Building upward, dividing deeper: Three-dimensional urban expansion assessment reveals regional heterogeneity of preferential developments worldwide

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Abstract

Urban areas are continuously expanding outward with economic development and demographic growth, while simultaneously growing higher vertically. However, few efforts have been made to evaluate the impact of development priorities in different regions on urban sustainability, which limited our understanding of how urbanization has been affected by imbalanced evolution rhythm. Here we developed a 3D structure-based approach to assess volumetric urban expansion, as well as a refined evaluation system for assessing urban imbalanced growth trends. Results show that the 3D expansion patterns of urban areas exhibited significant heterogeneity globally. As urbanization accelerates, urban areas in the Global South are showing a trend of faster expansion accompanied by faster vertical growth. In addition, imbalanced growth types across different dimensions are significantly more complicated in the Global South than in the Global North, indicating the variance of development priorities is greater in the Global South. Furthermore, the imbalances are intensifying over time, as indicated by the temporal indices. Our study enhances the understanding of urban 3D patterns and imbalanced urban evolution, providing crucial insights for more balanced urbanization especially in the Global South.

1. Introduction

Urban areas, as complex spatial entities with three-dimensional (3D) structures, exhibit significant variations in surface characteristics across the globe. Recently, urban construction and renewal around the world have exhibited increasingly upward trends (Frolking et al., 2024), and thus, the vertical differences have become more distinct globally. Therefore, urban-related 3D data that take building height into account allow for a more comprehensive and accurate representation of urban space, offering unparalleled advantages over two-dimensional (2D) data in related studies. However, existing studies have predominantly substituted the planar urban area for the overall spatial structure, representing spatial development solely through horizontal expansion (Angel et al., 2011, Li et al., 2021). This 2D perspective overlooks the vertical dimension, which leads to incorrect estimation of the urban spatial construction intensity, and further, potentially produces misinterpretations of urbanization sustainability. While a few studies have incorporated 3D data, they have primarily highlighted inter-regional development disparities (Brelsford et al., 2017, Pandey et al., 2022), with limited attention paid to imbalanced growth across different dimensions in the evolution of urbanization.

Serving as engines of economic growth and development, urban areas generate the majority of the gross domestic product (GDP) and create most of the private sector jobs (Güneralp et al., 2017). As proposed by the United Nations in the 2030 Agenda for Sustainable Development, the sustainability of urban regions is significantly crucial (Sayed, 2015). Considering the close relationship between urban structure and the performance of cities in terms of population absorption, urban thermal environment (Riahi et al., 2011, Lee et al., 2015, Li et al., 2020c), energy structure (Ratti et al., 2005, Chen et al., 2019), etc., it is urgent to understand the impact of the relative speed of different urbanization dimensions on urban sustainability. In a sense, the sustainability of urban areas requires balance between population growth, economic productivity, and infrastructure construction (Milán-García et al., 2019, Thacker et al., 2019). However, research on the development trends of urban structure and its relationship with dimensions such as population and economy remains scarce. Considering the new trend of urban areas growing taller (Li et al., 2020a, Li et al., 2020b), it is urgent to comprehensively evaluate the imbalanced urban growth from a 3D perspective.

In this study, we attempted to address the following research problems: (1) What are the 3D characteristics of urban expansion patterns globally? (2) How does the 3D expansion pattern affect urban sustainability, given its regional heterogeneity and the newly emerging upward growth features? To address the above problems, we first analyzed the horizontal expansion and vertical growth in 1,997 urban areas globally from 2010 to 2020, and compared the global urban building distribution. Then, we identified the potential imbalanced growth types across different urban dimensions through clustering. Finally, through comprehensive indicator analysis, we identified urban decline within global urban areas. Our study enhanced the importance of assessing urban form changes in a 3D perspective and further explored possible development misconceptions, providing valuable insights, especially for sustainable urbanization processes in the Global South.

2. Materials

2.1 Study area

We used the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type product version 6, to delineate the urban boundary ranges, with a spatial resolution of 500 m. Due to data coverage issues, only 1,997 urban areas were finally retained as the study units for this study.

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2.2 Building data

We primarily used building surface data, building volume data and microwave backscatter data in 2010 and 2020 in our study, while the last one served as proxy for urban vertical space. The building volume, building surface area were obtained from the European Union’s Global Human Settlement Layer (GHSL) dataset (Schiavina et al., 2022), with 100 m spatial resolution. The dataset offers a long time series of 1975-2030, 5-year interval. As there was no multi-temporal record of building heights, we further added microwave-backscatter- derived PR data which originally came from ASCAT (Frolking et al., 2022) to supplement the changes in building height.

