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Mitigating housing vacancy with urbanization in China

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The expansion of urban built-up areas encroaches on adjacent croplands and natural lands, thereby posing significant threats to food security and ecosystem services. Concurrently, a substantial proportion of urban housing remains unoccupied, resulting in the inefficient use of valuable resources and undermining sustainability. Reducing housing vacancy while promoting economic growth and urbanization is therefore imperative. Here we show a notable decline in the housing vacancy rate in Chinese urban areas, decreasing from 0.274 in 2000 to 0.220 in 2020, despite a 28% increase in urbanization levels during the same period. By 2020, vacant housing accounted for an underutilization of 7960 km² of housing space and an estimated loss of 15,020 billion USD in social benefits. Moreover, the full utilization of vacant housing could accommodate an additional 190 million people, offering possible pathways for the redistribution of land resources to alleviate housing shortages. With urbanization levels projected to rise from 64% in 2020 to 80% by 2050, the associated loss in social benefits due to vacant housing is expected to decline by 12,085 billion USD. To accelerate this transition and maximize societal gains, it is crucial to remove housing purchase restrictions, which would facilitate rapid urbanization and further reduce housing vacancy rates.

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Introduction

Housing vacancy is a critical global issue, leading to the waste of valuable housing resources and creating financial risks, including fears of real estate bubbles and potential market collapses (Ortalo-Magné and Rady, 2006; Deng et al., 2017). Rapid urbanization has resulted in a surge of commercial housing to meet expected living and developmental needs. However, due to uneven development in land, economy, and population, many residential properties remain vacant (Li and Wu, 2019; Yang et al., 2023). This is especially pronounced in cities known as "ghost cities", where substantial housing stocks and high vacancy rates are prevalent (Woodworth and Wallace, 2017; Williams et al., 2019). Consequently, housing vacancies serve as indicators of the real estate market's supply-demand balance, prompting policies aimed at reducing vacancy rates.

China's unprecedented urbanization has attracted significant attention due to its scale and its profound impact on global sustainability (Montgomery, 2008; Bai et al., 2014). Projections suggest that China's urbanization rate will reach 80% by 2050, with an urban population exceeding 1 billion, driven by the central government's urbanization initiatives (Wang et al., 2021). By 2016, over 3,500 new towns and districts had been planned and constructed, with more developments underway (Chen et al., 2018; Shi et al., 2020). Nonetheless, many of these new urban centers remain largely uninhabited, with construction halted due to investor withdrawal and increasing debts (Chen et al., 2015; Woodworth, 2015; Yu et al., 2023a). This mismatch between rapid construction and limited occupancy highlights resource underutilization and raises concerns about long-term urban planning. As a result, the potential of vacant housing to contribute to more targeted economic and demographic development strategies may be underappreciated, leaving the effects of urbanization on vacancy rates unclear.

Obtaining reliable official statistics on housing vacancy in China is challenging. Therefore, addressing housing oversupply requires significant institutional reforms and economic incentives. Unlike most existing studies, which either describe vacancy patterns qualitatively or rely on fragmented statistics, our work provides a systematic, data-driven analysis that quantifies spatiotemporal heterogeneity, evaluates economic losses, and simulates future trajectories. In this article, we use NPP-VIIRS-like nighttime (NTL) Data at a 500-meter spatial resolution and land use maps at 30 meters to achieve several objectives: (1) quantify and analyze housing vacancy rates and their spatiotemporal heterogeneity in Chinese urban areas from 2000 to 2020; (2) explore the relationship between housing vacancy rates and land area, Gross Domestic Product (GDP), and population; (3) estimate the losses from vacant housing through cost-benefit analysis by 2020; and (4) simulate housing vacancy rates and their cost-benefit implications in Chinese urban areas by 2050 using spatial statistics and scenario analysis. These contributions not only clarify the relationship between vacancy and urbanization in China but also offer broader methodological and policy insights for rapidly urbanizing countries facing similar challenges.

Methods

Data sources. Nighttime light data were obtained from the NPP-VIIRS-like NTL Data at 500 m spatial resolution; the data are available at the National Earth System Science Data Center, National Science and Technology Infrastructure of China (http://www.geodata.cn). NPP-VIIRS-like NTL Data has similar quality to NPP-VIIRS nighttime light data and clearly reflects detailed information about urban housing vacancy and its temporal variation (Chen et al., 2021; Zhai et al., 2022). The 30 m annual land cover dataset and its dynamics in China from 2000 to 2020 were employed, which can be downloaded at https://zenodo.org/records/8176941. In this database, we mainly utilized impervious data and extracted urban built-up areas. Population data are derived from the records of the Fifth, Sixth and Seventh National Censuses. GDP data, completed housing area data and housing investment data are from the China City Statistical Yearbook and can be downloaded at https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2019070173?z=Z012. Housing area per capita data were obtained from the records of the Seventh National Population Census; the data are available at https://www.stats.gov.cn/sj/pcsj/rkpc/d7c. Housing price data were sourced from Lianjia, the largest real estate intermediary website in China and can be downloaded at http://lianjia.com.

Simulation of housing vacancy rates from 2000 to 2020. We extracted the impervious data from the land cover data and considered as an urban built-up area (Fig. 1a). After that, the impervious data were overlaid with the nighttime light data. Due to the resolution difference between the nighttime light data and the impervious data, the impervious data at 30 m resolution was resampled to 10 m and then overlaid with the nighttime light data at 500 m resolution (Fig. 1b) (Chen et al., 2015). Consequently, each nighttime light pixel overlaps a maximum of 2500 impervious pixels (Eq. 1).

$$UAR = \frac{N_d}{N_t} \tag{1}$$

where UAR refers to the urban built-up area ratio, i.e. the ratio of impervious pixel in the nighttime light pixel. N_d is the number of impervious pixels contained in the d th pixel. N_t represents the maximum number of impervious pixels included in the nighttime light pixel. In this study, $N_t = 2500$. Previous studies have demonstrated that a 20 percent urban built-up area ratio is a critical value to distinguish between mixed areas and non-residential areas. Therefore, we classified pixels with urban built-up area ratios below 0.2 as non-residential areas, and others as mixed areas (mixed areas incorporate both residential areas and non-residential areas). As pixels with urban built-up area ratios higher than 0.2 are affected not only by lights from residential areas but also from non-residential light sources such as streetlights and commercial lights, the impact of non-residential light sources should be eliminated (Fig. 1c, Eq. 2 and 3).

$$ALI_{UAR<0.2} = \frac{\sum_{K=1}^{N} NTL}{N} \tag{2}$$

$$NTL_i = \begin{cases} NTL_{UAR \geq 0.2} - ALI_{UAR<0.2}, & \text{if } \mathrm{NTL_{li}} > \mathrm{ALI_{UAR<0.2}} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where $ALI_{UAR<0.2}$ is the average light intensity in non-residential areas. N represents the total number of pixels in non-residential areas. $\sum_{K=1}^{N} NTL$ is the sum of light intensity for all pixels in the non-residential areas. NTL_i means the filtered nighttime light value of the i th. $NTL_{UAR \geq 0.2}$ is a single pixel's light intensity of each mixed pixel before the non-residential influence is eliminated. Since the pixels have different urban built-up area ratios, we divided the filtered nighttime light value by the urban built-up area ratio to accurately estimate the unit lighting intensity by Eq. 4:

$$ULI_i = \frac{NTL_i}{UAR} \tag{4}$$

where ULI_i is i th urban built-up area ratio's unit lighting intensity per pixel. After obtaining the unit lighting intensity

