the distance from center i to the other centers, and x_i is the population of center i. The larger the values for *Polo*, the better the connectivity among the centers.

$$\mathrm{Lsi} = 1 - \frac{P_i}{2\sqrt{\pi S_i}}, \tag{18a}$$

$$Diver = \frac{P_{centre}}{P_{total}}, \tag{18b}$$

$$Polo = \frac{\sqrt{\sum_{i=1}^{n} \frac{(I_i - \bar{I})^2}{n}}}{\left(\frac{I_{max}}{2}\right)}; I_i = x_i{}^{*}d_i; I_{max} = x_{max}{}^{*}d_{imax}. \tag{18c}$$

(iii) We replaced the sample time interval: We removed the sample from the financial crisis period between 2007 and 2008 for robustness testing.

(iv) We replaced the sample's geographical interval: We used the sample with provincial capital cities removed. Note that the robustness test results are presented in Appendix E and are consistent with the conclusions in the main text.

5. Analyzing the expansion of monocentric and polycentric cities

Against the backdrop of promoting polycentric patterns in China's major cities (Zhang et al., 2019), urban spaces have gradually shifted from monocentric to polycentric structures. Considering that theoretical models were constructed under the assumptions of monocentrism, this section discusses the extent to which urban form affects housing affordability stress in monocentric versus polycentric cases. We identified the centers in China from 2005 to 2020 using the urban polycenter identification method, which is based on remote sensing data from LandScan[6] (Q. Wang et al., 2021). As shown in Fig. 6, the monocenter is more common in megalopolises and megacities, which developed rapidly in their early stages. However, the polycentric pattern (e.g., Beijing subcenter construction) is more common, as overcrowding brings stress to city operations. In large cities, such as Suzhou, spontaneous sprawling developments have led to inefficient agglomeration utility, and in recent years, there has been a tendency toward developing single main centers.

Using the number of identifiable city centers as the classification criterion, the grouped regression results of poly- and mono-center cities (Table 7) indicate that the compact urban form's effect on housing affordability stress in the polycentric case is significantly positive; however, the impact coefficient decreases because, in the polycentric case, by comparing the distribution of a polycentric city's layout and development zones, their spatial distribution was found to display high consistency. Thus, a polycentric city layout can promote rational industrial redistribution and deepen agglomeration externalities through the construction of peripheral industrial parks and lowered land costs in development zones. This enhances the compact urban form's impact on production efficiency vectors and reduces housing affordability stress (Zheng et al., 2021). However, a polycentric city layout increases the difficulty of managing regional public services and infrastructure and increases the cost of connection between centers, thereby weakening the compact urban form's positive effects on living amenities and reducing housing affordability stress (Yao & Wu, 2020). Therefore, the effect of increasing housing affordability stress caused by compact urban forms is weakened during the evolution of cities from monocentric to polycentric patterns.

As presented in Table 8, the regression results indicate that government public service fiscal expenditure efficiency's moderating effects on urban form and housing affordability stress are smaller in polycentric cities compared with monocentric cities, and the groupings' regression coefficients significantly pass the coefficient difference test. These results suggest that to mitigate the effects of the increased housing affordability stress caused by the compact urban form, adequate government revenue and active public service spending are needed in a polycentric urban development pattern. Difficulties in managing public services and infrastructure increase in a polycentric pattern, and the negative effects of irregular urban forms on housing affordability stress are less sensitive to changes in the proportion of marginal government public service efficiency. Currently, to effectively mitigate the negative externalities of the housing market in the urban sprawl process, the government must pay greater attention to the regulation of public service expenditures, housing market stability, and urban infrastructure promotion.

6. Discussion

6.1. Research contributions

6.1.1. Contributions to the field: perspectives and implications

Building upon the foundational works of prior research, our study offers nuanced perspectives and implications, deepening the understanding of the intricate relationship between urban form and housing affordability stress.

Redefining the Impact Mechanisms: In contrast to previous simple correlation studies, in our research, the impact mechanisms of urban form on housing affordability stress were mainly determined from an equilibrium of two vectors. On the one hand, a compact urban form promotes productive efficiency, raises wages, and reduces housing affordability stress. The finding that compact urban form promotes productive efficiencies strengthens the implication that the industry structure in China is shifting from land-intensive manufacturing to productive services (Ma et al., 2023). Moreover, the deliberative approach of this study emphasizes the perspective of developing countries as distinct from developed countries (Montejano et al., 2020). On the other hand, the compact form promotes living amenities, raises housing prices, and increases housing affordability stress. Although existing studies have generally concluded that urban form is a key factor in living amenities (Y. Fang & Bai, 2022), this paper focuses on the multiple dimensions of environment, healthcare, education, and transportation to provide additional evidence. The effect of the urban form on housing affordability stress varies across regions depending on the magnitude of the two vectors, and the mechanistic analysis of this paper provides a good explanation for the relationship between urban density and housing affordability, varying in different regions (Manville et al., 2022).