2.3 Population data

The population data we used in our study were mainly from GHSL, with a spatial resolution of 100 m in 2010 and 2020. Preprocessing such as cropping and reprojection are further utilized.

2.4 Nighttime light data

In this study, we utilized the ”NPP-VIIRS-like” nighttime light time series (2000–2020) dataset (Chen et al., 2020), which has a global coverage. This dataset achieves cross-sensor nighttime light data calibration through autoencoders, converting the Defense Meteorological Satellite Program’s Operational Line-Scan System (DMSP-OLS) nighttime light data from 2000–2012 into NPP-VIIRS-like data with parameters consistent with the NPP-VIIRS nighttime light data. The data for 2013–2020 are the annual composite nighttime light data from the NPP-VIIRS for the corresponding years. The two parts of the data together form a complete long-term nighttime light dataset for 2000–2020, which is currently available up to 2023.

3. Method

3.1 Measuring global urban horizonal expansion and vertical growth

We used the building surface area and PR as proxies for the horizontal and vertical extents of the urbanization in urban areas, respectively, to estimate the degree of urban spatial development and its changes over the decade. We calculated the horizontal expansion rate (HR) and vertical growth rate (VR) for each urban area using Equations (1) and (2):

$$HR = \frac{\sum_{i=1}^{m} S_{i,2020} - \sum_{i=1}^{m} S_{i,2010}}{\sum_{i=1}^{m} S_{i,2010}}, \tag{1}$$

$$VR = \frac{\sum_{i=1}^{n} PR_{i,2020} - \sum_{i=1}^{n} PR_{i,2010}}{\sum_{i=1}^{n} PR_{i,2010}}, \tag{2}$$

where S = building surface area
PR = power return ratio
m, n = the numbers of raster grids

3.2 Identification of imbalanced urbanization growth patterns globally

The dynamic imbalance trend over the decade from 2010 to 2020 is reflected by the change in urban population density, average nighttime light intensity and average building height. The imbalanced growth patterns refer to the significant differences in the rates of development across urban dimensions such as infrastructure, population and economy over a certain period, which is dynamic and process-oriented. Through K-means clustering algorithm, we classified all urban areas larger than 50 km² worldwide into 4 groups, including 3 types of imbalanced growth (Imbalanced Growth of Population, IBGP; Imbalanced Growth of Economy, IBGE; and Imbalanced Growth of Buildings, IBGB) and one types of relatively balanced growth (Balanced Growth). We determined the number of clusters using the mean deviation, within-cluster sum of squares and silhouette coefficient. If an urban area corresponds to an imbalanced evolution type of IBGP, it indicates that its population growth is among the top globally, while its economic development and urban construction are significantly slower than population changes. Similarly, IBGE and IBGB represent situations where there are more economic or architectural changes compared to the other two dimensions. The global dimensional growth patterns of urbanization and their data feature heatmap are as the heatmap shows (Figure 1). The heatmap individually ranks and color-codes each dimension’s data. $\triangle POP$, $\triangle ANLI$, and $\triangle PR$ indicate the changes in the urban population density, average nighttime light intensity and average building height during 2010–2020, respectively.

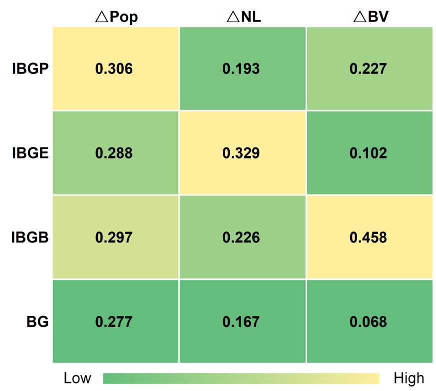

Figure 1. Data feature heatmap of global urban growth types.

3.3 Indices for quantifying imbalanced growth across different dimensions of urbanization

SDG11.3.1 (i.e., the ratio of the land consumption rate to the population growth rate, LCRPGR) measures the relationship between urban land consumption and population growth. The formula for calculating the LCRPGR is defined in the SDG Indicator Metadata Repository as Equation (3):

$$LCRPGR = \frac{LCR}{PGR} = \frac{LN(BS_{2020}/BS_{2010})}{LN(POP_{2020}/POP_{2010})}, \tag{3}$$

where BS = building surface area
POP = population
LN means taking the natural logarithm

In this study, referring to SDG 11.3.1, we developed the VCRPGR index, which takes the 3D characteristics of urban space into ac-