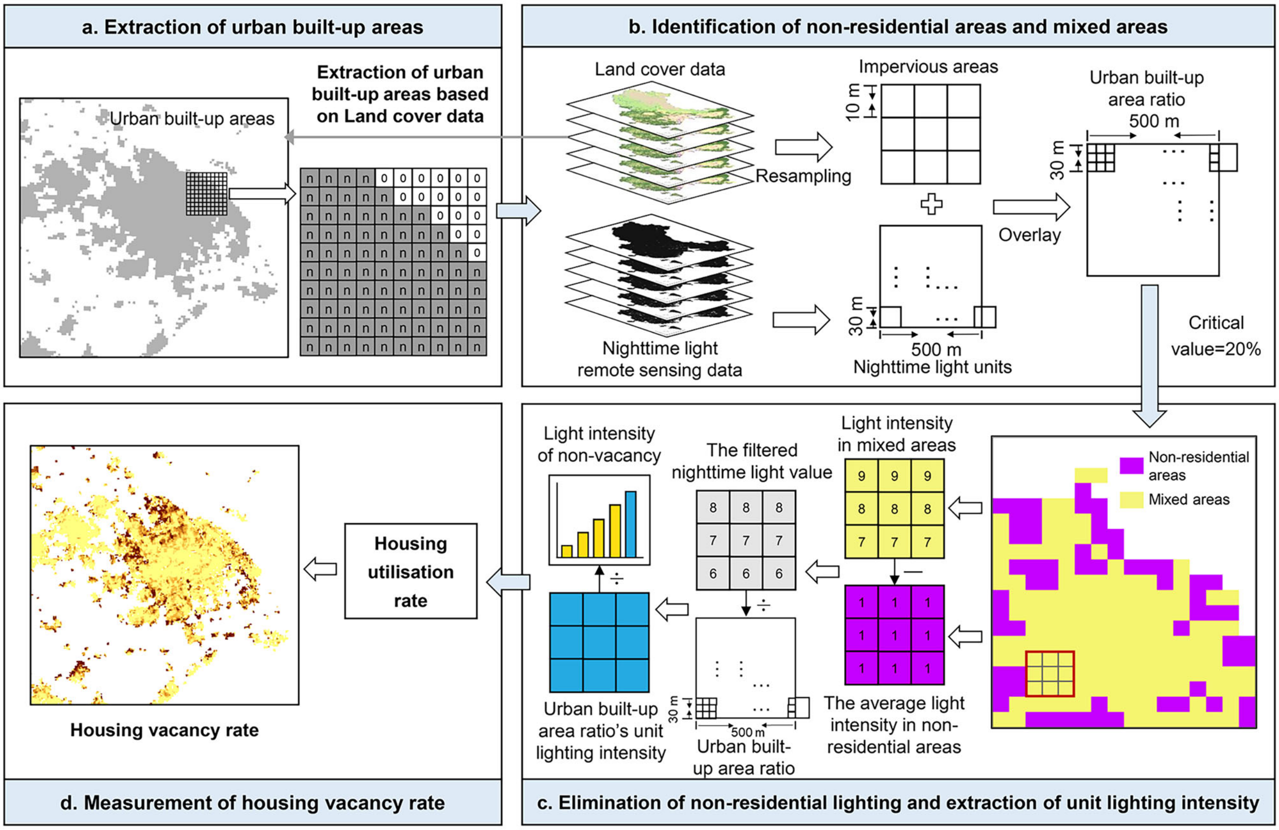

Fig. 1 Methods for simulating housing vacancy rates. a Impervious data was extracted from the land cover data and considered as an urban built-up area in 2020. **b** The impervious data at 30 m resolution was resampled to 10 m and then overlaid with the nighttime light data at 500 m resolution. **c** Identification of mixed areas and non-residential areas based on a 20 percent urban built-up area ratio. The yellow grids indicate mixed areas; and the purple grids denote non-residential areas. After that, non-residential lighting was eliminated and unit lighting intensity per pixel was extracted using Eq. (2) and Eq. (3). **d** The house vacancy rate for each pixel was estimated using Eq. (5) after obtaining the unit lighting intensity values at the pixel level. Example of simulated housing vacancy rate in 2020 in Shanghai built-up area was provided.

values at the pixel level, we further estimated the housing vacancy rate for each pixel by combining the light intensity of non-vacancy (Fig. 1d and Eq. 5).

$$HVR_i = 1 - \frac{ULI_i}{LINV_i} \tag{5}$$

HVR_i is the housing vacancy rate of the i th pixel. $LINV_i$ denotes light intensity of non-vacancy of the i th pixel. To reveal regional and national trends, pixel-level vacancy rates were aggregated spatially by computing the average vacancy rate within administrative boundaries.

Changes of land area, GDP and population. We estimated the changes in land area, GDP and population using Eqs. 6, 7 and 8.

$$VLAND_{a-b} = \frac{LAND_b - LAND_a}{LAND_a} \times 100\% \tag{6}$$

$$VGDP_{a-b} = \frac{GDP_b - GDP_a}{GDPD_a} \times 100\% \tag{7}$$

$$VPOP_{a-b} = \frac{POPD_b - POPD_a}{POPD_a} \times 100\% \tag{8}$$

where $VLAND_{a-b}$ is the change rate of land area from year a–b. $LAND_a$ and $LAND_b$ are land areas for years a and b. $VGDP_{a-b}$ is the change rate of per capita GDP from year a–b. GDP_a and GDP_b are per capita GDP for years a and b. $VPOP_{a-b}$ is the change rate of population from year a–b. POP_a and POP_b are population for years a and b.

Linear fixed effects model. The linear fixed effects model was applied to project future housing vacancy rates. Land area, GDP and population were included as explanatory variables in the linear fixed effects model. These variables were selected because they capture the three fundamental dimensions of urban development: land area reflects spatial expansion, GDP per capita indicates economic activity and purchasing power, and population represents demographic pressure (Yu et al., 2023b). Together, they provide a parsimonious but robust framework for analyzing the primary forces influencing housing vacancy. The urban built-up area and time are fixed to predict the housing vacancy rate through Eq. 9.

$$Y_{it} = \alpha_0 + \alpha_1 LAND_{it} + \alpha_2 GDP_{it} + \alpha_3 POP_{it} + a_i + u_{it} \tag{9}$$

Y_{it} is the housing vacancy rate of i th urban built-up area in year t. α_0 is the intercept term. $LAND_{it}$ is the land area of i th urban built-up area in year t. GDP_{it} is the per capita GDP of i th urban built-up area in year t. POP_{it} is the population of i th urban built-up area in year t. α_1, α_2 and α_3 are the coefficients of $LAND_{it}$, GDP_{it} and POP_{it}, respectively. a_i is the individual fixed effect. u_{it} is the individual-specific perturbation term.

Cost-benefit analysis. We collected data from urban built-up areas in 32 provinces/municipalities to estimate housing costs in Chinese urban built-up areas by 2020. The cost of vacant housing is associated with housing construction, and is related to housing vacancy rate, population, housing area per capita, housing investment and completed housing area. In this analysis, these determinants were combined in a multiplicative form so that their interaction yielded a coherent monetary expression of total housing cost. Based on this, the cost of vacant housing by 2020 was derived for each Chinese urban built-up area (Eq. 10).

$$C_j = HVR_j \times POP_j \times HA_j \times \frac{INV_j}{CHA_j} \tag{10}$$

where C_j is the housing cost in the j th urban built-up area. HVR_j refers to the housing vacancy rate in the j th urban built-up area. POP_j stands for the number of populations (unit: persons). HA_j is housing area per capita (unit: m^2/person). INV_j means housing investment (unit: USD/m^2). CHA_j denotes completed housing area (unit: m^2).

In addition, housing benefit refers to the market value of housing. We utilized the relationships among housing vacancy rate, population, housing area per capita and housing price to measure the wasted social benefit from vacant housing by 2020 (Eq. 11). This specification adopted a product form that translated the extent of vacancy and the value of housing space into an estimate of wasted social benefit.

$$B_j = HVR_j \times POP_j \times HA_j \times HP_j \tag{11}$$

where B_j is the wasted social benefit from vacant housing in the j th urban built-up area. HP_j is the housing price (unit: m^2/person) in the j th urban built-up area. In addition, considering only future population changes, we derived the contribution of urbanization to housing vacancy rate and the cost and wasted social benefit of vacant housing in Chinese urban built-up areas by 2030 and 2050.

