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Spatial Identification of Housing Vacancy in China

PAN Jinghu[1], DONG Leilei[1, 2]

(1. *College of Geography and Environmental Sciences*, *Northwest Normal University*, *Lanzhou* 730070, *China*; 2. *Northwest Institute of Eco-Environment and Resources*, *Lanzhou* 730000, *China*)

Abstract: The housing vacancy rate (HVR) is an important index in assessing the healthiness of residential real estate market. In China, it is hardly to take advantage of the basic data of real estate information due to the opaque of those data. In this paper, the HVR is estimated to two scales. At the grid level, urban area ratio was calculated by nighttime images after eliminating outliers of nighttime images and night light intensity of non-residential pixels in mixed pixels by a proposed modified optimal threshold method, and built-up areas in each pixel were extracted from the land-cover data. Then, the HVR is calculated by comparing the light intensity of specific grid with the light intensity of full occupancy rate regions. At the administrative scale, the GCI ('ghost city' index) is constructed by calculating the ratio of the total light radiation intensity of a city to the total construction land area of the city. The overall spatial differentiation pattern of the vacant houses in the national prefecture level administrative regions is analyzed. The following conclusions were drawn: vacant housing is rare in certain eastern coastal cities and regions in China with relatively fast economic development. Cities based on exhausted resources, some mountainous cities, and cities with relatively backward economic development more typically showed high levels of housing vacancy. The GCI of prefecture-level administrative units gradually declined from north to south, whereas the east-west distribution showed a parabolic shape. As city level decreased, the GCI registered a gradual upward trend. China's urban housing vacancy can be divided into five categories: industry or resources driven, government planned, epitaxy expansionary, environmental constraint and speculative activate by combining the spatial distribution of housing vacancy with the factors of natural environment, social economic development level, and population density into consideration.
Keywords: housing vacancy rate (HVR); spatial identification; nighttime light; spatial pattern; ghost city; China

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1 Introduction

Housing is for living, not for speculation, and even less for being left vacant. As a pillar industry of the national economy, the real estate industry occupies a crucial position in developing the national economy (Gabriel and Nothaft, 2001; Mittal and Kashyap, 2015). The steady development of the real estate market directly affects residents' quality of life, and the housing vacancy rate (HVR) is a significant indicator of the health of the real estate market (Gabriel and Nothaft, 1988). Over the last 20 years, as China's economy and society has been developing soundly at increasing speed while maintaining high quality, the real estate industry has been advancing steadily (Li et al., 2018). Countless buildings have mushroomed, from first-tier cities such as Beijing, Guangzhou, Shanghai, and Shenzhen to the fourth- and fifth-tier cities in the central and western regions of China (Liu et al., 2016). Meanwhile, to ease the pressure of population growth and land availability, 'city crea-

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Corresponding author: PAN Jinghu. E-mail: panjh_nwnu@nwnu.edu.cn

tion' campaigns have been launched in most cities, which have alleviated urban pressure to a certain extent. However, affected by political factors, land financing, and blind pursuit and emulation of urban growth, certain cities, while expanding on a massive scale, have done so without scientific research and evaluation, which has resulted in buildings of excessive scale, remote location, and backward infrastructure. The resulting new cities and districts are often sparsely populated, and urban vitality is low, hence the reports of 'ghost cities' that are widely seen in news reports (Jin et al., 2017). During 1990–2000 and 2000–2010, China's built-up urban land increased by 90.50% and 83.41% respectively. The coefficients of elasticity of urban land expansion (the ratio between the growth rate of urban built-up land and the growth of urban population) in China during the two periods mentioned were 1.71 and 1.85 respectively, which is much higher than the reasonable threshold of 1.12 (Liang, 2013), indicating serious resource mismatch and ineffective space utilization in urban planning and construction in some regions. High housing vacancy phenomenon has had a negative impact on urban spatial patterns and sustainable development. High HVR directly causes the waste of housing resources, causes the misallocation of housing resources, and increases the financial risk. In certain places, local officials lack efficient means of keeping track of house vacancy situation, and thus there exists a clear need to find vacant houses before their condition deteriorates and to find new use for them (Konomi et al., 2019). So, it is important to improve spatio-temporal identification and to implement assessment strategies that focus on 'housing vacancy' research (Ma et al., 2018).

The paucity of available real estate information in China means that many essential data are difficult to obtain, and the vacancy rate has become the 'Goldbach conjecture' of the domestic market for real estate. No official data have been released on vacant housing monitoring and evaluation in China (Jing et al., 2016), whereas academic research on this topic mainly relies on data obtained from questionnaires, interviews, and similar sources (Chi et al., 2015). These methods take a long time and require large amounts of manpower, material, and financial resources, yet can not reflect at the macro level the spatial differentiation pattern of housing vacancy. A research report entitled 'Urban Housing Vacancy Rate and Housing Market Development Trend' was released by the China Family Finance Research Center of Southwest University. This report showed that the Chinese urban HVR in 2017 was as high as 21.4% (CHFS, 2019). Tencent Real Estate Research Institute (2015) also released an analytical report showing that the vacancy rate of housing in major cities in China was 22%–26% in 2015. From 2014 to 2016, the third-party research institute Standard Ranking City Research Institute published a list of China's urban 'ghost city' index (GCI) values every year. Affected by many factors such as subjective disturbance, analyses of housing vacancies using statistical methods such as household surveys may underestimate or overestimate the HVR and lack objectivity (Bentley et al., 2015). Some special circumstances may be neglected in selecting samples, resulting in large errors in the survey results. An indicator of HVR is often used by countries in the West as a weathervane to indicate the state of supply and demand in the real estate market (Ortalo-Magné and Rady, 2006); it is regarded as one of the main bases for real estate regulation and control (Vakili-Zad and Hoekstra, 2011). Academic research on housing vacancy on the West is also systematic, covering the concept of housing vacancy (Couch and Cocks, 2013; Molloy, 2016), vacancy rate calculation, and relationships such as those between housing vacancy and socio-economic indicators or between the real estate market and vacancy rate (Gentili and Hoekstra, 2019). Topics of research include newly-built housing as well as the existing housing stock; the theoretical and computational models are mature, and data are transparent (Wood et al., 2006). In contrast, publication of data on China's official or authoritative HVR has been temporarily suspended; there is no consensus on basic statistics of the real estate market such as HVR, not to mention the spatial pattern and spatial evolution of urban housing vacancy and its influencing factors (Zheng et al., 2017). Most existing studies have focused on vacancy theory in the incremental commodity housing market, types of housing vacancy and their causes, and the relative weighing between new and existing housing stock in the calculation of vacancy rate (Jin et al., 2017; Du et al., 2018).

At the regional or urban level, scholars use the term 'ghost city' more to replace the phenomenon of housing vacancy. Xiao et al. (2014) develop a method for extracting China's urban expansion pattern and analyze the dynamics of urban areas in China to explain the phenomenon of 'ghost cities'. Chi et al. (2015) used Baidu positioning data derived from a mobile positioning app to distinguish between ghost cities and towns that are seasonally empty in China. However, because most of the existing studies are based on one-sided media information or statistical data, few studies can provide enough effective information to understand the phenomenon of housing vacancy or 'ghost city'. Two appellations of this phenomenon were proposed as a standard to make a comprehensive analysis, the existing housing vacancy and ghost city evaluation only provides the evaluation results on a coarse spatial scale, and there is a problem of time lag. Lack of spatial details and subjectivity have led to widespread questioning of these results. Some researchers attempted to investigate 'ghost cities' or housing vacancy using a 'ghost city' index based on built-up area by utilizing multi-source remote sensing datasets. Zheng et al. (2017) developed a 'ghost city' index to quantify and evaluate the intensity of 'ghost city' phenomenon in Yangtze River Delta. Jin et al. (2017) profile ghost cities in China from the view of residential development vitality. Niu (2018) proposed a practical model for estimating the HVR in Qingdao City using NPP-VIIRS nighttime light composed data. Lu et al. (2018) developed nighttime light's rate of change in newly built areas to determine the existence of specific ghost cities.