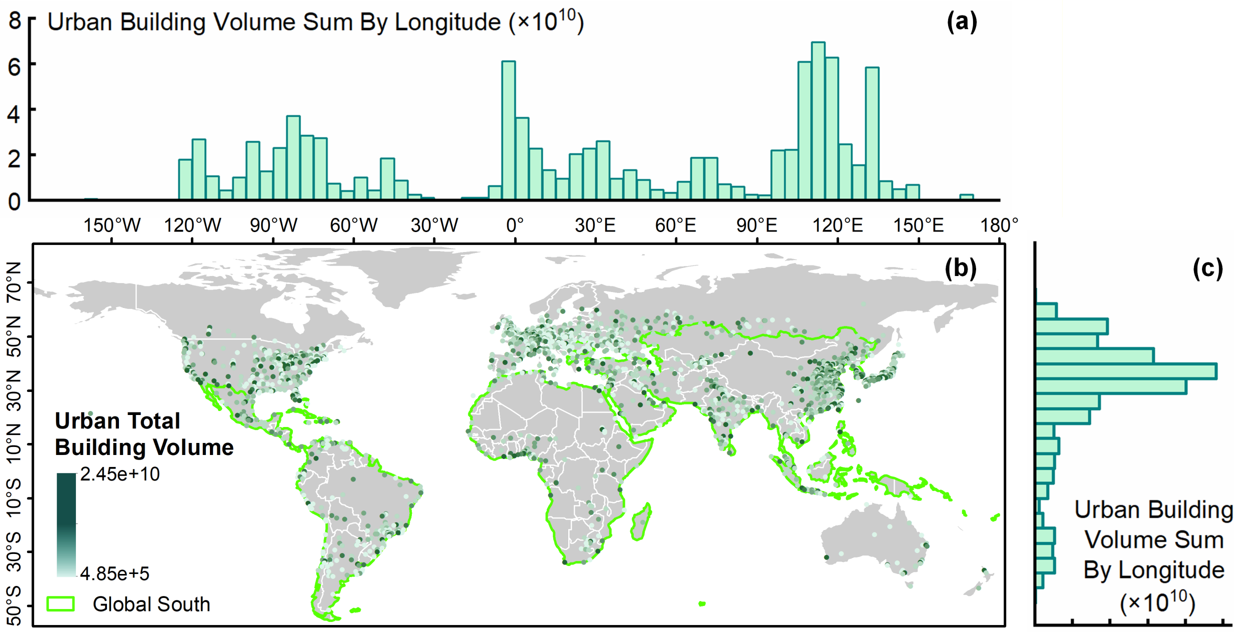

Figure 2. Distribution of global urban building volume. (a). The distribution of accumulated global urban building volumes along longitude. Each bin represents 5 degrees in longitude. (b). Global urban building volume spatial distribution map. Each point represents a morphological urban area, with the color represents the total building volume of this area. (c). The distribution of accumulated global urban building volumes along latitude. Each bin represents 5 degrees in latitude.

count. This index uses the building volume instead of the built-up area to calculate urban space consumption, thus measuring the relationship between the utilization of 3D urban space and population growth. The VCRPGR is calculated as Equation (4):

$$VCRPGR = \frac{VCR}{PGR} = \frac{LN(BV_{2020}/BV_{2010})}{LN(POP_{2020}/POP_{2010})}, \quad (4)$$

where BV = building volume

LCRPGR and VCRPGR are used to extract the relative relationship between urban expansion and population growth. In this study, we developed a new indicator, namely, the NGRVCR, which measures the relationship between urban economic growth and the degree of 3D spatial utilization. This indicator is calculated as Equation (5):

$$NGRVCR = \frac{NGR}{VCR} = \frac{LN(NL_{2020}/NL_{2010})}{LN(BV_{2020}/BV_{2010})}, \quad (5)$$

where NL = ANLI, the average nighttime light intensity

4. Results and Discussion

4.1 Heterogeneity of urban 3D expansion

The global distribution of urban building volume (Figure 2(a)) shows pronounced longitudinal clustering. More than half of the world’s total building volume concentrates within a few longitude bands, especially between 0°–60°E and 100°–140°E, corresponding to West Europe and East Asia. Building volume distribution is highly coupled with population and urbanization intensive areas (Figure 2(b)). The world’s major urban clusters, Europe, the Middle East, the Indian subcontinent, and eastern China, are the dominant contributors of global urban building volume. Although the building volume in North America (approximately 60°W-120°W) is high, it is much lower than the peak in Eurasia. From a latitude perspective, buildings worldwide are almost concentrated between 20°N-60°N (Figure 2(c)), not only because cities in the northern regions of the world are denser, but also because the northern hemisphere has a relatively higher intensity of urban spatial construction In contrast, the proportion of building volume in South America and Africa is relatively small (Figure 2(b)), and the bar shape is significantly lower (Figure 2(a), 2(c)). Most regions in the Global South contain numerous urban settlements but generally exhibit much lower building volumes, reflecting substantial disparities in urban structural capacity.