Results and discussion

Housing vacancy rate. Housing vacancy rates at the pixel level within each urban built-up area (Fig. 2) exhibit distinct patterns across urbanization levels in China. At urbanization level of 36.2%, 43.0%, 50.0%, 57.3%, and 63.9%, corresponding to the years 2000, 2005, 2010, 2015, and 2020, respectively, housing vacancy rates are recorded at 0.274, 0.308, 0.269, 0.255, and 0.220 (Fig. 3). On average, these rates exceed 0.2, indicating that over 20% of housing units are unoccupied. However, there has been a gradual decline in vacancy rates from 2000 to 2020, especially in rapidly urbanized regions like the Yangtze River Delta (Figs. 2a and 4a), the Beijing–Tianjin–Hebei region (Figs. 2b and 4b), and the Pearl River Delta (Figs. 2c and 4c).

Housing vacancy rates vary significantly across China's geographic regions (Fig. 3). Rapid urbanization and the attraction of major cities have notably reduced vacancy rates from 0.363 and 0.452 in 2000 to 0.263 and 0.289 in 2020 in East and North China, respectively. Northeast China recorded the highest urban vacancy rate at 0.392 in 2005, due to its industrial background and subsequent economic restructuring, which led to factory closures and labor outflows (Liu et al., 2020). Conversely, strategic initiatives to rejuvenate old industrial bases have boosted innovation and service sectors (Guo et al., 2023), mitigating vacancies. Northwest China faces challenges like drought and water scarcity (Wang et al., 2023), while Southwest China deals with rugged terrain, contributing to higher vacancy rates from 2000 to 2010. However, with economic growth and improved governmental oversight, vacancies in these regions have gradually decreased post-2010. Central South China has maintained relatively stable vacancy rates from 2000 to 2020. Overall, vacancy rates in Chinese urban areas increase from south to north, with urbanization's positive effects extending from the eastern coast to the western hinterland.

Furthermore, the distribution of vacant housing within urban areas shows heterogeneity (Figs. 2 and 5), concentrated in specific peripheral suburban zones, especially those with more social housing. A gradient decrease in vacancy rates from downtown to urban fringes is evident. Major urban centers like Beijing, Shanghai, and Shenzhen have experienced declining vacancy rates from 2000 to 2020 (Fig. 5), attributed to urbanization's impact on economic vitality and employment opportunities. As urbanization progresses, infrastructure and amenities in suburban areas improve livability, attracting more residents and reducing vacancy rates (Chen et al., 2016; Pan and Dong, 2021).

Land area, GDP and population. At urbanization levels of 36.2% in 2000 and 63.9% in 2020, the land area within Chinese urban built-up areas increased by 244%, resulting in a 63,373 km^2 expansion (Fig. 6a). During the same period, GDP surged by 869%, rising by 8,500 USD per capita (Fig. 6b), while the population grew by 98%, adding 446 million people (Fig. 6c). Notably, the growth rates of land area and GDP significantly outpaced that of the population. Central South and East China's urban areas experienced rapid growth, in contrast to the slower or negative economic and demographic changes in Northeast, Northwest, and Southwest China. These disparities contribute to the variability in housing vacancy rates across Chinese urban areas (Fig. 6d).

The linear fixed effects model results in Table 1 highlight the impact of land area, GDP, and population on housing vacancy rates from 2000 to 2020. Land area shows a significant correlation with vacancy rates; for each unit increase in land area, the vacancy rate decreases by 0.220 units ($P < 0.05$). Vacant housing is predominantly concentrated in urban areas with limited land, particularly in Northeast and North China, where market saturation through pre-sale systems and substantial loans often leads to vacancies if anticipated demand does not materialize (Yan et al., 2014; Martinez-Fernandez et al., 2016; Newman et al., 2019; Lu et al., 2021; Song et al., 2021).

Statistically, holding other conditions constant, the housing vacancy rate decreases by 0.1 units for each unit increase in GDP ($P < 0.1$). Urban areas with strong economies and ample employment opportunities attract investment and migrant workers, boosting housing demand and reducing vacancy rates (Wu et al., 2024). Conversely, regions with lower GDP per capita face economic stagnation, limited job prospects, and an oversupply of housing, leading to higher vacancy rates. Extensive construction that outpaces economic activity can result in "ghost cities" with empty dwellings and sparse populations (Williams et al., 2019; Shi et al., 2020).

Population dynamics also affect housing vacancy rates. Some areas in Northeast and Northwest China have experienced stagnant or declining population growth due to outmigration and limited employment opportunities, reducing housing demand. Overbuilding and speculative investments have exacerbated vacancy rates in these regions. For example, cities like Hegang, Ordos, Yichun, and Bayannur saw real estate booms in the early 2000s, leading to oversupply and increased vacancies (Woodworth and Wallace, 2017). Conversely, relaxed settlement policies have facilitated rural-to-urban migration to highly developed areas, decreasing vacancy rates (Liu et al., 2020; Deng et al., 2024). Consequently, the housing vacancy rate decreases by 0.015 units for each unit increase in population ($P < 0.1$). The linear fixed effects model underscores the significant impact of changes in land area, GDP, and population on housing vacancy rates in Chinese urban areas, amid a 27.67% increase in urbanization levels. Land development, GDP growth, and