Some progress has been made in these studies, but so far there is still a lack of consistent, reliable and national case study related to housing vacancies. There are several problems in the existing research, which need to be studied in more detail in the following areas.

(1) The aforementioned few studies on housing vacancy and ghost city identification mainly rely on the up-to-date urban planning images and related thematic data, such as population, land area and other statistical yearbook data, and do not fully consider the differences between the main functional areas within the inner city and the development of the whole city from a geographical perspective (Ma et al., 2018).

(2) In the past few studies using remote sensing images mostly focused on the whole city, but fail to consider the regional characteristics of housing vacancy from the local scale, i.e., according to different spatial regions to study, and detailed analysis of the internal situation of the city. The results can not be applied to every point (pixel) in space, and it is difficult to know the vacancy rate of each pixel.

(3) Some studies only pursue hot spots of 'ghost city' phenomenon rather than large-scale mapping of housing vacancy, while others may even come to the opposite conclusion (Zheng et al., 2017). Moreover, the time lag of the research results makes it impossible for policy makers to obtain timely information about current housing vacancies and formulate corresponding planning strategies to regulate them. Although the research based on mobile big data is timely, it has limitations due to the inevitable biases, inaccuracies, and data discontinuities in generating and acquiring big geographic behavioral data.

The purposes of this paper are as follows: 1) Taking the 295 prefecture-level administrative units in China as research objects, to use the GIS spatial analysis method to explore the spatial differentiation patterns and characteristics of housing vacancy in prefecture-level cities in China and to perform an in-depth study of overall trends, spatial heterogeneity, and correlations. Hong Kong, Macao, and Taiwan were not included in the study due to their particular geographical and social barriers, and inconsistent statistical procedures. Some prefecture-level units such as ethnic minority autonomous prefectures, leagues, and prefecture-level regions are not included in the analysis unit of this paper due to lack of data. 2) To introduce multi-source remote-sensing data to identify spatial patterns of vacancy and to provide new ideas for enriching housing vacancy research. 3) To summarize and discriminate housing vacancy modes, to identify their various causes, and to offer a scientific reference for the healthy development of the real estate industry, government macro-control, and academic research.

2 Data and Methods

2.1 Data sources

DMSP-OLS stable nighttime lighting data were sourced from the National Geophysical Data Center (NGDC, https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html). In order to match the land-cover data, NPP-VIIRS Night Lighting Synthetic Products for 2013 are from https://ngdc.noaa.gov/eog/viirs/download_dnb_composites.html. Because the proportion of impervious surface contained in each nighttime lighting image pixel is not the same, when estimating the national HVR, it is necessary to use national land-cover data to normalize the NPP-VIIRS night lighting data to make the measurement results more accurate. Land-cover products were obtained from the Earth Science Systems Research Center of Tsinghua University (Yu et al., 2013). Administrative division data were sourced from the National Geographic Information Resource Directory Service System.

The original NPP-VIIRS night lighting images will have negative and maximum outliers (Ma et al., 2015). In order to ensure the data consistency, the negative value is set to zero. The invariant target region method (Wu et al., 2013) is used to eliminate outliers. Firstly, the DMSP-OLS image is binarized, the pixels with gray value > 0 are assigned to 1, and the mask is processed (Li et al., 2016). The mask data and NPP-VIIRS data are multiplied and some abnormal values are eliminated. Four cities, Beijing, Shanghai, Guangzhou and Xi'an, were selected as reference objects, and the maximum threshold and neighborhood filtering were used to eliminate outliers.

2.2 Research methodology

The housing vacancy rate is defined as the ratio of the stock and incremental housing area of a certain area to the total stock and incremental housing area. The HVR in each city in China can not be calculated accurately only based on the existing data. In this paper, the concept is concreted to two scales: 1) At the grid level (section 2.2.1), using night light image to calculate the HVR based on grid; HVR describes the actual utilization ratio of a residential area, which can be modelled through the relationship between the intensity of a residential area and their light intensity (Wang et al., 2019). In fact, the HVR in grid-scale is calculated by comparing the light intensity of specific grid with the light intensity of full occupancy rate regions. 2) At the administrative scale (section 2.2.2), the GCI (the ratio of the total light radiation intensity of a city to the total construction land area of the city) is constructed by using the night lighting and land use data to analyze the overall spatial differentiation pattern of the vacant houses in the national prefecture level administrative regions.

2.2.1 Spatial identification of house vacancy rate based on night lighting

According to related studies, the intensity of nighttime radiance largely depends on the proportion of impervious surfaces in each pixel. Due to varying proportions of impervious surfaces in pixels, errors would occur in estimating the vacancy rate of the corresponding housing. Chen et al. (2015) proposed to perform a calculation based on the unit impervious surface of night lighting intensity, which consisted of four steps: pre-processing the night lighting data; extracting the national area of built-up land based on land-cover data; calculating the build-up area rate (UAR) of the built-up land in each pixel and screening out non-residential illumination; and last but not least, calculating the HVR by full-scale lighting (Fig. 1).

The first step was to extract the built-up land using national land-cover data. Because the NPP-VIIRS night lighting data and the built-up land data had different spatial resolutions, the two scene images were superimposed to estimate the proportion of built-up land in each night lighting pixel. In Fig. 2a, the large square indicates a NPP-VIIRS night lighting pixel (spatial resolution 500 m), and the small square represents a built-up site binarized pixel (spatial resolution 30 m). Using binarization, the built-up land data were re-sampled as 10 m × 10 m (Fig. 2b), enabling the 30 m × 30 m built-up land pixel to be divided into nine sub-pixels to reduce the information loss from re-sampling. The processed built-up land data were superimposed onto the NPP-VIIRS image with a spatial resolution of 500 m; each pixel of the NPP-VIIRS image contained 2500 grid cells with a resolution of 10 m (Fig. 2c). The proportion of built-up land for each night lighting pixel was obtained by calculating the number of 10-m built-up land grid cells contained in each NPP-VIIRS night lighting pixel (Chen et al., 2015). The equation for UAR is as follows (Chen et al., 2015).

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

where N_d is the number of built-up land pixels contained in the d pixel, and N_t is the total number of built-up land pixels contained in the nighttime light pixel (N_t is 2500 in this paper).

Night lighting data contain lighting pixels that include both residential areas and non-residential areas such as parks and roads, and the intensity of radiation is also affected by both residential and non-residential areas. Because the vacancy rate is mainly related to the

