Information on urban built-up infrastructure is essential to understand the role of cities in shaping environmental, economic, and social outcomes. The lack of data on built-up heights over large areas has limited our ability to characterize urban infrastructure and its spatial variations across the world. Here, we developed a global atlas of urban built-up heights circa 2015 at 500-m resolution from the Sentinel-1 Ground Range Detected satellite data. Results show extreme gaps in per capita urban built-up infrastructure in the Global South compared with the global average, and even larger gaps compared with the average levels in the Global North. Per capita urban built-up infrastructures in some countries in the Global North are more than 30 times higher than those in the Global South. The results also show that the built-up infrastructure in 45 countries in the Global North combined, with ~16% of the global population, is roughly equivalent to that of 114 countries in the Global South, with ~74% of the global population. The inequality in urban built-up infrastructure, as measured by an inequality index, is large in most countries, but the largest in the Global South compared with the Global North. Our analysis reveals the scale of infrastructure demand in the Global South that is required in order to meet sustainable development goals.

Satellite mapping of urban built-up heights reveals extreme infrastructure gaps and inequalities in the Global South

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Edited by B. Turner, Arizona State University, Tempe, AZ; received August 29, 2022; accepted October 12, 2022

Urban areas are home to 55% of the world’s population today, a proportion that is expected to increase to 68% by 2050 (1). About 80% of global GDP and two-thirds of greenhouse gas emissions are attributed to urban areas (2). However, cities across the world exhibit profound infrastructure inequality, with significant variation in infrastructure availability, provision, and access (3). Since urban infrastructure is highly correlated with urban economic growth and city-level gross domestic product (GDP) (4, 5), high levels of infrastructure inequality could contribute to lower levels of economic productivity, social capital, and human well-being (6, 7). Evaluating infrastructure inequality is critical for understanding the heterogeneous development patterns of cities across different regions and countries (8).

Urban form includes both the two-dimensional (2-D) urban areas and density and the three-dimensional (3-D) built-up heights (i.e., vertical characteristics of physical patterns, layouts, and structures of cities) (5, 9). Urban areas have been mapped extensively in 2-D using satellite imageries from nighttime lights (10) and time-series Landsat (11). With 60 ~ 80% of energy consumption occurring in urban areas (12), it is important to map urban forms, which have been shown to influence energy use and greenhouse gas emissions (13, 14). Since urban form includes the vertical dimension of the built environment, mapping urban built-up heights can provide information about critical elements of urban areas.

There is also a strong correlation among higher urban built-up density, taller buildings, and urban economic growth (4). A recent study of 477 large cities with a novel time-series satellite dataset showed that urban volumetric growth is strongly correlated with city-level GDP (5). Recent advances in remote sensing have enabled the development of several new datasets of 3-D built-up areas, including one of dataset on 3-D building stock worldwide (15), a high-resolution map of urban morphology (16), a three-decade time series of vertical built-up area (17), and typologies of urban 2-D and 3-D growth for nearly 478 cities worldwide (18). However, built-up height information over large areas is still limited, which obscures our understanding of urban development and its implications for energy use and greenhouse emissions (19, 20).

Here we estimated global urban built-up heights at a 500-m x 500-m grid level to characterize the distribution of infrastructure in urban areas (Fig. 1A and SI Appendix, Figs. S13–18). Built-up heights were calculated as the mean height within a 500-m grid, including both buildings and other infrastructures such as streets, parking lots, and green space, using a model we previously developed (21) based on the Sentinel-1 Ground Range Detected (GRD) data. We validated the GRD-derived, urban built-up

**Significance**

Information on urban built-up heights globally is needed to evaluate the effects of urban form and infrastructure on the environment, the economy, and human well-being. This study provides a global atlas of urban built-up heights and shows large spatial variations in built-up heights at continental, country, and city levels. The results reveal extreme gaps in urban built-up infrastructure availability in the Global South and large inequality in built-up infrastructure in most countries, but largest in the Global South compared with the Global North. The atlas has the potential to improve our understanding of the effects of urbanization on raw material demand, embodied and operational energy use, and urban development intensity.
heights using multiple sources of reference data. We found that the estimated urban built-up heights show good agreement with the reference data and can capture the variation in built-up heights from urban cores to peri-urban areas. This new global built-up heights dataset has significant potential to improve our understanding of how urban activities transform Earth’s surface, reveal spatial inequalities of urban infrastructure, and contribute to energy and climate studies.

