Science of the Total Environment 949 (2024) 174909

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Thirty years of 3-D urbanization in the Yangtze River Delta, China

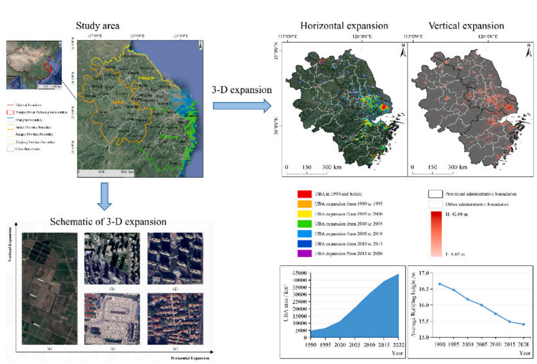
Chenglong Yin[a,b], Ruishan Chen[a,c,*,**], Xiangming Xiao[b,***], Tim Van de Voorde[d], Yuanwei Qin[b], Xiaona Guo[c], Fei Meng[e], Li Pan[b], Yuan Yao[b], Yinshuai Li[c]

[a] School of Geographic Sciences, East China Normal University, Shanghai 200241, China
[b] School of Biological Sciences, Center for Earth Observation and Modeling, University of Oklahoma, Norman, OK 73019, USA
[c] School of Design, Shanghai Jiao Tong University, Shanghai 200240, China
[d] Department of Geography, Ghent University, Ghent 9000, Belgium
[e] School of Surveying and Geo-Informatics, Shandong Jianzhu University, Jinan 250101, China

HIGHLIGHTS

- This study analyzed the 3-D urban expansion process in the YRD of China.
- Promoted the efficient development and sustainable utilization of urban land resources
- The average building height of the YRD and most cities showed a downward trend.
- There was significant unevenness in urban expansion across the YRD.
- This study typically represented China's 3-D urban development process.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Yuyu Zhou

Keywords:
3-D urban expansion
Yangtze River Delta
Couple analysis
Dominant type
Sustainable development
Urban land resources

ABSTRACT

Accurately capturing the urbanization process is essential for planning sustainable cities and realizing the United Nations Sustainable Development Goal 11. However, until recently, most of the studies on urban expansion in the world have focused on area growth but have little knowledge of height dynamics. This study mapped the spatial distribution of urban built-up areas (UBA) in the Yangtze River Delta (YRD), one of the most urbanized regions in China, to investigate the spatio-temporal evolution in both the horizontal and vertical directions from 1990 to 2020. We coupled and analyzed the horizontal and vertical urban expansion from the 3-D perspective and identified the dominant types. The results showed that 30 cities (73.17 % of the total number of cities) were increasing in the 3-D combined expansion intensity. The decreasing cities were mainly located in Anhui Province. Despite the increasing number of skyscrapers, horizontal growth has dominated urban expansion over the past three decades. The UBA area of the YRD has grown from 4,855.30 km^2 to 44,447.15 km^2, while the average building height has slowly decreased by 1.26 m. Significant unevenness and differences existed in horizontal and vertical expansions of varying provinces and cities. Our study can accurately grasp the 3-D urban expansion

* Correspondence to: R. Chen, School of Geographic Sciences, East China Normal University, Shanghai 200241, China.
** Correspondence to: R. Chen, School of Design, Shanghai Jiao Tong University, Shanghai 200240, China.
*** Corresponding author.
E-mail addresses: yinchenglong95@163.com (C. Yin), chenrsh04@gmail.com (R. Chen), xiangming.xiao@ou.edu (X. Xiao).

https://doi.org/10.1016/j.scitotenv.2024.174909
Received 11 March 2024; Received in revised form 15 July 2024; Accepted 18 July 2024
Available online 25 July 2024

process in the YRD and could promote the efficient development and sustainable utilization of urban land resources in China and beyond.

1. Introduction

Urban areas are home to 55 % of the world's population and are expected to grow to 68 % by 2050 (UN, 2022). The 21st century has witnessed rapid urbanization in developing countries, especially China, which increased the urbanization rate from 36.09 % to 63.89 % (Statistics, 2021b). The Yangtze River Delta (YRD) is a region that has experienced rapid development and is representative of China's future urban development pattern (Wang et al., 2023a; Yu and Zhou, 2017). The urbanization process can offer both significant employment opportunities and better public services to societies, but it also leads to global problems such as air pollution, resource depletion, loss of biodiversity and carbon stocks (Güneralp et al., 2017; He et al., 2023; Li et al., 2020b; Seto et al., 2012; Sun et al., 2016; Xiao et al., 2022). Accurately capturing the urban development process is essential for realizing the United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities).

As one of the essential parts of urbanization, urban expansion can explore the characteristics of urban development and reveal existing problems in the urbanization process (Yin et al., 2022). Much existing research has focused on studying the 2-D horizontal expansion across global, national, basin, city cluster, and city scales. (Barrington-Leigh and Millard-Ball, 2015; Gong et al., 2018; Gong et al., 2019; Guan et al., 2020; He et al., 2019a; Huang et al., 2019; Ren et al., 2022; Wu et al., 2021b; Xu et al., 2020; Yin et al., 2024; Zhong et al., 2019). Although scholars have invested a great effort in quantifying the spatial patterns, drivers, and ecological impacts of horizontal urban expansion, few studies exist on 3-D vertical expansion. In China, due to the scarcity of land resources and the acceleration of urbanization, the traditional model of urban expansion is no longer able to accommodate the increasing social activities effectively, and many cities are undergoing large-scale high-rise building construction (Al-Kodmany, 2018), which has evolved into complex horizontal and vertical structures. The rational utilization of urban 3-D space has proven to be an effective solution to increase urban space capacity, relieve land use pressure, and improve the efficiency of space utilization within cities (Rao et al., 2020; Zhao et al., 2022). Studying the changes in 3-D urban expansion is crucial for future urban science planning. Many biophysical and socio-economic processes are shaped by urban areas' vertical structure and form (Grafius et al., 2018). Urban 3-D structures also have climate impacts, such as changes in the urban thermal environment and wind fields (Chen et al., 2022; Tominaga and Shirzadi, 2021). Significant differences in vertical urban structure may exist between cities with similar 2-D morphology (Frolking et al., 2013). If the focus relies solely on horizontal expansion, much valuable information will be ignored in the long run, which is detrimental to the research of urban expansion. A better understanding of urbanization can be gained only by combining horizontal urban expansion with vertical building dynamics. Considering the urban 3-D form, particularly its vertical dimension, will bring new insights into projecting future emissions under urbanization and climate change (Zhu et al., 2019).

Significant progress has been made in estimating building height using data sources, such as Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LiDAR), and some datasets were publicly released (Frantz et al., 2021; Li et al., 2022; Li et al., 2020a; Ma et al., 2023). Several scholars have investigated urban vertical expansion using the above data or some other sources (Handayani et al., 2018; Qiao et al., 2019; Rao et al., 2020; Wang et al., 2022a; Yang and Zhao, 2022a; Zambon et al., 2019). However, detailed studies on urban vertical expansion's spatial and temporal dynamics are still lacking. Understanding the coupled dynamic characteristics and laws of horizontal and vertical urban expansion from a 3-D perspective is still limited. Determining the dominant type (horizontal vs. vertical) and magnitude of urban expansion is insufficient, especially given the lack of long time series analysis for many regions and cities worldwide.

The literature on global-scale land use after the 21st century mainly focused on the processes, characteristics, patterns, drivers, climate impacts and land use efficiency of land use change (Chakraborty et al., 2022; Foley et al., 2005; Seto and Shepherd, 2009; Wu et al., 2021a; Zheng et al., 2021). Land use research in China was closely related to global research priorities. Studies of urban land use change in China that were written in the first fifteen years since the 21st century have focused on the process, spatio-temporal pattern, and driving factors. The studies combined remote sensing techniques with landscape ecological and socio-economic indicators, and explored the rationale for land reform policies (Deng et al., 2010; Ding, 2003; Seto and Fragkias, 2005; Seto and Kaufmann, 2003; Wu and Zhang, 2012; Yin et al., 2011; Zhang et al., 2010). In rapidly urbanizing areas, this was often accompanied by a significant increase in construction land and a decrease in cropland (Han et al., 2009; Xiao et al., 2006). Studies published after 2015 began to focus extensively on assessing urban land use efficiency and analyzing the driving factors (Chen et al., 2016; Jiao et al., 2020; Song et al., 2022; Yu et al., 2019). In the YRD region, studies have found that regional economic integration policies have significantly improved urban land use efficiency (Pan et al., 2022; Zhao et al., 2021). Economic transformation, spatial development, population change, and the concept of green development are closely related to land use efficiency (Tang et al., 2021; Wu et al., 2017; Yang et al., 2023). Urban land use efficiency in the YRD city cluster shifted from dominated by inefficiency to polarization, with more at both levels and less in the middle from 2003 to 2017 (Tang et al., 2021).

The YRD is one of the six world-class city agglomerations with strong international influence (Fang, 2011). This study plans to address the identified gaps and deficiencies by investigating the 3-D expansion of the YRD from 1990 to 2020 and provide a basis for determining whether urban development has taken place in a sustainable 3-D way with efficient use of land resources. The research objectives are to identify the relative roles of the horizontal area and vertical height expansion, quantify the change of the relative roles time, and explore the reasons responsible for the dynamics. We also want to determine the dominant type (horizontal vs. vertical) of urban expansion under the long time series in the YRD, and provide methodological references and technical framework for related studies in other countries and regions worldwide. The research has two primary steps. Firstly, to gather accurate, spatially detailed data on the horizontal and vertical expansion of the YRD over this period, and to analyze for the dynamic changes at pixel, city, province, and region scales, respectively. Secondly, a coupled analysis of these expansions from a 3-D perspective will be conducted, and the predominant urban expansion patterns across different timeframes will be identified. The research methods and analytical ideas used in this study apply to many typical areas of the world. In particular, developing countries will occupy a dominant position in the future urbanization process of the world.

2. Materials and methods

2.1. Study area

The YRD is a vast alluvial plain formed by the Yangtze River before it enters the sea. Situated in the lower reaches of the Yangtze River Basin, it is bordered by the Yellow Sea and the East China Sea, notable for its numerous ports. According to the results of the Seventh National

Population Census, by the end of 2020, the resident population of the YRD had reached 235.21 million (Statistics, 2021b). In 2020, the GDP of the YRD reached RMB 24.47 trillion, and the urban population percentage exceeded 60 % (Statistics, 2021a). With less than 4 % of the total national land area (358,000 km^2), the YRD has created nearly one-quarter of the country's total economic output and one-third of its total imports and exports (China, 2019).

This study encompasses four provincial administrative districts (Jiangsu, Zhejiang, Anhui, and Shanghai) within China, consisting of 41 cities (Fig. 1), providing a unique setting for examining urban development. Unlike previous statistical surveys that considered only municipal districts, this study also considered the counties and county-level cities under the jurisdiction of municipalities.

2.2. Data sources and preprocessing

2.2.1. Impervious surface area distribution data

The global 30 m impervious surface area (ISA) dynamic dataset was produced by the Chinese Academy of Sciences (https://essd.copernicus.org/articles/14/1831/2022/) based on Landsat satellite images and by using the Google Earth Engine cloud-computing platform, with an overall accuracy of 90.1 % (Zhang et al., 2022). We downloaded the ISA distribution data from 1990 to 2020 with 5-year intervals and preprocessed it by performing mosaicing, masking, and extraction operations to align it with our study area and timeframe.