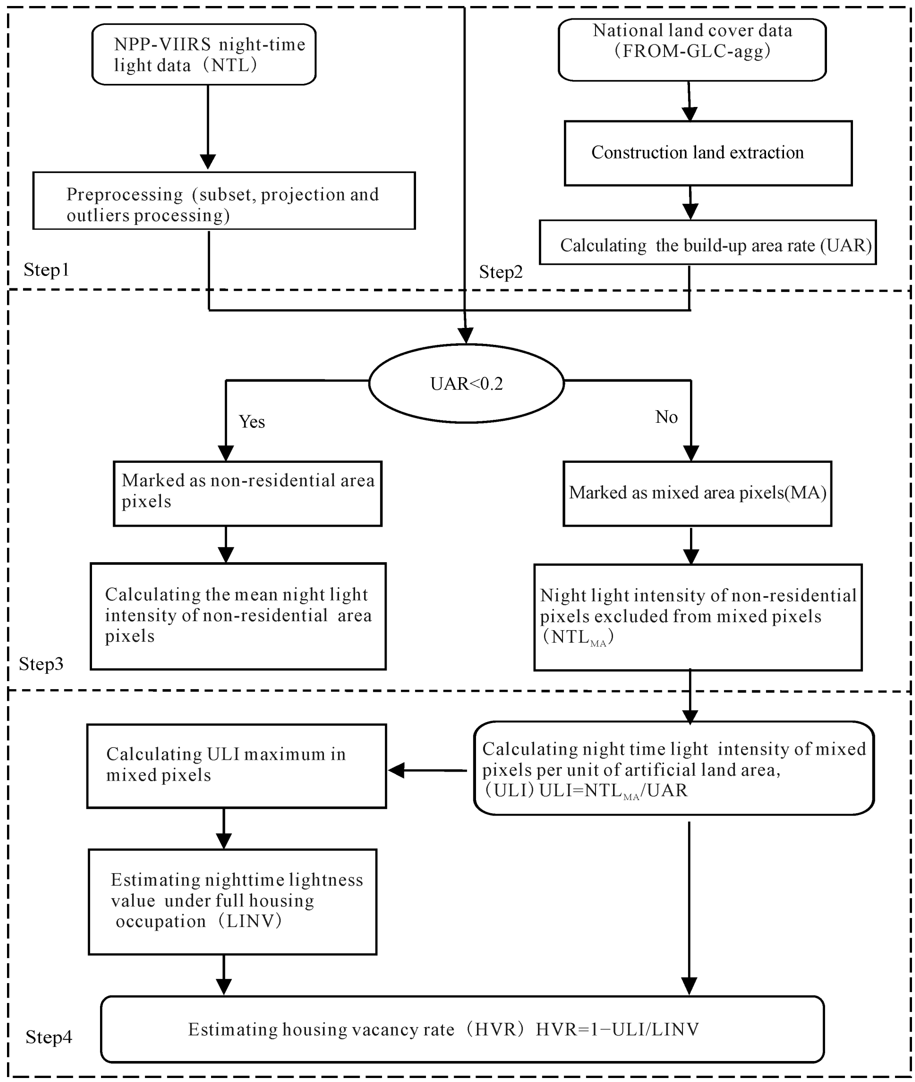

Fig. 1 Flowchart of house vacancy rate (HVR) estimation. NTL, night-time light; UAR, build-up area rate; FROM-GLC, Finer Resolution Observation and Monitoring: Global Land Cover; MA, mixed area pixels; ULI, urban light intensity; LINV, light intensity of non-vacancy; HVR, housing vacancy rate

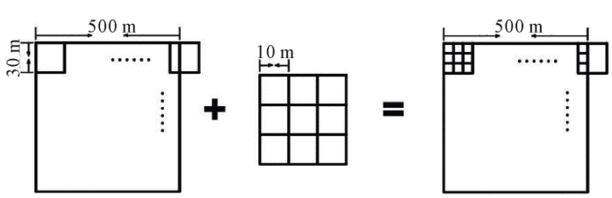

Fig. 2 Schematic diagram of urban area ratio calculation (Chen et al., 2015)

light intensity of residential areas, non-residential lighting should be subtracted out to make it possible to extract the HVR more accurately. This study randomly selected 200 non-residential area pixels to analyze the proportion of built-up land in the sample pixels. The built-up land ratio of more than 90% of the pixels was less than 0.2. Other studies have shown that it is reasonable to use 20% of built-up land as a threshold for non-residential area extraction. If the proportion of built-up land in a pixel is less than 0.2, it can be regarded as a non-residential area, and the remaining pixels can then be considered as mixed pixels containing both residential and non-residential information that must be further processed to improve the accuracy of the HVR calculation (Zhou et al., 2014; Chen et al., 2015). To do this, the average light intensity (ALI) of the pixels in the non-residential area was extracted, and the average light intensity of the non-residential area pixels was subtracted from the light intensity value in the mixed pixels so as to reduce the influence of the non-resident area pixels in the mixed pixels. The equation of ALI calculation process can be given as follows (Chen et al., 2015):

$$ALI = \frac{\sum_{k=1}^{N} NTL_k}{N_{non-resi}} \tag{2}$$

$$NTL_{MA} = \begin{cases} F(NTL, ALI) & if\ UAR \geq 0.2 \\ NULL & otherwise \end{cases} \tag{3}$$

$$F(NTL, ALI) = \begin{cases} NTL_{UAR\geq 0.2} - ALI_{UAR<0.2}, & if\ NTL_{UAR\geq 0.2} > ALI_{UAR<0.2} \\ 0 & otherwise \end{cases} \tag{4}$$

where $N_{non\text{-}resi}$ is the number of non-residential pixels, NTL_k is the light radiation value of the k-th pixel of non-residential area, NTL_{MA} is the light radiation value of mixed pixels after excluding the influence of residential area, $NTL_{UAR\geq 0.2}$ is the light radiation value of mixed pixels before eliminating the influence of non-residential area, and $ALI_{UAR<0.2}$ is the average light radiation value of non-residential area pixels.

Due to variations in the proportions of built-up land in each pixel in the nighttime lighting image, the accuracy of the vacancy rate calculation was greatly reduced. To avoid this phenomenon, this paper introduces a nighttime lighting intensity (ULI) parameter for a unit impervious layer area, which can further improve the relationship between nighttime lighting and built-up land proportion. The calculation formula is as follows (Chen et al., 2015):

$$ULI_i = NTL_{MA}^i / UAR \tag{5}$$

where ULI_i is the nighttime lighting intensity of the impervious layer area of each pixel of the i-th administrative unit, NTL^i_{MA} is the light radiation value of mixed pixels of the i-th administrative unit, except after the influence of residential area.

Once the nighttime light intensity per unit impervious layer area had been obtained, the nighttime lightness value (LINV) under full housing occupation was calculated, and based on this, the vacancy rate was estimated. The city center has a relatively concentrated population and is the area with the largest proportion of built-up land. However, influenced by factors such as the natural environment and socio-economic development, the nighttime lighting values in different areas under full housing occupation are different, indicating that different regions should set different night lighting values under full housing occupation when estimating the vacancy rate. As the earliest area in the city to be developed, the city center has relatively complete infrastructure and facilities. This paper assumes that housing in the downtown area is generally fully occupied. In view of certain changes in nighttime lighting in the city's central area, errors would occur if the average lighting value in this area were used as the nighttime lighting value under full occupation. Therefore, the mode of night lighting in the central area was selected as the value of LINV. The calculation formula is as follows (Chen et al., 2015):

$$HVR_i = 1 - ULI_i / LINV_i \tag{6}$$

where HVR_i is the vacancy rate of each pixel in the i-th administrative unit, ULI_i is the nighttime lighting intensity of each pixel's impervious area in the i-th administrative unit, and $LINV_i$ is the nighttime lighting intensity in the case of full housing occupation in the i-th administrative unit.

2.2.2 GCI estimation

The GCI is the ratio of the total regional light radiation intensity to the total area of built-up land and can be calculated as follows:

$$GCI = \frac{TLI}{A} \tag{7}$$

where *GCI* is the ghost city index of a city, *TLI* is the total intensity of the city's light radiation, and *A* is the total area of built-up land in the city. *TLI* is obtained by calculating the total intensity of light radiation in the administrative unit using NPP-VIIRS nighttime remote-sensing images. *A* is obtained by extracting the built-up land information in the urban administrative area using global surface coverage products. Therefore, the data for calculating the GCI were completely sourced from remote-sensing images, which ensured the objectivity and authenticity of the calculation results.