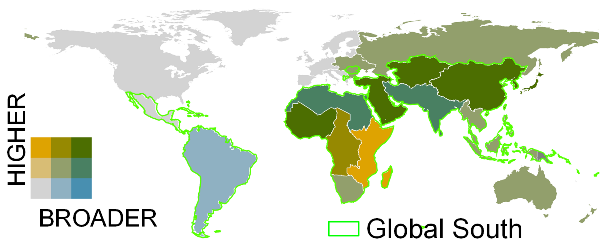

Figure 3. Bivariate mapping global map of the decadal HR and VR. The subregions with a color closer to the bottom-right corner of the legend tend to develop in the horizontal direction, while those with a color closer to the top-left corner of the legend tend to develop in the vertical direction.

The 3D expansion patterns of urban areas exhibit pronounced regional heterogeneity globally, while urban expansion worldwide exhibits a greater upward trend (Figure 3). Although the

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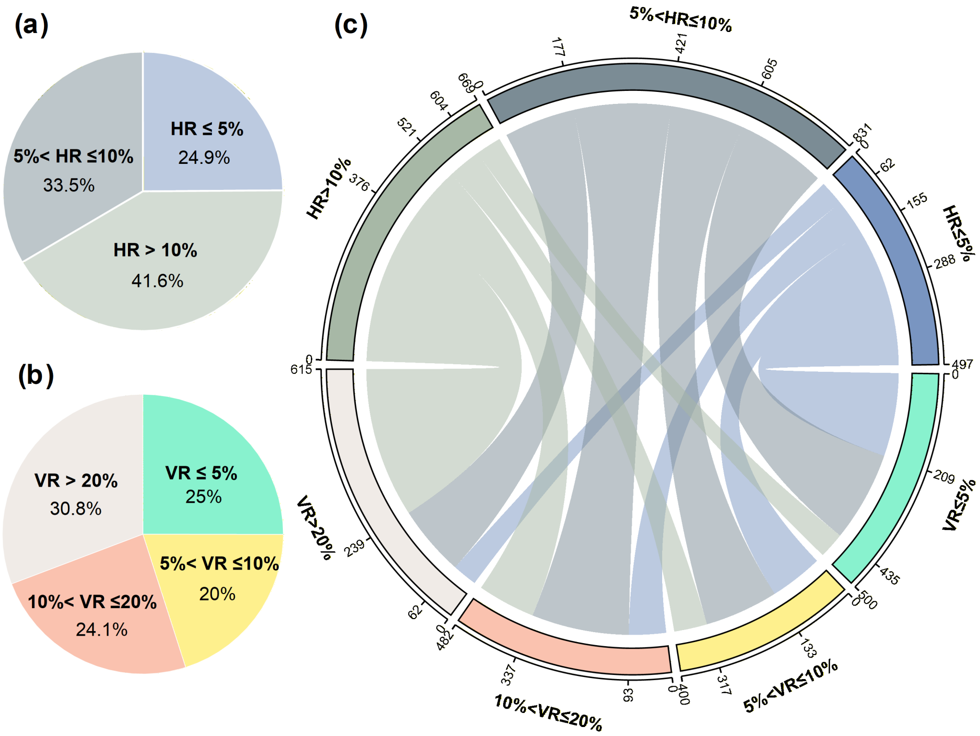

Figure 4. The distribution and correlation of urbanized land expansion rates in both horizontal and vertical directions globally. (a). Percentage distribution of horizontal expansion rates for global urbanized land. (b). Percentage distribution of vertical growth rates for global urbanized land. (c). Interrelationship between horizontal expansion rates (HRs) and vertical growth rates (VRs) between 2010 and 2020, with the width of each chord represents the number of urban areas corresponding to a certain relationship between the HR and VR.