2.2.2. Urban building height data

Urban building height data in the YRD in 2020 were obtained from Fudan University (https://zenodo.org/records/7923866). This dataset is the first 10 m resolution building height dataset available in China (Wu et al., 2023) and provides data support for a refined analysis of 3-D urban expansion. We used Geographic Information Science (GIS) technology to spatially aggregate this dataset to 30 m resolution and captured the pixels boundaries to the ISA pixels boundaries. This dataset was also preprocessed by mosaicing and masking to align it with our study area.

2.3. Methods

The methods of this study mainly include 3-D urban expansion extraction and analysis, as well as coupled analysis of horizontal and vertical expansion. Fig. 2 shows a schematic illustration of the city's horizontal expansion pattern compared to the vertical dynamics pattern.

2.3.1. 3-D urban extraction method

Urban built-up areas (UBA) are considered sections within the city's administrative district that are developed and equipped mainly with public facilities (Yin et al., 2020). This study used the object-based impervious surface aggregation density (ISAD) method to extract UBA (Yin et al., 2021). The ISAD of a pixel describes the degree of aggregation and distribution density of ISA within a certain radius centered on the given pixel (Meng et al., 2018). Distance is used as a weight, with the closer to the center point the greater the weight. The formula for calculating ISAD is as follows:

$$\mathrm{Density}_s(r) = \frac{\sum_{i=1}^{n} B_{si} \bullet \left(1 - \frac{D_i}{2r}\right)}{\sum_{i=1}^{n} \left(1 - \frac{D_i}{2r}\right)} \tag{1}$$

where s represents the focal pixel for the calculation, r represents the radius selected to calculate the aggregation density, B_{si} represents the pixels (0 or 1) within the range defined by the selected radius, and D_i represents the distance between pixels B_{si} and s.

The ISA distribution data in the YRD from 1990 to 2020 was input to calculate the ISAD. According to the latest urban planning standards in China, a residential area with comprehensive supporting facilities has a minimum population of 50,000 people (Design, 2018). Based on the data from the National Bureau of Statistics of China, the per capita living area of Chinese cities and towns in 2020 was 36.52 m^2. Using these statistics, the minimum patch area selected for UBA extraction should be 1.83 km^2. Following the classification of ISAD, zones categorized as the high, medium-high, and medium-density zones of the ISAD classification were used as input objects. Subsequently, patches exceeding 1.83

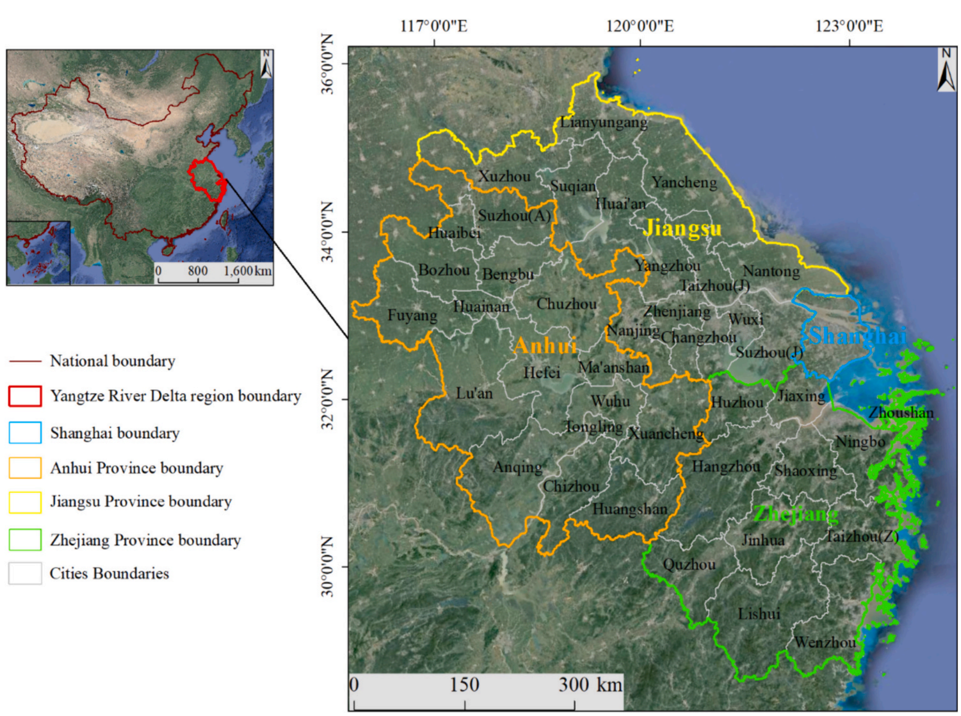


Fig. 1. Geographic location and administrative division of the YRD. Two groups of cities have the same name, distinguished by the initials of the province in which they are located. They are Suzhou (J), Suzhou (A), Taizhou (J), and Taizhou (Z).

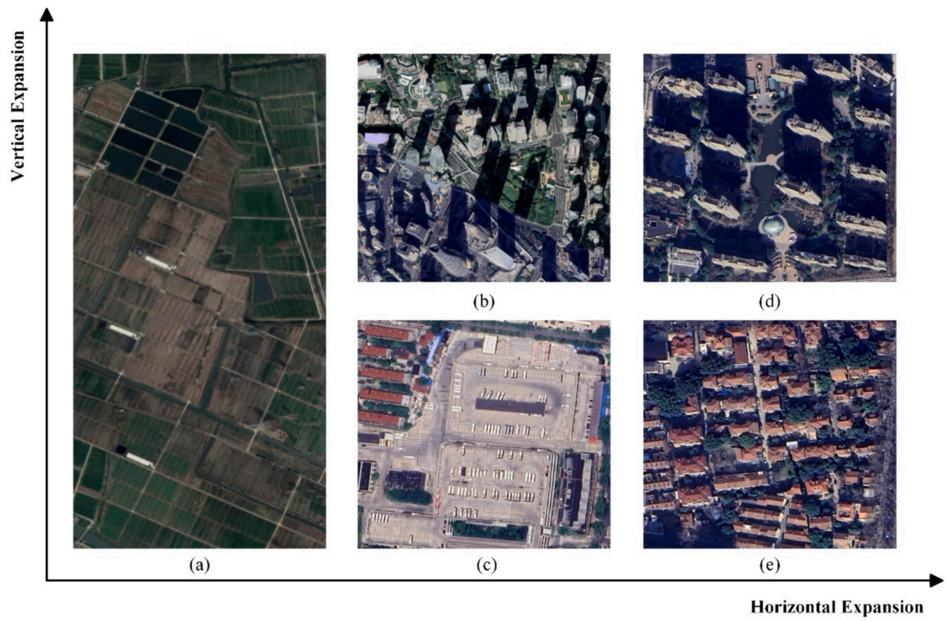


Fig. 2. Schematic illustration of the urban horizontal expansion pattern vs the vertical expansion pattern. (a) shows the non-built-up area; (b) and (c) indicate the vertical and horizontal expansion patterns for industrial-business land use; (d) and (e) show the vertical and horizontal expansion patterns for residential land use, respectively.

km^2 were delineated as UBA. Since the UBA comprises ISA and includes green areas and water bodies suitable for residents' living, the green areas and water bodies surrounded by the UBA were also extracted.

Due to the limitations of available satellite images, measuring building heights prior to 2010 directly by remote sensing is difficult. The extracted ISA distribution data from 1990 to 2020 was combined with the 2020 urban building height data to obtain the changes in building heights over the above period. The time change of ISA pixels was used to determine the time corresponding to each building height pixel. This indirect method allows for measuring long time series of large-scale building height changes. Fig. 3 shows the technical flowchart for 3-D urban expansion extraction in this study.

2.3.2. Research methods for the characterization of urban horizontal and vertical expansion

GIS spatial analysis methods and incremental urban area (Yin et al., 2022) were used to analyze the urban horizontal spatial evolution of the study area from 1990 to 2020. The characterization of urban vertical expansion was quantitatively calculated by average building height, total building volume, fluctuation degree index (FDI), and building spatial congestion degree index (BSCDI) (He et al., 2019b; Li et al., 2023), and will demonstrate the characteristics of urban vertical expansion in the YRD from 1990 to 2020. Among them, average building height and total building volume were used to characterize the base form of urban buildings. FDI was used to describe the flatness of buildings in the study area, with larger values representing more discrete building heights in the study area. BSCDI was used to characterize the density of buildings in the study area, with larger values representing more crowded buildings. The formulas for calculating the FDI and BSCDI are as follows:

$$\mathrm{FDI} = \frac{\sqrt{\sum_{i=1}^{n}\left(\mathrm{H_i} - \mathrm{H_{mean}}\right)^2 / \mathrm{n}}}{\mathrm{H_{mean}}} \quad (2)$$

$$\mathrm{BSCDI} = \mathrm{V}/(\mathrm{H_{max}} \times \mathrm{TA}) \quad (3)$$

$$\mathrm{V} = \mathrm{AUBA} \times \mathrm{H_{mean}} \quad (4)$$

where H_{mean} represents the mean building height, H_{max} represents the maximum building height, V represents the total volume of the building, TA represents the total area of the study area, and AUBA represents the area of the urban built-up areas.

2.3.3. Coupled analysis of horizontal and vertical expansion and determination of the dominant type

Total building volume is the most direct and simple coupling of horizontal and vertical expansion and can help assess land and space utilization efficiency in the study area. It is calculated as formula (4). The built-up land intensity index (BLII) is the physical condition of built-up land, consisting of the horizontal layout and vertical height (Ruan et al., 2022). In this study, we improved this index to the urban built-up areas intensity index (UBAII) by changing one of the input parameters from the ISA area to the UBA area. The UBAII can be used for the coupled urban horizontal and vertical expansion analysis. The formula for calculating the UBAII is as follows:

$$\mathrm{UBAII} = 1/2 \times \mathrm{UBAI} + 1/2 \times \mathrm{UBHI} \quad (5)$$

$$\mathrm{UBAI} = \mathrm{AUBA}/\mathrm{TA} \quad (6)$$

$$\mathrm{UBHI} = \mathrm{H_{mean}}/\mathrm{H_{max}} \quad (7)$$

where UBAI represents the urban built-up areas index, and UBHI represents the urban built-up areas height index.

The vertical-to-horizontal growth index (VHGI) was used to determine the dominant type of urban expansion over time (Zambon et al., 2019). In the original definition of the VHGI, the dominant type was determined by directly calculating the total count of buildings above or below a specific height benchmark (3 floors in Greece). This definition shows some shortcomings. For instance, it ignores the impact of new super-tall buildings on the city's height. These buildings, although fewer in number, exceed the heights and volumes of other conventional types of buildings by a wide margin. There would be a risk of underestimating the characteristics of urban expansion at the vertical scale if the number of buildings is used to quantify them. To address this issue, this study used the revised vertical-to-horizontal growth index (RVHGI) (Li et al., 2023) to determine the dominant type of urban expansion accurately.