Results

Urban Form of Cities by Combining Urban Density and Built-up Height. The global atlas of urban built-up heights (Fig. 1A) provides critical information to characterize urban form in 2-D to 3-D across the world. Overall, urban areas are dominated by low density and expansive development with low urban built-up heights. Built-up heights show large spatial variations across cities and regions. Cities with high levels of verticality are predominately located in East Asia and Western Europe. The two countries with the largest total urban extents, the United States and China, have contrasting patterns of built-up heights. The mean built-up height in China is two times higher than that in the United States. This corroborates other studies which have found similar differences in built-up heights between these two countries (5, 17). Although their total urban extents are similar, they differ in their capacity to accommodate urban populations, due to differences in built-up heights. We evaluated both urban density (i.e., imperviousness) and built-up heights (i.e., mean and variation within a city) and grouped cities worldwide into six categories. Some of these six types of cities show geographic clustering (Fig. 1B). For example, the South Atlantic region of the United States is dominated by cities with low density, and low and homogeneous built-up heights, while cities in East Asia are mainly tall and not very dense.

Although similarities in urban density and built-up heights at the city level can be discerned globally (Fig. 1B), high-spatial-resolution information on built-up heights is still needed because of the large variation in built-up heights within cities (Fig. 2). Generally, most cities have a distinct peak in built-up heights in the urban center, with declining heights from the center outward to surrounding areas. There are, however, some cities with multiple urban centers (e.g., Cape Town, South Africa, and New York City, USA).
Delhi, India), illustrated by more than one built-up height peak. In some cities such as New Delhi, where there are policy restrictions on building height (22), the results show both density and built-up heights to be generally low. Some large, low-rise cities such as Atlanta, Georgia in the United States, have high-rise buildings in their urban centers, but the proportion of such buildings is very low. Cities such as Seoul, Republic of Korea (South Korea), have large areas with high built-up heights outside of the urban centers, as do some European cities (e.g., Munich, Germany).

**Extreme Gaps in Urban Built-up Infrastructure in the Global South.** We found that the world’s wealthiest nations contribute disproportionately to the global total urban built-up infrastructure (Fig. 3). A total of 45 countries in the Global North with a combined ~16% of the global population have nearly equal amounts of global urban built-up infrastructure as 114 countries in the Global South, which have ~74% of the global population. Together, the top three countries with the largest amount of urban built-up infrastructure, China, the United States, and Japan, account for ~50% of the global total. Overall, there are more countries in the Global North (e.g., the United States, Japan, Russia, Germany, France, Italy) each contributing more than 2% to the global total built-up infrastructure. It is worth noting that lower urbanization levels in the Global South may lead to an underestimation of per capita built-up infrastructure because we only included urban infrastructures in this analysis.

The analysis uncovers large differences in per capita built-up infrastructure across countries and extreme gaps in per capita urban infrastructure availability between the Global North and Global South (Fig. 4A and B). Although the total urban built-up infrastructure is large in some countries such as China, the per capita level is still considerably lower compared to the Global North. The findings show that per capita infrastructure for ~90% of the global population is lower than the average level of the Global North. The average per capita urban built-up infrastructure is large in some countries such as China, the per capita level is still considerably lower compared to the Global North. The average per capita urban built-up infrastructure of the Global North is ~300 m³, which is approximately three times that in the Global South (108 m³). Some countries in the Global North (e.g., the United States) have per capita built-up infrastructure larger than 600 m³, while it is as low as 20 m³ in some countries in the Global South, such as Bangladesh, reflecting an extreme 30-fold disparity. The large

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**Table: ISA (%)**

| Continent          | Type                                      | Cities             |
|--------------------|-------------------------------------------|--------------------|
| Africa             | Sparse and homogeneously low              | Algiers, Ankara,   |
| Asia and Oceania   | Dense and homogeneously low               | Khartoum, Adelaide,|
| Europe             | Sparse and heterogeneously low            | New Delhi, Madrid,|
| North America      | Dense and heterogeneously low             | Minsk, Regina,     |
| South America      | Sparse and homogeneously high             | Nairobi, Seoul,    |
|                    | Dense and homogeneously high              | Munich, Medellin,  |

![Fig. 2. A 3-D view of representative cities for the six types of urban forms in Fig. 18. None indicates that there is no such city group in that continent.](image-url)
The global shares of built-up infrastructure in the Global North and South. A total of 45 countries in the Global North and 114 countries in the Global South have roughly equivalent percentages of global built-up infrastructure. Country names and their portions are shown in the figure.