Global South does not have an advantage in urban construction volume, urban areas in the Global South have shown an unparalleled trend in both horizontal expansion and vertical growth. According to the United Nations Geoscheme (M49 standard) and data coverage, we retained 18 geographic subregions as statistical units. Urban areas in Eastern Asia, Central Asia, Western Asia, and Eastern Africa exhibited relatively rapid vertical growth (Figure 3). Vertical growth rates in Eastern Asia, Eastern Africa, South-Eastern Asia, Western Asia, and Eastern Europe significantly exceeded their corresponding horizontal expansion rates (Figure 3). In contrast, regions in Southern Asia, Northern Africa, and South America exhibited high horizontal expansion rates, which was likely driven by rapid population growth or unplanned urban construction.

In general, from 2010 to 2020, urban areas characterized by slow horizontal expansion and vertical growth dominated globally (Figure 4(a), 4(b)), while areas with higher (lower) horizontal expansion rates tended to exhibit correspondingly higher (lower) vertical growth rates (Figure 4(c)). During 2010–2020, 58.4% and 45% of urban areas exhibited horizontal expansion and vertical growth rates of less than 10%, respectively (Figure 4(a), 4(b)). More than 37.19% of the areas exhibited both horizontal and vertical expansion rates of less than 10% (Figure 4(c)), indicating the similar expansion strategies in both horizontal and vertical directions. Besides, 54.9% of the global urban areas exhibit vertical growth rate higher than 10% during the decade (Figure 4(b)). The average building height in nearly one-third of urban areas has increased by more than 20% compared to the past, indicating that urban growth is a significant global trend.

The directional heterogeneity of geographic urbanization is closely linked to regional variations in land use practices, land tenure, construction costs and material budgets, building technologies, human activities, and policy directives. For example, the heights of urban buildings in East Asia tend to be higher than in other regions, which is largely driven by the population concentration. In addition, although urban areas in India have high population densities, stringent floor-area ratio restrictions (Sridhar and Mahendra, 2025) hinder the development of high-rise structures, resulting in predominantly horizontal expansion and a relatively flat urban form. This expansion pattern not only intensifies the encroachment on peripheral farmland but also exacerbates issues of limited land resources and population overload, further contributing to the emergence of slums. Moreover, the timing of urbanization indirectly shapes the urban morphology by influencing these factors (Frolking et al., 2013). In East Asia, the relatively late start of urbanization in China and South Korea enabled the adoption of modern urban design principles and advanced construction technologies. Combined with rapid population agglomeration and scarce land resources, these conditions have propelled vertical urban growth. In contrast, urbanization in many developed countries in the Global North started during the Industrial Revolution, or even earlier. The presence of extensive historical buildings and legacy infrastructure has constrained both the renovations of urban centers and the construction of super high-rise structures. The results also reveal that the spatial expansion characteristics of global urban areas exhibit significant spatiotemporal clustering, with geographically proximate countries and regions tending to adopt similar urban expansion patterns. This finding further underscores the mutual influence and con-

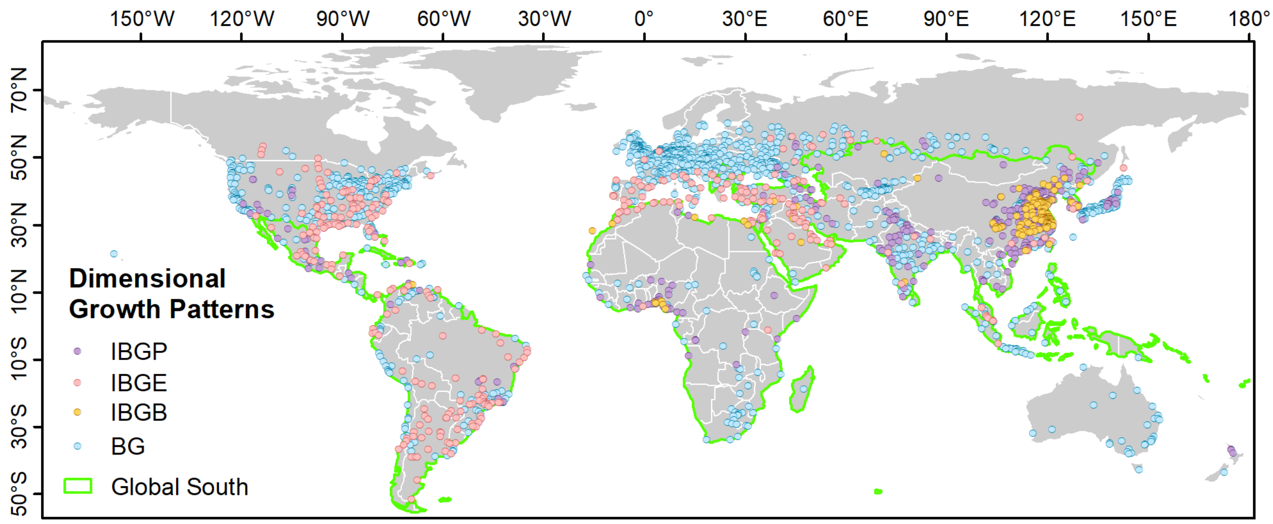

Figure 5. Global distribution of dimensional growth patterns.

vergence trends of urbanization processes across regions.

