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Scaling law reveals unbalanced urban development in China

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ABSTRACT

Managing complex cities for sustainability requires coordinated development of different urban functions. Urban scaling theory provides a quantitative framework to explore the temporal change of urban properties against city size and reveal if urbanization is balanced or not. We modeled urban allometries for Chinese cities from 1984 to 2019 and quantified the variation in the scaling exponents for assessing the degree of unbalanced development across urban functions. We found urban China had weaker scaling relationships than its developed counterparts. The exponents for most urban functions showed different trajectories from those of developed countries and did not converge to the theoretical exponents. The temporally divergent exponents showed a strong unbalanced development, particularly between socio-economic and social service functions. Our study indicates that although unbalanced development could stimulate urban growth, excessive imbalance ultimately limits urban development of Chinese cities. The best urban development is achieved at an intermediate functional imbalance.

1. Introduction

Cities are multi-dimensional complex systems with different features interwoven and co-evolved (Batty, 2007). Building cities that are economically, socially, and environmentally sustainable requires the quantitative and functional understanding of various entangled urban attributes, such as productivity, infrastructure provision, access of public services, and natural resources (DESA, 2019). Urban scaling, which roots in these complexities, provides a general framework to model different urban components and their relationships (Batty, 2013; Bettencourt, 2013; Bettencourt et al., 2007). Integrating fundamental concepts in economic geography and allometries in complex science (Bettencourt, 2013), urban scaling theory offers a quantitative framework necessary for understanding the complex relationships and their dynamics of multifaceted attributes inherent to cities (Batty, 2013). Urban scaling has been used to model the processes underlying city development (Hong et al., 2020; Sahasranaman & Bettencourt, 2019), test if the development of urban attributes is in balance (Lei et al., 2021; Pumain & Rozenblat, 2019), and assess city sustainability (Akuraju et al., 2020; Sugar & Kennedy, 2021). The scaling law describes the relationship between an urban attribute Y and city (population) size N, in the form: $Y = \alpha N^{\beta}$, where α is a constant, β is a dimensionless scaling exponent quantifying the relative development of the urban function against population agglomeration, with large β indicating strong positive agglomerative feedback (Batty, 2013; Marshall, 1890). Taking the isometric relationship as a benchmark, $\beta = 1$ indicates the per-capita amount of an urban function provided to residents is independent of city size. When $\beta > 1$, this urban function grows at an accelerating rate with respect to population size (Bettencourt et al., 2007). When $\beta < 1$, this urban function saves cost at the decreased per-capita supply (Batty, 2013; Bettencourt et al., 2007) but restricts urban growth with the sustainable challenge of overburden during the cause of population aggregation (Henderson, 2010; Pumain, 2012). As a metric for measuring the agglomeration effect of population change, β is useful for capturing the features of urban functions (Balland et al., 2020; Oliveira et al., 2014) and the development status of urban systems (Lei et al., 2021; Pumain & Rozenblat, 2019; Sahasranaman & Bettencourt, 2019) in relation to the change of city size.

Supported by empirical data from both ancient societies (Ortman et al., 2015) and modern urban systems (Bettencourt & Lobo, 2016;

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Bettencourt et al., 2007), and for attributes of both human activities (Balland et al., 2020; Hong et al., 2020; Schläpfer et al., 2014) and natural environment (Kennedy et al., 2015; Manoli et al., 2019), four types of scaling properties of cities have been generalized (Bettencourt, 2013; Bettencourt et al., 2007): scaling that describes increasing returns to scale in socio-economic interactions ($\beta \approx 7/6 > 1$), the service required to meet the basic needs of the population ($\beta \approx 1$), economies of scale in infrastructure ($\beta \approx 5/6 < 1$), and geometric expansion of urban area ($\beta \approx 2/3 < 1$). Bettencourt (2013) later showed that these scaling allometries can be derived from a theoretical model that describes an ideal (mature) city balanced by two forces that agglomerate people and maintain their life: (1) socio-economic benefits and (2) transportation costs. This theoretical model offers a general framework for understanding urban scaling behaviors (Batty, 2013), although other mechanisms have also been proposed to explain urban scaling allometries (Arbesman et al., 2009; Bettencourt, 2020; Li et al., 2017; Pumain et al., 2006; Yakubo et al., 2014). From the light shed by the mature city model, we can expect the scaling exponent to change depending on whether a city is at equilibrium or not (Bettencourt, 2013, 2020), how social interactions generate social output and promote infrastructure construction (Bettencourt, 2013; Li et al., 2017; Yakubo et al., 2014), and what developmental stage of an urban function is at (Pumain et al., 2006).

In the effort to test the universality of urban scaling laws against a greater diversity of urban systems, some studies suggest that, in rapidly developing urban systems such as those in China (Lang et al., 2019; Lei et al., 2021; Zhao et al., 2018; Zünd & Bettencourt, 2019), India (Sahasranaman & Bettencourt, 2019) and Brazil (Meirelles et al., 2018), the urban scaling exponents are bound to change over time and deviate from the above four scaling exponents. It is thus critically important to assess and interpret the temporal change in scaling exponents and the difference in scaling behaviors between different, e.g., developing and developed, urban systems for understanding and predicting the change of rapidly developing urban systems. Although studies find that developing urban systems have a tendency to converge to the four exponent values reported above, most of them were based on a small number of urban attributes or data of a short time span (Lei et al., 2021; Meirelles et al., 2018; Sahasranaman & Bettencourt, 2019; Zünd & Bettencourt, 2019). Lacking long-term data and multi-indicator quantification, the understanding of complex urban dynamics could be incomplete or even biased (Lei et al., 2021; Pumain et al., 2006). Knowledge of scaling dynamics in the early stage of urban transformation is particularly critical to revealing the evolution of cities. Cities in developing countries are far from equilibrium and are very different from their developed counterparts (Chauvin et al., 2017). Many of them have undergone drastic urbanization, with strong top-down government regulation and limited resources (Cao et al., 2014; Henderson, 2010). This could drive a rapid change in the scaling relationship of developing systems and shift their scaling properties. By comparing to the above four scaling allometries of mature urban systems using long-term data, we can identify distinctive features and processes of urban evolution and provide insights into their origin, transformation, and sustainable development.

The temporal change of scaling exponents indicates the change in allometries of different urban aspects with population (i.e., different agglomeration effects on different urban functions), which addresses concerns about the relative development of individual urban sectors. The balanced development of key urban functional sectors is critical for urban sustainability to ensure optimal productivity, necessary infrastructure for transportation and energy use, fair access to services and resources, and maintenance of a healthy social and natural environment (Cohen, 2006; DESA, 2019). This is consistent with the theory of development economics which hypothesizes that simultaneous growth across multiple sectors creates sectoral complementarity and spillover effects, leading to rapid growth (Jiang et al., 2020; Nurkse, 1966; Rosenstein-Rodan, 1943). But some have also argued that the inter-sectoral imbalance within directly productive activities, or between the directly productive activities and social overhead capital (mainly including infrastructure and basic services) is a necessary impetus for rapid development and may make better use of scarce resources in developing countries (Hirschman, 1958; Khakee, 2014; Streeten, 1959). Despite the difference in theory and their implied strategies for urban development and sustainability, both predict urban systems evolve to converge to the state of developed, mature cities (Streeten, 1959). However, it is an unanswered question whether this prediction applies to rapidly urbanizing systems with a fast-growing population.