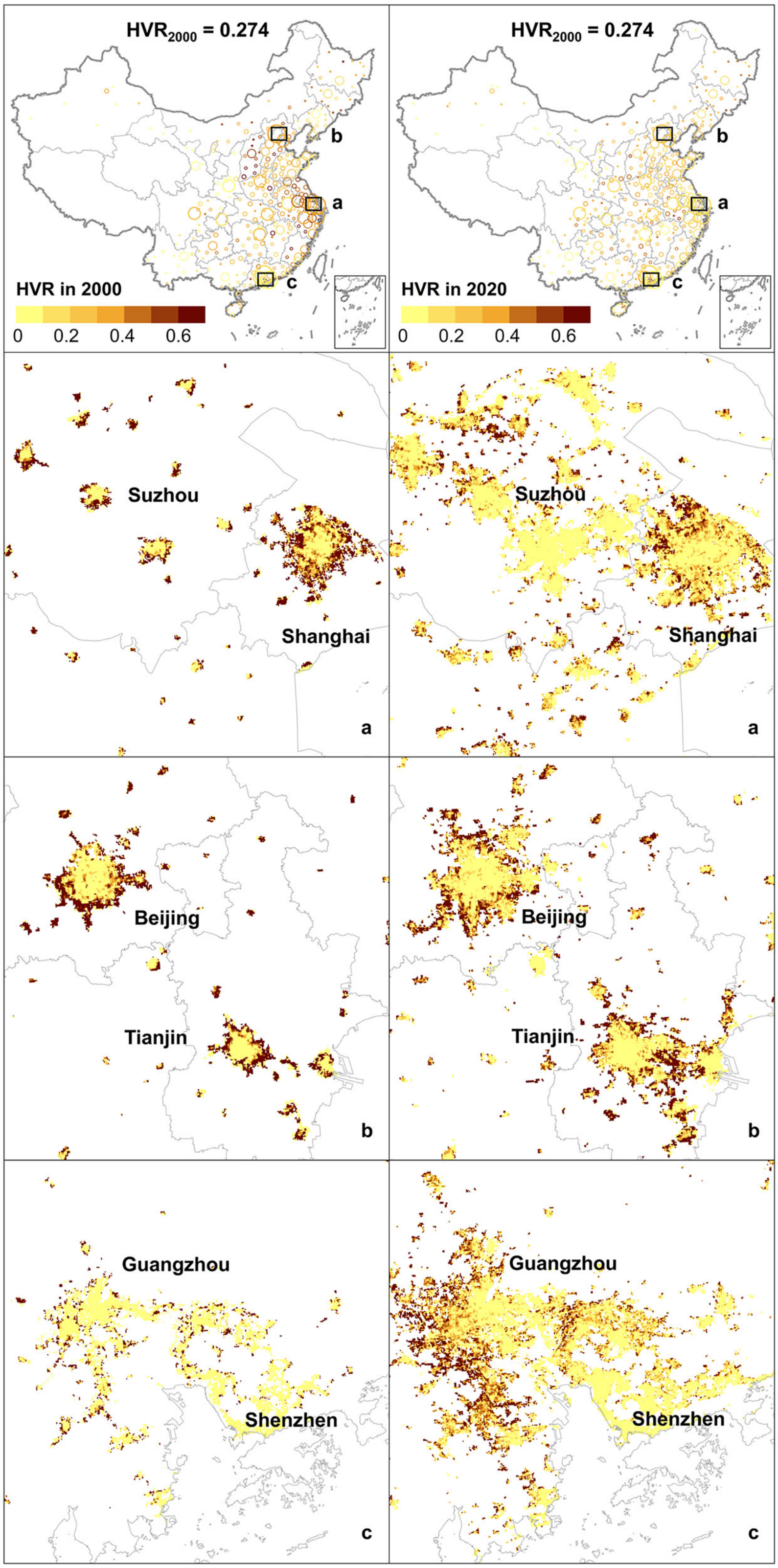

Fig. 2 Housing vacancy rates in urban China in 2000 and 2020. From 2000–2020, housing vacancy rate reduction was concentrated in the Yangtze River Delta (**a**), Beijing–Tianjin–Hebei region (**b**) and Pearl River Delta (**c**). Map showing housing vacancy rates in Chinese urban built-up areas of 0.274, 0.308, 0.269, 0.255 and 0.220 at urbanization levels of 36.2%, 43.0%, 50.0%, 57.3% and 63.9% by 2000, 2005, 2010, 2015 and 2020, respectively, are provided in Fig. 3. In addition, spatial distributions of housing vacancy rates in typical Chinese urban built-up areas at the pixel level from 2000–2020 are provided in Fig. 5. HVR is an acronym for housing vacancy rate. The base map was applied from the Database of Global Administrative Areas (GADM; https://gadm.org/).

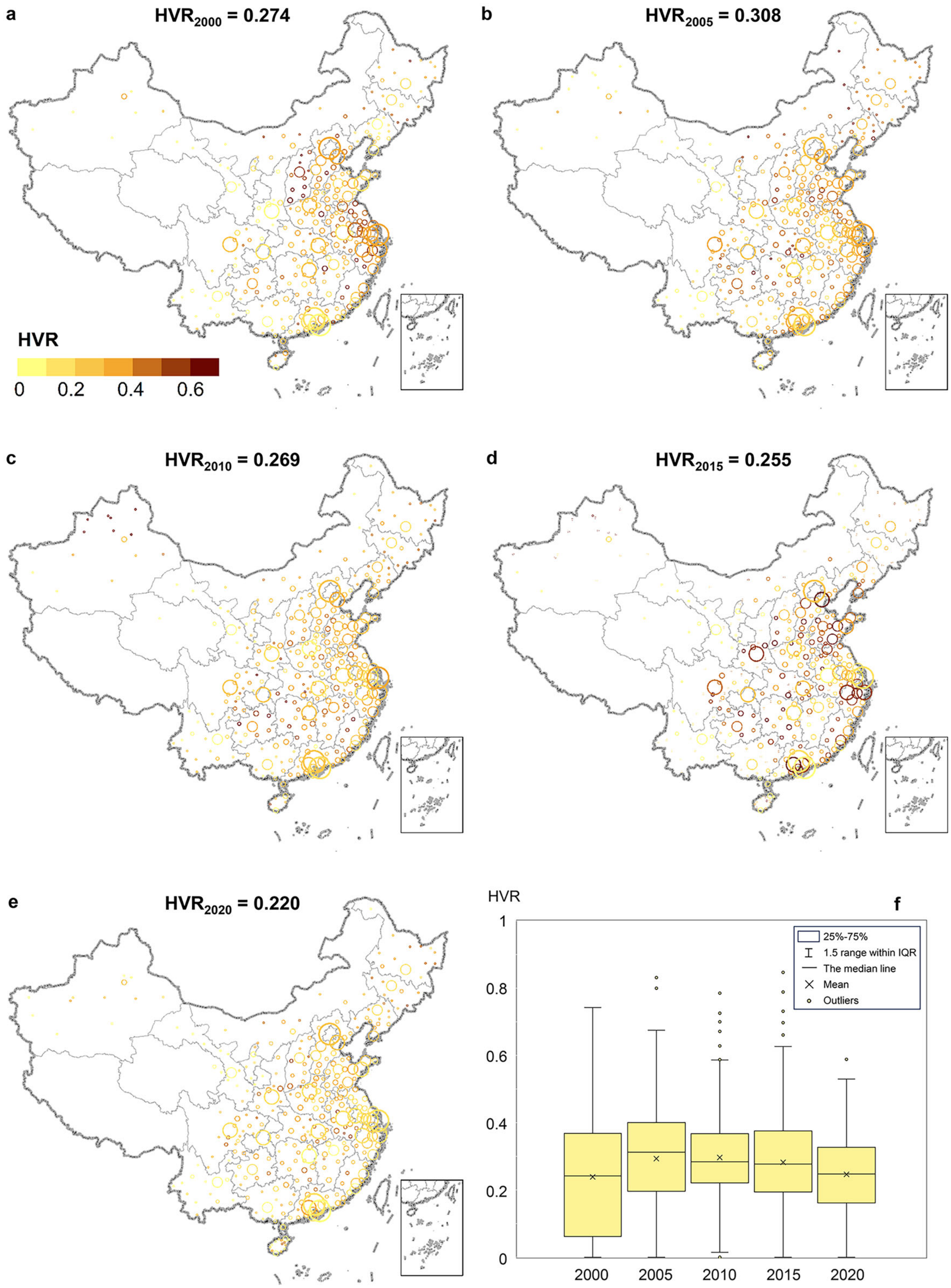

Fig. 3 Spatial distribution of housing vacancy rates in Chinese urban built-up areas. Housing vacancy rates in Chinese built-up areas were 0.274, 0.308, 0.269, 0.255 and 0.220 in 2000 (**a**), 2005 (**b**), 2010 (**c**), 2015 (**d**) and 2020 (**e**), respectively. (**f**) Bar chart of housing vacancy rates in Chinese urban built-up areas from 2000–2020. HVR is an acronym for housing vacancy rate. The base map was applied from the GADM (https://gadm.org/).

population influxes are crucial in mitigating housing vacancy rates.

Cost and benefit. Vacant housing represents a significant misallocation of social resources and poses substantial financial risks. Our analysis shows that by 2020, the completed housing area in Chinese urban built-up areas had expanded to an impressive 3830 km^2, highlighting the vast scale of housing construction. This expansion involved considerable financial expenditure, totaling 1387 billion USD. By 2020, the cost associated with vacant housing in these areas reached a staggering 5,836 billion