According to the national standards for buildings in China, an upper limit of 27 m (9 floors) for medium-rise buildings was selected as the

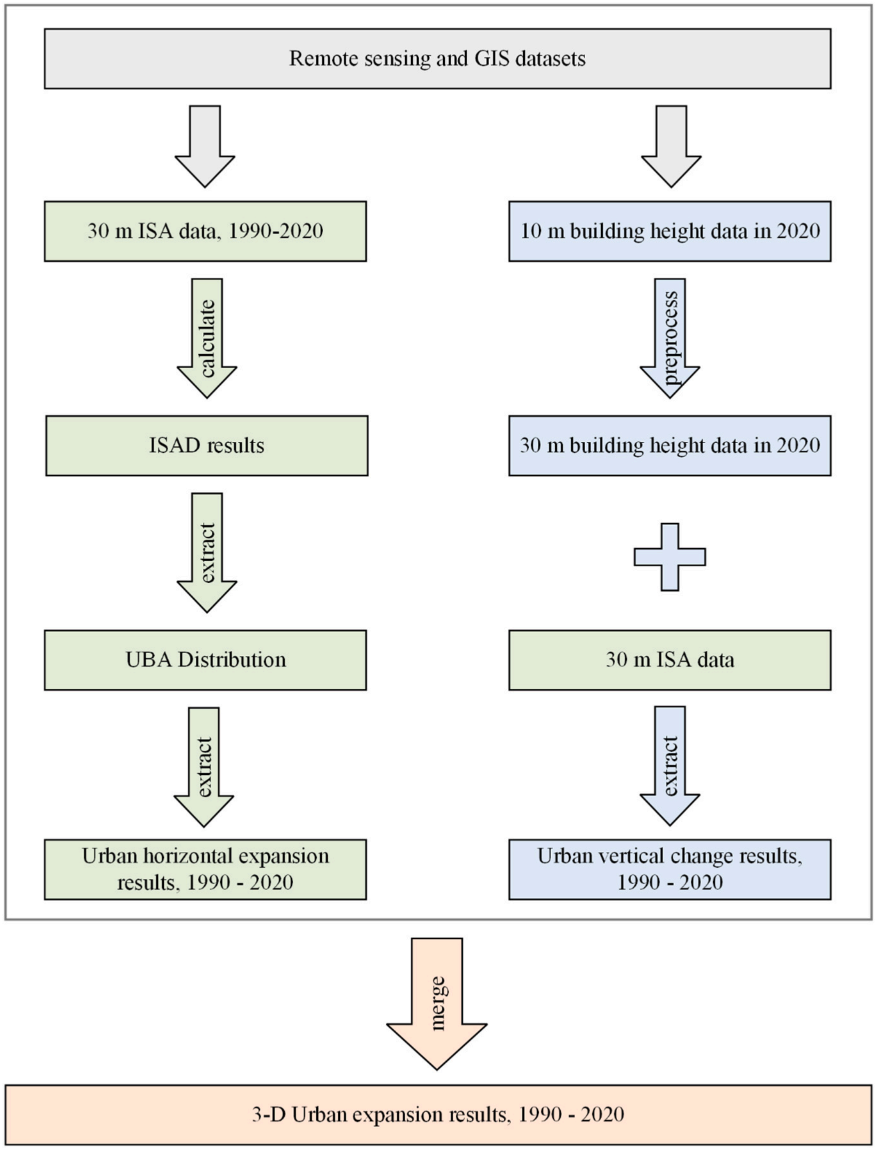


Fig. 3. Technical flowchart for 3-D urban extraction.

height benchmark. If a new building of less than 27 m were added, the expansion type of the site would be judged as horizontal expansion, and vice versa as vertical expansion. The formula for calculating the RVHGI is as follows:

$$RVHGI = V_{t+1}^{H\geq b} / V_{t+1}^{H<b} - V_{t}^{H\geq b} / V_{t}^{H<b} \quad (8)$$

where H represents the building height, b represents the height benchmark, and t represents the time. The positive value of RVHGI means that the trend of urban vertical expansion was more evident than the horizontal expansion in this period, and the magnitude of the value was positively proportional to the dominant position. The negative value of RVHGI means that the trend of urban horizontal expansion was more evident than the vertical expansion in this period, and the magnitude of the value was inversely proportional to the dominant position. The value of 0 means that both horizontal and vertical expansions had the same trend.

3. Results

3.1. Multiple spatio-temporal scales of urban horizontal and vertical expansion

3.1.1. Pixel and the YRD region scales

Fig. 4 shows the changes in UBA area and building heights in the YRD and pixel scales from 1990 to 2020. The urban boundary dataset created for the period 1990–2020 for the YRD aptly captures the comprehensive profile and intricate details of the UBA within these 41 cities (Fig. 4a). Each city's expansion trajectory exhibits unique characteristics, leading to diverse UBA distributions. At the regional scale, the UBA area increased rapidly from 4,855.30 km^2 in 1990 to 44,447.15 km^2 in 2020, with an average annual growth rate of 1,319.73 km^2 (Fig. 4c). We started with the most intuitive change in urban average heights to measure the results of vertical expansion. In contrast, the average building height at the YRD regional scale has shown a slow downward trend, dropping by 1.26 m over the past 30 years (Fig. 4d).

3.1.2. City and provincial administrative unit scales

Fig. 5 illustrates the changes in the UBA area for 41 cities and four

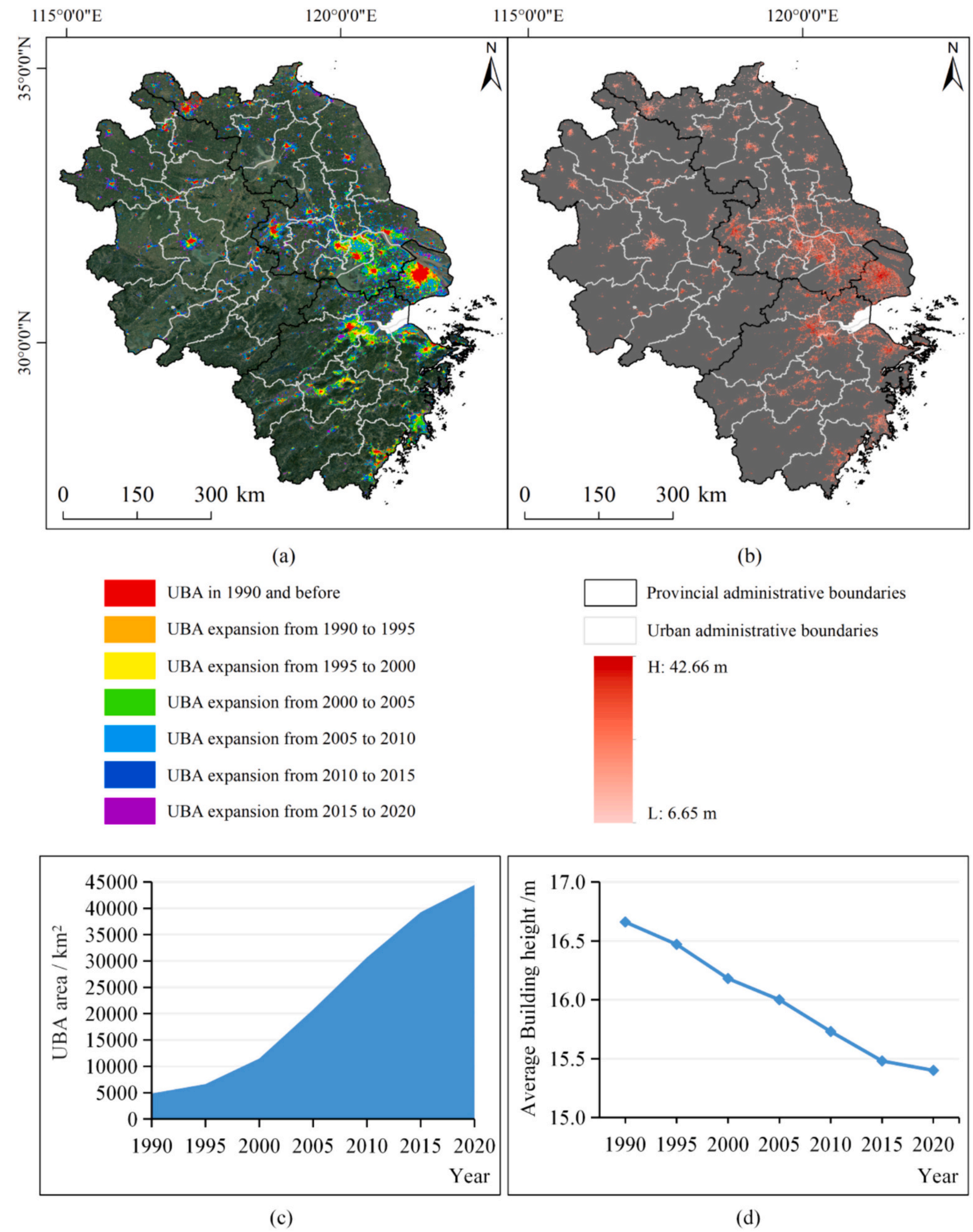


Fig. 4. Changes in UBA area and average building heights in the YRD and pixel scales from 1990 to 2020. (a) shows the spatio-temporal dynamics of the UBA across the YRD; (b) shows the 2020 urban building height data; (c) and (d) show the changes in UBA area and average building height in the YRD from 1990 to 2020, respectively.

provincial administrative units within the YRD from 1990 to 2020. On the city scale, the largest UBA within the study area is Shanghai, with an area of 4,382.64 km^2. The city that followed closely behind is Suzhou (J) in Jiangsu Province, geographically located near Shanghai, with an area of 3,950.83 km^2. In addition to Shanghai and Suzhou (J), the cities with UBA area over 2,000 km^2 include Wuxi (2,219.14 km^2) and Nantong (2,239.56 km^2) in Jiangsu Province, and Hangzhou (2,490.17 km^2) and Ningbo (2,539.88 km^2) in Zhejiang Province. There were 23 cities with a UBA area of less than 1,000 km^2. Among them, Jiangsu and Zhejiang Province had four cities each, while the remaining 15 cities were located in Anhui Province. The cities with the smallest UBA area were Tongling and Chizhou in Anhui Province, with 103.60 km^2 and 108.52 km^2, respectively. While among the four provincial administrative units, the area of Jiangsu and Zhejiang is much larger than that of Anhui and Shanghai.

Fig. 6 and S1 show the average building heights changed from 1990 to 2020 for the 41 cities and the four provincial administrative units. Overall, the average building heights of the entire YRD and the four provincial administrative units under its jurisdiction have shown a slow downward trend over the past three decades. Among them, Shanghai had the fastest decline, from 20.17 m in 1990 to 18.07 m in 2020, but was always the unit with the highest average building height among the four provincial administrative regions. The average heights in Shanghai and Zhejiang were consistently higher than the average for the whole YRD during the same period, while Jiangsu and Anhui were consistently lower than the average for the entire region. Among the 41 cities, except for Bozhou and Huainan, which showed an overall upward trend, all other cities showed a downward trend. Shanghai is always the highest city, and Lianyungang is always the lowest.