3 Results

3.1 Spatial pattern of national HVR at pixel scale

This study obtained national vacant housing results in 2013 (Fig. 3) based on the HVR estimation model. As can be seen from Fig. 4, the closer the pixel value is to 0, the lower is the HVR, whereas the closer the value is to 1, the higher the rate. By simply calculating statistics for the HVR of the pixels contained in each city, the average vacancy rate of the cities at prefecture level and above in 2013 was determined to be 27.3%. Some general characteristics of vacant housing in China can also be discovered from Fig. 3. It should be noted that, according to the interpretation of the National Development and Reform Commission of China, the division of the East, the middle and the west of China is based on the national policies. The east refers to the provinces with the earliest coastal opening policy and higher level of economic development; the central refers to the sub-developed provinces, while the western part refers to the less developed western provinces.

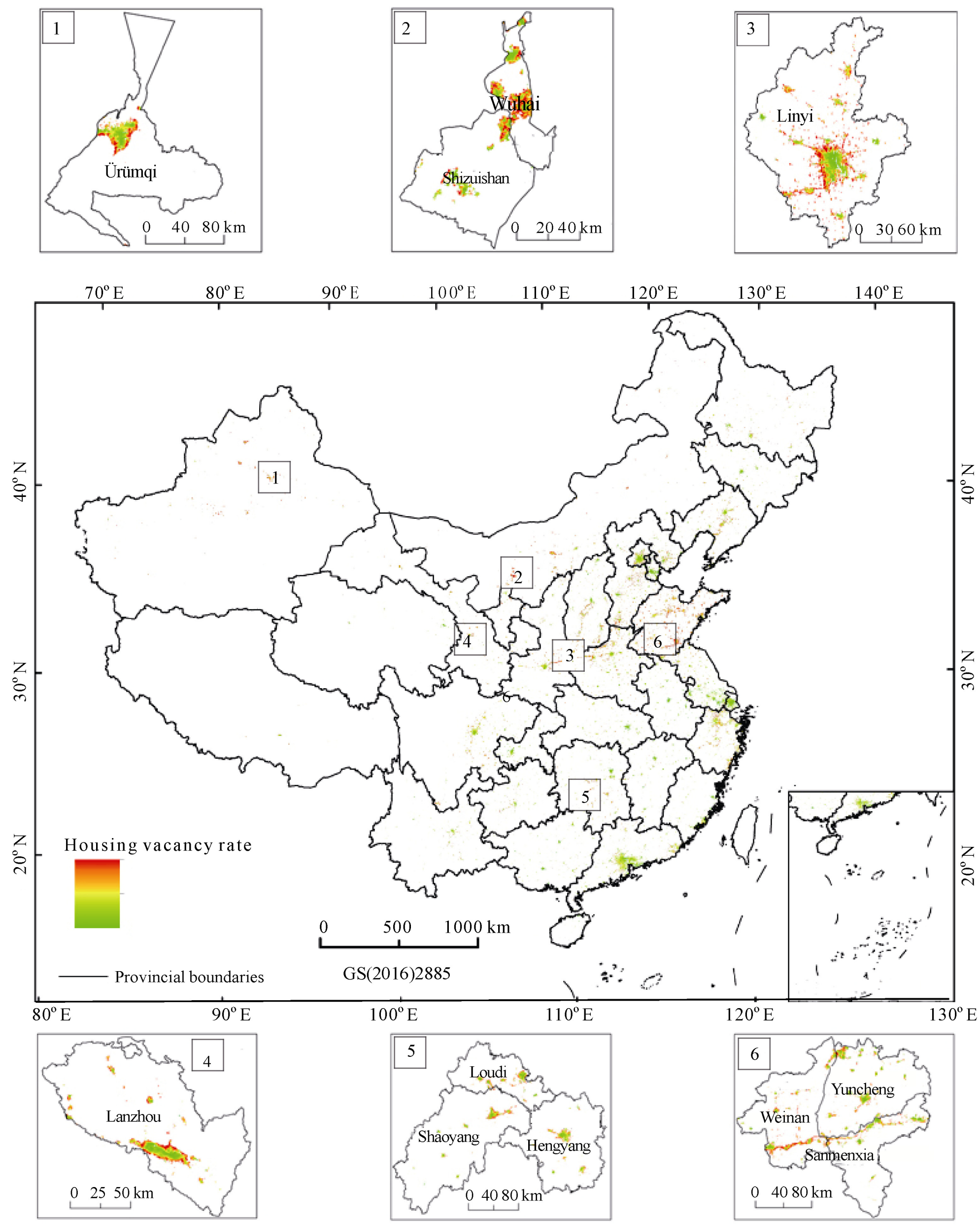

Fig. 3 Spatial distribution of house vacancy rate (HVR) in China

(1) Judging from internal changes in cities, areas with high vacancy rates are mainly concentrated in the areas surrounding low-vacancy-rate areas and gradually increase outward around city centers. China now enjoys rapid urbanization, with an extensive style for most spatial urban expansions, and the areas surrounding cities have become the preferred area for urban expansion. However, distance from the city center and incomplete infrastructure results in insufficient space for population congregation in the areas surrounding cities, such as suburbs, which in turn results in a high vacancy rate.

(2) From a national perspective, the more economically developed areas in eastern China, such as the Yangtze River Delta, the Pearl River Delta, and the Beijing-Tianjin-Hebei region, have higher land-use intensities and lower vacancy rates; the high-density areas of built-up land often coincide with strong radiation areas of night lighting. By contrast, the central and western regions have lower land-use intensities and higher vacancy rates; HVR hence show a spatially increasing trend from coastal to inland regions.

(3) From the perspective of urban development scale, areas with high HVR are more prominent in small and medium-sized cities. In the process of urbanization, when limited by economic conditions and urban development levels, small and medium-sized cities lack employment opportunities to attract immigration, which restricts their development.

From a national perspective, the pixel-scale urban housing vacancy areas identified by nighttime lighting are spatially dispersed, with smaller vacant areas than in non-urbanized areas. Combining with the spatial distribution of housing vacancy, categories of housing vacancies in China can be derived from the perspectives of HVR, natural environment, social and economic development level, and population concentration. However, length restrictions on this paper precluded the presentation of the spatial distribution of all vacant housing areas on a national scale. In this light, based on factors such as the vacancy rate of housing and the type of urban planning, six sample areas in China were selected to analyze various types of housing vacancy: Ürümqi, Shizuishan-Wuhai, Linyi, Lanzhou, Shaoyang-Hengyang-Loudi, and Weinan-Yuncheng-Sanmenxia (Fig. 3). Taking into consideration the differences between the every districts of China, topography, industrial structures, and urbanization development levels, this study selected different types of cities: plains cities, valley cities, resource cities, agricultural cities, and comprehensive cities.

(1) Industry (resource)-driven housing vacancy. The local economy develops rapidly driven by certain industries (resources), but as the industry becomes depressed or the resource is depleted, the city eventually declines. Shizuishan City and Wuhai City are both famous old coal-based industrial cities. Due to Shizuishan in Ningxia Hui Autonomous Region and Wuhai in Inner Mongolia Autonomous region have economies that rely heavily on coal, energy, and heavy chemical industries, which resulted in a lack of diversity in industrial structure and limited employment opportunities in some areas after the resources were depleted. Technological development zones in Shizuishan, and the central and northern parts in Wuhai have become the areas with high HVR. Erdos, Wuhai, and Yulin also belong to the industrial (resource)-driven housing vacancy class.

(2) Government-planning housing vacancy. With urban development and population increase, central urban areas are over-saturated with population and short of land resources. Local governments therefore build new districts and cities to alleviate urban pressure. Due to lack of scientific planning and reasonable layout, the planned development differs widely from actual needs, and the infrastructure is often imperfect, resulting in sparsely populated new districts and new towns and vacant housing. A typical case of government-planning housing vacancy is the Lanzhou New District. Lanzhou is a typical valley-type city, located between mountains to the north and south, with the Yellow River flowing through from west to east, giving it the characteristics of a strip-shaped basin city. Limited by geographical conditions, available land resources in the urban area are limited. In recent years, Lanzhou has been developing low hilly and gently sloping lands north of the Yellow River. However, this newly-built district is far from the main urban area, resulting in serious housing vacancy in this area.