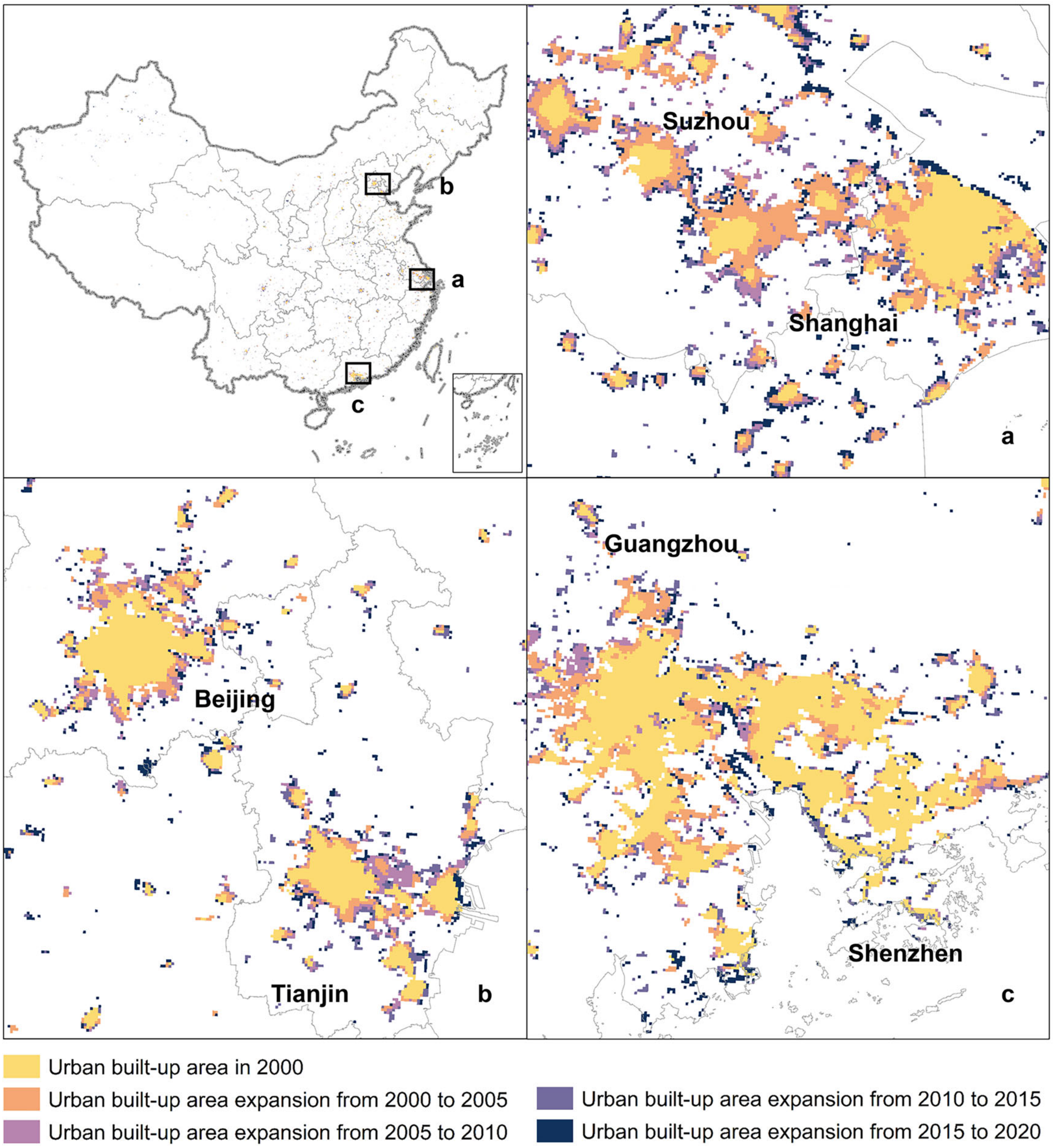

Fig. 4 Spatial changes in Chinese urban built-up area expansion from 2000–2020. Chinese urban built-up area expansion was concentrated in the Yangtze River Delta (**a**), Beijing–Tianjin–Hebei region (**b**) and Pearl River Delta (**c**) from urbanization level 36.22% (2000) to urbanization level 63.89% (2020). The base map was applied from the GADM (https://gadm.org/).

USD (Fig. 7a), with Beijing and Shanghai alone accounting for 593 billion USD and 326 billion USD, respectively. These findings underscore the profound economic implications and potential losses caused by vacant housing in Chinese urban areas.

Beyond economic impacts, housing vacancy is critically significant from a national strategy perspective, closely linked with urban development and housing security, extending beyond cost-benefit analysis. For instance, China's central government has implemented standardized housing purchase restriction policies in 40 major cities to ensure housing security (Zou et al., 2022). These policies limit local household registration holders and talent residence permit holders to owning a maximum of two properties per city, while non-local residents are restricted to one property, and corporate purchases are limited within a two-year holding period. Such measures highlight the government's commitment to housing security, despite the associated costs. However, focusing solely on increasing housing supply through these policies may inadvertently lead to more vacant properties. The lost social benefit from vacant housing in Chinese urban areas amounted to 15,020 billion USD (Fig. 7b), compounded by the waste of 7960 km^2 of housing space by 2020, which could accommodate an additional 190 million people if fully utilized (Fig. 7c). These insights suggest that the housing market in Chinese urban areas is not reaching its full potential, leading to substantial economic losses.

Our analysis further reveals that well-managed housing markets in major urban areas have the potential to generate even greater economic returns. By 2020, the cost of vacant housing in these regions had reached 5383 billion USD, resulting in a lost social benefit of 14,605 billion USD. In contrast, the cost of vacant housing in smaller urban areas was 453 billion USD, translating to a wasted social benefit of 416 billion USD (Fig. 7d). This discrepancy highlights that housing vacancy in major urban areas entails more pronounced economic losses compared to smaller counterparts. Moreover, with regards to wasted housing space, major urban areas squandered 7521 km^2 by 2020, while

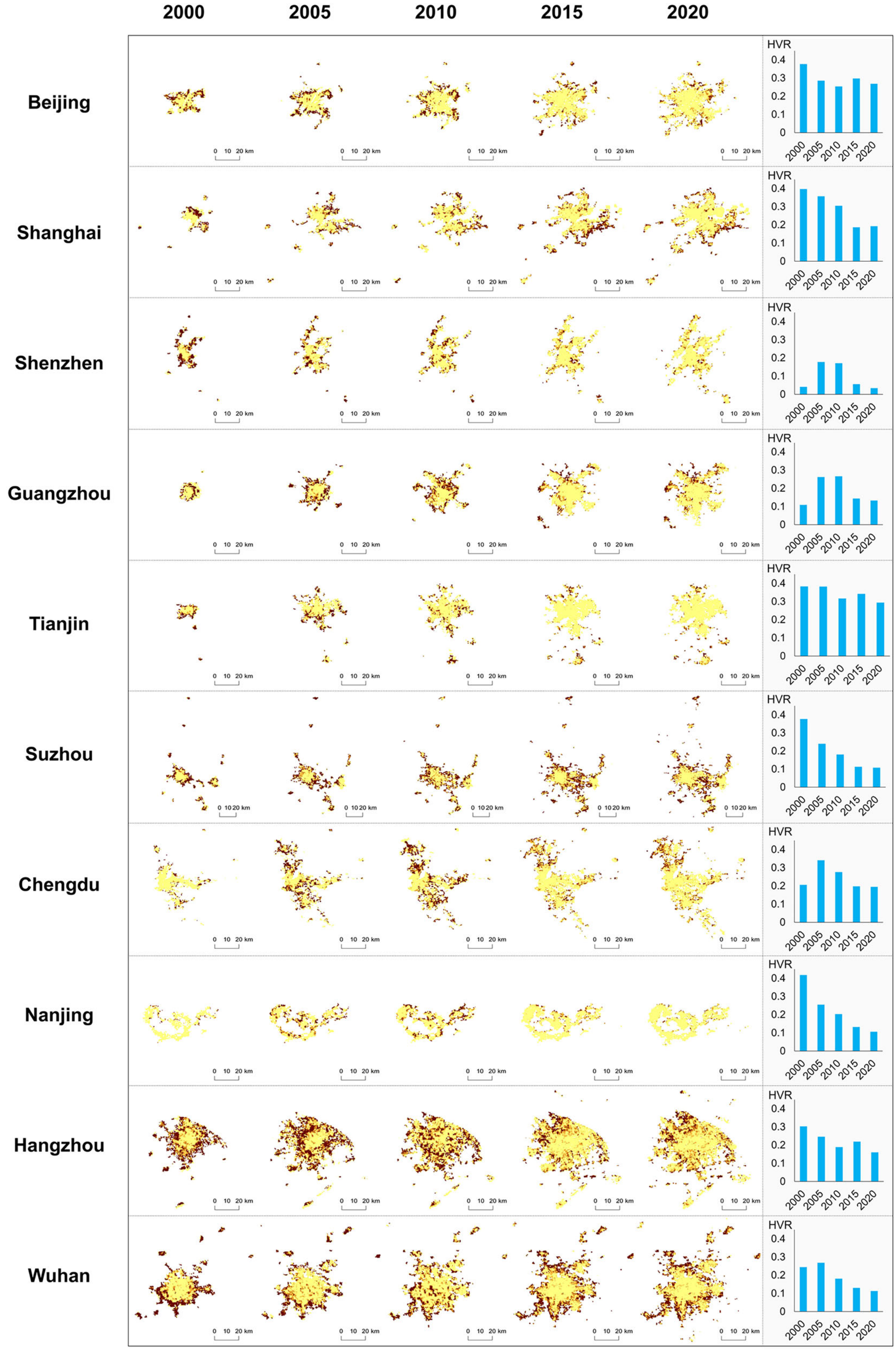

Fig. 5 Spatial distributions of housing vacancy rates in typical Chinese urban built-up areas from 2000 to 2020. The inset bar chart shows the overall reduction of housing vacancy rates in typical Chinese urban built-up areas from urbanization level 36.22% (2000) to urbanization level 63.89% (2020). HVR is an acronym for housing vacancy rate. The base map was applied from the GADM (https://gadm.org/).

smaller areas wasted only 439 km^2 (Fig. 7e). This underscores the vast potential for unlocking additional housing capacity through rapid urbanization in major urban areas. By effectively harnessing this latent potential, major urban areas can accommodate more residents and contribute to economic prosperity. Addressing housing vacancies in Chinese urban areas is imperative to optimize resource utilization, reduce waste, and promote economic development and neighborhood sustainability.