Revisiting the Government's Role in Urban Development: Historically, local governments have utilized various tools, such as land transactions, urban planning decisions, infrastructure developments,

[6] Developed by the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL), LandScan Global Population Dynamics Data is a high-quality and high-precision spatial distribution of the global population. For details regarding the multicenter identification method, please refer to the annex of Wang et al. (2021) (http://ciejournal.ajcass.org).

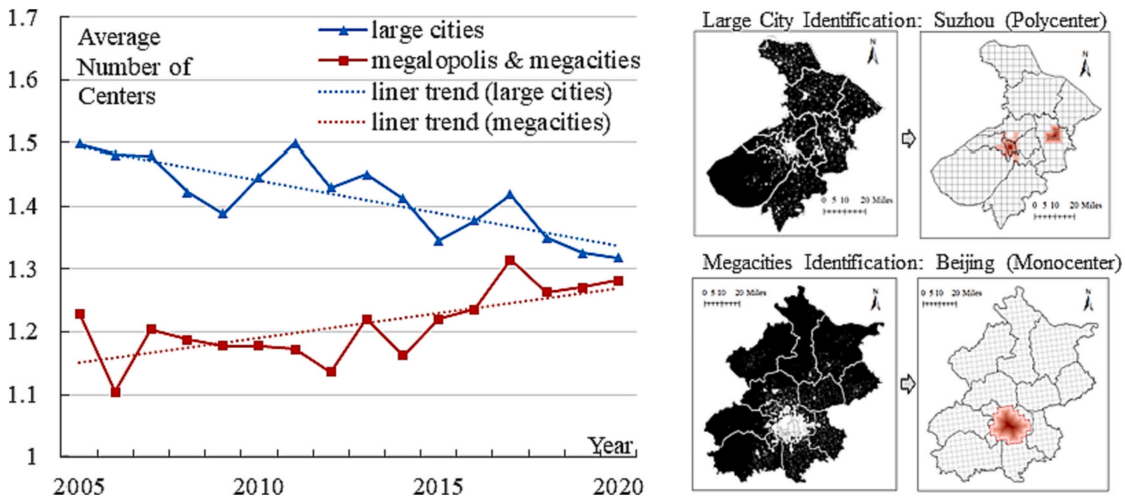

Fig. 6. Trend and examples of urban centers in China based on LandScan. Based on review number GS (2019) No. 1822, the base map has not been modified. *Notes*: Examples of Beijing and Suzhou are from 2020; criteria for classification of cities are the same as those in Table 1 (National Development [2014] No. 51).

Table 7
Basic regression results of monocentric and polycentric city groupings.

Rhw	*Circle*		*Cohesion*		*Continuity*	
	(1)	(2)	(3)	(4)	(5)	(6)
Group	*Muti*	*Single*	*Muti*	*Single*	*Muti*	*Single*
Shape	37.862***	65.370***	11.470**	59.040***	28.664***	30.909***
	(3.373)	(2.676)	(2.395)	(2.712)	(4.706)	(4.328)
Control	YES	YES	YES	YES	YES	YES
Year/ Province	YES	YES	YES	YES	YES	YES
Observations	1714	2445	1714	2445	1714	2445
UI test	10.74***	6.16**	7.02**	24.19***	40.03***	36.78***
WI test	11.12**	8.14*	8.72*	12.98***	22.11***	22.72***
Chow test	−27.51**		−47.57*		−2.245**	

Table 8
Regression results for the moderating effect of monocentric and polycentric city groupings.

Rhw	*Circle*		*Cohesion*		*Continuity*	
	(1)	(2)	(3)	(4)	(5)	(6)
Group	*Muti*	*Single*	*Muti*	*Single*	*Muti*	*Single*
Shape	13.656**	32.202***	10.027*	35.904***	18.725***	22.479***
	(2.570)	(2.797)	(1.927)	(3.126)	(3.321)	(3.244)
c.Shape#c.Govserv	−76.070***	−174.534***	−122.669***	−166.381***	−71.438***	−75.272***
	(−3.559)	(−4.425)	(−5.386)	(−4.308)	(−3.822)	(−3.484)
Control	YES	YES	YES	YES	YES	YES
Year/Province	YES	YES	YES	YES	YES	YES
Observations	1714	2445	1714	2445	1714	2445
UI test	13.03**	19.59***	25.75***	24.67***	38.89***	13.03***
WI test	6.686	6.548	12.09**	12.09**	7.857*	14.18***
Chow test- *Shape*	−18.546***		−25.878*		−3.755*	
Chow test- c.*S#c.G*	98.464**		43.712*		3.834*	

and allocations of public service expenditures, to shape the urban form (Carruthers & Ulfarsson, 2002; Miguel et al., 2016). Although governments have predominantly acted as interveners in urban sprawl (Zhu et al., 2022), a significant lacuna persists in the understanding of the direct role of political entities in influencing the urban form's interaction with the real estate market (Lee, 2022). Our research offers a blend of theoretical perspectives and empirical data to elucidate the ways in which governmental fiscal strategies and land-use decisions affect the relationship between urban form and housing affordability stress. Notably, public service input efficiency serves as a negative moderator in this core relationship, suggesting that enhancing governmental expenditure efficiency in public services can ameliorate housing affordability challenges, given a stable urban form. While the comprehensive linkage between public spending and sustainable development objectives remains to be thoroughly explored (Cristobal et al., 2021), our investigation furnishes reliable insights into the convergence of government public service expenditures and sustainable urban spatial designs.