To quantitatively analyze the degree of discrete building heights and

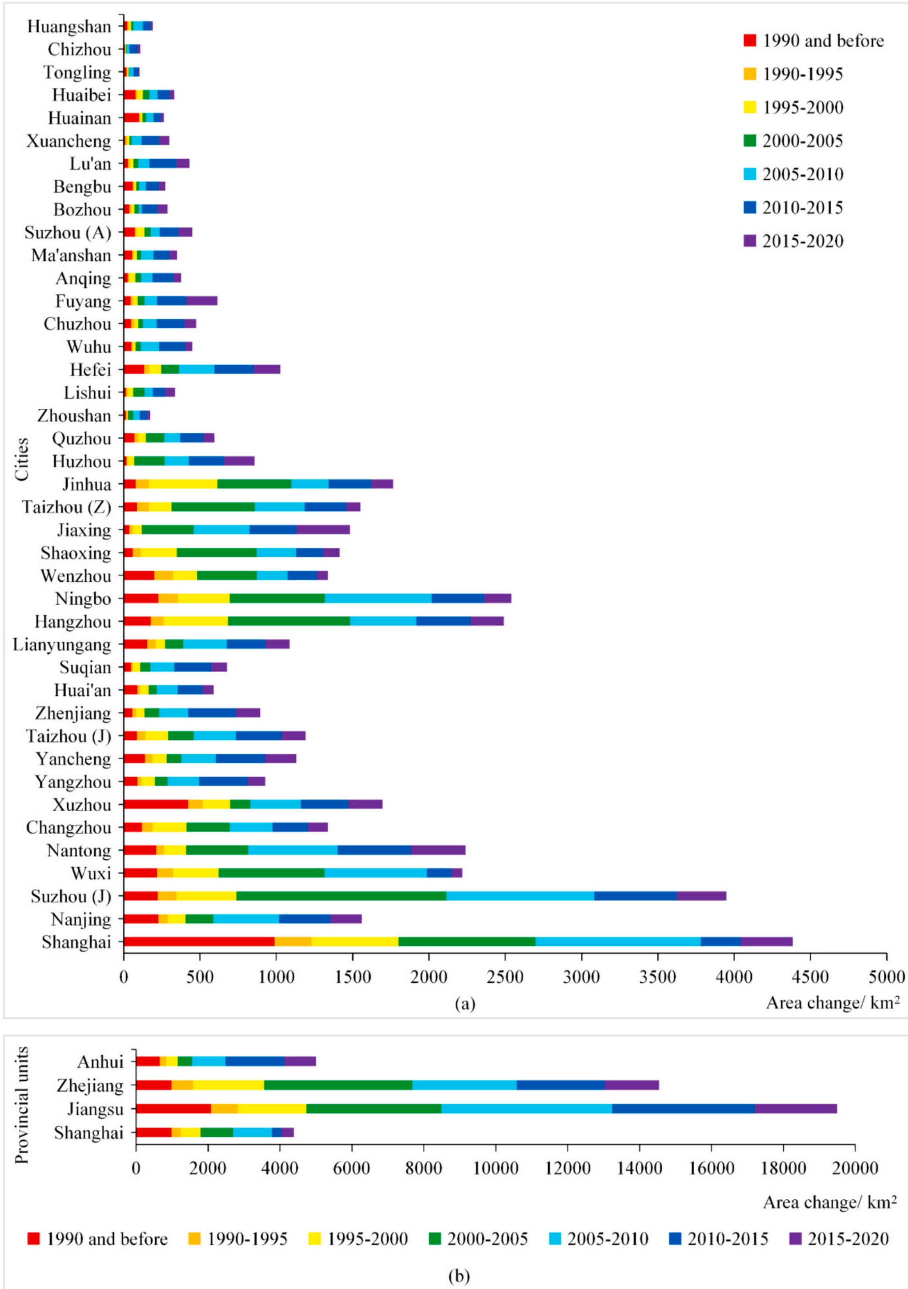


Fig. 5. Change in the UBA area of 41 cities (a) and four provincial administrative units (b) in the YRD from 1990 to 2020. The horizontal axis denotes the area increment, and the vertical axis lists the names of the city or provincial administrative units.

the degree of congestion of urban buildings in the YRD, FDI and BSCDI indicators were calculated further, and the results are shown in Fig. 7 and S2–S3.

Overall, building heights in the YRD have shown an increasingly aggregated trend over the past 30 years, with a decreasing degree of fluctuation (Fig. 7a). Only Shanghai and Anhui remained almost unchanged among the four provincial administrative units, while the building heights in Jiangsu and Zhejiang became increasingly aggregated. Moreover, the building heights of Shanghai and Zhejiang were always more aggregated than the average level of the YRD during the same period, while Jiangsu and Anhui were always more discrete. Regarding building congestion (Fig. 7b), both the whole YRD and the four provincial administrative units showed upward trends, with Shanghai being the most congested, while Anhui was consistently lower than the average level of the whole YRD. While 24 out of all 41 cities in the YRD have become increasingly aggregated in building heights, the rest have become increasingly discrete. Building congestion has increased in all cities, with the most significant increase in Shanghai, Suzhou (J), Wuxi, Changzhou, and Jiaxing.

Based on the above results, the section Discussion of this paper is introduced to analyze further the spatial and temporal characteristics and evolutionary patterns of urban expansion.

3.2. Coupled analysis of horizontal and vertical expansion

Fig. 8(a) and S4 show the growth of total building volume in the YRD from 1990 to 2020. The growth momentum of total building volume in the YRD during the three decades was significant. While among the four provincial units, Jiangsu Province had the largest volume increment and was the provincial unit with the largest total volume in each different

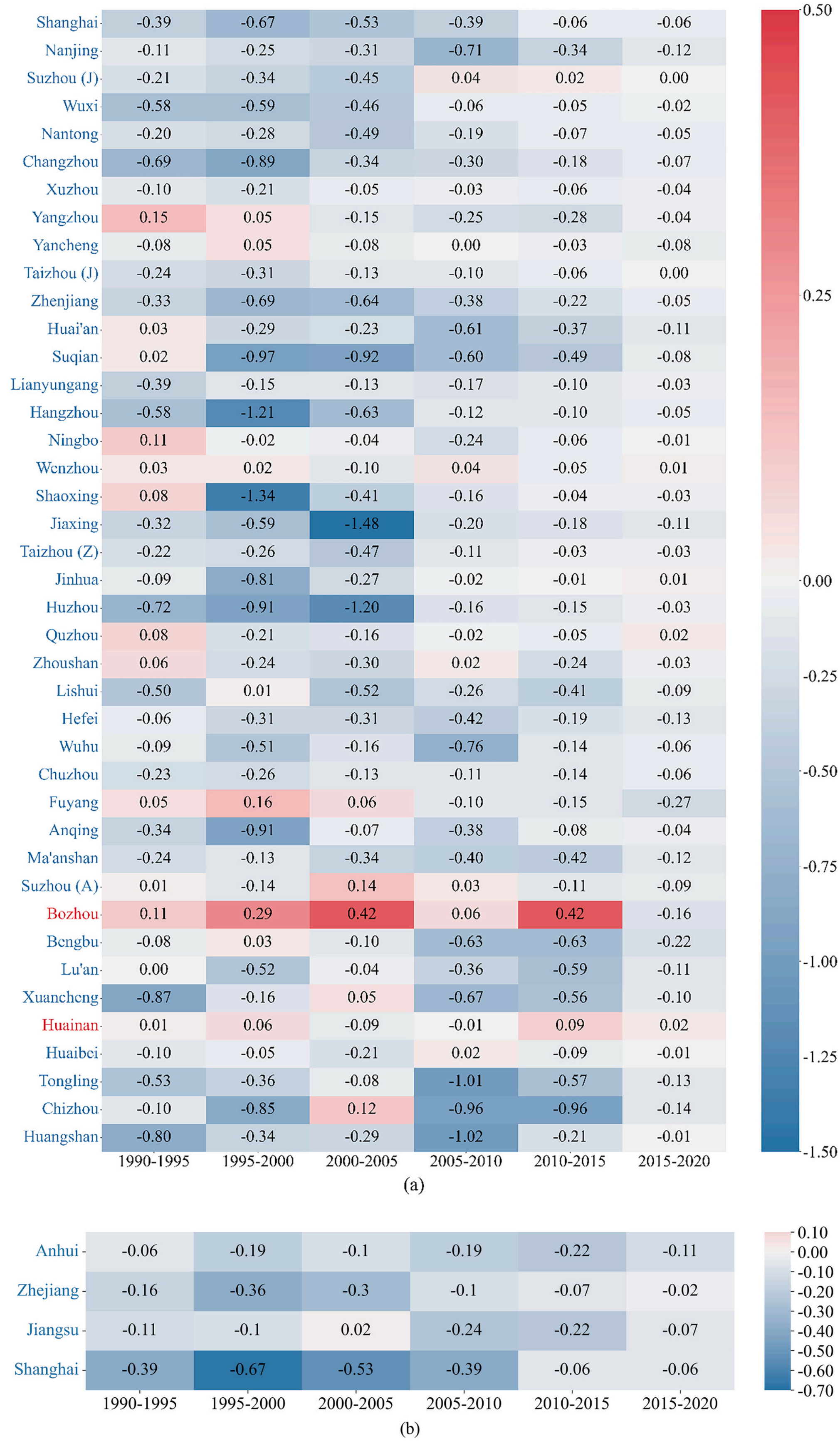


Fig. 6. Change in the average building heights (m) of 41 cities (a) and four provincial administrative units (b) in the YRD from 1990 to 2020. The red square represents an increase in the average height of the province or city in the corresponding period, and the blue square represents a decrease. Similarly, the names of cities and provinces in red represent a positive total change in building heights over the entire period, and blue represents a negative change.

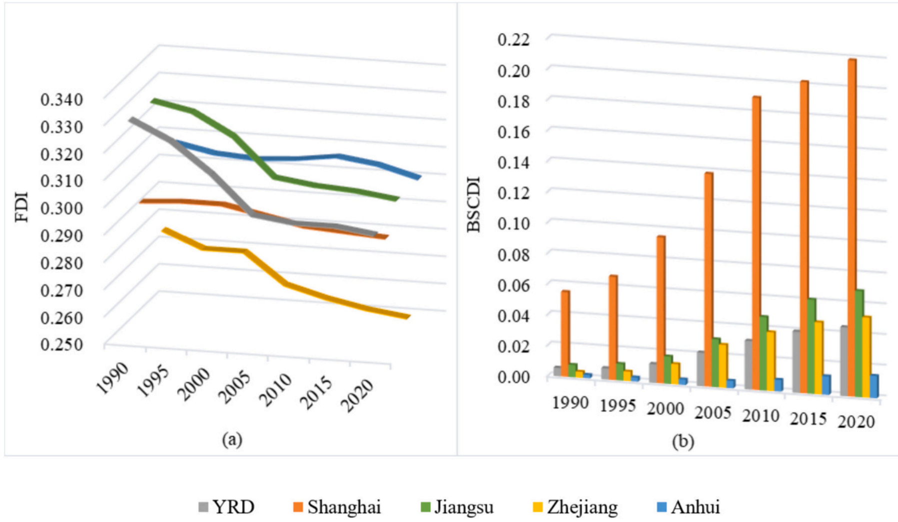


Fig. 7. FDI (a) and BSCDI (b) in the YRD from 1990 to 2020.