Large Inequality in Urban Built-up Infrastructure in the Global South. We found large inequalities in urban built-up infrastructure in most countries, but largest in countries in the Global North (mean: 0.49) (Fig. 5B). Furthermore, results show a significant and strong association between per capita GDP and per capita urban infrastructure (Fig. 4C and SI Appendix, Fig. S7). This relationship suggests a large demand for future infrastructure in the Global South.

The extreme gap in per capita built-up infrastructure in the Global South suggests impending large global demand for materials and increases in embodied energy and greenhouse emissions if the gap is filled. The results also suggest increasing demands for infrastructure with economic development. More than the current total amounts of global built-up infrastructure will be needed to address climate change mitigation. Urbanization is a feature of urbanization (3).

Implications of the Global Urban Built-up Heights. The global atlas of built-up heights has important implications for energy use and climate change mitigation. For example, urban transport-related energy consumption is of particular importance because of its large share of total energy use and potential for climate change mitigation. Higher population densities are correlated with lower vehicle miles traveled and energy consumption (24). Built-up heights provide a more direct and spatiotemporally consistent measure of urban form than population density, which often needs to be downscaled from regional-level data (25). Furthermore, we found a negative relationship between a city’s mean built-up heights and transport-related energy consumption (Fig. 6). We did not find a strong relationship between transport-related energy use and 2-D measures of urban extent (SI Appendix, Fig. S9). Cities with lower built-up heights have higher transport-related energy consumption compared with more vertical cities. This suggests that strategies to lower transport-energy use may be achieved through strategic vertical growth that puts more people in closer proximity to jobs. However, the tradeoffs between lower transport energy and greater material and energy intensity to build and operate tall buildings must be considered.

Discussion

The large spatial variations in built-up heights can be attributed to various factors such as land-use histories and policies, especially with regard to early infrastructure investments, zoning, building codes, and height restrictions. Land-use restrictions and transportation infrastructure and policy are among the most important factors behind building heights. Built-up heights in East Asia are generally higher than in North America and Europe, while relatively lower population density in the most United States cities is a reflection of lower urban built-up heights. Despite high population densities in both China and India, urban built-up heights in China are notably taller compared with India, mainly due to floor area ratio regulations in India (22). Built-up heights are generally higher in countries that have undergone significant urbanization in recent decades compared to those whose urbanization transition occurred many decades ago (26). Moreover, the limited land resources and high land prices are correlated with higher urban heights in Asia and Europe (27, 28).

The extreme gap in per capita built-up infrastructure in the Global South suggests impending large global demand for materials and increases in embodied energy and greenhouse emissions if the gap is filled. The results also suggest increasing demands for infrastructure with economic development. More than the current total amounts of global built-up infrastructure will be
needed to meet the infrastructure gap, even assuming no population growth. With expected population growth, this demand could increase by $\sim 1.25$ to $1.65$ times the current global total urban built-up infrastructure under Shared Socioeconomic Pathway 1 (sustainability) and Shared Socioeconomic Pathway 3 (regional rivalry) scenarios (29), respectively. With a growing demand for construction materials and specialized rare earths, there may be a continued lag in infrastructure development in the Global South, resulting in low levels of human development. Moreover, most projections of future urbanization in most studies only considered lateral urban land expansion. An improved understanding of vertical urban growth is needed to develop a more realistic projection of future demand for built-up infrastructure.

The large inequality in urban built-up infrastructure worldwide implies great challenges for sustainable development, because infrastructure either directly or indirectly influences $72\%$ of the targets of the United Nations Sustainable Development Goals (30). The challenge is largest in the Global South, with greater infrastructure inequality, especially in African countries. Because economic development itself will not decrease infrastructure inequality, other efforts and strategies are needed to reduce urban built-up infrastructure inequality. Even though this study explored global infrastructure inequality, the limited scope of the study warrants further investigation into the efficient, effective, and economical practices that can mitigate infrastructure inequality. Additionally, further investigation of infrastructure inequality beyond the national level in large countries (e.g., China) with substantial regional variations of built-up infrastructure can offer new insights for sustainable development at finer scales.

Information on built-up height variations within a city has significant potential to advance studies such as urban climate and energy-use modeling (31, 32). Outdoor ventilation can be influenced by building height variation (33). Gridded built-up heights also serve as a key input for estimating other important urban surface parameters such as roughness, which can significantly affect the urban atmospheric environment. Transportation energy consumption and emissions are generally higher in
cities with a single center, compared with those cities with multiple centers (34) which can increase the overall accessibility, shorten the trip length, and optimize public transport services (35). The frequency of different built-up heights within the city can help reveal urban land uses and travel patterns and, therefore, support studies on urban transportation and energy use.