Shedding Light on Polycentric Development: This research uniquely contributes to the understanding of the externalities introduced by polycentric spatial structures. Although established models suggest that the rise of subcenters is an inherent outcome of metropolitan growth (Barr & Tassier, 2016), our findings offer a novel perspective: polycentric urban designs can mitigate housing affordability stress induced by compact urban forms, which aligns with existing findings emphasizing the decentralizing effects of subcenters (L. Li & Xia, 2023). This paper also emphasizes the role of government in polycentric pattern-making. While previous research has emphasized the role of substantial government investments in promoting growth in specific areas through urban polycentrism (Kwon, 2021), our study shows that in polycentric cities, more efficient government fiscal spending on public services is needed to alleviate the increased housing affordability stress caused by compact urban forms.

6.1.2. Contributions to the scientific field

In this study, we engaged in a thorough examination of the mechanism through which urban form influences housing affordability stress. Elevating the scientific rigor of our research hinges on several pivotal methodologies: resolving the theoretical model of spatial general equilibrium, employing remote sensing data, and devising instrumental variables to fortify the robustness of the empirical findings.

Redefining Urban Form Analysis: Our research departs from the conventional paradigms employed to study urban form (Jahanmiri & Parker, 2022) and their associated environmental ramifications (Sun et al., 2022). Instead, we seamlessly blended theoretical frameworks with empirical methodologies. This combined theoretical and empirical approach can unravel the nuanced intricacies between urban form and housing market dynamics, shedding light on the multifaceted challenges of residential affordability and sustainable urban evolution (S. G. Yin et al., 2019). In both our theoretical and empirical designs, we not only validated the pathway through which urban form influences housing affordability stress by enhancing productive efficiency and living amenities but also incorporated the moderating role of government interventions.

Tackling Methodological Quandaries: We acknowledge the potential pitfalls and endogeneity concerns that often plague the assessment of the relationship between urban form and housing affordability stress. To circumvent these challenges, our study employed instrumental variables, enhancing the reliability and precision of our findings. In addition, we used multi-dimensional remote sensing data, including nighttime lighting data, digital elevation models (DEM), and LandScan population data. This allowed us to not only validate the multi-indicator composite of urban form from multiple perspectives, but it also extended our discussion of the polycentric revelation of population distributions, which ensures the robustness of the conclusions.

Insightful Sampling and Broader Implications: It is essential to highlight the comprehensiveness and granularity of our sample, which encompasses all prefecture-level cities in China spanning an extended period. This comprehensive dataset not only elucidates China's urban trajectory but also provides invaluable insights for cities in rapid urbanization. As the global call intensifies to uplift living conditions against the backdrop of sprawling urban landscapes, our research serves as an illuminating guidepost, charting avenues toward sustainable urban transformations and ensuring enhanced living environments for global citizenry.

6.2. Policy and practice recommendations for urban planning

These results can be used to enlighten policymakers about the compact urban forms that impact both production efficiencies and the accessibility of living amenities, noting that these constructs directly affect housing markets. Based on our findings, this study shows that urban sprawl boundaries should be reasonably controlled to avoid excessive growth and disorderly expansion. Urban planning efforts can strictly apply spatial planning layouts and boundary control schemes while fully utilizing land planning to encourage similar industrial clustering, which can lead to the proactive management of abandoned spaces for subsidized housing, ultimately leading to the effective avoidance of the tragedy of the commons.

Moreover, these results show that the efficiency of government public service expenditures can be improved to alleviate the negative externalities of compact urban spaces. Urban planning in China must further emphasize the regulatory role of the government while enhancing the efficiency of government spending on public services. To strengthen the cooperation between urban planners and local governments, planners should focus on the efficiency of fiscal expenditures for urban public services and communicate the evaluation and planning results to municipal decision-makers. Governments should, in turn, adopt uniform and coordinated approaches to ensure that the allocation of public service expenditures meets the specific needs of each region. This may include incentivizing government entities to improve expenditure efficiencies through standardized performance assessment standards or matching public service supply-and-demand protocols via an intelligent integration platform.