Urban scaling quantification of Chinese cities has been much studied with interest being focused on land use (Jiao et al., 2020; Lang et al., 2019), socio-economy (Chen, 2017; Zünd & Bettencourt, 2019), infrastructure (Liu & Zou, 2020), social services (Lei et al., 2021), and energy consumption (Lei et al., 2021; Zhao et al., 2018). Similar scaling behaviors of urban China to developed urban systems have been reported (Lei et al., 2021; Liu & Zou, 2020). Some of these studies also reported that the scaling exponents varied according to different industrial types (Liu & Zou, 2020), geographical regions (Lei et al., 2021), and time (Lang et al., 2019; Lei et al., 2021; Zhao et al., 2018; Zünd & Bettencourt, 2019). It has been suggested that scaling exponents for GDP, employment, and built-up area of Chinese cities are generally stable over time (Lei et al., 2021; Zünd & Bettencourt, 2019). However, these studies were either conducted on a small number of urban attributes (Chen, 2017; Jiao et al., 2020; Lang et al., 2019; Zünd & Bettencourt, 2019), or for a small set of "relatively developed" cities (≤ 114) (Liu & Zou, 2020; Zhao et al., 2018), or in a short period of time (missing the critical economic reform period before 2000) (Lei et al., 2021). The omission of emerging cities is particularly a problem because they are not only large in number but also the force driving the rapid change of Chinese urban systems. It is necessary to be more inclusive in urban scaling analysis as data at the early stage of urban transformation are especially revealing (Lei et al., 2021).

In this study, we focus on quantifying the temporal change of urban functions for a large set of cities (including all 297 cities at the prefecture-level and above) in China over the past 35 years from 1984 to 2019, a period that has transformed China from one of the poorest countries to the second largest economy in the world. With these long-term, inclusive data, we aim to address the following three questions: (1) Do the functional attributes of Chinese cities follow urban scaling laws? (2) Over the past decades, have cities in China evolved to be more balanced or less balanced in terms of their functions across economic, social, infrastructure, and land use aspects, or toward the cities of more developed countries? (3) Is urban performance in China better achieved by balanced or unbalanced development among different urban sectors?

2. Data and methods

2.1. The definition of cities in this study

A city can be defined and delineated in different ways, for example, based on human settlement density (Li et al., 2015), commute time (Arcaute et al., 2015), or more traditionally, administrative division (Bettencourt & Lobo, 2016; Bettencourt et al., 2007). There are two common versions of administrative "city" in China. One refers to the urban area composed of municipal districts that essentially form a continuously spread settlement area, namely "shiqu". The other is defined based on the jurisdiction boundary that covers an area typically much larger than the urban area and includes the satellite counties surrounding the municipal districts, namely "shi". *China Urban Construction Statistical Yearbook* yet has another, less commonly used, delineation of the urbanized area consisting of urbanized subdistricts and towns in municipal districts and counties, namely "chengqu". The city in this study is referred to the first definition, i.e., the collection of municipal districts within a municipality or prefecture-level city, in line with the traditional concept of city as given by the United Nations

(Chan, 2007; DESA, 2019) or the definition of the functional city as metropolitan statistical areas (MSAs) in the USA or large urban zones (LUZs) in Europe (Lei et al., 2021; Zhao et al., 2018). Although the criteria for urban territory definition constantly evolve (Lang et al., 2019; Li & Wang, 2019), the municipality and prefecture-level city and municipal district are stable nomenclatures referring to where social interactions occur with a certain urban population size (Lei et al., 2021; Pumain, 2012). Different from some sampling schemes that sample a fixed list of "cities" over a given period of years regardless of whether they are cities in a year or not (Lei et al., 2021; Zünd & Bettencourt, 2019), we included cities if only they met the above definition of city so that to keep the definition consistent and the data comparable. The number of cities (i.e., the sample size) over our study period changed from 151 in 1984 to 297 in 2019. We conducted two sensitivity analyses to assess the possible impact of sample size on scaling exponent estimation by fixing the sample size of 151 cities as in 1984 across 1984–2019 (i.e., keeping the same cities as in 1984) and also that of 297 cities as in 2019 from 1984 to 2019, respectively. Note in the latter case many "cities" before 2019 were actually not cities according to the above definition. Different sampling strategies did not change our qualitative results (Figs. S1 and S2).

2.2. Data sources and variable selection

For each of the 297 cities, we compiled data on urban population and other 12 attributes, including city gross domestic product (GDP), total wage, the area of urban roads, etc. (see the descriptions of the variables in Table S1). The data were collected from various sources in the public domain, including *The Population Census of the People's Republic of China* (1990, 2000, and 2010; http://www.stats.gov.cn/tjsj/pcsj/), *China City Statistical Yearbooks* (1985–2020), and a series of official statistical compilation data for commemorating the fiftieth year and sixtieth year anniversaries of the People's Republic.

These urban attributes were selected to cover different aspects of city functions including economy, finance, education, health care, social welfare, infrastructure networks, and land use. Following Bettencourt et al. (2007), we categorized these attributes into four dimensions of urban functioning: socio-economic, basic services, infrastructure, and land use, to better represent the major urban functions and also make our study comparable to previous studies (Bettencourt, 2013; Bettencourt & Lobo, 2016; Li et al., 2017; Meirelles et al., 2018; Sahasranaman & Bettencourt, 2019; Zünd & Bettencourt, 2019).

Population data have been considered a problem for studying Chinese urbanization (Anu et al., 2017; Zünd & Bettencourt, 2019) because the demographic caliber of most population data used by the National Bureau of Statistics is registered population, or called "hukou" (Chan, 2009), ignoring the migrant population. *China Urban Construction Statistical Yearbook* provides data on the temporary resident population, i.e., the registered migrant population, but there could still be a big gap between the registered resident population (i.e., registered permanent + registered temporary population; Lei et al., 2021) and the actual resident population (that was only reported in population census which takes place every 10 years). Although both the hukou and migrant population make to the actual resident population that drives city development, the registered population data were used in this study because of the lack of the data on migrant population in most years. We conducted an analysis to assess the difference between the registered population and the total population for those years when census data were available and found using the registered population did not change our qualitative results (Figs. S3–S6).

2.3. Estimating scaling parameters

Following approaches commonly used in urban studies, we investigated transversal scaling relationships, i.e., the scaling law across cities, for each year separately from 1984 to 2019. While longitudinal scaling - the scaling law for the temporal development of a single city – can integrate scale and temporal change, the transversal approach describes the pure scaling effect while controlling for the temporal variation and is thus more informative for inferring the change of agglomeration effects if the scaling exponents are compared across region and time (Bettencourt et al., 2020; Ribeiro et al., 2020). For each urban variable Y, the scaling allometry was estimated using the ordinary least-squares linear regression to log-transformed data separately for each year t:

$$logY_{it} = log\alpha_{it} + \beta_{it} logN_t, \tag{1}$$

where Y_{it} and N_t are the observed value of the urban attribute i and the population size in year t, respectively. The exponent β_{it} captures the time dependent average effect of the change in city size on the urban attribute. To explore the scaling behavior of an urban attribute with city size, we examined the statistical significance of α and β and also the coefficient of determination of the fitting. This exercise produced a time series of the urban scaling parameters α and β from 1984 to 2019. We then analyzed the temporal change of β to compare scaling behaviors of study urban attributes, and also the attributes between the Chinese and developed urban systems.