(3) Expansion housing vacancy. During urban expansion, the suburban and urban periphery is considered as the primary area to be developed for urban expansion. Housing is eventually left vacant due to incomplete infrastructure such as transportation in urban suburbs or surrounding areas and low population concentration. Such vacancies mainly occur in areas surrounding some western cities with extensive land use and large reserved

built-up lands. Typical case is Ürümqi in Xinjiang. In Ürümqi, the high-vacancy areas are located on the periphery, in the suburbs, this city vigorously attracting investment for developing real estate. As a result, housing vacancies occurred along with the development of real estate in new city districts. Jiayuguan in Gansu and Karamay also belong to this situation.

(4) Environmentally constrained housing vacancy. Limited by features of the natural environment such as landforms, some small and medium-sized cities are located in mountainous areas with low urbanization levels and underdeveloped industries. In addition, the scale of the city center is small, industry is underdeveloped, the urban planning layout is scattered, and rural residential areas are scattered over large areas. Because nighttime lights are not bright, remote sensing may capture this phenomenon. Areas with prominent housing vacancy of this type are Linyi City in Shandong Province and Hengyang City in Hunan Province. Linyi City is surrounded by mountains on the west, north and east, with an alluvial fan plain in the south; the undulating terrain plus the extensive distribution of rural settlements creates high HVR in areas such as Tanghe Town. In the areas bordering Hengyang, Shaoyang, and Loudi in Hunan Province, the areas of housing vacancy have mainly resulted from expansion of the main urban area without space for population congregation in new suburban districts.

(5) Speculative stimulation housing vacancy. Although Weinan is only a third tier city, it has convenient transportation and superior location advantages because it is close to Xi'an. The real estate market in Weinan has been stimulated by the introduction of real estate regulation policies such as loan restriction in Xi'an. Speculators seeking quick profit overstimulate real estate development and generate a false prosperity in the short term, resulting in bubbles and vacant housing after the bubble bursts. The surrounding area of the national road which leading to Xi'an in Weinan have become high HVR areas. In addition, typical examples are Rushan City, Longkou City in Shandong Province and some cities in Hainan Province are also typical housing vacancy due to speculative stimulation, where population migration has a dramatic seasonal component. Real estate developers seek profits and throw supply and demand in the real estate market into serious imbalance. Lackluster demand for housing by most local residents together with slow migration flows have directly led to vacant housing.

3.2 Spatial differentiation of GCI in prefecture-level cities

The HVR is one of the most important indicators to evaluate the health of real estate in each city. However, it is difficult to obtain real estate data and population data with high spatial resolution. The resolution of night-time light images is rather large in contrast to the residential projects, making it difficult to differentiate the small scale variations in terms of housing vacancy. As Chinese cities pursue economic growth through urbanization and thus implement ambitious land development projects, some of them have inadvertently turned themselves into ghost cities. In China, the city governs the county, and the prefecture level cities are the political, economic and cultural centers of the region. We developed a GCI to quantify and evaluate the intensity of 'ghost city' phenomenon in China at prefecture level city. The purpose of this section is to explore the spatial differentiation pattern and characteristics of housing vacancy in China's prefecture level cities through the GCI, and further study the overall changing trend, spatial heterogeneity and spatial correlation pattern, so as to reveal the spatial differentiation pattern of housing vacancy in China from the administrative region level.

3.2.1 Overall differences

The GCI of 295 cities at prefecture level and above in China was calculated and divided into five levels (lower, low, medium, high, and higher) using the natural breakpoint method (Fig. 4). The results were as follows: 1) the spatial distribution of GCI in China's cities at prefecture level and above showed substantial variation, being low in economically developed parts of the eastern coastal areas and high in the central and western areas and also being low in some provincial capitals. Due to differences in land-use intensity, the GCI of northern cities was higher than in southern cities; 2) from the viewpoint of city categories, the GCI of small and medium-sized cities in China was relatively high; with increasing urbanization, small and medium-sized cities have rapidly expanded to their surrounding areas, and this disorderly expansion has resulted in waste of land resources and insufficient space for population congregation, which elevates the GCI. 3) The average GCI of 295 cities at prefecture level and above was 10.56; 181 cities were higher than this average value.

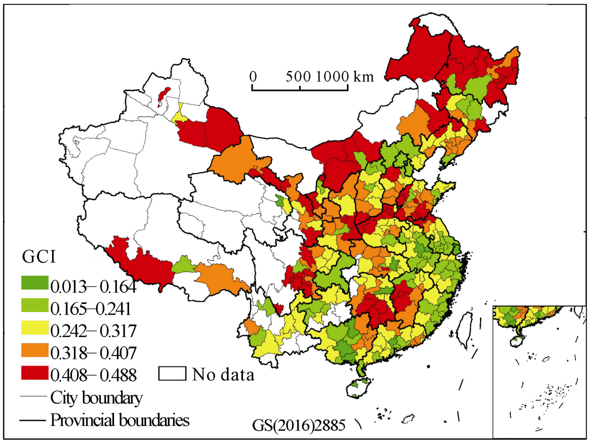

Fig. 4 Distribution of 'ghost cities' index (GCI) in China's prefecture level cities

One hundred thirty-four (134) cities showed higher GCIs, accounting for 45% of the total, of which 46 GCIs were extremely high. Sixty-two (62) and twenty-eight (28) cities had GCIs in the lower and low categories respectively, accounting for 21% and 9% of the total number of administrative units. This result was consistent with the above spatial distribution analysis of housing vacancies.

Using the ArcGIS general trend analysis method (McLeod et al., 1991), with the *x*- and *y*-axes representing east and north respectively and the *z*-axis being the GCI, a three-dimensional map was generated to present the spatial distribution of the GCI in China's cities at prefecture level and above. Fig. 5(a) shows that, for Chinese administrative units at prefecture level and above, the spatial differentiation in the north-south direction is more dramatic than that in the east-west direction, showing a decreasing trend from north to south, i.e., the north > the central > the south, and a 'parabolic' shape from east to west, i.e., the central > the west > the east.

A 3D trend map was then drawn using the Surfer software. Fig. 5(b) reveals more directly the spatial differences in the GCI for each city: cities with a low GCI were mainly distributed in the southeast coastal areas and Xi'an, Chengdu, Lanzhou, Taiyuan, Chongqing, whereas the index was higher in the north and southwest. From the perspective of spatial pattern, it showed a patchy distribution in the north, but in the central and southwestern areas, it showed alternating highs and lows.

3.2.2 Spatial association characteristics

Using the Geoda software, the general Moran's *I* value of the GCI of China's cities at prefecture level and above in 2013 was calculated as 0.454, and the overall statistical Z value of Moran's *I* was found to exceed the critical value of 1.96 at the 5% confidence level, reflecting the autocorrelation of the GCI of China's cities at prefecture level and above, with the high-index cities tending to cluster and the low-index cities also doing so (Niu, 2018).