As cities evolve from monocentric to polycentric types, public service spending in subcentral areas can be designed to relieve housing affordability stress. Therefore, when planning polycentric cities, it is particularly important to monitor the externalities of the urban form and the effectiveness of public service expenditures in a timely manner. Modern technologies, such as big data, artificial intelligence, cloud computing, and blockchain, have become important tools for urban management. Urban planners can use the results of this study to derive empirical evidence about urban forms and housing affordability stress. They can then utilize digital platforms and timely assessments to evaluate the impact of urban spatial planning on production efficiencies, the accessibility of living amenities, and the real-estate market to adjust various urban planning variables.

6.3. Limitations and future prospects

This study provides pivotal insights while remaining acutely aware of its inherent limitations. A significant concern was the potential oversight of individual attributes and detailed behavioral patterns. To address this, we incorporated a comprehensive range of socio-demographic variables into our assessment. However, this action underscores the challenge of accurately representing the diverse individual tendencies caused by their multifaceted nature. Furthermore, understanding the depth and authenticity that primary data collection offers, we augmented our primary data with meticulously chosen secondary sources, which aimed to enhance our understanding of housing affordability stress and living amenity accessibility. However, it must be acknowledged that secondary data cannot entirely substitute direct insights. Concerning our methodology, we employed advanced geographic information system tools in tandem with innovative spatial statistical methods. Although these methods enriched our findings, it is important to mention that they may not capture all nuances of regional industrial spatial configurations or the distribution patterns of public services.

In contemplating future research directions, several areas warrant exploration. A nuanced analysis of individual attributes and behavioral patterns is indispensable. Utilizing machine learning and comprehensive qualitative methods should allow us to more precisely delineate individual characteristics, and exhaustive surveys and interviews will offer unparalleled insights into these research areas (Saldaña & Omasta, 2017). Spatial analysis, which is fundamental to our methodology, can be significantly enriched through technological advancements in the future. The deployment of high-definition satellite imagery in conjunction with state-of-the-art geographic information system tools holds promise for enhancing our grasp of regional industrial configurations and the spatial distribution of public services. Further, an interdisciplinary methodology that draws on expertise from urban planning, sociology, and economics will offer a multifaceted lens through which to view our research questions.

7. Conclusion

Utilizing the Rosen–Roback spatial equilibrium theoretical model and empirical expertise, this research investigates the nuanced interactions between urban form, housing affordability stress, and governmental interventions within China's urbanizing milieu, providing a bedrock for subsequent urban planning research and policy deliberation. The results identify a dual-faceted impact of compact urban forms that affect production efficiencies while potentially intensifying housing affordability stress due to the elevation of urban living amenities. Such findings highlight an inherent tension in urban planning, where the push for compact urban forms can inadvertently compromise housing affordability. Based on this, governmental public service expenditure efficiency emerges as a significant moderator in this dynamic in which efficient fiscal fund allocations can temper the affordability stresses induced by compact urban form. The data further reveal that as cities transition from monocentric to polycentric configurations, the adverse affordability implications of compact urban forms can be mitigated. However, the evolution of urban polycenters also signals an increased onus on governmental entities to refine their public service delivery mechanisms.

In light of these insights, urban planning in China should consider a nuanced approach to land use. Controlled sprawl, augmented by heightened public service efficiency, offers a potential pathway for balancing production optimization with housing affordability. As urban configurations trend polycentric, policies must adapt to address the divergent needs of multiple urban cores, ensuring a more equitable amenity and opportunity spread. Future studies could investigate fiscal dynamics in polycentric urban areas, examine the viability of public–private collaborations in urban planning, and evaluate the potential of innovative technologies for land-use enhancement.

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CRediT authorship contribution statement

Sun Jiuwen: Conceptualization; Supervision; Funding acquisition.
Xing Xiaoxu: Roles/Writing - original draft; Methodology; Visualization.
Xi Qiangmin: Project administration; Writing - review & editing; Formal analysis; Funding acquisition.
Shi Weihao: Data curation; Validation.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Appendix A. Urban form indicators' specific definitions

Table A-1
Variable *Circle* definition.

Related circumscribing circle	
$\frac{A_i}{A_{circle\ i}} \times \frac{A_i}{\sum_{i=1}^{n} A_i}$	A_i of patch *i*; $A_{circle\ i}$ area of smallest circumscribing circle around patch *ij*.
Description	*Circle* equals patch area (A_i) divided by area ($A_{circle\ i}$) of the smallest circumscribing circle.
Units	None
Range	$0 < Circle < 1$ *Circle* approaches one for circular patches and zero for elongated ones; linear patches are one cell in width.
Comments	The related circumscribing circle is derived from Baker and Cai (1992). Notably, this index is not influenced by patch size. Additionally, the index never quite equals one because the grid data format does not allow patches to be perfectly circular; however, the circumscribing circle's area is geometrically computed based on the patch radius.

Table A-2
Variable *Cohesion* definition.