2.4. Quantifying the degree of unbalanced urban development

Scaling exponent β measures the agglomeration effect of population (city size) on urban functions, indicating the degree of development of an urban attribute driven by city size. Neither a large nor a small β for individual urban functions is optimal for the development of a city because that creates unbalanced development with city size and other urban functions. For example, a small β for social services means the urban function of social services lags behind the growth of the population, which would eventually constrain the development of the city. But a large β for social services means the social service may not be affordable over long term. Similarly, a small β for infrastructure suggests the development of infrastructure may not meet the need of city growth. In contrast, a large β for infrastructure indicates a risk that the infrastructure becomes overly sprawled compared to the growth of the population, which could rise high costs of transportation and maintenance and thus is detrimental to urban development. As clear, β indicates the development degree of each urban function in relative to city size. In analogy to the widely used UNDP (2010) sustainable development index, the Human Development Index, we proposed a composite index by summing β's across urban functions of different dimensions to assess urban sustainable development. Assuming an urban functional dimension, denoted as j, has n_j urban attributes, the development of the urban dimension can be defined as geometrical mean of these attributes: $\overline{Y}_j = \sqrt[n_j]{Y_1 Y_2 \ldots Y_{n_j}}$. It scales with city size as $\overline{Y}_j \sim N^{\overline{g}_j}$. It is easy to show $\overline{g}_j$ is the arithmetic mean of scaling exponents for each of these n_j urban attributes estimated from Eq. (1):

$$\overline{g}_j = \frac{1}{n_j}\left(\beta_1 + \beta_2 + \ldots + \beta_{n_j}\right). \tag{2}$$

This averaged exponent $\overline{g}_j$ measures the development degree of the urban functional dimension j with respect to the change in city size. We can then define an aggregate functional development (denoted by G) by averaging the development ($\overline{g}_j$) across k urban functional dimensions:

$$G = \frac{1}{k}\sum_{j}^{k} \overline{g}_j. \tag{3}$$

G is an indicator for the degree of city sustainable development which in this study consists of four ($k = 4$) basic dimensions of urban functioning including socio-economic, basic services, infrastructure, and land use. A high G means that on average an urban system offers high levels of functions as the population increases, likely leading to a high urban growth rate. If G is smaller than 1, the per-capita urban functioning decreases as urban grows, indicating the process of urbanization cannot sustain urban functional provision for the increasing population. Very small G would lead to stagnation and collapse of an urban system.

Similar to the methods for quantifying the dimensional or sectoral imbalance in the context of development economics (Swamy, 1967; Yotopoulos & Lau, 1970), we can also quantify the imbalance of urban functional development based on the variation in G. To do that, we quantify the variation in scaling exponent β among functions within a dimension and also between dimensions. This defines an overall functional development imbalance (VT) and allow partitioning VT into within-dimensional imbalance (VW) and between-dimensional imbalance (VB) for an urban system. The VT is the total variance in β among all urban attributes:

$$VT = \frac{1}{k}\sum_{j}^{k}\frac{1}{n_j}\sum_{i}^{n_j}\left(\beta_{ij} - G\right)^2, \quad (4)$$

where β_{ij} is the scaling exponent of the ith attribute of the jth functional dimension. The between-dimensional imbalance is defined as the variation between dimensions:

$$VB = \frac{1}{k}\sum_{j}^{k}\left(\overline{g}_j - G\right)^2, \quad (5)$$

and the within-dimensional imbalance is the variation in β among the functions within a dimension:

$$VW = \frac{1}{k}\sum_{j}^{k}\frac{1}{n_j}\sum_{i}^{n_j}\left(\beta_{ij} - \overline{g}_j\right)^2 = VT - VB, \quad (6)$$

where $\overline{g}_j$ and G are given by Eqs. (2) and (3), respectively. We calculated G, VT, VB, VW for Chinese cities in each year. For comparison, we also calculated the theoretical level of urban development and imbalance for "ideal cities" (i.e., mature cities that are at development equilibrium). This is done by assigning the four theoretical scaling exponents to each attribute according to their functional types, leading to $G = 0.917$, $VT = VB = 0.035$, $VW = 0$.

2.5. Comparing Chinese urban scaling behavior with that of developed urban systems

While the isometric relationship is the benchmark to identify the nonlinear property of cities, the theoretical scaling exponents for different dimensions of developed urban systems (i.e., 7/6 for socio-economic, 1 for basic services, 5/6 for infrastructure, 2/3 for urban area) are the benchmarks against which to identify the functional deviation of developing cities from mature systems. These scaling properties emerge at spatial equilibrium between social benefits and transportation costs driven by the urban agglomeration effect and spatial densification (Bettencourt, 2013). Thus, the differences between empirical β of Chinese cities and the above four theoretical exponent values offer insights into the difference between the compared systems and indicate how far Chinese cities are from equilibrium. Scaling exponents $> 7/6$ for socio-economy or $< 5/6$ for infrastructure suggest a stronger agglomeration effect than developed cities, i.e., with more increasing returns to scale and more economies of scale, respectively. Exponents < 1 for basic services suggests less per-capita service a city can provide to residents when the city is growing, while there is no such tension in developed cities. Exponents $< 2/3$ for urban area means faster population densification as a city grows. In addition to scaling exponents, we also compared the aggregate functional development (G) and the overall functional development imbalance (VT) between Chinese cities and developed cities, as described in the above section.

3. Results

3.1. Urban scaling allometric models

The exponents β of the scaling allometries in this study were all highly significant ($p < 0.0001$), although the R^2 of the scaling models were all lower than that of other urban systems reported before (Bettencourt, 2013; Bettencourt et al., 2007) (Fig. 1). Overall, the variables related to socio-economy and basic services showed relatively high R^2, while R^2 for variables of infrastructure and land use were low. Of all the urban functions over the 35-year study period, the scaling relationship between the number of primary school teachers and city size was always the strongest ($R^2 = 0.91 \pm 0.02$), while that between urban area and city (population) size was the weakest ($R^2 = 0.17 \pm 0.04$) (Fig. 1).

3.2. Temporal change of scaling behavior of urban functions

As shown in Fig. 2, there were considerable changes in scaling relations between urban functions and city size over time. Although the trajectories of changes were different among the urban functions, the overwhelming trends of the change showed an increase over time, except for the attributes of the basic service dimension and the city area of the land use dimension whose β either decreased over time or remained little changed (Fig. 2). Regardless of the patterns of change, it is striking to observe that almost all of the scaling exponents were smaller than 1 (sublinear) in the early years (e.g., before 1990) and that there were abrupt changes in the scaling relationship around 2000–2005 for all variables except for the number of hospital beds and primary school teachers. These changes made a scaling relationship either approach the theoretical relationship after 2000 (e.g., the socio-economic attributes that approached the red theoretical superlinear line; Fig. 2a) or departed from the theoretical relationship (e.g., the infrastructure attributes deviated from the blue theoretical line after 2000; Fig. 2c).

3.3. Unbalanced development of urban functions

The degree of urban development and the level of functional imbalance in China are shown in Fig. 3. The imbalance in the development of urban functions has intensified over time with a sudden rise around 2000, much exceeding the theoretical level after 2003 (Fig. 3a). The between-dimensional imbalance was much higher than the within-dimensional imbalance.

The development level of urban functioning sharply increased from 1984 to 2004, exceeding the theoretical prediction after 2001, and then declined from 2005 to 2019 (Fig. 3b). We observed a strong inverse U-shape curve between the level of development and the degree of functional imbalance (Fig. 3c). The development level peaks at an intermediate imbalance level, occurring at imbalance level = 0.052 (the dashed line in Fig. 3c). The fitted curve closely passes through the theoretical prediction of Bettencourt's mature city model ($G = 0.917$, $VT = 0.035$; the intersection in Fig. 3c).