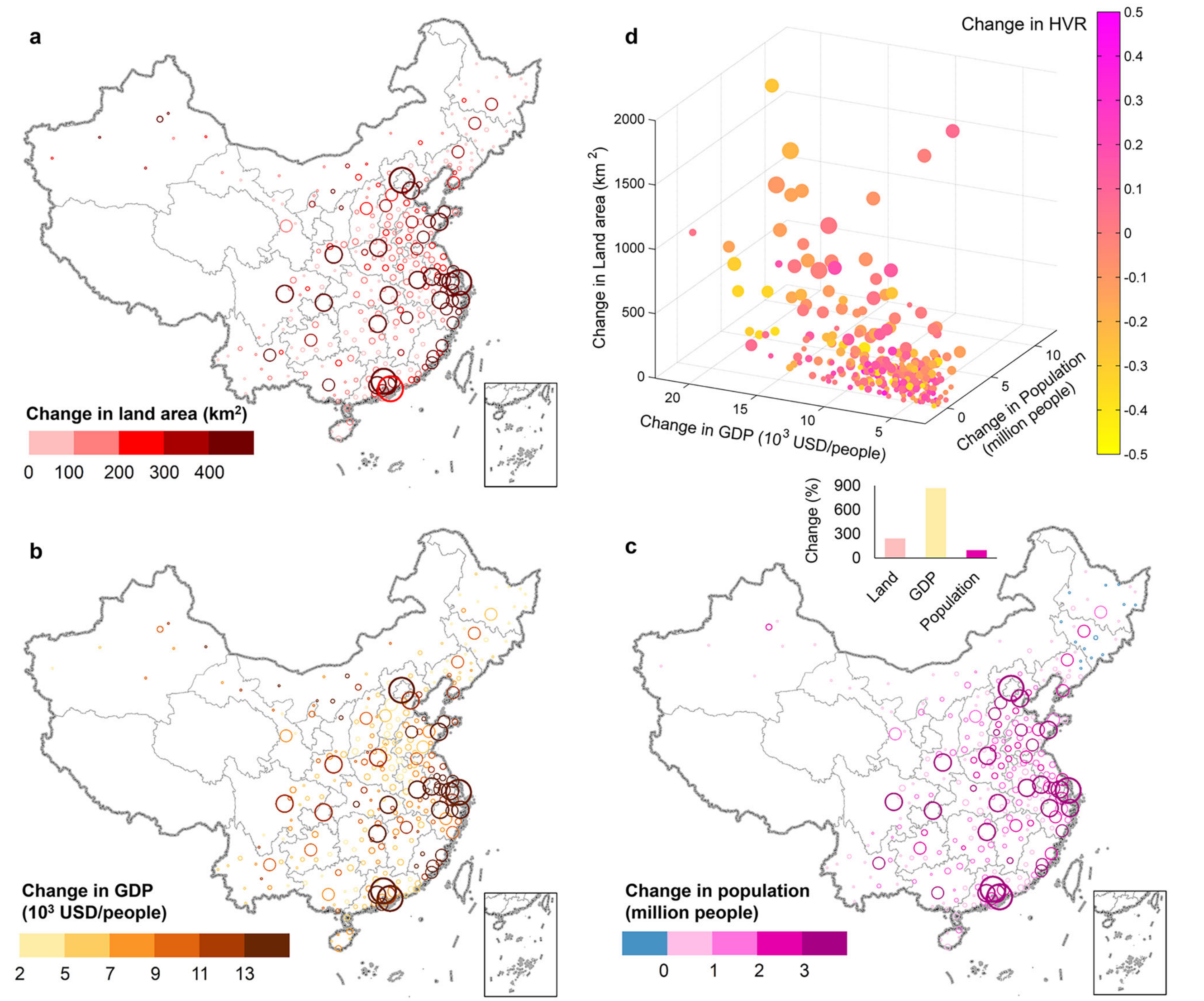

Fig. 6 Spatial changes of land area, GDP and population expansion from 2000 to 2020. **a** From 2000 to 2020, the land area in Chinese urban built-up areas increased by 63,373 km^2. **b** From 2000 to 2020, the GDP in Chinese urban built-up areas increased by 8,500 USD/people. **c** From 2000 to 2020, the population in Chinese urban built-up areas increased by 446 million. **d** Housing vacancy rates and corresponding land area, GDP and population changes from 2000 to 2020 with urbanization level increasing by 27.7%. The inset bar charts show the overall changes in land area, GDP and population in Chinese urban built-up areas from 2000 to 2020. HVR is an acronym for housing vacancy rate. The base map was applied from the GADM (https://gadm.org/).

Table 1 Linear fixed effects model determining on housing vacancy rate.

		Housing vacancy rate
Land area	Coefficient	−0.220**
	s.e.	0.086
	P values	0.011
GDP	Coefficient	−0.100*
	s.e.	0.054
	P values	0.065
Population	Coefficient	−0.015*
R^2	s.e.	0.008
	P values	0.062
	0.596	

The asterisks indicate the statistical significance level based on *P* values: *P < 0.1, **P < 0.05, ***P < 0.01, which is assessed using a two-sided t-test. Standard errors (s.e.) are clustered at the urban built-up area level. Land area means the area of urban built-up areas. GDP is the per capita GDP of the urban built-up area, which is often used as an indicator of economic activity and development. Population emphasizes the number of people. The model includes urban built-up area and time fixed effect.

Future scenario. It is projected that the housing vacancy rate in Chinese built-up areas will decrease to 0.092 by 2030 (at an urbanization level of 70%) and further to 0.064 by 2050 (at an urbanization level of 80%). This trend indicates a positive trajectory towards reducing housing vacancies over time. Specifically, from an urbanization level of 63.9% in 2020 to 70% by 2030, the housing vacancy rate is expected to decrease by 0.128. Similarly, a decline of 0.156 is anticipated as urbanization reaches 80% by 2050 (Fig. 8a, c). These estimates suggest a favorable trend of declining housing vacancies, promising better utilization of housing resources in Chinese urban areas.