The atlas of built-up heights can improve our understanding of the demand for building construction material, embodied and operational energy use, and associated carbon (36–38). For example, building heights have been used to estimate building floor space, a critical variable in energy and material demands modeling (39). It is clear that areas with high built-up heights contain more building materials such as cement. However, the large spatial variation of built-up heights has not been considered in most carbon studies due to limited data availability, especially in the Global South (40, 41). Compared with 2-D maps of urban areas, built-up heights can be notably different in cities with similar urban areas, leading to large differences in urban volume and embodied energy use among these cities (42). In addition, high-rise buildings consume more energy and emit more anthropogenic heat flux to the atmosphere than low-rise buildings (42). Accurate estimation of building anthropogenic heat flux is helpful to better understand the contribution of buildings to urban climate and further support sustainable development.

The atlas of built-up heights also provides unique information for the estimation and projection of building energy consumption and associated emissions. The information on built-up heights can significantly improve the quantification of building floor space, one of the key variables in modeling building-embodied and operational energy consumption. For example, building floor space is one of the key variables in the integrated assessment models, such as the GCAM (Global Change Assessment Model) (43) and MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) (44), which can project future building energy demands to evaluate the impact of climate change and develop mitigation strategies. However, current information about building floor space, especially in the Global South, is limited (39). Although building floor space scales linearly with urban extent, there are still significant discrepancies because of the variations in
different functions can be better identified and, therefore, temporal dynamics (e.g., diurnal) of populations can be better characterized.

The dataset on global urban built-up heights and infrastructure can also support applications such as urban scaling (45, 46) and mapping population distribution and dynamics (25, 45, 46). Studies show that urban infrastructure volume scales faster with population than urban extent (45). Consistent measurements of 3-D urban built-up infrastructure provide a more comprehensive urban indicator to investigate the power-law scaling relations of city size. Built-up heights can also advance our capacity to downscale national population to finer spatial scales. Compared with the traditional approaches that consider only 2-D urban areas (e.g., nighttime lights) (47), built-up heights can differentiate population in grids with similar urban extents and human activities. For example, built-up heights have been used to map hourly population dynamics together with other remotely sensed and geospatial data (25). Moreover, built-up heights can help map urban land uses (e.g., commercial, residential, industrial) (48). With the help of vertical information, urban land uses with different functions can be better identified and, therefore, temporal dynamics (e.g., diurnal) of populations can be better characterized.

Materials and Methods

Data.

**Sentinel-1 data.** We collected the Sentinel-1 GRD data as the main data source in mapping global urban built-up height. The Sentinel-1 GRD data, both with ascending and descending orbits, were collected circa 2015 when a global coverage of Sentinel-1 data became available (49). Here, the used GRD scenes were collected from the instrument mode of the interferometric wide swath, of which backscatter coefficients (i.e., VV [copolization] and VH [cross-polarization]) from a dual-polarization C-band SAR instrument onboard were included with a raw spatial resolution of 10 m.

**Reference built-up height data.** We collected reference built-up height data in 37 cities in the United States (7) and Europe (30) (SI Appendix, Fig. S6) for model development and evaluation. These fine spatial resolution (<10 m) reference datasets were mainly derived from airborne light detection and ranging data in the United States (21) and stereo images in Europe (50). It is worth noting that reference built-up heights of 27 cities in the United States and Europe were used to calibrate the urban built-up height model, while those of the remaining 10 cities were used to evaluate the estimated heights from the Sentinel-1 data. The reference data recorded as the floor number in 20 cities in China (https://www.amap.com), reference height data in Sao Paulo, Brazil (https://osmbuildings.org), Vancouver, Canada (https://opendata.vancouver.ca), and the gridded (10 m) built-up height product in Germany derived from satellite observations (51) were also collected as additional datasets for evaluation.

**Urban boundary data.** We collected the boundary of urban areas at a fine resolution (30 m) in 2015 from the global urban boundary dataset (52). Urban areas defined in this dataset were used to calculate per capita infrastructure for countries and counties and to delineate urban boundaries of representative cities.