4. Discussion

Cities are dynamic, complex systems with ever changing attributes and functions (Batty, 2007). Quantifying the trajectories of the relative changes of the key urban attributes is critical for understanding urban evolution and for sustainable urban management. Arguably, no society in human history has ever undergone such rapid and profound changes as the current urban society in China. The unprecedented urbanization in China is driven by a multitude of factors, including immigration from rural areas, strong government regulation, and economic reform to optimize productivity, which simultaneously create scenarios that challenge the theory of urban science and practices of urban management. Our study shows that the urban scaling allometries are useful in

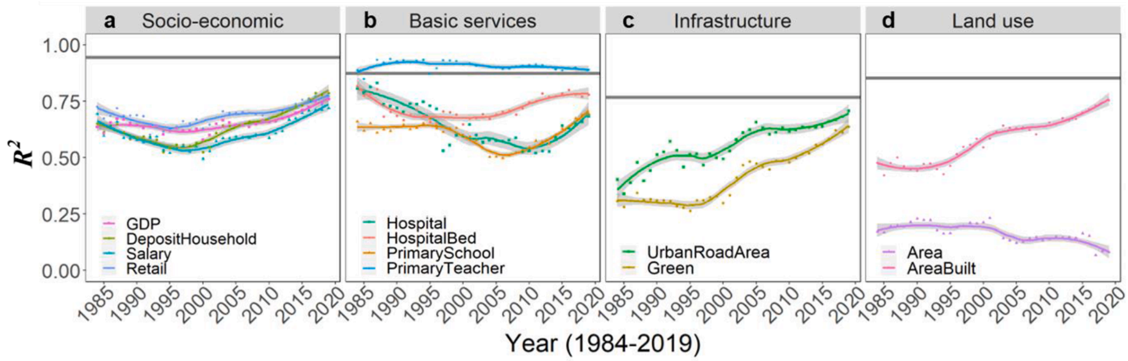

Fig. 1. R^2 of the log-log urban scaling relationships for urban variables of the four dimensions (socio-economic, basic services, infrastructure, and land use) with the population of the study cities in China across years. The horizontal lines are the average value of R^2 for developed, mature urban systems as reported in Bettencourt et al. (2007) and Bettencourt (2013).

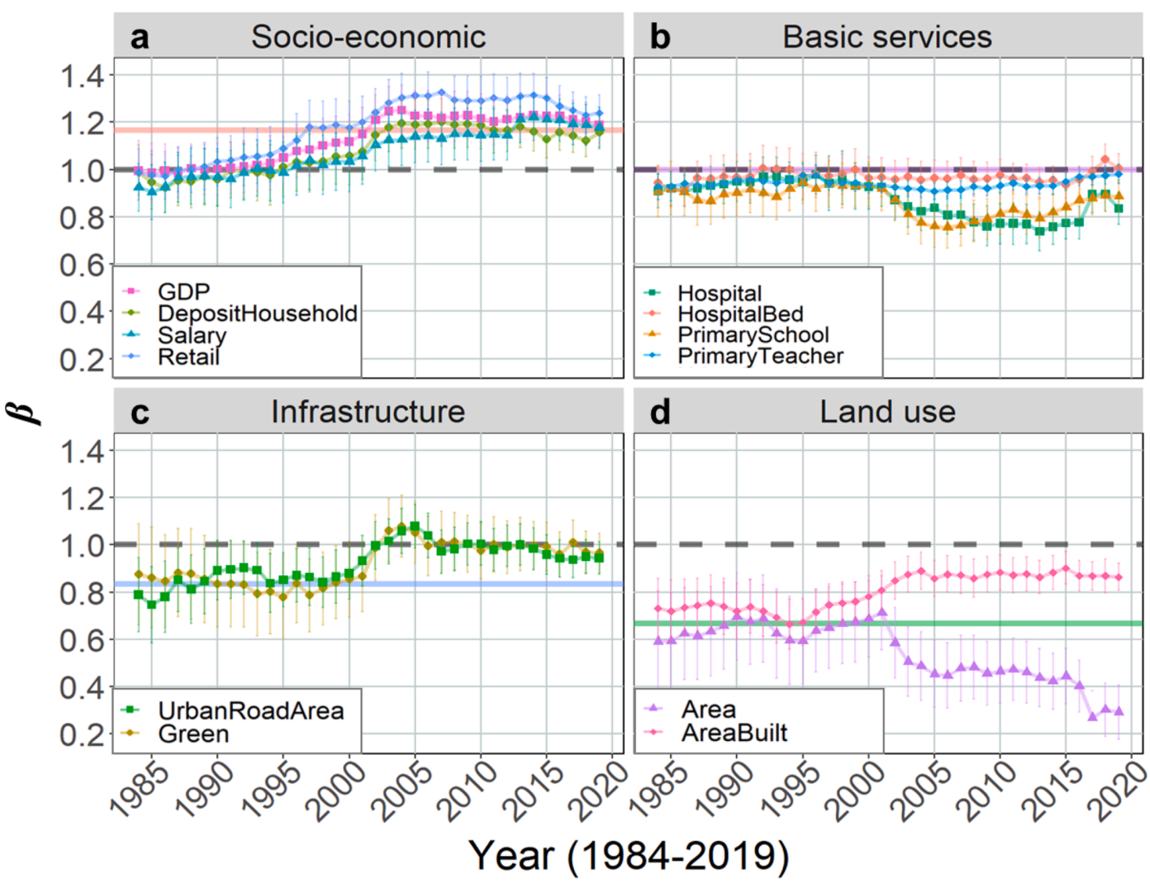

Fig. 2. Yearly change (1984–2019) in scaling exponent β for different urban variables in each of the four urban dimensions (socio-economic, basic services, infrastructure, and land use). Each dot represents the exponent of the best-fit log-log scaling allometries of an urban variable against population size. The 95% confidence interval is indicated by the vertical bars. The colored horizontal lines are the theoretical exponent values of Bettencourt's (2013) mature city model. The dashed horizontal gray lines are the isometric scaling relationship.

describing the evolution of many functions of Chinese cities, although the scaling relationships are generally weaker in most cases than those of mature urban systems (Bettencourt, 2013; Bettencourt et al., 2007). The weak scaling found in this study speaks to the fact that on one hand Chinese cities share commonality with developed, mature cities as driven by population agglomeration but on the other hand also present strong unique development caused by other context-dependent factors. For instance, the positioning and planning of cities by the government can greatly affect the development of cities, resulting in cities with similar sizes diverging in urban aspects (e.g., Shenzhen versus Tongling in Fig. 4), or cities with different sizes converging in development (e.g., Shenzhen versus Guangzhou), while Tongling and Guangzhou had a roughly parallel development (Fig. 4). The colossal differences in the development of Shenzhen from other two cities were simply due to the establishment of Shenzhen as the first Special Economic Zone in China in 1980. Despite these variations, it is important to note that all the attributes of the three cities consistently increased over time with population growth, typical of the development of Chinese cities, thus the scaling relationships found in this study. In addition to the dictating role of government's top-down economic policy (e.g., planned economy; Wu,