Patch Cohesion Index	
$Cohesion = \left[1 - \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} P_i \sqrt{A_i}}\right]\left[1 - \frac{1}{\sqrt{n}}\right]^{-1}$	P_i = perimeter of patch *i* in terms of the number of cell surfaces. A_i = area of patch *i* in terms of the number of cells N = total number of cells in the landscape.
Description Units	*Cohesion* equals one minus the sum of the patch perimeter in terms of number of cell surfaces divided by the sum of the patch perimeter times the square root of the patch area in terms of number of cells for patches of the corresponding patch type, divided by one minus one over the square root of the total number of cells in the landscape, multiplied by 100 to convert to a percentage). Notably, the total landscape area (*n*) excludes any internal background present.
Range	$0 < Cohesion < 1$ *Cohesion* approaches zero as the proportion of the landscape comprising the focal class decreases and becomes increasingly subdivided and less physically connected. *Cohesion* increases monotonically as the proportion of the landscape comprising the focal class increases until an asymptote is reached near the percolation threshold. *Cohesion* is zero if the landscape comprises a single non-background cell.
Comments	The patch cohesion index measures the corresponding patch type's physical connectedness. Below the percolation threshold, patch cohesion is sensitive to the aggregation of the focal class. Patch cohesion increases as the patch type becomes more clumped or aggregated in its distribution; hence, it is more physically connected. Above the percolation threshold, patch cohesion does not appear to be sensitive to the patch configuration (Gustafson, 1998).

Table A-3
Variable *Continuity* definition.

(C3) Adjacency Aggregation Index	
$\frac{M_{real\ i}}{M_{access\ i}}$	$M_{real\ i}$ = number of like adjacencies (joins) between pixels of patch type (class) *i* based on the single-count method $M_{access\ i}$ = maximum number of like adjacencies (joins) between pixels of patch type (class) *i* (see below) based on the single-count method.
Description	*Continuity* is the number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies involving the corresponding class, which is achieved when the class is maximally clumped into a single, compact patch; multiplied by 100 (to convert to a percentage). If *Continuity* is the area of class *i* in terms of the number of cells, *n* is the side of a largest integer square smaller than *Continuity*, and *m* = *Continuity* - *n2*, the largest number of shared edges for class i, $M_{access\ i}$, will assume one of the following three forms: $M_{access\ i}$ = 2n (n−1), when m = 0, or $M_{access\ i}$ = 2n (n - 1) + 2 m - 1, when m = n, or $M_{access\ i}$ = 2n(n - 1) + 2 m −2, when m > n. Notably, because of the design of the metric, like adjacencies are tallied using the single-count method, and all landscape boundary edge segments are ignored, even if a border is provided.
Units	Percent
Range	0 ≤ *Continuity* ≤ 1 considering any pi, *Continuity* is zero when the focal patch type is maximally disaggregated (i.e., when there are no like adjacencies); *Continuity* increases as the focal patch type is increasingly aggregated and equals one when the patch type is maximally aggregated into a single, compact patch. *Continuity* is undefined and reported as "N/A" in the "base-name" class file if the class comprises a single cell.

Continuity is calculated from an adjacency matrix, which presents the frequency in which different pairs of patch types, including like adjacencies between the same patch type, appear side-by-side on the map. *Continuity* only considers the like adjacencies involving the focal class, not those with other patch types. Additionally, in contrast to all other metrics based on adjacencies, the aggregation index is based on like adjacencies tallied using the single-count method, wherein each cell side is counted only once. Consequently, the tallies provided in the "basename".adj output file are incorrect for this metric. Furthermore, owing to the metric's design, landscape boundary edge segments are ignored, even if a border is provided, FRAGSTATS handles this case by distinguishing between internal like adjacencies involving cells inside the landscape and external like adjacencies between cells inside the landscape and those in the border. Only internal like adjacencies are used to calculate this metric; a landscape border has no effect on this metric. *Continuity* is scaled to account for the maximum possible number of like adjacencies given any pi. The maximum aggregation is achieved when the patch type comprises a single, compact patch, which is not necessarily a square patch.

Source: Fragstat4.2 official document.

Appendix B. Variable descriptive statistics

Table B-1
Descriptive statistics table.

Variable	Name		Mean	S.D.
Explained variable	*Rhw*		1.20	2.17
Explanatory variables:	*Circle*		0.12	0.04
Shape	*Cohesion*		0.14	0.03
	Continuity		0.22	0.05
Tool variables:	*Ratio05*		0.93	0.11
Instru	*Ratio03*		0.91	0.11
Production mechanism variables:	*LLP*		0.38	0.23
Producing	*LOP*		0.38	0.24
	ILP		0.66	0.10
	IOP		0.18	0.13
Resident mechanism variables:	Environment	*IW*	0.74	0.28
Living		*DW*	0.72	0.27
	Healthcare	*MI*	0.38	0.19
		HD	0.61	0.25
	Education	*MT*	0.41	0.25
		UT	0.3	0.21
	Transportation	*RA*	0.29	0.27
		RL	0.36	0.23
Moderating variables	Govserv		0.09	0.07
Control variables:	*Bigcity*		1.99	1.01
Control	*Terrain*		1352.71	933.65
	Elevat		510.01	579.24
	Street		128.72	67.07
	Agdp		3.80	2.79
	Invest		0.66	0.28
	Area		117.76	127.84
	Chur		0.53	0.16
	People		5.88	0.62

Appendix C. Instrument variables one-stage regression results

The following table presents the regression results when the instrumental variables are Ratio03 and Ratio05; both are considered instrumental variables.