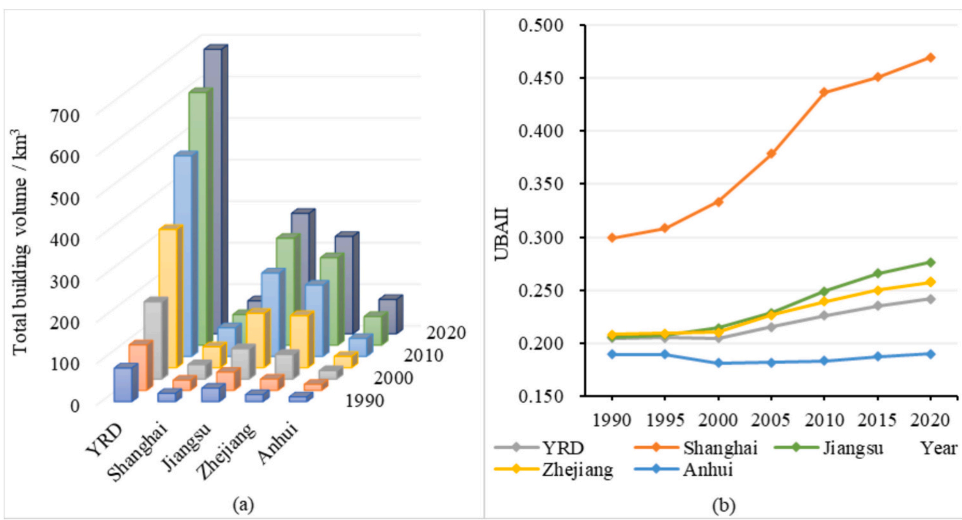


Fig. 8. Total building volume (a) and UBAII (b) in the YRD from 1990 to 2020.

period, Zhejiang Province followed closely, and Anhui Province and Shanghai had little difference. Among the 41 cities in the YRD, Shanghai had the largest volume, followed by Suzhou (J). The smallest cities were Tongling and Chizhou.

Fig. 8(b) and S5 show the comprehensive evaluation results of the urban expansion intensity after coupling the horizontal and vertical dynamics. Overall, the expansion intensity in the YRD showed increasing trends and was higher than the regional average, except for Anhui Province. Shanghai has seen the most significant increase, from 0.299 in 1990 to 0.469 in 2020. With the year 2000 as the turning point, Anhui Province has experienced a "V"-shaped process of change, and the overall change over the past three decades has been flat. While at the city scale, there were 11 cities with decreased expansion intensity. Among them are eight cities in Anhui Province, two in Jiangsu Province, and one in Zhejiang Province. Half of the cities in Anhui Province had declining expansion intensity, leading to results at the provincial scale.

To determine whether the dominant direction of urban expansion in the YRD was horizontal or vertical, we calculated the RVHGI for the region, as shown in Fig. 9 and S6. Overall, the values for the entire YRD and the four provincial administrative units included were negative, representing that urban expansion was primarily horizontal during this period. Only Anhui Province had a value very close to zero between 2000 and 2010, which means that the horizontal and vertical urban expansion trends in Anhui Province were almost the same during this decade. It is important to note that the absolute value of RVHGI has been decreasing in all provinces except Anhui, implying that the dominance of horizontal urban expansion has become less and less significant, and that vertical growth may dominate in the future. Of the 41 cities, 28 experienced more than one period of vertical growth domination. Over the entire period, 22 cities showed a weakening trend in the dominance of horizontal expansion, with the possibility of further strengthening the dominance of vertical expansion over time. These cities will probably shift from rapid horizontal development to a 3-D and efficient use of urban land resources.

4. Discussion

4.1. 3-D urban expansion characterization

4.1.1. Uneven and rapid horizontal development of cities and provinces in the YRD

The studies of urban horizontal expansion are extensive and diverse. In studies on the YRD, for various reasons (factors such as policy, planning, economic and natural environmental differences), not many

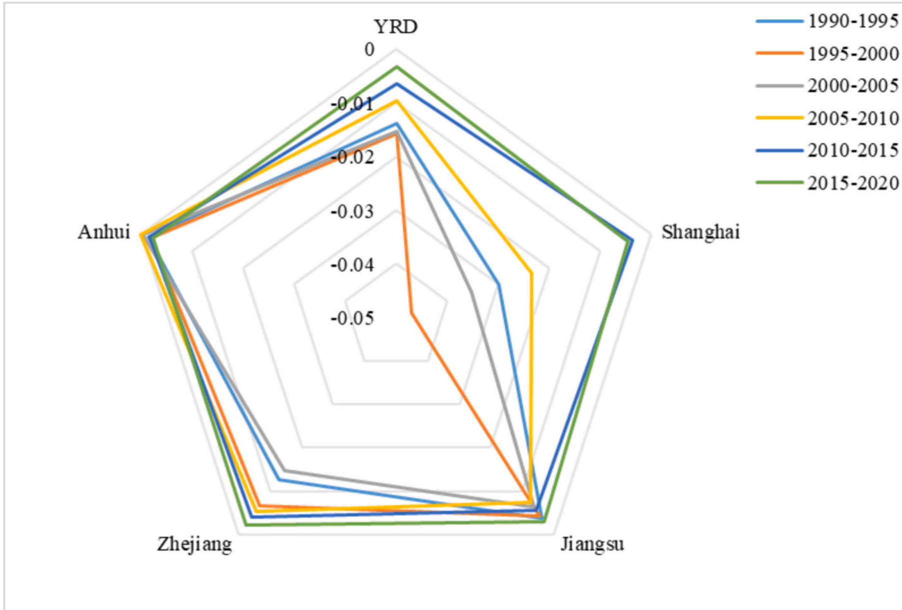


Fig. 9. RVHGI in the YRD from 1990 to 2020.

include all 41 cities in the four provincial administrative units in the study area. Most of the studies that have been done explored the urban agglomerations or typical cities in the region (Fang and Zhao, 2018; Lu et al., 2018; Sun et al., 2020). It is only in the last four years that a handful of articles have taken the entire YRD into account, and concluded that there were spatial imbalances in the distribution of urban expansion patterns in the region (Tian and Mao, 2022; Wang et al., 2023a; Yu et al., 2021). Our study of the YRD's horizontal expansion revealed notable imbalances across its four provincial administrative units and their 41 constituent cities. At the level of provincial administrative units, Jiangsu Province exhibited the largest UBA, a status closely tied to its position as China's second-largest economy by GDP. Zhejiang Province followed suit, with both provinces significantly outpacing Anhui Province and Shanghai City regarding UBA size. However, it is important to consider the unique status of Shanghai as a provincial-level central government municipality, which suggests that direct comparisons with other provinces may not accurately reflect its distinct urban dynamics. In contrast to Jiangsu and Zhejiang Province, Anhui Province, which governs 16 cities, maintained a smaller UBA than Shanghai until 2015. It was only in 2020 that the gap between Anhui's UBA and Shanghai's became more pronounced. At the city level, there were huge differences between the non-provincial capitals and the three provincial capitals. Except for the capital city of Hangzhou in Zhejiang Province, neither the capital cities of Nanjing in Jiangsu Province nor Hefei in Anhui Province had more than 2,000 km^2. The above results highlight the varied expansion dynamics across different levels of administrative units in the YRD.

While Hefei ranked as the foremost city in Anhui Province regarding urban development, Nanjing was only the 5th-ranked city in Jiangsu Province. Jiangsu Province exhibited the most uneven development within the same provincial boundary. This phenomenon was accompanied by various humorous remarks circulating in Jiangsu and China for a long time (e.g., "bulk Jiangsu"). Nanjing has been jokingly called the province' s capital next door because of its location and development. According to the latest city classification standards in China, cities with more than 5 million and less than 10 million permanent residents in the urban area are defined as megacities. The megacities in the YRD are Shanghai (a municipality under the central government), Hangzhou, Nanjing, Hefei, and Suzhou (J), and we also compared these five most typical representative cities in the YRD at the same time (Fig. S7a). The results suggest that the classification of megacities in terms of urban resident population may not truly reflect the size of the UBA. The five megacities vary significantly from each other, and there was an inconsistency between the size of the UBA and the urban resident population.

In conclusion, while the YRD stands as China's most urbanized region, it exhibits notable disparities in urban horizontal expansion, both among and within its provinces and cities. This highlights urbanization's varied pace and nature in one of China's most dynamic regions.

4.1.2. The dominant type of urban expansion was still horizontal growth

Many studies focusing on urban vertical dynamics only conducted mapping of building heights in a particular year and did not conduct time series analysis (He et al., 2023; Ma et al., 2023; Wu et al., 2023; Zhou et al., 2022). In this way, they could only analyze the building height spatial distribution characteristics in a particular year, but not the spatio-temporal characteristics. Wang et al. (2022a) conducted a ten-year time series analysis of the vertical dynamics in Jiangsu Province from 2009 to 2018. Nevertheless, they used the plot ratio to characterize the vertical expansion rather than the building heights (Wang et al., 2022a). Using building heights, our study analyzed the spatio-temporal dynamic characterization of urban vertical dynamics in the YRD over three decades from 1990 to 2020, which was a valuable addition to the previous studies.

As the results show, the average height decreased in all the provinces and most cities. The main reason for this result is most pixels in the entire region were horizontal expansion types. High-rise buildings did not contribute as much to the average as low-rise buildings, especially outside the city center. Both Anhui Province, one of the four provincial administrative units, and Hefei City, the capital of Anhui Province, one of the five megacities, consistently had the lowest average height over the three decades. This trend in vertical development is closely linked to the patterns observed in horizontal expansion. Among the five megacities (Fig. S7b), except for Suzhou (J), the other four cities also showed a slow downward trend, with Hangzhou showing the most significant decline of 2.69 m. The urban building height in Suzhou (J) took 2005 as the turning point, and showed a V-shaped development trend, from 17.84 m in 1990 to 16.84 m in 2005 and back to 16.90 m in 2020. The average building height in Shanghai is consistently the highest, while Hefei is consistently the lowest.

In terms of the coupled analysis for urban horizontal and vertical expansion, Yang and Zhao (2022a) analyzed the evolution of three cities in China with relatively high urbanization, namely Beijing, Shanghai, and Shenzhen, from 1985 to 2017. This study had a long time-series, but did not determine the dominant type of urban expansion (Yang and Zhao, 2022a). Wang et al. (2023b) determined the dominant type of urban expansion in Beijing from 1990 to 2020 and found that horizontal expansion was the dominant type of urban expansion in Beijing from 1990 to 2000. The dominant type changed to vertical growth after 2000, but the vertical growth slowed down after 2010 (Wang et al., 2023b). This study was consistent with our selected timeframe, but considered only one city, Beijing, in northern China. Li et al. (2023) found that the dominant type of urban expansion in Wuhan, located in central China, was vertical growth from 2000 to 2018 (Li et al., 2023). However, the study area selected was only the central urban district of Wuhan, which could not reflect the actual situation of the whole city. Our study area was not limited to the main urban district of the YRD but also included the entire region. In short, there has not been any relevant research focused on the whole YRD. Our work could fill the above gaps found in previous studies.