China's prefecture-level city GCI can be divided into the following four categories under the 5% confidence level (Fig. 6): 1) High-high (H-H). The GCI of each city and its neighboring cities is relatively high, with dramatic positive correlation. 2) Low-low (L-L). The GCI of each city and its neighboring cities is relatively low. 3) High-low (H-L). The GCI of a particular city is higher than those of its adjacent cities. 4) Low-high

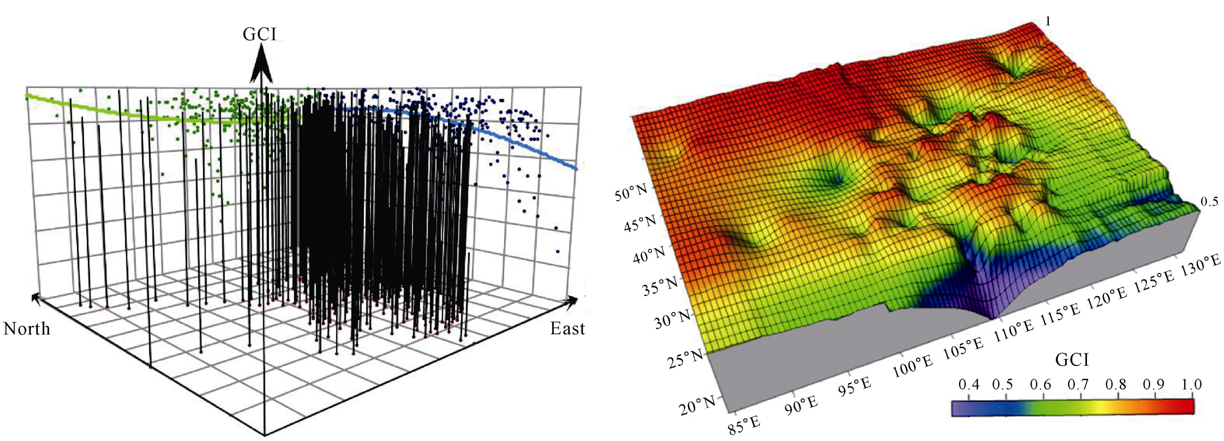

Fig. 5 Overall trend face of 'ghost cities' index (GCI) in China's prefecture level cities

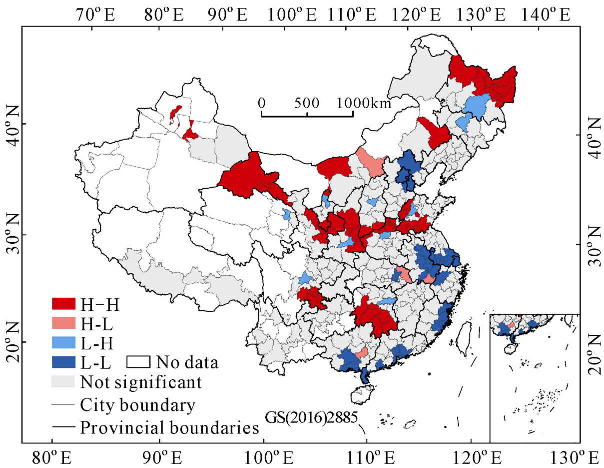

Fig. 6 Spatial interaction clustering of 'ghost cities' index (GCI) in China's prefecture level cities

(L-H). The GCI of a particular city is lower than those of its neighboring cities. In terms of the distribution of the GCI in each city, category 1 (44) > category 2 (35) > category 4 (6) > category 3 (4). In terms of the spatial distribution of the GCI of the prefecture-level units, the high-high category was spatially concentrated in the Wuling Mountain area and southwestern Sichuan; the low-low category was mainly distributed in city clusters such as Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta; the high-low category was mainly distributed in Fuxin in Liaoning, Ulanqab in Inner Mongolia, and Baoding in Hebei, and the low-high category was mainly distributed in cities such as Xi'an, Chengdu, and Changsha.

3.2.3 Hot-spot analysis

The Getis-Ord G_i^* function of the ArcGIS software was used to calculate the high and low value agglomerations of the GCI in different spatial locations (Malleson and Andresen, 2015). It can be seen that the hot and cold regions of the GCI of China's cities at prefecture level and above are spatially contiguous in hot spots and discrete in cold spots; the hot spot of the GCI in prefecture-level cities is extensively distributed. With the 400 mm precipitation line as the reference axis, the hot spots in the northern region were mainly located along the axis and to its north, whereas those in the south were mainly distributed to the southeast of the axis, forming a 'T' shape. Among these, the Gansu-Ningxia-Shaanxi-Shanxi-Hebei-Inner Mongolia line forms the horizontal axis of the 'T' line, and the Dabie Mountain-Wuling Mountain-Yungui Plateau line forms the vertical axis. Compared with the hot spot areas, the cold spots are very widely distributed, showing a certain fragmentation in their spatial distribution. Sub-hot spots were also extensively distributed, forming six contiguous areas, and were mostly distributed on the outer edge of the cold spot area, showing a fragmented trend.

3.2.4 GCI variations in cities at different levels

China's cities are divided into first-tier, second-tier, third-tier, fourth-tier, fifth-tier, and ethnic regions based on main indicators including brand entry density and quantity, GDP, per capita income, '211' key universities, global top 500 companies, airport throughput, city rankings, number of embassies and consulates, and number of international air routes. This classification yielded 19 first-tier cities, 36 second-tier cities, 59 third-tier cities, 60 fourth-tier cities, and 121 fifth-tier cities. According to the average value of each city's GCI, the highest GCI among the first-tier cities was 11.19 for Chongqing, whereas the lowest was 0.206 for Xiamen; the average GCI was 5.27 (Table 1). For first-tier cities, the GCI exhibited a wide distribution range and great spatial variation, yet showed the lowest values of the entire five-level city hierarchy. This reveals that such regions have high livability, economic axis power, and attractiveness, a high degree of intensive land development, and low HVR. As for the second-tier cities, the GCI was the highest at 13.82 for Linyi and the lowest at 1.30 for Hefei, with an average of 8.14. Its distribution was similar to that of first-tier cities, yet with dramatically higher GCI values. In general, as the city level continued to drop (Tiers 1–5), the GCI showed a gradual upward trend, increasing from 5.27 to 11.17, and the distribution pattern of the index also changed from discrete to concentrated. In addition, the upper and lower limits of the index in high-level cities were generally closer than the index limits of low-level cities, indicating that the more developed the city is, the weaker the 'ghost city' attribute.

Table 1 Ghost city index (GCI) of cities rank

Urban hierarchy	GCI		
	Minimum value	Maximum value	Average value
First-tier cities	0.0134	0.2437	0.1241
Second-tier cities	0.0747	0.4331	0.2072
Third-tier cities	0.1060	0.4877	0.2623
Forth-tier cities	0.1451	0.4886	0.3016
Fifth-tier cities	0.1212	0.4840	0.2912

3.3 Summary of spatial differentiation characteristics

On the two different spatial scales of grid and administrative region, the spatial differentiation characteristics of housing vacancy are generally similar, but the local differences are significant. The housing vacancy in China as a whole shows a trend that the east is lower than the west and the north is larger than the south. The reason is that the eastern region is economically developed, the land use intensity is high, and the HVR is low. The high-density area of the built-up area usually coincides with the strong radiation area of night lighting. In contrast, the central and western regions have lower land use intensity and higher HVR. Therefore, HVR shows a gradual increasing trend from coastal areas to inland areas. Urban shrinkage is both the cause and result of housing vacancy. Before the reform and opening up, the level of urbanization and industrialization in Northeast China was relatively mature, but in the later period of industrialization, due to the relatively lagging industrial upgrading, relatively few job opportunities, and relatively low income, it caused the outflow of urban population in Northeast China, and a large number of housing vacancies followed.

This study found that the HVR of small and medium-sized cities is significantly higher than that of large cities, and HVR of first-tier cities is lower than that of other types of cities, which means the population of cities will highly promote the decreasing of HVR due to higher housing demand, in addition, cities with higher development level provides more attraction for residents. The high HVR in small and medium-sized cities is largely due to over-construction. For example, the new districts of third- and fourth-tier cities such as Ordos and Changzhou are sparsely populated, but the large-scale rise of the city-building movement has led to a serious oversupply, which has directly led to an increase in the HVR. Small and medium-sized cities should change their inertial incremental planning thinking, strictly control the increment and revitalize the stock, and guide population and public resources to concentrate in urban areas.