**World Bank data.** We collected the population and GDP data of each country in 2015 from the World Bank (https://data.worldbank.org). The population was used to calculate per capita GDP and built-up infrastructure shown in Figs. 3 and 4. In total, we examined 159 countries, of which 45 countries are in the Global North (e.g., the United States and Australia) and 114 countries are in the Global South (e.g., China, Egypt, India). The Global North and Global South have been defined according to socioeconomic and political characteristics, and the countries in these two groups vary slightly across studies (53). In this article, the names of countries in the Global South, which refer to those developing countries that share a set of vulnerabilities and challenges, were obtained from the United Nations Development Program (54).

**Building floor-space data.** We collected per capita building floor space of the selected United States counties from Arehart et al. (39) to explore the implication of urban built-up heights in energy modeling. Taking county as the geographical unit, we calculated the mean built-up height and urban percentage (the ratio of the urban area in a county to the area of a county). The top 25 counties were selected by sorting urban percentages in descending order in the United States with the total county area smaller than 400 km² to highlight the importance of built-up heights.

**Urban transport energy consumption data.** We used the transport-related energy consumption dataset (24) to show the relationship between urban built-up height and transported-related energy consumption. This dataset included per capita transport-related energy consumption in 31 cities. The mean built-up height for each city was calculated from the gridded built-up height based on the urban boundary.

Methods

**Mapping global urban built-up height.** We estimated urban built-up heights worldwide using a model we previously developed (21) based on Sentinel-1 GRD data. We defined the urban built-up height as the mean height within a 500-m grid in the urban domain, including buildings and nonbuildings such as streets and parking lots (SI Appendix, Fig. S1). First, we aggregated the Sentinel-1 GRD data (i.e., backscatters from VV and VH) in 2015 and the reference building height data in 27 of 37 cities in the United States and Europe (SI Appendix, Fig. S6) to a 500-m resolution, which was determined by sensitivity analysis of the resolution from 100 m to 1 km (21). To mitigate the impact of elevated objects (e.g., trees), we masked out nonurban areas in Sentinel-1 GRD data using the urban extent map from the global human settlement layer (55). Then, we derived the VH, an indicator of urban heights, by integrating backscatters from the dual-polarization information (i.e., VV and VH) from the Sentinel-1 GRD data at a 500-m resolution (Eq. 1). Finally, we calibrated the urban built-up height model (Eq. 2; i.e., the relationship between the VH and the log-transformed urban built-up height):

\[
VVH = VV \times r^{VH} \tag{1}
\]

and

\[
\ln H = a + VH^b + c \tag{2}
\]

where \(\gamma\) is the parameter to characterize the relative impact of VH on the derived VH, \(H\) is the log-transformed urban built-up height, and \(a, b, c\) are the coefficients to be estimated in the urban height model. In this study, \(\gamma\) was set as 5,
as suggested by Li et al. (21). Such a physical-based, built-up height model can be used to estimate urban built-up heights worldwide. We developed the building height models using the Sentinel-1 data with ascending and descending orbits, with calibrated parameters (i.e., a, b, and c) of $-2.16$, $-0.45$, 4.78, and $-0.61$, $-0.79$, and 2.31, respectively. The final global built-up heights derived by merging results from the ascending and descending observations can be downloaded from https://figshare.com/s/72b254ed11f3a8eb7a0.

We evaluated the estimated global urban built-up heights based on three indicators: correlation coefficient, root mean square error (RMSE), and mean absolute error (MAE). First, we conducted a leave-one-out cross-validation using the reference built-up height data in 27 of the 37 cities in the 10 km \times 10 km domain in the urban area in the United States and Europe (SI Appendix, Fig. S2). The reference built-up height data were randomly divided into 10 folds, and each time, one fold was used for evaluation. Second, we evaluated the estimated urban height using the remaining 10 of the 37 cities in the 10 km \times 10 km domain in the urban area (SI Appendix, Fig. S3), and in the entire urban area in all 37 cities. Finally, we evaluated the estimated urban built-up height using the reference data of floor numbers in 20 cities in China (SI Appendix, Fig. S4), the reference data of building height in Sao Paulo, Brazil; Vancouver, Canada; and the national built-up height product (10 m) in Germany from satellite observations (SI Appendix, Fig. S5).