Table C-1
Instrument variable one-stage regression results (Ratio03).

Rhw	(1)	(2)	(3)
	Circle	*Cohesion*	*Continuity*
Ratio03	0.037**	0.066***	0.061***
	(2.514)	(4.920)	(3.895)
Observations	4160	4160	4160
Control	YES	YES	YES
Year/Province	YES	YES	YES

Table C-2
Instrument variable one-stage regression results (Ratio05).

	(1)	(2)	(3)
VARIABLES	*Circle*	*Cohesion*	*Continuity*
Ratio03	0.024*	0.054***	0.081***
	(1.685)	(4.081)	(7.161)
Observations	4160	4160	4160
Control	YES	YES	YES
Year/Province	YES	YES	YES

Table C-3
Instrument variable one-stage regression results (Ratio03 and Ratio05).

	(1)	(2)	(3)
VARIABLES	*Circle*	*Cohesion*	*Continuity*
Ratio03	0.142***	0.147***	0.187**
	(5.270)	(6.016)	(2.249)
Ratio05	0.109***	0.084***	0.256***
	(3.958)	(3.395)	(3.399)
Observations	4160	4160	4160
Control	YES	YES	YES
Year/Province	YES	YES	YES

Appendix D. Linkages from productivity to real wages and amenities to housing prices

D.1. Linkages from productivity to real wages

Table D-1a lists the OLS and IV regression results of TFP on real wage, where *Wages* is based on gross wages per unit of employees per year. The results show that productivity positively affects wages. To mitigate the two-way causal problem between TFP and wages, we used *total post and telecommunications business* at the end of 1984 (*Tele_1984*) as the instrumental variable. The instrumental variable regression results of the first stage are listed in the Table D-1b.

Table D-1a
Regression results of productivity on real wage.

Wages	(1)	(2)	(3)	(4)
	OLS	OLS	IV	IV
LLP	0.014**		0.330**	
	(2.576)		(2.122)	
LOP		0.016***		0.286**
		(2.921)		(2.139)
Observations	4160	4160	2340	2340
Control	YES	YES	YES	YES
Year	YES	YES	YES	YES
WI test			34.04***	39.18***

Table D-1b
Instrument variable one-stage regression results (*Tele_1984*).

Tele_1984	(1)	(2)
	LLP	*LOP*
Tele_1984	0.306***	0.258***
	(5.655)	(5.853)
Observations	4160	4160
Control	YES	YES
Year	YES	YES

D.2. Linkages from amenities to housing prices

Table D-2a lists the instrumental variable regression results of the second stage of amenities on housing price, where *HousePrice* uses local gross wages per unit of employees per year. The results show that amenities positively affect housing prices. To mitigate the two-way causal problem between environment, healthcare, education, and transportation indicators and housing prices, we used related historical data as the instrumental variable. For the environment indicators, average wind speed data by city (2001–2021; *Wind*) was used as the instrumental variable for industry waste (*IW*) and dirty water (*DW*). For healthcare indicators, the number of doctors from the Qin to Ming Dynasties (~221 BCE–1644 AE; *HisDoctor)* was used as the instrumental variable of medical insurance (*MI*) and hospital doctor (*HD*). For education indicators, the number of scholarships from the Ming to Qing Dynasties (~1368–1912) (*HisScholar)* was used as the instrumental variable for middle school teacher (*MT*) and university teachers (*UT*). For the transportation indicators, If the railroad was opened during the Republican period (1933), *HisRoad* is used as the instrumental variable of road area (*RA*) and road length (*RL*). The instrumental variable regression results of the first stage are shown in Table D-2b.

Table D-2a
Regression results of amenities on housing prices.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
HousePrice	IV	IV	IV	IV	IV	IV	IV	IV
IW	0.651*							
	(1.775)							
DW		0.183**						
		(2.454)						
MI			4.661***					
			(3.179)					
HD				1.281***				
				(7.057)				
MT					1.957***			
					(4.024)			
UT						2.380**		
						(2.203)		
RA							0.269**	
							(2.332)	
RL								0.241***
								(3.122)
Observations	4160	4160	4160	4160	4160	4160	1583	1583
Control	YES	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES	YES
WI test	6.324**	55.01***	12.01***	82.97***	25.23***	5.682*	2.993	53.80***

Notes: *IW*, *DW*, *MI*, *HD*, *MT*, *UT*, *RA*, and *RL* represent industry waste, dirty water, medical insurance, hospital doctor, middle school teacher, university teachers, road area, and road length indicators.