Our study takes a novel approach by coupling the analyses of both horizontal and vertical expansions of cities within the YRD, adopting a 3-D perspective. While horizontal growth across the YRD and its four constituent provincial administrative units was substantial, the combined urban expansion intensity varied significantly. Shanghai stands out with a clear upward trend in combined urban expansion intensity. In contrast, the other provinces exhibited slower expansion rates, with Anhui Province even experiencing declines in some periods. This trend is intrinsically linked to the urban vertical height dynamics in these regions. Upon examining the dominant type of urban expansion in the YRD, we found that horizontal growth remains the dominant form despite the increasing prevalence of skyscrapers. However, it should be noted that the dominance of horizontal growth in the YRD, except in Anhui Province, is gradually diminishing. There is a growing indication that vertical growth will supplant horizontal expansion as the primary urban development trend in the YRD in the future. We conducted further calculations for the five typically representative megacities included in the YRD (Fig. S8), and the results showed that all of them were negative, except for Nanjing in 1995–2005 and Suzhou (J) in 1990–1995 and 2005–2010, respectively. This indicated that the dominant type of all cities was horizontal expansion, and only Nanjing and Suzhou (J) were dominated by vertical expansion in the above periods. In addition, the horizontal dominance of Shanghai and Hangzhou has gradually weakened and may shift to a predominantly vertical expansion in the future, but the other three cities have not shown this trend.

4.2. Driving mechanism analysis of 3-D urban expansion

Past literature has analyzed the driving factors of horizontal expansion in the YRD region (Lv et al., 2024; Wu et al., 2024; Zhong et al., 2020; Zhu et al., 2022). It mainly includes five categories of factors: economic (GDP, total fixed asset investment, total retail sales of consumer goods, industrial structure), population, policy, transportation, and nature (topography, land resources). Since there are fewer studies of vertical expansion in the YRD, less literature is available for driver analysis. Wang et al. (2022a) analysis of vertical expansion of new residential land in Jiangsu Province showed that real estate development investment and slope had a significant positive impact on urban vertical expansion, while urban disposable income per capita and economic structure had a nonlinear impact (Wang et al., 2022a). As the economy developed, the plot ratio of residential land first increased. When economic development reached a certain level, residents would pursue the comfort of living conditions, resulting in a decreased residential plot ratio. Yang and Zhao (2022b) and Shi et al. (2009) found that urbanization development policies and industrial structure are the main influencing factors of vertical expansion (Shi et al., 2009; Yang and Zhao, 2022b). Based on combing existing literature, we establish a theoretical framework for the driving mechanism of 3-D urban expansion (Fig. 10).

When coupling analyzed the YRD's urban development through the lens of both horizontal and vertical dynamics, Anhui Province's comprehensive expansion intensity consistently ranked at the lowest level, falling below the region's average. This outcome is intricately linked to Anhui's complex integration history into the YRD. Geographically distant from the Yangtze River's mouth and lacking proximity to the sea, Anhui was initially excluded from the Chinese government's concept of the YRD Economic Zone in the 1980s. Throughout the 1990s and into the early 2000s, Jiangsu, Zhejiang, and Shanghai progressively fortified their cooperative mechanisms within the YRD, culminating in an economic agreement in 2003. Although Anhui Province endeavored to merge into the YRD framework, it wasn't until 2016 that some of its cities were recognized as part of the YRD urban agglomeration, with the entire province finally being included in 2019. In the future, with the promotion of the YRD integration strategy, Anhui Province's complementary strengths with other provinces may significantly narrow the development gap.

The results on the dominant type of expansion can be attributed to several key observations. While the number of skyscrapers has increased, strong vertical urban growth remains largely confined to the urban core zones. In contrast, much of the city outskirts continue to experience low-density, horizontal expansion. Urban cores, particularly business districts, are characterized by extremely high plot ratios and densities. However, the prevailing trend in the Chinese real estate market leans towards low-density, high-quality housing developments, which are typically marketed as more desirable. Most suburban residential buildings are low-rise residences, contributing to horizontal expansion. Although some high-rise residential buildings belong to vertical growth in individual height and the relevant supporting and ancillary facilities, the density and plot ratio of the entire neighborhood or unit was still low. High-density building complexes, it seems, are less liveable and do not meet market demand. This was also confirmed in a study by He et al. (2023), which showed that building heights in Shanghai display a gradual downward trend from the urban center to the suburban district. The highest building distribution was found in the old urban district of Shanghai, centered on the west bank of the Huangpu River, with high-rise buildings accounting for more than half of Shanghai. The farther away from the urban center, building density and average height were lower, and the proportion of pervious surfaces, such as water bodies and green spaces, gradually increased (He et al., 2023). Another significant factor influencing the urban expansion patterns in the YRD is that many countries have strong economic power, especially in Jiangsu and Zhejiang Province. Although counties are subordinate to cities and their administrative level is equivalent to municipal districts, they have a certain degree of autonomy and independence in urban development. The urban expansion of county-level units was not as substantial as municipal districts in terms of vertical dynamics and was dominated by horizontal growth. In addition, Ma et al.'s (2023) study even mentioned that Zhejiang Province was vigorously developing small towns and was the first province in China to take small towns as an economic pillar, encouraging the development of small administrative towns (Hu et al., 2022; Ma et al., 2023). Therefore, it has increased the share of horizontal growth accounted for by the city in which it is located and the whole YRD.

4.3. Research insights

4.3.1. Reference value of the technical framework

Although the technical framework for 3-D urban extraction used in this study has only been applied to the YRD region, it also has good replicability and referability for other regions worldwide. Specifically, regarding horizontal urban expansion extraction, the ISAD method can accurately extract the UBA boundary and ensure its continuity, which is a stable and reliable method. For vertical urban growth extraction,

Fig. 10. A theoretical framework for 3-D urban expansion driving mechanisms.

previous studies are limited by data sources, making it difficult to obtain building height information before 2010 and to conduct long time series studies. We provide the possibility for large-scale and long time series vertical growth studies through an indirect method. In summary, our technical framework can support 3-D urban expansion studies.

4.3.2. *Implications for policy development*

Based on our findings, the 3-D expansion characteristics of the YRD could have some positive policy impacts. Firstly, policy formulation regarding vertical urban development should continue to encourage high-density and multifunctional vertical development, given the current downward trend in average building heights across the YRD. This is especially true in urban core areas where public transportation is accessible. The government should incentivize developers and investors to participate in high-rise projects through policy incentives such as tax breaks and plot ratio bonuses. They should also establish minimum building heights, especially in mixed commercial and residential areas, to improve land use efficiency. Secondly, urban planning and land use policies should continue to be improved by updating and optimizing urban overall plans, clarifying guidelines and restrictions on land use, and ensuring balanced and sustainable urban development. 3-D spatial utilization should be integrated into urban planning to ensure the coordinated development of horizontal and vertical expansion. Finally, regional coordinated development policies should be strengthened. Differentiated urban expansion policies should be formulated to address the development characteristics of each province and city. In particular, in regions such as Anhui Province, specific measures should be formulated to promote vertical expansion and reduce disorderly horizontal sprawl. Continue to promote the integrated development strategy of the YRD and strengthen cooperation between the regions. By implementing these policy recommendations, urban development in the YRD region will be more efficient and sustainable, and better able to cope with the challenges arising from the urbanization process.

4.3.3. *Relationship between 3-D urban expansion and land resource efficient utilization*

Sustainable land use was first formally proposed in the 1990s at the World Land Use Symposium. As the population grows, available land for urban buildings becomes increasingly scarce, which is an important problem facing urbanization (Tan et al., 2021). Facing the massive demand for urban land due to economic growth, improving land utilization efficiency is the only way to conserve limited land resources (Wu et al., 2017). It has been shown that there is a close relationship between urban expansion and urban land resource utilization efficiency. For example, in a study of 466 cities worldwide, Chakraborty et al. (2022) found that different patterns of urban expansion could lead to different impacts on land use efficiency (Chakraborty et al., 2022). He et al. (2020) used a spatial regression model to demonstrate the significance of the spatial impact of urban expansion patterns on land use efficiency using 336 cities in China as a sample (He et al., 2020). However, few studies assess land resources from a 3-D perspective. Studying the 3-D urban expansion can deepen the understanding of land resources utilization efficiency.

Rational planning of urban growth can promote sustainable regional development (Wang et al., 2022b). Here, we take a qualitative approach to analyze the potential impact of 3-D urban expansion on land resources use efficiency and its relationship with the problems of the urbanization process. Urban growth in the vertical direction can create more useable space on limited land resources. Increasing building heights and compounding functional uses (e.g., commercial and residential buildings) can increase the utilization efficiency within a unit area and reduce the demand for new land. It is also vital for maintaining ecological balance and reducing infrastructure costs. The 2-D horizontal expansion has the potential to result in an unbridled increase in urban areas, increasing traffic congestion and air pollution. 3-D expansion contributes to alleviating these problems by optimizing the urban spatial layout. In addition, regarding urban equity, 2-D urban expansion may be accompanied by segregation between neighborhoods, which increases social inequality. In contrast, vertical growth within cities may promote people of different economic levels to live and work in the center region, contributing to social integration. The balanced promotion of 3-D urban development can help achieve a rational distribution of social resources and promote social stability and economic growth.

4.4. Research shortcomings and prospects

This study is a successful attempt to demonstrate the potential of our research methods. Although the results and analysis of this study are specific to the YRD of China, the methods used can be applied to other countries and regions. Due to the limitations of data sources and other factors, this study still has two shortcomings. One is that the indirect method used to extract building heights from 1990 to 2020 assumes that there is no urban building rebuilding in this period, but there are certainly a few pixels that have been redeveloped in this period. The second is that the time interval used in this study is five years, which captures trends over multiple timespans but fails to capture the dynamics of inter-annual change.

In the future, we plan to conduct further research in the following areas. Firstly, we will set the temporal resolution to one year to capture the dynamics of inter-annual changes in the 3-D urban expansion and explore methods to consider rebuilding buildings. Secondly, we will provide further details of the trend analysis of vertical growth. Not only using the average height of the statistical results to analyze the trend but also introducing more refined trend analysis methods. Thirdly, regarding the applied value of 3-D expansion, we will further enrich the study of the relationship between 3-D urban expansion and the efficient utilization of land resources and combine it with other ecological and environmental changes. Finally, to further enhance the international contribution, we will conduct global-scale research, especially in developing countries that have experienced rapid urbanization in the last three decades.

5. Conclusion

In this study, we extracted and analyzed the 3-D urban expansion process in the YRD of China from 1990 to 2020 and explored the spatio-temporal evolution of horizontal and vertical expansion. We also analyzed the coupling of horizontal and vertical urban expansion from a 3-D perspective, determined the dominant types of urban expansion in different periods, and explored the reasons. At the same time, we extracted and mapped the UBA distribution in the YRD from 1990 to 2020. We found that over the past three decades, the YRD, one of China's most urbanized regions, was still dominated by horizontal growth despite the increasing number of skyscrapers, whatever the regional, provincial, or city scales. The average building height of the region and most cities showed a downward trend. The UBA area of the YRD has grown from 4,855.30 km^2 to 44,447.15 km^2 during three decades, while the average building height has slowly decreased by 1.26 m. 73.17 % of the combined expansion intensity of the cities was increasing from the 3-D perspective, and the decreasing cities were mainly located in Anhui Province. Except for Anhui Province, the dominance of horizontal expansion in the rest of the provinces and the entire YRD has been less and less significant, and may be replaced by vertical growth in the future along with a shift to efficient use of urban land resources. There was significant unevenness in urban expansion across the YRD. Both horizontal and vertical expansion differ significantly between different provinces and cities.