Urbanization is expected to significantly reduce vacant housing in the future. By 2030 and 2050, the area occupied by vacant housing in Chinese built-up areas is estimated to shrink to 3326 km^2 and 2301 km^2, respectively (Fig. 8b, c). This reduction represents a decrease of 4634 km^2 and 5659 km^2 compared to 2020. The analysis also considers the impact of future population shifts due to rapid urbanization on vacant housing by 2030 and

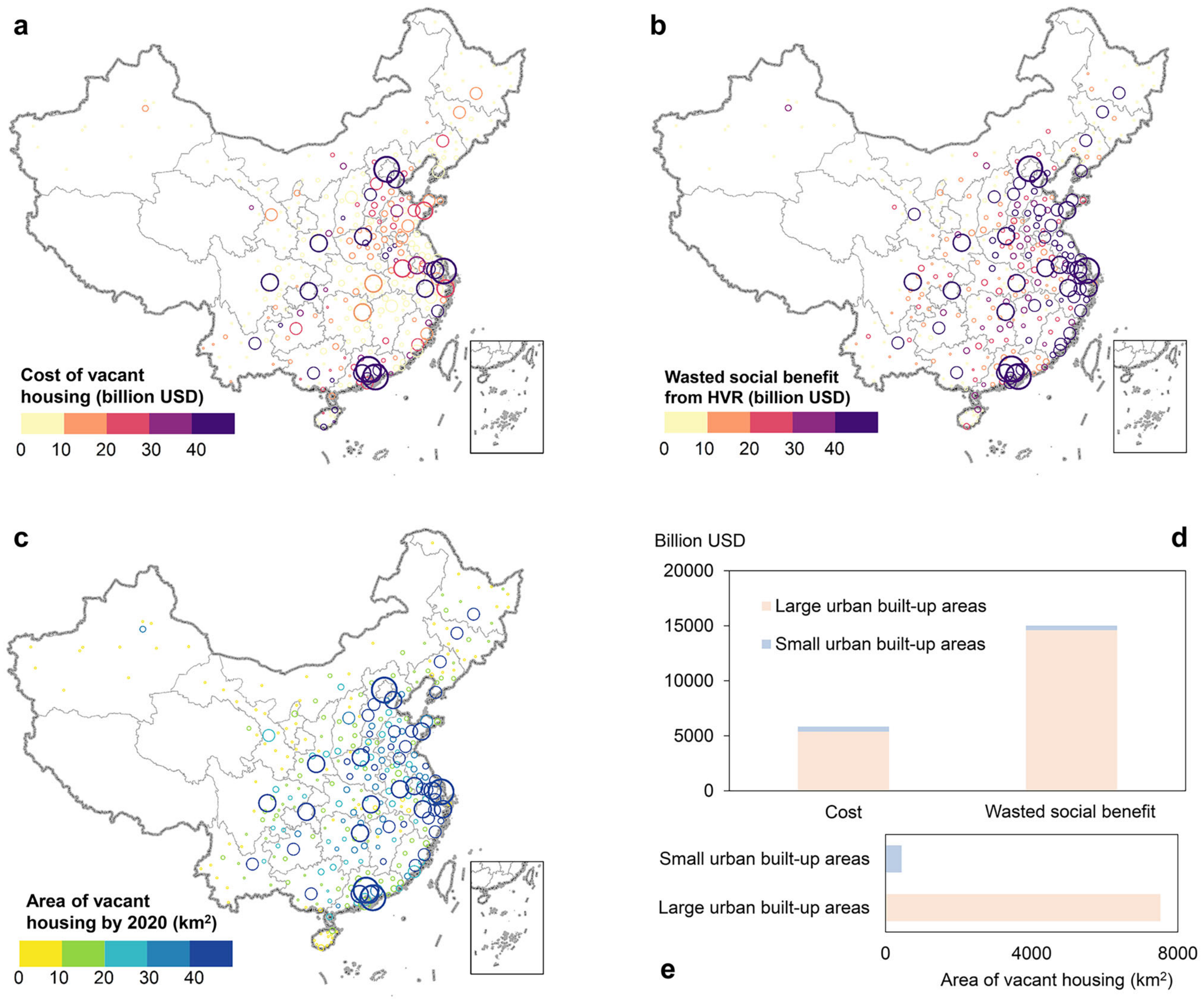

Fig. 7 Cost-benefit analysis of housing vacancy at urbanization level of 63.9% by 2020. Cost (**a**), wasted social benefit (**b**) and area (**c**) of vacant housing in Chinese urban built-up areas by 2020. Cost, wasted social benefit (**d**) and area (**e**) of vacant housing in large and small urban built-up areas. Large urban built-up areas have more than 1 million people, small urban built-up areas have less than 1 million people. HVR is an acronym for housing vacancy rate. The base map was applied from the GADM (https://gadm.org/).

2050 (Fig. 8d), focusing on the cost and squandered social benefits of vacant housing. From an urbanization level of 63.9% in 2020 to 70% in 2030, the cost of vacant housing is projected to decline from 5836 billion USD to 1204 billion USD, with wasted social benefits decreasing from 15,020 billion USD to 4243 billion USD. By 2050, the cost of vacant housing is expected to fall to 833 billion USD, a reduction of 5002 billion USD compared to 2020, while the wasted social benefit is estimated at 2,936 billion USD, a decrease of 12,084 billion USD. These projections highlight the positive role of sustained urbanization in reducing the potential waste of social benefits associated with vacant housing.

The release of vacant housing depends on the urbanization process and effective housing management strategies. In developed countries, mature real estate markets, well-established public services, and limited population mobility characterize the landscape, with urban expansion potentially exacerbating housing vacancies. Conversely, developing countries with lower urbanization levels and prevalent migration patterns offer greater prospects for releasing vacant housing through strategic regional planning, land use management, and housing policies. As migrants integrate into major cities, urbanization reduces the need to maintain vacant housing in smaller towns, optimizing urban resource allocation, fostering market development, and enhancing housing utilization.

Conclusions and policy implications

To address the issue of housing vacancy and ensure optimal utilization of housing resources, China's central government has implemented many regulations, including restrictions on housing purchases through land auctions and allocations, and real estate taxation policies (Zheng et al., 2023) (Fig. 9). While these measures have bolstered housing supply and curbed investment speculation, they have also led to unintended consequences, such as rising housing prices (Bai et al., 2014), incomplete housing projects (Adabre et al., 2022), and gentrification (Zhang et al., 2013). Our findings highlight that urbanization holds promise for reducing vacant housing by facilitating population migration. Nonetheless, comprehensive and coordinated reforms addressing supply and demand dynamics in the housing market are essential to mitigate negative externalities. Key institutions like the household registration system and speculative investment practices play a pivotal role in the housing supply-demand mismatch. The Hukou system, in particular, restricts non-local populations'