Table D-2b
Instrument variable one-stage regression results.

IV	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Environment		Healthcare		Education		Transportation	
	IW	*DW*	*MI*	*HD*	*IW*	*DW*	*MI*	*HD*
Wind	0.030**	0.106***						
	(0.119)	(0.014)						
HisDoctor			0.001***	0.005***				
			(0.000)	(0.001)				
HisScholar					0.056***	0.025**		
					(0011)	(0.010)		
HisRoad							0.053*	0.059***
							(0.030)	(0.008)
Observations	4160	4160	4160	4160	4160	4160	1583	1583
Control	YES	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES	YES

Appendix E. Robustness testing

E.1. Explanatory variable replacement

We replaced the urban form's explanatory variables for robustness testing. We considered the landscape morphology index (*Lsi*) without area weighting as a substitute for *Circle* and the degree of urban polycentricity (*Diver*) and degree of accumulation between centers (*Polo*) as substitutes for *Cohesion* and *Continuity*, for robustness testing.

Table E-1a
Base model regression results for substituting explanatory variables.

Rhw	*LSI*		*Diver*		*Polo*	
	(1)	(2)	(3)	(4)	(5)	(6)
IV	Ratio03	Ratio05	Ratio03	Ratio05	Ratio03	Ratio05
Shape	1260.266*	589.619***	11.975***	13.711***	19.450***	23.528***
	(1.672)	(4.613)	(5.771)	(5.814)	(5.057)	(4.750)
Observations	4160	4160	4160	4160	4160	4160
Control	YES	YES	YES	YES	YES	YES
Year/Province	YES	YES	YES	YES	YES	YES
UI test	2.777*	22.69***	50.40***	48.19***	34.91***	28.36***
WI test	7.742*	22.80***	53.16***	51.14***	34.78***	28.39***

Table E-1b
Mechanism regression results for substituting explanatory variables.

Rhw	*Basic*	*Control Producing*		*Control Living*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mediator	*None*	*LLP*	*ILP*	*IW*	*MI*	*MT*	*RA*
LSI	0.749***	1.377***	1.195***	0.736***	0.695***	0.745***	0.660***
	(3.185)	(5.344)	(3.888)	(3.351)	(2.985)	(3.216)	(2.757)
Producing/Living		−0.060**	−0.034**	0.085***	0.104***	0.040	0.068
		(−2.194)	(−2.226)	(2.938)	(4.305)	(1.503)	(1.405)
UI test	72.75***	75.94***	29.47***	90.29***	68.83***	77.88***	62.29***
WI test	41.27***	42.77***	15.60***	54.95***	38.44***	45.00***	34.40***
Diver	1.059***	1.260***	1.169***	0.966***	0.933***	1.033***	1.027***
	(4.275)	(5.901)	(5.117)	(4.228)	(4.330)	(4.187)	(4.105)
Producing/Living		−0.108***	−0.032	0.059***	0.208***	0.016	0.025
		(−4.800)	(−1.592)	(3.080)	(6.430)	(0.828)	(0.655)
UI test	35.62***	55.04***	44.87***	36.88***	40.78***	34.44***	33.48***
WI test	18.65***	29.43***	23.90***	19.38***	21.41***	18.04***	17.48***
Polo	1.102***	1.375***	1.562***	0.999***	0.977***	1.058***	1.025***
	(3.788)	(5.171)	(4.098)	(3.625)	(3.774)	(3.646)	(3.602)
Producing/Living		−0.106***	−0.049*	0.033*	0.176***	0.012	0.020
		(−4.520)	(−1.924)	(1.670)	(5.953)	(0.567)	(0.450)
UI test	27.02***	41.34***	24.40***	26.31***	29.62***	26.07***	27.05***
WI test	13.17***	20.18***	11.98***	12.83***	14.32***	12.56***	13.15***

Table E-1c
Moderating effect regression results for substituting explanatory variables.

Rhw	(1)	(2)	(3)
	LSI	*Diver*	*Polo*
Shape	136.819***	12.647***	10.901***
	(5.597)	(3.076)	(3.670)
	−556.317***	−54.349***	−32.730***
	(−4.267)	(−14.256)	(−13.779)
Observations	4160	4160	4160
Control	YES	YES	YES
Year/Province	YES	YES	YES
UI test	87.29***	53.18***	66.97***
WI test	31.52***	12.89***	14.27***

E.2. Explained variable replacement

We tested the basic model's robustness by replacing the explained variable. Considering public accumulation funds' impact on urban housing, the revised house price income ratio (*Rhw_check*) of housing funds in 43 large and medium-sized cities between 2010 and 2020 was used as the explained variable for regression. The variable is the ratio of house price to income after correcting for housing provident fund, which is the average transaction price of residential buildings multiplied by the building area of residential buildings per capita, divided by the product of disposable income per capita and the correction coefficient of housing provident fund, where the correction coefficient of housing accumulation fund is the housing accumulation fund deposit amount plus the disposable income per capita times the urban population, divided by the product of disposable income per capita and urban population. The data were collected from the Wind database, and the regression results are presented in Table E-2a are consistent with the regression results in the text.