The methods, frameworks, and analytical ideas used in this study are universal and can be applied to other world regions. Our 3-D urban expansion extraction framework provides the possibility of large-scale and long time series 3-D urbanization studies. It effectively reveals the spatio-temporal and structural characteristics of 3-D urban expansion and offers a new perspective on urban development. The 3-D expansion characteristics of the YRD could have some positive policy impacts. The government should continue to promote the integrated development strategy of the YRD and strengthen cooperation between the regions, guiding cities towards more efficient and sustainable development. Studying 3-D urban expansion can deepen the understanding of land resources utilization efficiency and promote urban sustainable development.

In conclusion, this study filled the gap in 3-D urban expansion research in the YRD and had a typical representation of China's 3-D urban development process. The findings of this study can also be used as a basis for determining whether urban land resources have been utilized sustainably and efficiently. In the future, we will further enrich the study of the relationship between 3-D urban expansion and the efficient utilization of land resources and combine it with other ecological and environmental changes.

CRediT authorship contribution statement

Chenglong Yin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruishan Chen:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Xiangming Xiao:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Tim Van de Voorde:** Writing – review & editing, Formal analysis. **Yuanwei Qin:** Writing – review & editing, Formal analysis. **Xiaona Guo:** Writing – review & editing, Formal analysis. **Fei Meng:** Writing – review & editing, Conceptualization. **Li Pan:** Writing – review & editing, Formal analysis. **Yuan Yao:** Writing – review & editing, Visualization. **Yinshuai Li:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Ruishan Chen was supported by a grant from the China National Social Science Foundation (20ZDA085), and Xiangming Xiao was supported by grants from the U.S. National Science Foundation (1911955, 2200310). We appreciate the University of Oklahoma Writing Center for reviewing the manuscript's language. We would like to express our gratitude and respect to the editors and anonymous reviewers for their valuable comments and suggestions, which greatly improved the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.174909.

References

Al-Kodmany, K., 2018. The sustainability of tall building developments: a conceptual framework. Buildings 8, 7.
Barrington-Leigh, C., Millard-Ball, A., 2015. A century of sprawl in the United States. Proc. Natl. Acad. Sci. USA 112, 8244–8249.
Chakraborty, S., Maity, I., Dadashpoor, H., Novotný, J., Banerji, S., 2022. Building in or out? Examining urban expansion patterns and land use efficiency across the global sample of 466 cities with million+ inhabitants. Habitat Int. 120, 102503.
Chen, Y., Chen, Z.G., Xu, G.L., Tian, Z.Q., 2016. Built-up land efficiency in urban China: insights from the general land use plan (2006–2020). Habitat Int. 51, 31–38.
Chen, Y.Q., Shan, B.Y., Yu, X.W., Zhang, Q., Ren, Q.X., 2022. Comprehensive effect of the three-dimensional spatial distribution pattern of buildings on the urban thermal environment. Urban Clim. 46, 101324.
China, S.C.o.t.P.s.R.o, 2019. The Outline of the Plan for the Integrated Development of the Yangtze River Delta Region. State Council of the People's Republic of China.
Deng, X.Z., Huang, J.K., Rozelle, S., Uchida, E., 2010. Economic growth and the expansion of urban land in China. Urban Stud. 47, 813–843.
Design, C.A.o.U.P, 2018. Planning and Design Standards for Urban Residential Areas.

Ding, C.R., 2003. Land policy reform in China: assessment and prospects. Land Use Policy 20, 109–120.
Fang, C.L., 2011. 2010 China City Agglomeration Development Report. Science Press, Beijing, China.
Fang, C.Y., Zhao, S.Q., 2018. A comparative study of spatiotemporal patterns of urban expansion in six major cities of the Yangtze River Delta from 1980 to 2015. Ecosyst. Health Sustain. 4, 95–114.
Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.
Frantz, D., Schug, F., Okujeni, A., Navacchi, C., Wagner, W., van der Linden, S., Hostert, P., 2021. National-scale mapping of building height using Sentinel-1 and Sentinel-2 time series. Remote Sens. Environ. 252, 112128.
Frolking, S., Milliman, T., Seto, K.C., Friedl, M.A., 2013. A global fingerprint of macro-scale changes in urban structure from 1999 to 2009. Environ. Res. Lett. 8, 024004.
Gong, J.Z., Hu, Z.R., Chen, W.L., Liu, Y.S., Wang, J.Y., 2018. Urban expansion dynamics and modes in metropolitan Guangzhou, China. Land Use Policy 72, 100–109.
Gong, P., Li, X.C., Zhang, W., 2019. 40-Year (1978–2017) human settlement changes in China reflected by impervious surfaces from satellite remote sensing. Sci. Bull. 64, 756–763.
Grafius, D.R., Corstanje, R., Harris, J.A., 2018. Linking ecosystem services, urban form and green space configuration using multivariate landscape metric analysis. Landsc. Ecol. 33, 557–573.
Guan, D., He, X., He, C., Cheng, L., Qu, S., 2020. Does the urban sprawl matter in Yangtze River Economic Belt, China? An integrated analysis with urban sprawl index and one scenario analysis model. Cities 99, 102611.
Güneralp, B., Zhou, Y.Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P.L., Fragkias, M., Li, X.M., Seto, K.C., 2017. Global scenarios of urban density and its impacts on building energy use through 2050. Proc. Natl. Acad. Sci. USA 114, 8945–8950.
Han, J., Hayashi, Y., Cao, X., Imura, H., 2009. Evaluating land-use change in rapidly urbanizing China: case study of Shanghai. J. Urban Plan. Dev. 135, 166–171.
Handayani, H.H., Murayama, Y., Ranagalage, M., Liu, F., Dissanayake, D.M.S.L.B., 2018. Geospatial analysis of horizontal and vertical urban expansion using multi-spatial resolution data: a case study of Surabaya, Indonesia. Remote Sens. 10, 1599.
He, Q.S., Zeng, C., Xie, P., Tan, S.K., Wu, J.Y., 2019a. Comparison of urban growth patterns and changes between three urban agglomerations in China and three metropolises in the USA from 1995 to 2015. Sustain. Cities Soc. 50, 101649.
He, S.J., Wang, X.Y., Dong, J.R., Wei, B.C., Duan, H.M., Jiao, J.Z., Xie, Y.W., 2019b. Three-dimensional urban expansion analysis of valley-type cities: a case study of Chengguan District, Lanzhou, China. Sustainability 11, 5663.
He, S.W., Yu, S., Li, G.D., Zhang, J.F., 2020. Exploring the influence of urban form on land-use efficiency from a spatiotemporal heterogeneity perspective: evidence from 336 Chinese cities. Land Use Policy 95.
He, T.T., Wang, K.C., Xiao, W., Xu, S.C., Li, M.M., Yang, R.J., Yue, W.Z., 2023. Global 30 meters spatiotemporal 3D urban expansion dataset from 1990 to 2010. Sci. Data 10, 321.
Hu, X.H., Wu, Q.B., Xu, W., Li, Y.W., 2022. Specialty towns in China: towards a typological policy approach. Land Use Policy 114, 105933.
Huang, K.N., Li, X., Liu, X.P., Seto, K.C., 2019. Projecting global urban land expansion and heat island intensification through 2050. Environ. Res. Lett. 14, 114037.
Jiao, L.M., Xu, Z.B., Xu, G., Zhao, R., Liu, J.F., Wang, W.L., 2020. Assessment of urban land use efficiency in China: a perspective of scaling law. Habitat Int. 99.
Li, X.C., Zhou, Y.Y., Gong, P., Seto, K.C., Clinton, N., 2020a. Developing a method to estimate building height from Sentinel-1 data. Remote Sens. Environ. 240, 111705.
Li, Y.F., Schubert, S., Kropp, J.P., Rybski, D., 2020b. On the influence of density and morphology on the Urban Heat Island intensity. Nat. Commun. 11, 2647.
Li, M.M., Wang, Y., Rosier, J.F., Verburg, P.H., van Vliet, J., 2022. Global maps of 3D built-up patterns for urban morphological analysis. Int. J. Appl. Earth Obs. Geoinf. 114.
Li, B., Peng, M., Tan, R., 2023. Analysis of the evolution characteristics and driving factors of the three-dimensional morphology of the city space: a case study of Wuhan Main Urban Area. In: Geomatics and Information Science of Wuhan University, vol. 10 (13203).
Lu, H.M., Zhang, M.L., Sun, W.W., Li, W.Y., 2018. Expansion analysis of Yangtze River Delta urban agglomeration using DMSP/OLS nighttime light imagery for 1993 to 2012. ISPRS Int. J. Geo Inf. 7, 52.
Lv, T., Hu, H., Han, H., Zhang, X., Fan, H., Yan, K., 2024. Towards sustainability: the spatiotemporal patterns and influence mechanism of urban sprawl intensity in the Yangtze River Delta urban agglomeration. Habitat Int. 148, 103089.
Ma, X., Zheng, G., Chi, X., Yang, L., Geng, Q., Li, J., Qiao, Y., 2023. Mapping fine-scale building heights in urban agglomeration with spaceborne lidar. Remote Sens. Environ. 285, 113392.
Meng, Q.Y., Zhang, L.L., Sun, Z.H., Meng, F., Wang, L., Sun, Y.X., 2018. Characterizing spatial and temporal trends of surface urban heat island effect in an urban main built-up area: a 12-year case study in Beijing, China. Remote Sens. Environ. 204, 826–837.
Pan, L.S., Hu, H.G., Jing, X., Chen, Y., Li, G., Xu, Z.G., Zhuo, Y.F., Wang, X.Q., 2022. The impacts of regional cooperation on urban land-use efficiency: evidence from the Yangtze River Delta, China. Land 11.
Qiao, W.F., Wang, Y.H., Ji, Q.Q., Hu, Y., Ge, D.Z., Cao, M., 2019. Analysis of the evolution of urban three-dimensional morphology: the case of Nanjing City, China. J. Maps 15, 30–38.
Rao, Y.X., Zhou, J., Zhou, M., He, Q.S., Wu, J.Y., 2020. Comparisons of three-dimensional urban forms in different urban expansion types: 58 sample cities in China. Growth Chang. 51, 1766–1783.
Ren, Q., He, C.Y., Huang, Q.X., Shi, P.J., Zhang, D., Güneralp, B., 2022. Impacts of urban expansion on natural habitats in global drylands. Nat. Sustain. 5, 869–878.
Ruan, L.L., He, T.T., Xiao, W., Chen, W.Q., Lu, D.B., Liu, S.C., 2022. Measuring the coupling of built-up land intensity and use efficiency: an example of the Yangtze River Delta urban agglomeration. Sustain. Cities Soc. 87, 104224.
Seto, K.C., Fragkias, M., 2005. Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. Landsc. Ecol. 20, 871–888.
Seto, K.C., Kaufmann, R.K., 2003. Modeling the drivers of urban land use change in the Pearl River Delta, China: integrating remote sensing with socioeconomic data. Land Econ. 79, 106–121.
Seto, K.C., Shepherd, J.M., 2009. Global urban land-use trends and climate impacts. Curr. Opin. Environ. Sustain. 1, 89–95.
Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. USA 109, 16083–16088.
Shi, L.Y., Shao, G.F., Cui, S.H., Li, X.Q., Lin, T., Yin, K., Zhao, J.Z., 2009. Urban three-dimensional expansion and its driving forces - a case study of Shanghai, China. Chin. Geogr. Sci. 19, 291–298.
Song, Y., Yeung, G., Zhu, D.L., Xu, Y., Zhang, L.X., 2022. Efficiency of urban land use in China's resource-based cities, 2000–2018. Land Use Policy 115.
Statistics, C.N.B.o, 2021a. China Statistical Yearbook.
Statistics, C.N.B.o, 2021b. Seventh National Population Census. China National Bureau of Statistics.
Sun, Y., Zhang, X.B., Ren, G.Y., Zwiers, F.W., Hu, T., 2016. Contribution of urbanization to warming in China. Nat. Clim. Chang. 6, 706–709.
Sun, W., Shan, J., Wang, Z.M., Wang, L., Lu, D.M., Jin, Z.F., Yu, K., 2020. Geospatial analysis of urban expansion using remote sensing methods and data: a case study of Yangtze River Delta, China. In: Complexity, 2020.
Tan, S.K., Hu, B.X., Kuang, B., Zhou, M., 2021. Regional differences and dynamic evolution of urban land green use efficiency within the Yangtze River Delta, China. Land Use Policy 106.
Tang, Y.K., Wang, K., Ji, X.M., Xu, H., Xiao, Y.Q., 2021. Assessment and spatial-temporal evolution analysis of urban land use efficiency under green development orientation: case of the Yangtze River Delta urban agglomerations. Land 10.
Tian, Y.S., Mao, Q.H., 2022. The effect of regional integration on urban sprawl in urban agglomeration areas: a case study of the Yangtze River Delta, China. Habitat Int. 130, 102695.
Tominaga, Y., Shirzadi, M., 2021. Wind tunnel measurement of three-dimensional turbulent flow structures around a building group: impact of high-rise buildings on pedestrian wind environment. Build. Environ. 206, 108389.
UN, 2022. World Population Prospects 2022: Summary of Results. Department of Economic and Social Affairs Population Division, New York.
Wang, N., Chen, Z.G., Li, T.S., Zhen, M.J., 2022a. Spatiotemporal pattern evolution and influence mechanism of urban vertical expansion: a case study of Jiangsu Province, China. Land 11, 433.
Wang, Q., Wang, H.J., Chang, R.H., Zeng, H.R., Bai, X.P., 2022b. Dynamic simulation patterns and spatiotemporal analysis of land-use/land-cover changes in the Wuhan metropolitan area, China. Ecol. Model. 464.
Wang, J., Zhang, Y.Z., Zhang, X.L., Song, M.Q., Ye, J.P., 2023a. The spatio-temporal trends of urban green space and its interactions with urban growth: evidence from the Yangtze River Delta region, China. Land Use Policy 128, 106598.
Wang, Y.X., Li, X.C., Yin, P.Y., Yu, G.J., Cao, W.T., Liu, J.X., Pei, L., Hu, T.Y., Zhou, Y.Y., Liu, X.P., Huang, J.X., Gong, P., 2023b. Characterizing annual dynamics of urban form at the horizontal and vertical dimensions using long-term Landsat time series data. J. Photogramm. Remote Sens. 203, 199–210.
Wu, K.Y., Zhang, H., 2012. Land use dynamics, built-up land expansion patterns, and driving forces analysis of the fast-growing Hangzhou metropolitan area, eastern China (1978–2008). Appl. Geogr. 34, 137–145.
Wu, C.Y., Wei, Y.H.D., Huang, X.J., Chen, B.W., 2017. Economic transition, spatial development and urban land use efficiency in the Yangtze River Delta, China. Habitat Int. 63, 67–78.
Wu, H., Lin, A., Xing, X., Song, D., Li, Y., 2021a. Identifying core driving factors of urban land use change from global land cover products and POI data using the random forest method. Int. J. Appl. Earth Obs. Geoinf. 103, 102475.
Wu, J.S., Li, X.C., Luo, Y.H., Zhang, D.N., 2021b. Spatiotemporal effects of urban sprawl on habitat quality in the Pearl River Delta from 1990 to 2018. Sci. Rep. 11, 13981.
Wu, W.B., Ma, J., Banzhaf, E., Meadows, M.E., Yu, Z.W., Guo, F.X., Sengupta, D., Cai, X. X., Zhao, B., 2023. A first Chinese building height estimate at 10 m resolution (CNBH-10 m) using multi-source earth observations and machine learning. Remote Sens. Environ. 291, 113578.
Wu, Y., Han, Z.X., Koko, A.F., Zhang, S.Y., 2024. Spatio-temporal analysis of the driving factors of urban land use expansion in China: a study of the Yangtze River Delta region. Open Geosci. 16.
Xiao, J.Y., Shen, Y.J., Ge, J.F., Tateishi, R., Tang, C.Y., Liang, Y.Q., Huang, Z.Y., 2006. Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing. Landsc. Urban Plan. 75, 69–80.
Xiao, W., Chen, W.Q., Yue, W.Z., Mu, J.X., Xu, J.P., 2022. Waterbody loss due to urban expansion of large Chinese cities in last three decades. Sci. Rep. 12, 17498.
Xu, G., Zhou, Z.Z., Jiao, L.M., Zhao, R., 2020. Compact urban form and expansion pattern slow down the decline in urban densities: a global perspective. Land Use Policy 94, 104563.
Yang, C., Zhao, S.Q., 2022a. Urban vertical profiles of three most urbanized Chinese cities and the spatial coupling with horizontal urban expansion. Land Use Policy 113, 105919.