4.2 Imbalanced growth across dimensions indicating differentiated development priorities

In general, the imbalanced urban growth in the Global North is relatively mild, which in contrast, is more severe and has more complex causes in the Global South (Figure 5). In the Global North, especially in Western Europe, Australia and Japan, BG (Balanced Growth) points are relatively concentrated, indicating that these regions have relatively balanced development in population, economy, and construction. In most regions of the Global South, such as Latin America and Africa, there are relatively more IBGP, IBGE, and IBGB points, indicating that there is a certain dimension of uneven growth in these regions. As to the imbalanced aspects, the development of urban areas in the Global North tends to prioritize economic growth generally, while in the Global South, urban development is characterized by imbalances in which priority is often given either to population growth or to physical space construction (Figure 5).

IBGP (Imbalanced Growth of Population) is more prevalent in some regions of Africa, South Asia, and central China (Figure 5), suggesting that the population growth rate in these areas is higher than economic or construction development. This form of imbalanced growth demands urgent attention as it gives rise to critical challenges to social stability, including a rise in homelessness, overcrowding, and the proliferation of informal settlements. IBGE (Imbalanced Growth of Economy) appears mainly in the Middle East, the Americas and Mediterranean coast (Figure 5), indicating that the economy is developing rapidly in these areas, while the population or construction is not growing synchronously. This characterizes a phase of decentralized urbanization, potentially entailing excessive energy consumption. IBGB (Imbalanced Growth of Buildings) could been detected briefly in China, South Korea, and part of the Middle East (Figure 5), reflecting that the development of buildings (urban expansion or infrastructure construction) is faster than population or economic growth. While planning is inherently forward-looking, a justifiable concern remains regarding the inefficient allocation or vacancy of resources that may result.

These findings profoundly validates and visualizes the inevitability and potential risks of imbalanced growth as a specific stage of reality for developing countries, suggesting that theoretical research must focus on the diffusion and transmission mechanisms of growth drivers. At the policy level, it highlights the importance of abandoning the “one size fits all” strategy, and instead, promoting precise collaborative governance.

4.3 VCRPGR and NGRVCR expose increasing numbers of shrinking cities over time

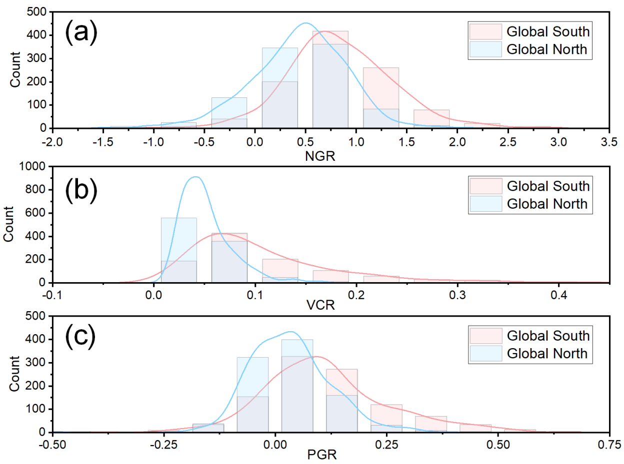

Figure 6. Histogram and kernel density distribution curves of the NGR, PGR, and VCR for the Global North and Global South.

By analogy with SDG 11.3.1, we introduce two novel metrics, the ratio of the building volume consumption rate to the population growth rate (VCRPGR) and the ratio of the nighttime light growth rate to the building volume consumption rate (NGRVCR), to quantify the relationships between urban population growth, economic development, and 3D space utilization. Both of these metrics are defined as ratios, with higher values indicating that the dimensions located in the numerator develop faster than those located in the denominator. Conversely, values that tend towards 0 indicate the opposite. Notably, all of the urban areas had positive building volume consumption rates (VCRs) between 2010 and 2020, indicating a universal increase in building levels, while the population growth rates (PGRs) and