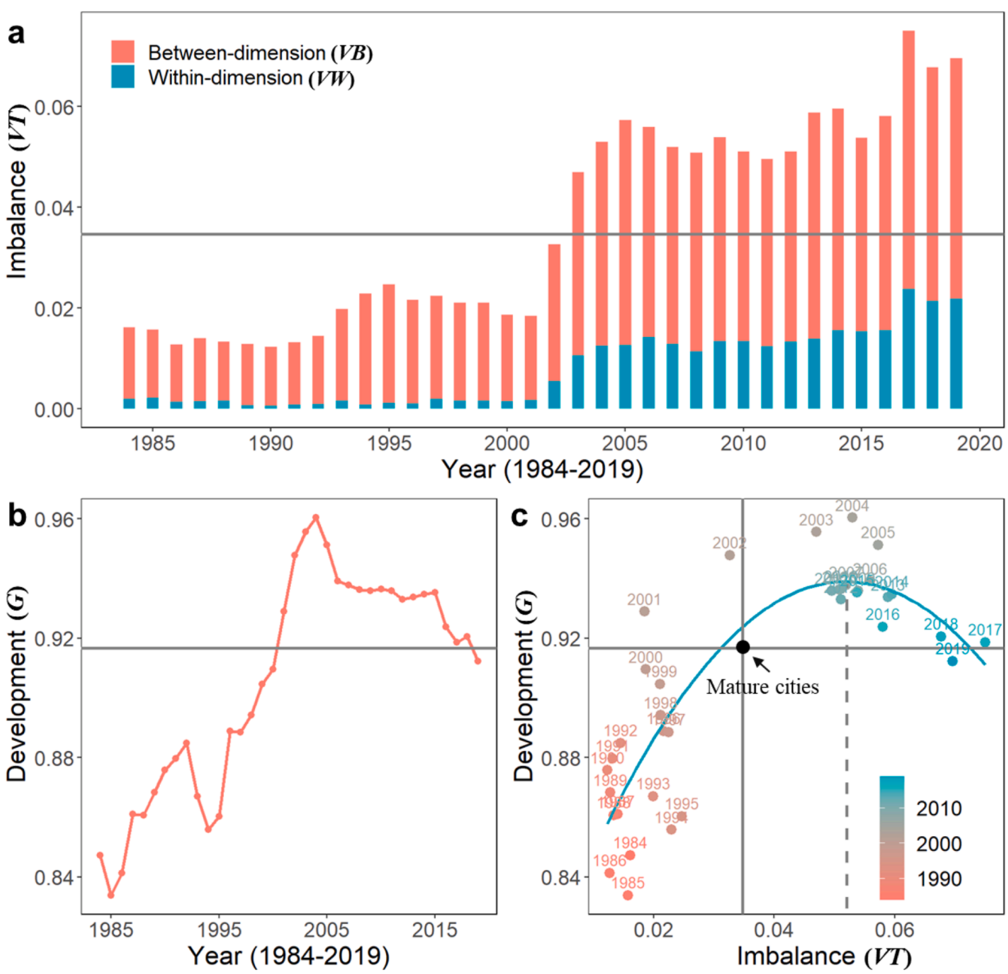

Fig. 3. The level of urban functional imbalance and its relationship with urban development. (a) The imbalance level of urban functions in 1984–2019, showing the inter-dimensional imbalance (red, Eq. (5)) and intra-dimensional imbalance (cyan, Eq. (6)). The horizontal line is the theoretical imbalance level of Bettencourt's (2013) model. (b) The temporal change of urban functional development (Eq. (3)). The horizontal line is the predicted development level. (c) The relationship between the imbalance and development of urban functioning, fitted by a quadratic curve. Each colored dot represents a combination of imbalance and development in each year. The dashed line marks the peak of the development level occurring at imbalance level = 0.052. The solid lines mark the theoretical imbalance level 0.035 (vertical line) and development level of 0.917 (horizontal line). Their intersection point indicates an equilibrial urban state given by Bettencourt's (2013) model.

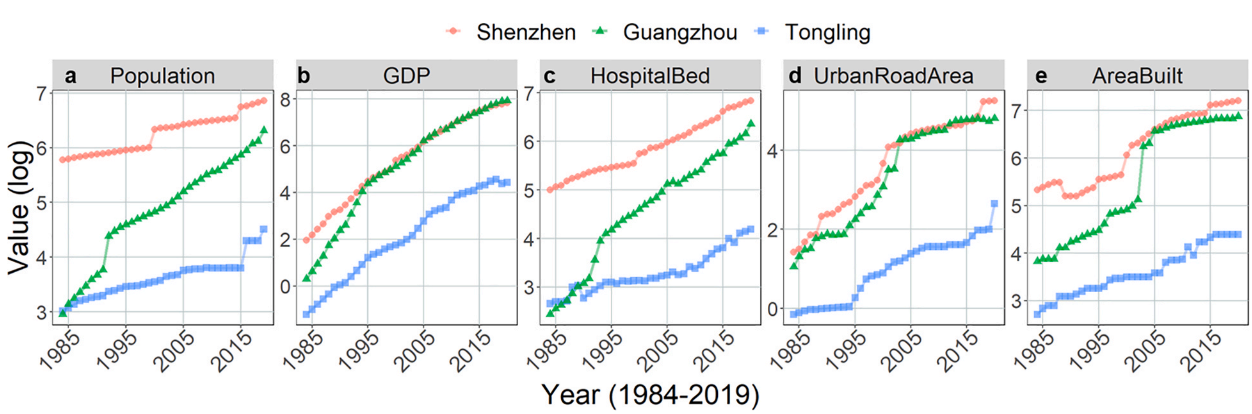

Fig. 4. The population and four other urban attributes of Shenzhen (Guangdong Province; green), Tongling (Anhui Province; blue), and Guangzhou (Guangdong Province; red). Shenzhen and Tongling started off with similar population size, but the latter had slacked behind in all attributes over the years. In contrast, Shenzhen and Guangzhou started with two orders of magnitude difference in population size, but converged in all urban functions over time. Units in the figure: Population, 10 thousand persons; GDP, billion yuan; Hospital beds, 100 beds; Urban roads area, million m^2; Built-up area, km^2.

2015), other important context-dependent factors could include distinctive history and culture (e.g., a society dominated by strong social ties; Bian, 1997), large environmental and geographic constraints (e.g., diverse natural endowment of cities, land nationalization; Ding & Lichtenberg, 2011). All these would weaken scaling relationships between urban attributes and population size for Chinese cities. The unique development of Chinese cities offers an explanation why many of the functional attributes (e.g., those in the infrastructure dimension), with the exception of the socio-economic functions, did not approach the theoretical scaling relationships typical of developed, mature cities (Fig. 2). However, our results are consistent with previously reported Chinese urban scaling behaviors with respect to GDP (Lei et al., 2021; Zhao et al., 2018; Zünd & Bettencourt, 2019), built-up area (Lang et al., 2019; Lei et al., 2021; Zünd & Bettencourt, 2019), and other urban indicators (Lei et al., 2021). Despite these agreements, our data of 35 years on a full list of urban functions in four key dimensions however revealed that cities in China have diverged from mature urban systems, contrary to what were found in previous studies (Meirelles et al., 2018; Sahasranaman & Bettencourt, 2019; Zünd & Bettencourt, 2019). This finding does not only have important implications for sustainable urban management in China but also indicates the unique development pathways of Chinese cities as transformed from a close to open economy as discussed below.