Yang, C., Zhao, S.Q., 2022b. Urban vertical profiles of three most urbanized Chinese cities and the spatial coupling with horizontal urban expansion. Land Use Policy 113.
Yang, Q.K., Ding, L.L., Wang, L., Liu, C., Fan, Y.T., Li, Y., Wang, Y.Z., 2023. Influence mechanism of new-type urbanization on urban land use efficiency in the Yangtze River Delta, China. Chin. Geogr. Sci. 33, 474–488.
Yin, J., Yin, Z.E., Zhong, H.D., Xu, S.Y., Hu, X.M., Wang, J., Wu, J.P., 2011. Monitoring urban expansion and land use/land cover changes of Shanghai metropolitan area during the transitional economy (1979–2009) in China. Environ. Monit. Assess. 177, 609–621.
Yin, C.L., Meng, F., Xu, Y.N., Yang, X.Y., Xing, H.Q., Fu, P.J., 2020. Developing urban built-up area extraction method based on land surface emissivity differences. Infrared Phys. Technol. 110, 103475.
Yin, C.L., Meng, F., Guo, L., Zhang, Y.X., Zhao, Z., Xing, H.Q., Yao, G.B., 2021. Extraction and evolution analysis of urban built-up areas in Beijing, 1984–2018. Appl. Spat. Anal. Policy 14, 731–753.
Yin, C.L., Meng, F., Yang, X.Y., Yang, F.S., Fu, P.J., Yao, G.B., Chen, R.S., 2022. Spatio-temporal evolution of urban built-up areas and analysis of driving factors - a comparison of typical cities in north and south China. Land Use Policy 117, 106114.
Yin, C.L., Zhu, A.L., Zhou, Q., Meng, F., Chen, R.S., Liu, F.G., Chen, Q., Guo, X.A., 2024. Rapid urban expansion and potential disaster risk on the Qinghai-Tibetan Plateau in the 21st century. Landsc. Ecol. 39.
Yu, W.J., Zhou, W.Q., 2017. The spatiotemporal pattern of urban expansion in China: a comparison study of three urban megaregions. Remote Sens. 9, 45.
Yu, J.Q., Zhou, K.L., Yang, S.L., 2019. Land use efficiency and influencing factors of urban agglomerations in China. Land Use Policy 88.
Yu, Z.Q., Chen, L.Q., Li, L., Zhang, T., Yuan, L.A., Liu, R.Y., Wang, Z.Q., Zang, J.Y., Shi, S., 2021. Spatiotemporal characterization of the urban expansion patterns in the Yangtze River Delta Region. Remote Sens. 13, 4484.
Zambon, I., Colantoni, A., Salvati, L., 2019. Horizontal vs vertical growth: understanding latent patterns of urban expansion in large metropolitan regions. Sci. Total Environ. 654, 778–785.
Zhang, S.M., Zhang, B.L., Zhang, L., Lu, C.X., Cheng, X.L., 2010. Spatiotemporal evolution of urban land uses in modern urbanization of China. Chin. Geogr. Sci. 20, 132–138.
Zhang, X., Liu, L.Y., Zhao, T.T., Gao, Y., Chen, X.D., Mi, J., 2022. GISD30: global 30 m impervious-surface dynamic dataset from 1985 to 2020 using time-series Landsat imagery on the Google Earth Engine platform. Earth Syst. Sci. Data 14, 1831–1856.
Zhao, J.M., Zhu, D.L., Cheng, J., Jiang, X., Lun, F., Zhang, Q., 2021. Does regional economic integration promote urban land use efficiency? Evidence from the Yangtze River Delta, China. Habitat Int. 116.
Zhao, L.F., Liu, X.P., Xu, X.C., Liu, C.M., Chen, K.Y., 2022. Three-dimensional simulation model for synergistically simulating urban horizontal expansion and vertical growth. Remote Sens. 14, 1503.
Zheng, Q., Weng, Q., Wang, K., 2021. Characterizing urban land changes of 30 global megacities using nighttime light time series stacks. ISPRS J. Photogramm. Remote Sens. 173, 10–23.
Zhong, Q.Y., Ma, J., Zhao, B., Wang, X.X., Zong, J.M., Xiao, X.M., 2019. Assessing spatial-temporal dynamics of urban expansion, vegetation greenness and photosynthesis in megacity Shanghai, China during 2000–2016. Remote Sens. Environ. 233, 111374.
Zhong, Y., Lin, A.W., He, L.J., Zhou, Z.G., Yuan, M.X., 2020. Spatiotemporal dynamics and driving forces of urban land-use expansion: a case study of the Yangtze River Economic Belt, China. Remote Sens. 12, 287.
Zhou, Y.Y., Li, X.C., Chen, W., Meng, L., Wu, Q.S., Gong, P., Seto, K.C., 2022. Satellite mapping of urban built-up heights reveals extreme infrastructure gaps and inequalities in the Global South. Proc. Natl. Acad. Sci. USA 119, e2214813119.
Zhu, Z., Zhou, Y.Y., Seto, K.C., Stokes, E.C., Deng, C.B., Pickett, S.T.A., Taubenböck, H., 2019. Understanding an urbanizing planet: strategic directions for remote sensing. Remote Sens. Environ. 228, 164–182.
Zhu, H.X., Ou, X.J., Yang, Z., Yang, Y.W., Ren, H.X., Tang, L., 2022. Spatiotemporal dynamics and driving forces of land urbanization in the Yangtze River Delta urban agglomeration. Land 11.