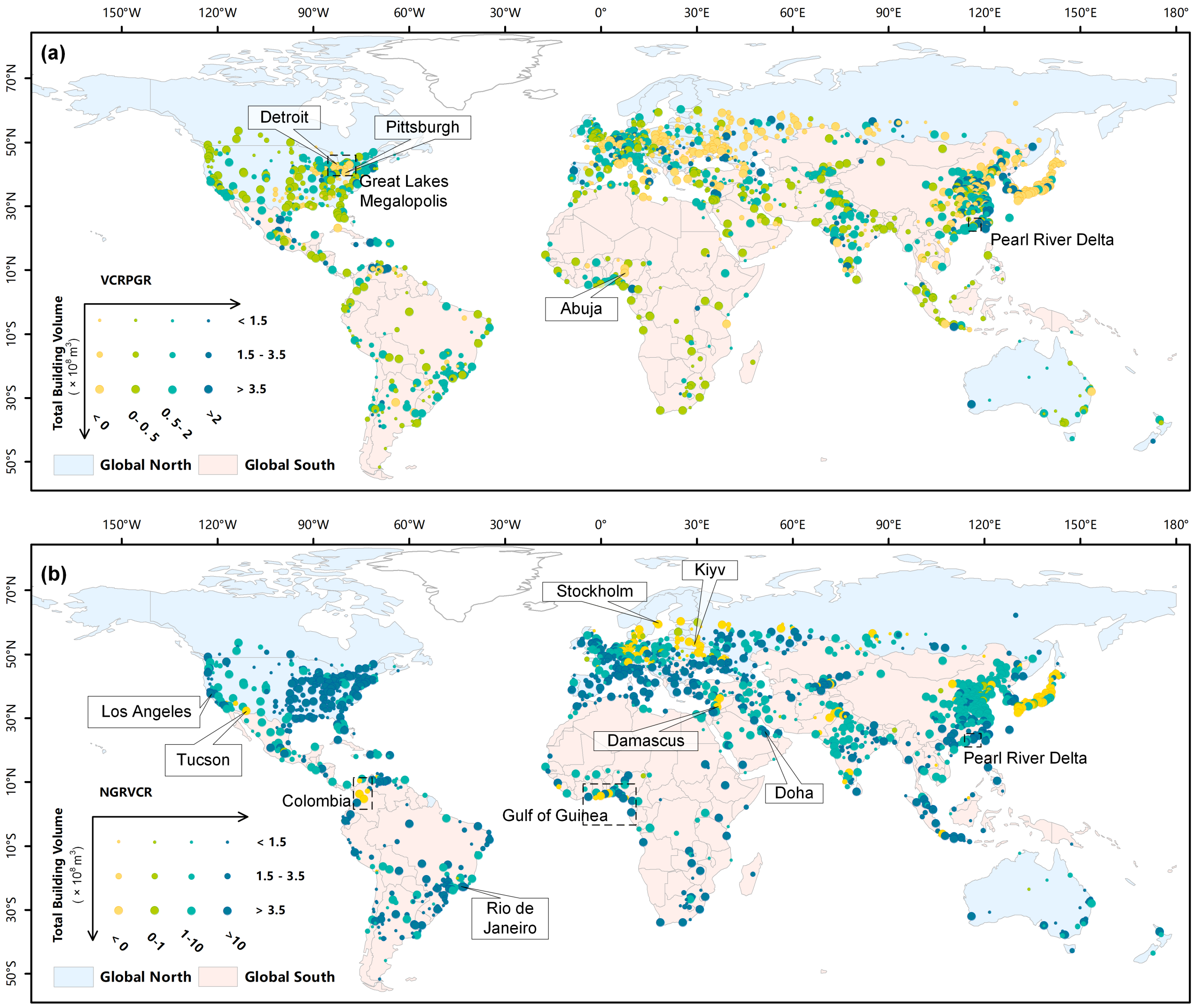

Figure 7. The trends of urban population, space construction, and economic activities during 2010–2020. The color of each point indicates the area's VCRPGR or NGRVCR, and the size indicates its total urban building volume.

nighttime light growth rates (NGRs) exhibited clear divergence, with both positive and negative trends (Figure 6). Thus, negative values of the VCRPGR and NGRVCR metrics indicate a decline in the population or nighttime light in the region.

Calculation of the VCRPGR revealed that many of the urban areas were confronted with challenges related to population decline or infrastructure overexpansion (Figure 7(a)). Areas with VCRPGR values greater than 2 exhibited significantly faster spatial expansion compared to population growth, accounting for about 10% of the total number of urban regions. These regions were primarily located in East Asian countries such as China, South Korea, and parts of Europe (Figure 7(a)). Approximately 28% of the total urban areas, which were mainly located in the Eastern Central United States, Europe, Japan, and Northeast and Central China (Figure 7(a)), had negative VCRPGR values. In these locales, population decline persisted despite continued spatial expansion. The urban areas in these two data intervals may face potential issues such as resource wastage, underutilized assets, and imbalances in urban functionality.