The economic reform from a strictly state-controlled economy to a more open market economy over the past four decades has profoundly changed urban economic, social, and spatial organization in China in the aspects of the labor market, population migration from the rural, land policy, fiscal and governance (Ding & Lichtenberg, 2011; Meng et al., 2013; Wu, 2015). This rapid process of urbanization upset the critical cost-benefit equilibrium underlying the theoretical models (Bettencourt, 2013, 2020) and led to uncoordinated development of the urban systems. Like in other developing urban systems (Henderson, 2002; Meirelles et al., 2018; Sahasranaman & Bettencourt, 2019), some urban functions have received disproportionately more investment and advanced faster than others in Chinese cities. As a result, the scaling relationships for the functions of the four dimensions in Fig. 2 change in different directions. For example, the massive investment in infrastructure and socio-economic development over the past decades (Fu, 2010; Zhang et al., 2007) have driven their functions to increase towards larger exponent values than that of developed cities ($\beta = 7/6$ for socio-economic dimension and $\beta = 5/6$ for infrastructure) (Fig. 2a and c), suggesting stronger agglomeration effect of increasing returns to scale but weaker in terms of economies of scale. On the contrary, the basic services (e.g., hospital and school functions) formed sublinear scaling relationships ($\beta < 1$) with population size (Fig. 2b), and they either remained little change (e.g., the hospital service) or lagged behind population growth (e.g., school service). It is obvious that the space available for urban expansion (i.e., area in the land use dimension; Fig. 2d) also fell behind population growth more than theory predicted ($\beta = 2/3$). The smaller exponent values of basic services and urban area than theoretical predictions indicate less per-capita service and space a city can provide for residents when city is growing, while there is no such large tension in developed cities. The increased scaling exponents β for socio-economic functions as revealed in Fig. 2a indicate the increased per-capita urban economic efficiency (Zhao et al., 2018; Zünd & Bettencourt, 2019). This could lead to further population agglomeration and in turn heighten demand for basic services and more urban space in order to sustain urban growth. The short supply of basic services and land would seriously restrict urban development. These results suggest the current urban development in China is neither balanced nor sustainable.

A striking feature of urban development in China is the abrupt changes in the scaling relationship around 2000 for most functions (Fig. 2). This transition most likely resulted from the critical period of reform, starting from 1993 when the 14th Central Committee roadmapped the Socialist Market Economy System to 2002 when the 16th National Congress declared the successful establishment of the early socialist market economy. This roadmap profoundly transformed the society and economy in China around 2000, including a drastic increase in the number of cities (Li & Wang, 2019), urbanization rate (Li et al., 2016), urban population density (Ruibo & Linna, 2013), the share of land revenue (Chen & Kung, 2016), as well as the change of labor force structure (Meng et al., 2013). These changes greatly improved the efficiency and the volume of social interactions (Bian, 2018) and bolstered the vitality of cities and the agglomeration effect as evidenced by socio-economic functions in Fig. 2a. The increased fiscal revenue allowed local governments to further invest in an already heavy infrastructure (Fu, 2010; Zhang et al., 2007) as shown in Fig. 2c.

Using the scaling relationships, we quantified the degree of urban development and the level of imbalance with reference to city size. Models (Bettencourt, 2013; Li et al., 2017; Yakubo et al., 2014) predict unsustainable growth of cities with the constraint that per-capita urban functioning decreases as urban grows ($G = 0.917 < 1$). The constraint stemmed from economies of scale in infrastructure dimension and densification in urban space, which saved cost but increased the burden per unit infrastructure and space in cities. Since the economic reform started in 1984, urban development in China has made remarkable progress and exceeded the predicted level, but since 2005 urban development has been in a continuous recession and by 2019 it had fallen below the predicted level (Fig. 3b). The four universal regimes of scaling exponents observed in mature cities and predicted by models suggest an intrinsic and constant difference in the proportional growth of different urban functions against the population. Cities in China were more balanced before early 2000, but were less so after that presumably due to the rapid urbanization starting around 2000 (Fig. 3a). The source of overall imbalance in urban development mainly arose from the between-dimensional difference (Fig. 3a), caused by an enlarging gap between basic social services and other urban functions (Fig. 2).

The inverse U relationship between the functional imbalance and development (Fig. 3c) indicates the highest level of urban development was achieved at an intermediate level of functional imbalance. A similar observation is also reported in a study on Europe's OECD Countries that used a traditional framework for quantifying development (Koźmiński et al., 2020). This inverse U curve provides a reconciliation to the two hypotheses from development economics that debate whether sectoral balance benefits aggregate development or not. The curve shows that the inter-sectoral imbalance could make better use of scarce resources in developing countries and stimulates urban development in the early stage of urbanization where the imbalance level is relatively low (Hirschman, 1958; Khakee, 2014; Streeten, 1959), but could inhibit the sectoral complementarity and spillover effects and eventually restrain urban development when the imbalance level is high (Jiang et al., 2020; Nurkse, 1966; Rosenstein-Rodan, 1943). The observed peak urban development in China does not stop at but is higher than that predicted by theory, and is achieved at a functional imbalance level at 0.052 (Fig. 3c), which falls into the range of high imbalance. The plausible explanation is that urban planning and development in China have continuously focused on economic growth and infrastructure construction over the past decades, with disproportionally low investment in social service and welfare (Fu, 2010). This is not surprising given that economic development, particularly maintaining a high GDP, has been the main target of any municipal government in China. This unbalanced development strategy breaks the cost-benefit equilibrium (Bettencourt, 2013) and provides an extra driving force for development. This strategy could be effective until the imbalance becomes too high. However, the current development at such a high imbalance level in urban China would not be sustainable (Jiang et al., 2020; Nurkse, 1966; Rosenstein-Rodan, 1943). Urbanization in China has slowed down since 2005 (DESA, 2019), in consistent with the temporal trend of the functional development G shown in Fig. 3b. But China's urbanization rate (60.31%) still drags behind that of developed countries (80% ~ 90%) (DESA, 2019). If the functional imbalance continues to worsen, China's urban system may usher in stagnation. We suggest it be necessary to reduce functional imbalance to achieve the outcome of sustainable urban development, e.g., by increasing investment in education and health care, adjusting the urban administrative boundaries in time to adapt and facilitate population agglomeration and social interactions, and including non-economic dimensions in assessing the performance of local municipal governments, e.g., by green GDP (Wang, 2016), Genuine Progress Indicator (Talberth et al., 2007) and other sustainability measurements (Huang et al., 2015).

5. Conclusions

Our study has shown that urban scaling is a useful tool not only for revealing the evolution of urban functions, but also for quantifying the degree of urban development and the level of imbalance with respect to city size, shedding light on urban sustainable growth that balances economic development, urban environment, and human well-being. By analyzing urban allometries from 1984 to 2019, we found that Chinese cities manifested relatively weak scaling properties. They have undergone rapid change with the scaling exponents varying greatly over time, with little sign of convergence to theory-predicted mature urban societies. The urban scaling allometries revealed how China's economic prosperity emerged with the increase of imbalance among functional dimensions. Chinese cities reached their highest functional development state at a functional imbalance level higher than the theory predicts. But with the further aggravation of functional imbalance, this high development state could not sustain. We would argue the deviation of Chinese cities from the scaling property of developed cities is typical of developing urban systems with heavy investment in infrastructure and massive rural-to-urban migration that breaks the critical cost-benefit equilibrium underlying the theoretical models. The unbalanced development strategy aiming at economic development is effective to provide additional impetus for overall urban development until the imbalance becomes too high. Improving social services to lessen the excessive functional imbalance is critical for sustainable urban development in China and possibly in other rapidly urbanizing countries as well. Further study is warranted to identify and model the fundamental evolutionary mechanisms of scaling relationships in developing countries by focusing on the key processes leading to unbalanced development in the urban system, in order to find pathways toward city sustainable growth.