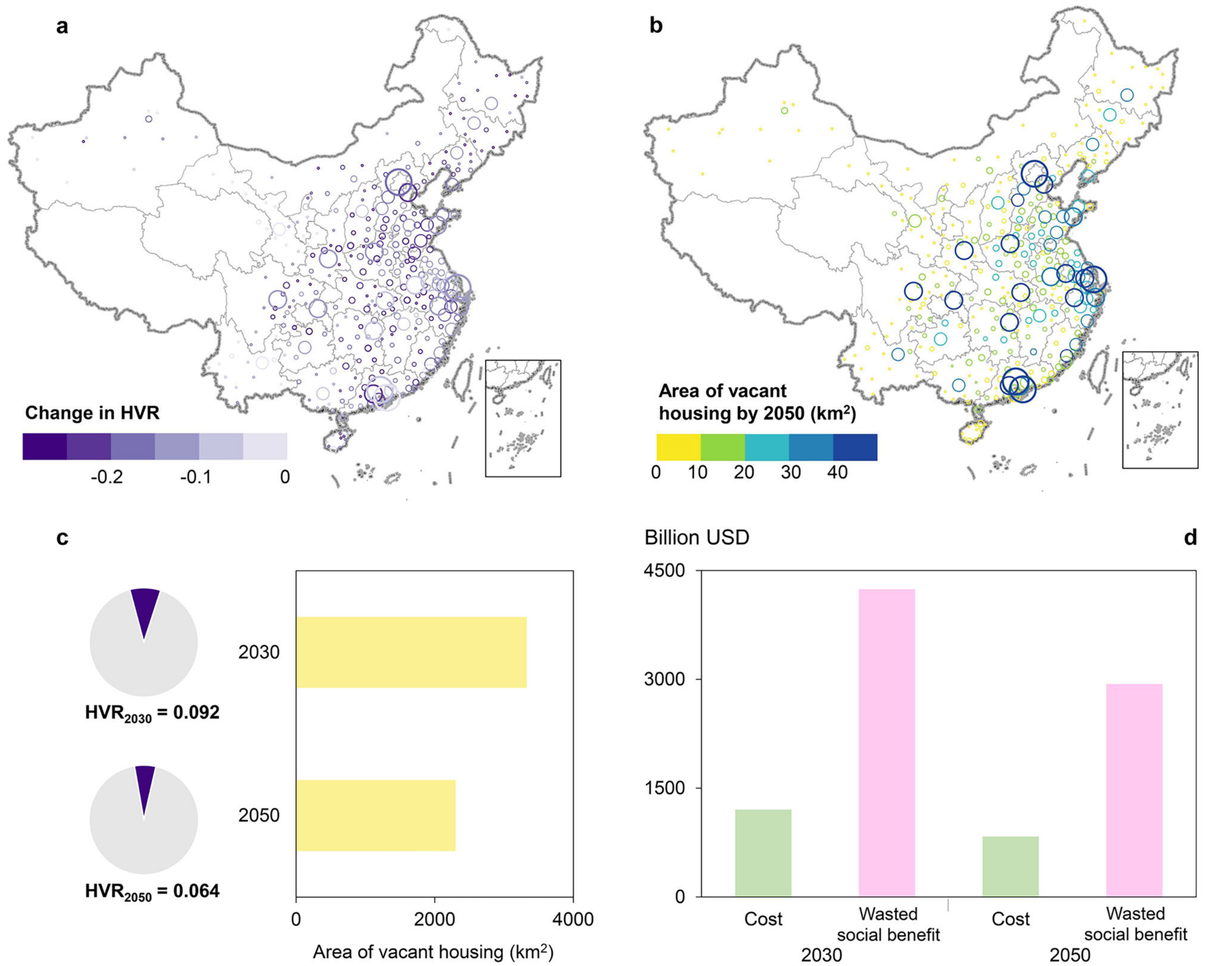

Fig. 8 Spatial changes of housing vacancy rates and cost-benefit analysis by 2030 and 2050. a From urbanization level 63.89% (2020) to urbanization level 80% (2050), the housing vacancy rate in Chinese urban built-up areas would decline by 0.156. **b** Spatial distributions of vacant housing areas by 2050. Housing vacancy rates, vacant housing areas (**c**) and the cost and wasted social benefit of vacant housing (**d**) in Chinese urban built-up areas by 2030 and 2050. HVR is an acronym for housing vacancy rate. The base map was applied from the GADM (https://gadm.org/).

rights and access to urban public services, often forcing them to remain in local vacant housing due to residency hurdles (Chen et al., 2016). Additionally, speculative investments driven by anticipated price appreciation frequently result in vacant properties, especially in smaller city built-up areas.

To date, China's central government has initiated reforms to the Hukou system in select urban areas, relaxing residency restrictions for non-Hukou populations and granting them rental or homeownership opportunities (Gu et al., 2022; Gu and Zhao, 2025). These reforms aim to foster population migration, urban-rural integration, and bolster housing supply while alleviating demand pressures (Gu et al., 2019). Concurrently, pilot reform policies have been implemented for both rental and homeownership sectors, treating public rental housing and commercial housing equally. These policies incentivize the development of the rental housing market through tax breaks, streamlined leasing procedures, and rent regulation mechanisms (Zhou and Ronald, 2017; Zhou and Musterd, 2018). Public rental housing initiatives provide affordable, price-restricted, or subsidized rental options to meet the housing needs of low- and middle-income families. Such pilot policies have the potential to release vacant housing, mitigate housing shortages, foster urban vibrancy, and promote social equity and inclusion.

To mitigate the adverse impacts of bottlenecks like the Hukou system and speculative investments on sustainable housing development in China, it is crucial to address housing market supply-demand mismatches promptly. In urban areas experiencing net population inflows and persistent housing demand, policymakers could attract more urban populations while reducing excessive vacant stock through measures like industry promotion and lifting housing purchase restrictions (Fig. 9). Residential area expansion should be regulated to prevent overdevelopment, enhance public services, and ensure convenient transportation. Conversely, for areas experiencing population decline and economic downturns, local initiatives such as New Urbanism should be embraced to devise smart shrinkage solutions. To address existing housing vacancies, affordable housing availability should be augmented through subsidies and inclusionary zoning policies, catering to low-income households while reducing vacancy rates.

Furthermore, policies promoting the rental market, such as repurposing vacant housing into rental units, offering tax incentives, or implementing rental subsidy programs, should be advanced (Zhang et al., 2016). This would bolster rental housing supply and reduce vacancy rates while ensuring equitable rights and benefits for renters and homeowners. Measures to deter multiple property ownership, such as increased housing

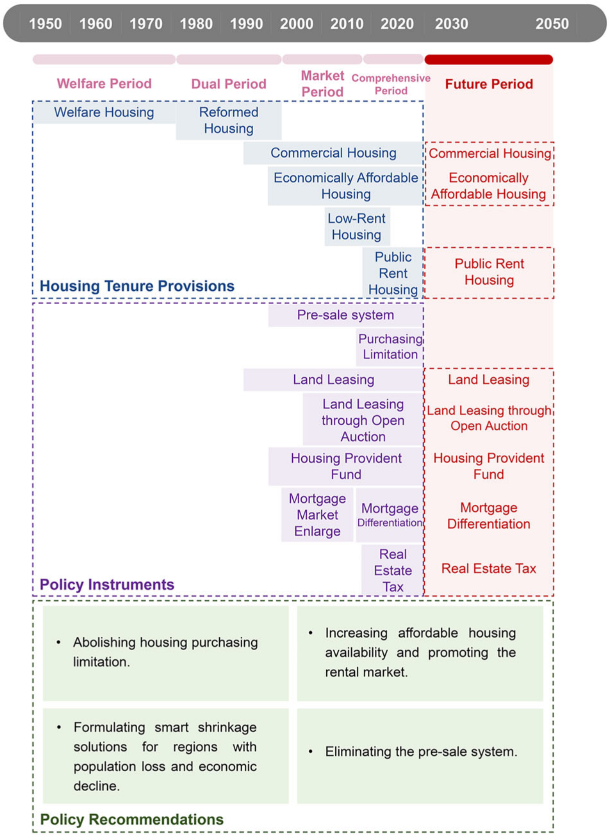

Fig. 9 Change of housing policy in China. It includes five stages: welfare period, dual period, market period, comprehensive period and future period. It is proposed that the future housing tenure provisions include commercial housing, economically affordable housing and public rent housing. It is recommended that future policy instruments eliminate the pre-sale system and purchase limitation.

ownership costs and curbs on speculation via vacancy taxes and property levies, should be implemented. These measures can help stabilize housing prices and lessen reliance on land finance. Lastly, to tackle incremental housing vacancies, eliminating the pre-sale system, ensuring housing quality, strengthening planning approvals and management, reducing real estate debt burdens, and curbing irregular sales practices are essential steps.

From a strategic national perspective, reducing housing vacancy aligns with broader national goals such as improving economic efficiency, ensuring housing security, and supporting sustainable urban growth. It contributes to optimizing resource allocation and enhancing social equity, thereby supporting China's long-term development agenda. While this study focuses on China, the implications extend to other rapidly urbanizing countries facing similar challenges, such as inefficient land use, speculative housing investment, and mismatches between housing supply and population needs. Countries in Asia, Africa, and Latin America undergoing fast-paced urbanization may draw valuable lessons from China's experience, particularly in balancing urban expansion with housing utilization. International reflection on housing vacancy patterns can foster globally informed urban policies aimed at sustainable and inclusive development.

Data availability

Data supporting the findings of this study are available within the article and its supplementary information files or are available from the corresponding author upon reasonable request.

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BJG: Conceptualization, methodology; validation, supervision, writing-review and editing. PHY: Conceptualization, methodology, software, investigation, writing-original draft, review and editing. YYC: Methodology, software, formal analysis. YLC: Methodology, software, formal analysis. XMZ: Investigation, validation, formal analysis. XZD: Investigation, writing-review and editing, formal analysis. EHKY: Investigation, writing-review and editing. EHWC: Investigation, writing-review and editing.

Competing interests
The authors declare no competing interests.

Ethical approval
Ethical approval was not required as the study did not involve human participants.

Informed consent
This article does not contain any study with human participants performed by any of the authors.

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