Roughly one-quarter of the urban areas had VCRPGR values between 0 and 0.5, suggesting a trend of population densification. These areas were widely distributed, with a Global North to Global South ratio of approximately 4:6. Accounting for the overall disparity in the numbers of urban areas in these regions, the proportional distribution within this interval was comparable. This indicates that in the Global North, we cannot afford to overlook localized population increases that outpace local development, despite an overall slowdown in population growth. These areas also face infrastructure pressures and social instability risks due to population densification. VCRPGR values between 0.5 and 2 signify a relatively balanced interplay between building volume and population growth. Only 33.4% of cities fell within this range, suggesting a low risk of short-term population or resource challenges.

The NGRVCR varied significantly among global urban areas and exhibited pronounced spatial concentration. In the Eastern Central United States, Southern Europe, South America, South-Eastern Asia, and along China's southeastern coast, the NGRVCR mostly exceeded 10 (Figure 7(b)), indicating markedly elevated economic activity that had not been matched by urban construction. In contrast, urban areas in European countries such as Syria, Ukraine, and Poland, as well as in Japan, had negative NGRVCR values, exhibiting a pronounced decline in nighttime light. Notably, over 70% of Japanese urban areas had negative NGRVCR values during the studied decade (Figure 7(b)). It is important to note that a reduction in nighttime light does not necessarily imply diminished economic or human activity. It may also reflect the implementation of environmental policies or advancements in lighting technology.

4.4 Comparison with previous findings on urban expansion

Previous studies on urban expansion have predominantly characterized urban growth using two-dimensional representations and area-based indicators (Mahtta et al., 2022), often focusing on land-use efficiency and the relationship between land consumption and population growth. These studies have consistently reported widespread mismatches between land expansion and demographic change, particularly in rapidly urbanizing regions, highlighting concerns regarding inefficient land use and unsustainable urban sprawl.

Our findings are broadly consistent with these observations in that imbalances between spatial expansion and population growth are also evident in our results. However, by incorporating volumetric measures of urban space, this study reveals that such mismatches are not solely a function of horizontal land expansion, but also reflect divergent dynamics between vertical and horizontal development. In particular, we find that many urban areas—especially in the Global South—simultaneously exhibit rapid vertical growth alongside horizontal expansion, a pattern that cannot be captured using conventional area-based approaches.

Moreover, while previous studies have primarily interpreted these mismatches from an efficiency perspective (Cai et al., 2020, Huang et al., 2024), our results suggest that they are better understood as manifestations of asynchronous development across multiple urban dimensions, including population, economic activity, and spatial structure. The identification of distinct imbalanced growth types (e.g., IBGP, IBGE, and IBGB) further extends existing findings by demonstrating that urban expansion is not governed by a single dominant process, but rather by differing development priorities across regions.

Therefore, this study not only confirms the existence of uneven urban growth identified in prior research, but also provides a more comprehensive and mechanistic interpretation of these patterns through a three-dimensional and multi-dimensional analytical framework.

5. Conclusion

This study addressed a fundamental question in urban science: how asynchronous growth across population, economy, and three-dimensional urban space can be quantified and interpreted using volumetric urban expansion, and how such imbalances vary globally. We delineated global patterns of volumetric urban development by employing a 3D architectural perspective, developed a novel 3D-based framework for evaluating urban growth, and further, reframed urban expansion as a multi-dimensional and inherently imbalanced process. Rather than treating urban growth as a question of efficiency, our findings highlight that urbanization is fundamentally characterized by relative development dynamics across interacting subsystems. This 3D-based framework further refines our understanding of imbalanced growth across urban dimensions, highlighting the priority of adopting policies tailored to local conditions. Our findings could provide valuable insights into urban sustainability, especially for countries in the Global South. This perspective not only improves the measurement of urban spatial development, but also provides a new lens for interpreting regional heterogeneity, particularly in the Global South, where vertical and horizontal growth frequently evolve at different speeds. More broadly, it suggests that sustainable urbanization should be understood not merely as controlling expansion, but as coordinating development priorities across demographic, economic, and spatial dimensions.

However, this study also has certain limitations. Currently, globally consistent long-term datasets on building height remain scarce, and the available sources suffer from both relatively low spatial and temporal resolutions and limited time ranges. In the future, we will strive to produce building height datasets with longer time series and global coverage to support research related to urbanization.

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