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CRediT authorship contribution statement

Zheyi Liu: Conceptualization, Visualization, Data curation, Formal analysis, Writing – review & editing. **Hanlun Liu:** Writing – review & editing. **Wei Lang:** Writing – review & editing. **Suqin Fang:** Writing – review & editing. **Chengjin Chu:** Writing – review & editing. **Fangliang He:** Conceptualization, Visualization, Data curation, Writing – review & editing.

Declaration of Competing Interest

Competing financial interests: The authors declare no competing financial interests.

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2022.104157.

References

Akuraju, V., Pradhan, P., Haase, D., Kropp, J. P., & Rybski, D. (2020). Relating SDG11 indicators and urban scaling – An exploratory study. *Sustainable Cities and Society, 52*, Article 101853. https://doi.org/10.1016/j.scs.2019.101853

Anu, R., Daqian, J., Kangkang, T., & Jerry, Z. (2017). Impact of the economic structure of cities on urban scaling factors: Implications for urban material and energy flows in China. *Journal of Industrial Ecology, 22*(2), 392–405. https://doi.org/10.1111/jiec.12563

Arbesman, S., Kleinberg, J. M., & Strogatz, S. H. (2009). Superlinear scaling for innovation in cities. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics, 79*(1), 1–5. https://doi.org/10.1103/PhysRevE.79.016115

Arcaute, E., Hatna, E., Ferguson, P., Youn, H., Johansson, A., & Batty, M. (2015). Constructing cities, deconstructing scaling laws. *Journal of the Royal Society Interface, 12*(102). https://doi.org/10.1098/rsif.2014.0745, 20140745–20140745.

Balland, P. A., Jara-Figueroa, C., Petralia, S. G., Steijn, M. P. A., Rigby, D. L., & Hidalgo, C. A. (2020). Complex economic activities concentrate in large cities. *Nature Human Behaviour, 4*(3). https://doi.org/10.1038/s41562-019-0803-3

Batty, M. (2007). Complexity in city systems: Understanding, evolution, and design. *A planner's encounter with complexity* (pp. 99–122). Ltd: Ashgate Publishing.

Batty, M. (2013). A theory of city size. *Science, 340*(6139), 1418–1419. https://doi.org/10.1126/science.1239870 *(New York, N.Y.)*.

Bettencourt, L. M. A. (2013). The origins of scaling in cities. *Science, 340*(6139), 1438–1441. https://doi.org/10.1126/science.1235823 *(New York, N.Y.)*.

Bettencourt, L. M. A. (2020). Urban growth and the emergent statistics of cities. *Science Advances, 6*(34). https://doi.org/10.1126/sciadv.aat8812. eaat8812.

Bettencourt, L. M. A., & Lobo, J. (2016). Urban scaling in Europe. *Journal of the Royal Society Interface, 13*(116). https://doi.org/10.1098/rsif.2016.0005

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences, 104*(17), 7301–7306. https://doi.org/10.1073/pnas.0610172104

Bettencourt, L. M. A., Yang, V. C., Lobo, J., Kempes, C. P., Rybski, D., & Hamilton, M. J. (2020). The interpretation of urban scaling analysis in time. *Journal of the Royal Society Interface, 17*(163). https://doi.org/10.1098/rsif.2019.0846

Bian, Y. (1997). Bringing strong ties back in: Indirect ties, network bridges, and job searches in China. *American Sociological Review*, 366–385. https://doi.org/10.2307/2657311

Bian, Y. (2018). The prevalence and the increasing significance of guanxi. *The China Quarterly, 235*, 597–621. https://doi.org/10.1017/S0305741018000541

Cao, S., Lv, Y., Zheng, H., & Wang, X. (2014). Challenges facing China's unbalanced urbanization strategy. *Land Use policy, 39*, 412–415. https://doi.org/10.1016/J.LANDUSEPOL.2013.12.004

Chan, K. W. (2007). Misconceptions and complexities in the study of China's cities: Definitions, statistics, and implications. *Eurasian Geography and Economics, 48*(4), 383–412. https://doi.org/10.2747/1538-7216.48.4.383

Chan, K. W. (2009). The Chinese Hukou system at 50. *Eurasian Geography and Economics, 50*(2), 197–221. https://doi.org/10.2747/1539-7216.50.2.197

Chauvin, J. P., Glaeser, E., Ma, Y., & Tobio, K. (2017). What is different about urbanization in rich and poor countries? Cities in Brazil, China, India and the United States. *Journal of Urban Economics, 98*, 17–49. https://doi.org/10.1016/j.jue.2016.05.003

Chen, T., & Kung, J. S. (2016). Do land revenue windfalls create a political resource curse? Evidence from China. *Journal of Development Economics, 123*, 86–106. https://doi.org/10.1016/j.jdeveco.2016.08.005

Chen, Y. (2017). Multi-scaling allometric analysis for urban and regional development. *Physica A: Statistical Mechanics and Its Applications, 465*, 673–689. https://doi.org/10.1016/j.physa.2016.08.008

Cohen, B. (2006). Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. *Technology In Society, 28*(1–2), 63–80. https://doi.org/10.1016/j.techsoc.2005.10.005

DESA. (2019). *World urbanization prospects: The 2018 revision*. Department of Economic and Social Affairs, and Population Division. https://doi.org/10.18356/b9e995fe-en. United Nations.

Ding, C., & Lichtenberg, E. (2011). Land and urban economic growth in China. *Journal of Regional Science, 51*(2), 299–317. https://doi.org/10.1111/j.1467-9787.2010.00686.x

Fu, Y. (2010). Fiscal decentralization, governance and non-economic public goods provision. *Economic Research Journal, 8*, 4–15.

Henderson, J. V. (2010). Cities and development. *Journal of Regional Science, 50*(1), 515–540. https://doi.org/10.1111/j.1467-9787.2009.00636.x

Henderson, V. (2002). Urbanization in developing countries. *The World Bank Research Observer, 17*(1), 89–112. https://doi.org/10.1093/wbro/17.1.89

Hirschman, A. O. (1958). *The strategy of economic development*. New Haven: Yale University Press.