In addition, a large number of migrants leave rural areas, small and medium-sized cities and small towns, and enter large cities. This is the main feature of China's current population movement, which also pushes up the HVR. This type of situation is caused by resource mismatch. Today, urban development has evolved from 'single fighting' among cities to 'hugging' competition between urban agglomerations and metropolitan areas, and the trend of population movement to regional central cities has become more apparent. The metropolitan area with spillover effect is the primary gathering place for the flow of migrant workers. The competitiveness of these cities will be further improved under the conditions of relaxed settlement policies. This has also become a powerful 'pull' for the outflow of population in some cities, which eventually produces housing prices rise in large cities and housing vacancy in small and medium-sized cities.

Many cities have built satellite cities and satellite towns. These suburbs, and even emerging urbanized areas in the outer suburbs, often have poor industrial functions, insufficient surrounding employment, lack of commercial, transportation, medical, and educational facilities. The occupancy rate is low and it has become an 'empty city' or 'ghost city'. This situation is common not only in eastern cities, but also in central and western cities, which is especially prominent in the results of housing vacancy at grid scale.

China's huge real estate bubble has profoundly affected the vitality of the real economy and increased the burden on citizens. Although population growth provides more development potential for cities, HVR is still higher than 20%. If high housing prices are not effectively restricted, the demographic dividend will also decrease. However, considering the urban development level and population in urban construction will also help control HVR, especially in third-tier and fourth-tier cities.

4 Discussion

4.1 Uncertainties and limitations

Real estate as a pillar industry of national economy plays an important role in social and economical development. The stable development of real estate market can directly influence the life quality of residents. The house vacancy rate is an important index in assessing the healthiness of residential real estate market. In China, it is hardly to take advantage of the basic data of real estate information due to the opaque of those data. This paper quantitatively analyzed spatial identification and difference pattern of house vacancy at different scale and administrative units in China by using nighttime light data, in order to make up the deficiency of traditional methods in the aspects of data missing and differential approach. This method shown spatial visualization of house vacancy more directly compared with traditional methods, such as sampling, questionnaire survey, and substitutive indexes. And it is also hopeful to provide a new means for monitoring house vacancy.

Verifying the accuracy of estimates at the national or regional level is always a difficult and very controversial issue of remote-sensing quantitative inversion. Accuracy verification often involves the following two methods: first, comparing the estimated value with the actual measured value; and second, comparing the estimated result with those obtained by others using other methods for the same area. In 2011 and 2013, the China Family Finance Research Center of the Southwestern University of Finance and Economics conducted a sample survey of national vacant housing, covering 29 provinces, 262 counties, and 1048 communities. According to the results, as can be seen from the overall layout, housing vacancy in the central and western regions was more prominent than in the eastern regions; the overall vacancy rate of third-tier cities was slightly higher than that of first- and second-tier cities. Detailed analyses were carried out for six cities (Beijing, Shanghai, Chongqing, Chengdu, Wuhan, and Tianjin), which revealed that the highest vacancy rate was in Chongqing, whereas the lowest were in Beijing and Shanghai. These conclusions are basically consistent with the estimations of this paper.

The overall housing vacancy situation can be determined to a certain extent using traditional methods such as questionnaire sampling surveys. However, large amounts of manpower and material resources are needed for a nationwide sampling survey, and the timeliness is not good, with hysteresis. Chi et al. (2015) used Baidu positioning data and a density-based clustering algorithm to conduct in-depth research on the phenomenon of 'ghost cities' in China. Their results showed that typical areas with high HVR were: 1) resource-based cities in the central and western regions that once enjoyed rapid economic development, but fell victim to resource depletion, such as Erdos in Inner Mongolia; 2) new cities that emerged due to saturation of main urban areas and land-use progression due to urban expansion, such as Tianjin Binhai New Area; and 3) areas with accelerated urban expansion, which occurs mostly in the vicinity of emerging small and medium-sized cities with flat terrain, such as Dongying and Tongliao. These conclusions are basically consistent with the estimations of this paper. Chen et al. (2015) found that most of the areas with low HVR in the United States are clustered at the center of urban areas, whereas the areas with high HVRs are generally located outside the low HVR area. Similar spatial distribution of HVR is obtained in this paper.

Compared with other research studies and media reports, our framework has several advantages. First, it offers more timely and objective spatial information on housing vacancy and 'ghost cities', and can assist policy makers in identifying high HVR regions and adjusting regional planning strategies correspondingly. Second, our study is carried out at a fine scale. According to the obtained comparison results, the proposed method has good performance for identifying and evaluating the real regions subjected to the housing vacancy and 'ghost city' phenomenon. There are also some differences between this paper and the existing research. Chi et al. (2015) showed that cities with a large vacant housing area are mostly second-tier and third-tier cities. Zheng et al. (2017) proved that third-tier and fourth-tier cities are inclined to become 'ghost cities'. In this paper, it is found that with the increase of city level, the GCI shows a gradual downward trend, that is to say, fourth tier cities and fifth tier cities have the highest vacancy rate.

The explorations described this paper were subject to insufficient accuracy in city area extraction because this was limited by the shortcomings of remote-sensing data as well as by the possible defects of data processing methods and the inevitable variations in geographical location, natural environment, and urban planning layout. Besides, there are not many quantitative research cases for reference due to the extremely complex nature of housing vacancy measurement. Hence, there are uncertainties in the measured results of this paper, as described below:

1) This study used NPP-VIIRS nighttime lighting data, which is currently the highest-resolution product for nighttime remote-sensing data. However, when conducting urban internal research, problems are encountered such as limited scale, low spatial resolution, and low data accuracy.

2) Some noise points are included in the data due to

the high sensitivity of nighttime lighting data, arising from phenomena such as volcanic eruptions, fishing boat lights, high-albedo snow surfaces, and background noise. A variety of methods have been proposed by domestic and foreign researchers to reduce noise, remove saturation, and reduce spillover effects. However, these methods have various limitations, and no universally accepted treatment method has been discovered so far. In spite of the use of NPP-VIIRS nighttime lighting data with higher resolution and on-board calibration in this study, some measurement errors still occurred in the estimation of HVR.

3) The land-use data used in this paper have a spatial resolution of 30 m × 30 m, with an overall interpretation accuracy of 65.51%. Such accuracy met the experimental requirements for nationwide accuracy, yet is still low to obtain good estimation accuracy of vacant housing in urban areas; therefore, the estimation was affected to some extent.

This paper only makes a static analysis of a single year, and lacks the evolution trend and comparative study of different years. In addition, in the future research, we can use flexible space scanning detection to identify the high incidence area of house vacancy in different scales; on this basis, we use the geographical detector to reveal the dominant factors of house vacancy. The HVR of some small-scale regions is still difficult to estimate because of the low light intensity in these places. In future work, we will provide more convincing estimates by introducing new data sources and building better models.