Table E-2a
Base model regression results for substituting explained variables.

Rhw_check	*Circle*		*Cohesion*		*Continuity*	
	(1)	(2)	(3)	(4)	(5)	(6)
IV	*Ratio03*	*Ratio05*	*Ratio03*	*Ratio05*	*Ratio03*	*Ratio05*
Shape	73.146***	69.532***	2861.549***	4198.876**	1069.318***	1543.179**
	(5.394)	(6.000)	(2.623)	(2.299)	(2.967)	(2.499)
Observations	473	473	473	473	(2.967)	473
Control	YES	YES	YES	YES	YES	YES
Year/Province	YES	YES	YES	YES	YES	YES
UI test	13.35*	17.23***	11.84***	7.421***	9.771***	6.031**
WI test	19.67*	27.13***	11.10***	6.915**	10.40***	6.300**

Table E-2b
Mechanism regression results for substituting explained variables.

Rhw	(1)	(2)	(3)
	Circle	*Cohesion*	*Continuity*
Shape	20.179***	3.302***	3.007***
	(4.762)	(3.421)	(3.111)
	−86.909***	−46.166***	−17.837
	(−2.898)	(−2.752)	(−1.159)
Observations	473	473	473
Control	YES	YES	YES
Year/Province	YES	YES	YES
UI test	20.53**	13.96***	15.05***
WI test	4.815***	5.282***	14.712***

E.3. Sample time interval replacement

We deleted samples from the financial crisis period between 2007 and 2008 for robustness testing. The regression results are presented in Table E-2a and are consistent with the main text regression results.

Table E-3a
Base model regression results for changing sample time interval.

Rhw	*Circle*		*Cohesion*		*Continuity*	
	(1)	(2)	(3)	(4)	(5)	(6)
IV	*Ratio03*	*Ratio05*	*Ratio03*	*Ratio03*	*Ratio05*	*Ratio03*
Shape	114.037*	104.922*	50.927***	66.141***	45.801***	39.932***
	(1.725)	(1.726)	(4.041)	(3.428)	(3.829)	(6.039)
Observations	3640	3640	3640	3640	3640	3640
Control	YES	YES	YES	YES	YES	YES
Year/Province	YES	YES	YES	YES	YES	YES
UI test	2.96*	2.96*	17.17***	11.87***	15.71***	44.36**
WI test	2.97*	11.71*	17.83***	12.08**	15.94***	49.18**

Table E-3b
Moderation effect regression results for the changing sample time interval.

Rhw	(1)	(2)	(3)
	Circle	*Cohesion*	*Continuity*
Shape	21.860***	18.245***	12.846***
	(2.700)	(3.643)	(3.222)
	−218.454***	−53.469***	−32.066***
	(−3.585)	(−13.807)	(−13.259)

(*continued on next page*)

Table E-3b (*continued*)

Rhw	(1)	(2)	(3)
	Circle	*Cohesion*	*Continuity*
Observations	3640	3640	3640
Control	YES	YES	YES
Year/Province	YES	YES	YES
UI test	22.74***	32.24***	62.29***
WI test	8.186**	9.213***	15.08***

E.4. Sample's geographic interval replacement

We used the sample from the deleted capital city for robustness testing. The regression results are presented in Table E-4a and are consistent with the main text regression results.

Table E-4a
Basic model regression results for changing sample geographic intervals.

Rhw	*Circle*		*Cohesion*		*Continuity*	
	(1)	(2)	(3)	(4)	(5)	(6)
	Ratio03	*Ratio05*	*Ratio03*	*Ratio03*	*Ratio05*	*Ratio03*
Shape	69.790**	116.465*	40.212***	54.564***	43.307***	36.833***
	(2.570)	(1.743)	(4.626)	(3.970)	(3.736)	(6.145)
Observations	3776	3776	3776	3776	3776	3776
Control	YES	YES	YES	YES	YES	YES
Year/Province	YES	YES	YES	YES	YES	YES
UI test	2.96*	6.443**	22.01***	15.44***	14.59***	43.95***
WI test	10.97*	2.961*	23.05***	15.83***	14.72	48.77***

Table E-4b
Moderation effect regression results for the changing sample geographic interval.

Rhw	(1)	(2)	(3)
	Circle	*Cohesion*	*Continuity*
Shape	17.592***	11.601***	13.749***
	(2.932)	(2.955)	(3.832)
	−177.968***	−58.084***	−35.798***
	(−3.388)	(−14.541)	(−14.247)
Observations	3776	3776	3776
Control	YES	YES	YES
Year/Province	YES	YES	YES
UI test	29.57***	36.31***	63.58***
WI test	11.27***	11.23***	15.69***

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