The global urban built-up heights show a good agreement with the reference data and can capture the variation of built-up heights (SI Appendix, Fig. S2). The RMSE between the reference and estimated urban built-up heights is below 0.50 m, and the correlation coefficient is greater than 0.80 (SI Appendix, Fig. S3). The estimated urban built-up heights in China are also reliable, as indicated by the indicators of RMSE and MAE using the reference data of floor numbers (SI Appendix, Fig. S4), with a slightly lower correlation coefficient due to the difference between the floor number and heights. Similar results (i.e., RMSE: 0.37–0.47 and MAE: 0.40–0.49) were obtained in Sao Paulo, Brazil; Vancouver, Canada; and Germany (SI Appendix, Fig. S5), using the reference data of building height and the gridded built-up height product from satellites. Urban form by combining 2-D density and 3-D height. We grouped the world cities into six types based on the feature space of their 2-D urban density (imper- viousness) as well as 3-D built-up heights (mean and variation within the city) (SI Appendix, Fig. S11). We calculated the mean and the quartile coefficient of dispersion (QCD) (Eq. 3) of built-up heights as well as the mean of impervious surface areas (ISA) in each city to describe urban form in vertical and horizontal dimensions:

$$\text{(QCD)} = \frac{Q_3 - Q_1}{Q_1 + Q_3}, \quad [3]$$

where $Q_1$ and $Q_3$ are the first (25th percentile) and third (75th percentile) quantiles of built-up height in each urban area. QCD can capture the variation of built-up heights within the city and is also comparable between cities with different mean heights. Mean ISA can represent the overall impervious density of the city and was calculated from the 30-m global ISA data (56). We defined thresholds of imperviousness, mean, and QCD of built-up heights (mean height: 3; QCD: 0.6; mean ISA: 0.75) to classify cities globally into six types, mainly based on the data distribution of each feature. The main purpose is to compare cities and to show a general view of the global landscape of urban form with the consideration of both 2-D density and 3-D height. These thresholds can be adjusted easily to reclassify the world cities. We found that the variation of built-up heights in tall cities tends to be low. Therefore, we did not have types of cities that are both tall and heterogeneous in built-up heights. These six types of cities are (1) sparse and homogeneously low, (2) dense and homogeneously low, (3) sparse and heterogeneously low, (4) dense and heterogeneously low, (5) sparse and homogeneously high, and (6) dense and homogeneously high. Per capita and inequality of urban built-up infrastructure. In this study, we proposed that the urban built-up volume by multiplying urban area and heights can be considered as a proxy for urban built-up infrastructure. We calculated urban built-up infrastructure in each grid and added up all pixels in each country. The accumulative population percentage and per capita infrastructure in each country were calculated using the population records from the World Bank. A total of 159 countries worldwide (those without GDP records, such as Democratic People’s Republic of Korea [North Korea] were excluded) were examined in Figs. 3 and 4. In Fig. 3, the area of each rectangle represents the percentage of total built-up infrastructure in each country. We also explored the relationship between per capita infrastructure and GDP in each country, using data from the World Bank.

Using the method proposed by Pandey et al. (3) and Brelsford et al. (23) (i.e., Eq. 4), we calculated the inequality index of urban built-up infrastructure that can measure the level of spatial inequality in infrastructure in each of 119 countries (with the total number of urban areas delineated by the 2015 urban boundary data larger than 10) in the Global South and North:

$$I = \frac{\sigma}{\sqrt{\mu (1-\mu)}} : 0 < \mu < 1, \quad [4]$$

where $I$ is the inequality index ranging from 0 (lowest inequality) to 1 (highest inequality), and $\mu$ and $\sigma$ are the mean and SD, respectively, of built-up infrastructure distributions constrained by an upper bound in each geographic region. This index examines how between-region (SI Appendix, Figs. S8 and S12) heterogeneities vary with the overall mean of infrastructure distributions constrained by an upper bound (3). We also tested three upper bounds (i.e., 90, 95, and 100 quantiles in infrastructure distributions) in calculating the inequality index. First, we calculated quartiles of 90, 95, and 100 from the infrastructure distribution in each geographic region as three upper bounds. Second, we generated infrastructure distributions in each geographic region constrained by those three upper bounds. Finally, under each constrained upper bound, SD ($\sigma$) and mean values ($\mu$) were derived to calculate the inequality indexes. Our results are robust to varied upper bounds, as shown in SI Appendix, Fig. S8.

Data, Materials, and Software Availability. All data needed to evaluate the conclusions in the paper are present in the article and/or the SI Appendix. The datasets analyzed in this study are publicly available, as referenced in the article.

ACKNOWLEDGMENTS. This research was funded by the NSF (grant CBET-2041859) and the College of Liberal Arts and Science Dean’s Emerging Faculty Leaders award at the Iowa State University.

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