4.2 Policy implications

Housing vacancies are caused by many reasons, which can be generally divided into three aspects: the natural environment, social and economic development, and governmental administrative power (Fig. 7). In other words, the phenomenon of vacant housing is a combination of the natural environment, the level of socio-economic development, and the administrative power

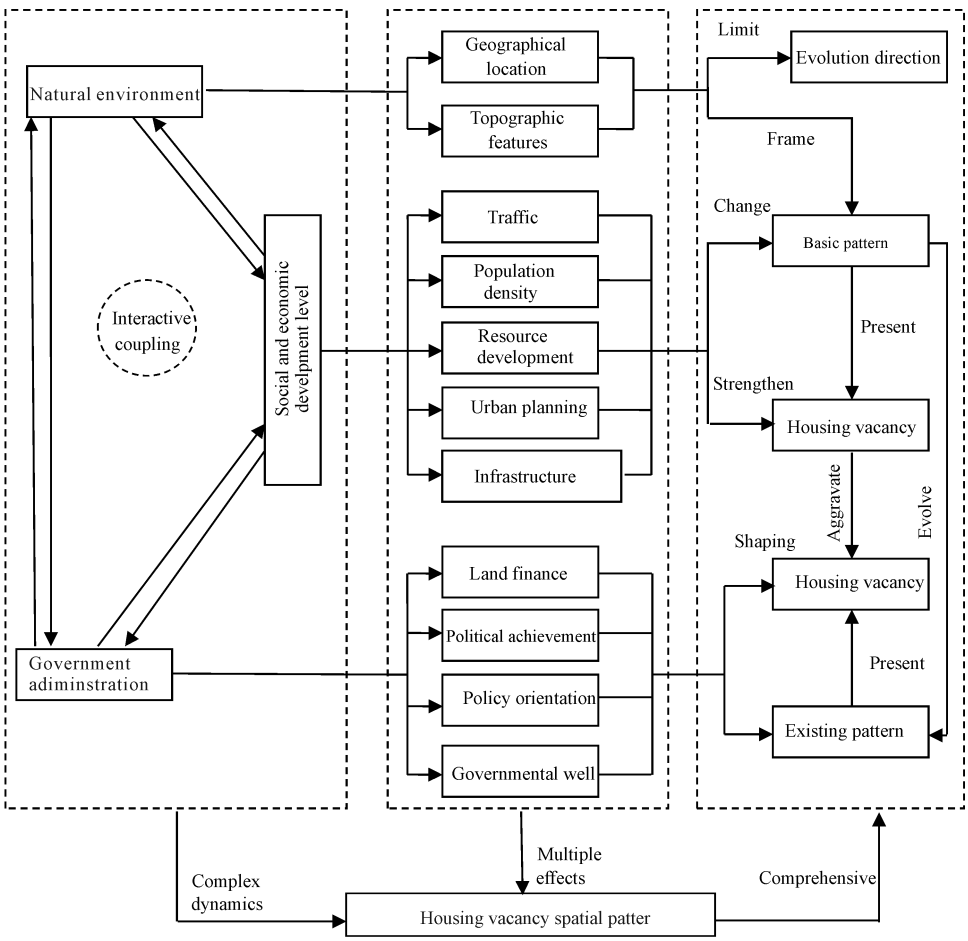

Fig. 7 Impact mechanism of the spatial evolution of housing vacancy in China

of the government (Hoekstra and Vakili-Zad, 2011; Sorace and Hurst, 2016). Specifically, within the limits of the natural environment such as geographical location, topography, and climate, as well as regional differences, there are prominent differences in the spatial structure of different cities, which shape the basic pattern of urban development and limit the evolution of urban space. The imbalance of urban spatial layout is strengthened due to the impact of socio-economic development factors such as traffic location, population density, and infrastructure services, as well as the impact of resource development and natural environmental factors on urban planning and layout (Zhang et al., 2016). Local governments pursuing good performance appraisals are often influenced by GDP, investment, and investment attractiveness in decision-making, making local governments over-reliant on land finance and inclined to pursue large projects with large investments (Newman et al., 2019). This has inevitably resulted in redundant construction. In this process, an extreme phenomenon of investment-driven economic growth can occur, the so-called vacant town ('ghost city') phenomenon, which is also the root cause of housing vacancy (Wu, 2016).

The policy insights presented in this paper are the following: 1) At the government level, to reduce the HVR, first, the traditional performance evaluation model should be changed so that GDP is no longer the main standard used to assess officials' performance, which would in turn change the economic development model of local governments relying on land finance. Second, efforts shall be made to adjust and deepen the tax distribution model between the central and local governments; as 'tax-division system' reform is carried out, due to the ambiguous and mismatched division of financial and administrative power between the central government and local governments, the management of land transfer fees is often 'unclearly' dealt with by local governments. Third, it will be necessary to develop a nationwide real estate information system, improve the real estate management system, make information about the real estate industry more open and transparent, and strictly regulate speculative behavior. Last but not least, policies on macro-control of real estate should be further improved to make real estate management policy more scientific and rational.

As for urban development, many tough contradictions are encountered in the process of urban development that are difficult to resolve only by means of laws and regulations because they are influenced by city planning concepts and values. The construction of new towns and districts is an important part of urbanization, but it should meet actual urban needs and be designed from a national perspective. Due to the obvious geographical differences in China, the 'one size fits all' approach to urbanization, with blind adherence to formulas and precedents, should be avoided, but instead the actual needs of urban development should be met to promote an orderly progression of urbanization and new urban construction, thus preventing the occurrence of vacant housing.

For real-estate developers, as a special commodity, commercial housing is a permanent and unmovable bulk commodity. Real estate developers should scientifically and reasonably assess market demand and accurately calibrate the grade and scale of construction investment based on local consumption level so as to improve the efficiency of land use. As for illegal developers who are purposefully holding onto housing and even hyping up housing prices, taxes on vacant housing and real estate should be required in pilot areas to curb speculation and bring housing prices to market level.

Until now, there has been no universally accepted definition of housing vacancy, either from government policy formulation and implementation, or from the real estate industry and academia. What can be expected is that, as China's real estate market develops, new housing on the market will inevitably transition to the existing housing stock, and therefore the calculation of HVR should also fall into line with international standards for the entire housing stock, including all newly built housing (Yao and Li, 2011). As the 'most complex commodity', the complexity of China's urban housing market is beyond imagination. Data on real HVR could not be obtained due to inconsistent understanding, a complex housing market, and lack of organization of vacancy rate calculations. This paper explores a macroscopic situation at the national level; with the promotion of supply-side structural reforms in China's real estate industry and the in-depth development of new urban areas, the existing residential housing stock will inevitably become the main body of the real estate market and fall into line with international standards; calculating HVR should thus gradually become the mainstream.

5 Conclusions

An important indicator to measure the healthy development of the real estate market is vacant housing. Using NPP-VIIRS nighttime remote-sensing images, the spatial differentiation pattern of vacant urban space in China's cities at prefecture level and above can be quickly and effectively reflected. The intuitive spatial visualization effect is more effective than statistical data because it compensates for the shortcomings of traditional statistical methods such as data loss and inconsistent numerical scales. It is expected to become a new spatial detection method for monitoring housing vacancies. The evaluation results can be used for informing local decision makers to deliver necessary policies. The national wide study also enables the understanding of regional variation conditions.

Analysis has shown that vacant housing is rare in certain eastern coastal cities and regions in China with relatively fast economic development. Cities based on exhausted resources, some mountainous cities, and cities with relatively backward economic development more typically showed high levels of housing vacancy. From a national perspective, the city with the highest GCI was Shaoyang, whereas the lowest was Xiamen. Prefecture-level administrative units with high GCI accounted for 16% of the total, whereas low-index units accounted for 9%. As for the north-south distribution, the GCI of prefecture-level administrative units gradually declined from north to south, i.e., north > middle > south, whereas the east-west distribution showed a parabolic shape, i.e., middle > west > east. In 2013, the global Moran's I value of the GCI of China's prefecture-level administrative units was 0.454, indicating an overall autocorrelation of China's prefecture-level ghost city index. As city level decreased (Tiers 1–5), the GCI registered a gradual upward trend, with the index spatial distribution range changing from discrete to concentrated. China's urban housing vacancy can be divided into five categories: industry (resource)-driven housing vacancy, government-planning housing vacancy, expansion-based housing vacancy, environmentally constrained housing vacancy, and speculative stimulation housing vacancy.

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