Hong, I., Frank, M. R., Rahwan, I., Jung, W. S., & Youn, H. (2020). The universal pathway to innovative urban economies. *Science Advances, 6*(34), 1–8. https://doi.org/10.1126/sciadv.aba4934

Huang, L., Wu, J., & Yan, L. (2015). Defining and measuring urban sustainability: A review of indicators. *Landscape Ecology, 30*(7), 1175–1193. https://doi.org/10.1007/s10980-015-0208-2

Jiang, X., Caraballo-Cueto, J., & Nguyen, C. (2020). Balanced versus unbalanced growth: Revisiting the forgotten debate with new empirics. *Review of Development Economics, 24*(4), 1430–1446. https://doi.org/10.1111/rode.12688

Jiao, L., Xu, Z., Xu, G., Zhao, R., Liu, J., & Wang, W. (2020). Assessment of urban land use efficiency in China: A perspective of scaling law. *Habitat International, 99*(129), Article 102172. https://doi.org/10.1016/j.habitatint.2020.102172

Kennedy, C. A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., et al. (2015). Energy and material flows of megacities. *Proceedings of the National Academy of Sciences, 112*(19), 5985–5990. https://doi.org/10.1073/pnas.1504315112

Khakee, A. (2014). An unbalanced model for sustainable urban development. *International Journal of Urban Sustainable Development, 6*(1), 52–64. https://doi.org/10.1080/19463138.2013.870765

Koźmiński, A. K., Noga, A., Piotrowska, K., & Zagórski, K. (2020). *The balanced development index for Europe's OECD countries, 1999–2017*. Springer Nature. https://doi.org/10.1007/978-3-030-39240-6

Lang, W., Long, Y., Chen, T., & Li, X. (2019). Reinvestigating China's urbanization through the lens of allometric scaling. *Physica A: Statistical Mechanics and Its Applications, 525*, 1429–1439. https://doi.org/10.1016/J.PHYSA.2019.04.075

Lei, W., Jiao, L., Xu, G., & Zhou, Z. (2021). Urban scaling in rapidly urbanising China. *Urban Studies*. https://doi.org/10.1177/00420980211017817, 00420980211017817.

Li, H., Wei, Y., & Ning, Y. (2016). Spatial and temporal evolution of urban systems in China during rapid urbanization. *Sustainability, 8*(12), 651. https://doi.org/10.3390/su8070651

Li, R., Dong, L., Zhang, J., Wang, X., Wang, W. X., Di, Z., et al. (2017). Simple spatial scaling rules behind complex cities. *Nature Communications, 8*(1), 1–7. https://doi.org/10.1038/s41467-017-01882-w

Li, X., Wang, X., Zhang, J., & Wu, L. (2015). Allometric scaling, size distribution and pattern formation of natural cities. *Palgrave Communications, 1*(1), 15017. https://doi.org/10.1057/palcomms.2015.17

Li, Y., & Wang, K. (2019). Classification evolution process and law analysis of cities in China since reform and opening-up. *Economic Geography, 39*(11), 49–59. https://doi.org/10.15957/j.cnki.jjdl.2019.11.007

Liu, X., & Zou, Z. (2020). Analysis on urban scaling characteristics of China's relatively developed cities. *PloS one, 15*(7), Article e0236593. https://doi.org/10.1371/journal.pone.0236593

Manoli, G., Fatichi, S., Schläpfer, M., Yu, K., Crowther, T. W., Meili, N., et al. (2019). Magnitude of urban heat islands largely explained by climate and population. *Nature, 573*(7772), 55–60. https://doi.org/10.1038/s41586-019-1512-9

Marshall, A. (1890). *Principles of economics*. London: Mac-Millan.

Meirelles, J., Neto, C. R., Ferreira, F. F., Ribeiro, F. L., & Binder, C. R. (2018). Evolution of urban scaling: Evidence from Brazil. *PloS One, 13*(10), 1–15. https://doi.org/10.1371/journal.pone.0204574

Meng, X., Shen, K., & Xue, S. (2013). Economic reform, education expansion, and earnings inequality for urban males in China, 1988–2009. *Journal of Comparative Economics, 41*(1), 227–244. https://doi.org/10.1016/j.jce.2012.04.004

Nurkse, R. (1966). *Problems of capital formation in underdeveloped countries*. Oxford University Press.

Oliveira, E. A., Andrade, J. S., & Makse, H. A. (2014). Large cities are less green. *Scientific Reports, 4*. https://doi.org/10.1038/srep04235

Ortman, S. G., Cabaniss, A. H. F., Sturm, J. O., & Bettencourt, L. M. A. (2015). Settlement scaling and increasing returns in an ancient society. *Science Advances, 1*(1), Article e1400066. https://doi.org/10.1126/sciadv.1400066

Pumain, D. (2012). Urban systems dynamics, urban growth and scaling laws: The question of ergodicity. *Complexity theories of cities have come of age* (pp. 91–103). Berlin Heidelberg: Springer. https://doi.org/10.1007/978-3-642-24544-2_6

Pumain, D., Paulus, F., Vacchiani-Marcuzzo, C., & Lobo, J. (2006). An evolutionary theory for interpreting urban scaling laws. *Cybergeo: European Journal of Geography*. https://doi.org/10.4000/cybergeo.2519

Pumain, D., & Rozenblat, C. (2019). Two metropolisation gradients in the European system of cities revealed by scaling laws. *Environment and Planning B: Urban Analytics and City Science, 46*(9), 1645–1662. https://doi.org/10.1177/2399808318785633

Ribeiro, F. L., Meirelles, J., Netto, V. M., Neto, C. R., & Baronchelli, A. (2020). On the relation between transversal and longitudinal scaling in cities. *PloS One, 15*(5), Article e0233003. https://doi.org/10.1371/journal.pone.0233003

Rosenstein-Rodan, P. N. (1943). Problems of industrialisation of eastern and south-eastern Europe. *The Economic Journal, 53*(210/211), 202–211. https://doi.org/10.2307/2226317

Ruibo, H., & Linna, W. (2013). Challenges and opportunities facing China's urban development in the new era. *China Perspectives, 2013*(2013/2), 15–27. https://doi.org/10.4000/chinaperspectives.6149

Sahasranaman, A., & Bettencourt, L. M. A. (2019). Urban geography and scaling of contemporary Indian cities. *Journal of the Royal Society Interface, 16*(152), Article 20180758. https://doi.org/10.1098/rsif.2018.0758

Schläpfer, M., Bettencourt, L. M. A., Grauwin, S., Raschke, M., Claxton, R., Smoreda, Z., et al. (2014). The scaling of human interactions with city size. *Journal of the Royal Society Interface, 11*(98), Article 20130789. https://doi.org/10.1098/rsif.2013.0789

Streeten, P. (1959). Unbalanced Growth. *Oxford Economic Papers, 11*(2), 167–190.

Sugar, L., & Kennedy, C. (2021). Urban scaling and the benefits of living in cities. *Sustainable Cities and Society, 66*, Article 102617. https://doi.org/10.1016/j.scs.2020.102617

Swamy, D. S. (1967). Statistical evidence of balanced and unbalanced growth. *The Review of Economics and Statistics, 49*(3), 288–303. https://doi.org/10.2307/1926640

Talberth, J., Cobb, C., & Slattery, N. (2007). *The genuine progress indicator 2006* (p. 26). Oakland, CA: Redefining Progress.

UNDP. (2010). *Human development report 2010: The real wealth of nations*.

Wang, J. (2016). Revive China's green GDP programme. *Nature, 534*(7605), 37. https://doi.org/10.1038/534037b. –37.

Wu, F. (2015). *Planning for growth: Urban and regional planning in China*. New York: Routledge. https://doi.org/10.4324/9780203067345

Yakubo, K., Saijo, Y., & Korošak, D. (2014). Superlinear and sublinear urban scaling in geographical networks modeling cities. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics, 90*(2), 1–10. https://doi.org/10.1103/PhysRevE.90.022803

Yotopoulos, P. A., & Lau, L. J. (1970). A test for balanced and unbalanced growth. *The Review of Economics and Statistics, 39*(3), 245–251. https://doi.org/10.2307/1926314

Zhang, J., Gao, Y., Fu, Y., & Zhang, H. (2007). Why does China enjoy so much better physical infrastructure? *Economic Research Journal, 3*(3), 4–19.

Zhao, S., Liu, S., Xu, C., Yuan, W., Sun, Y., Yan, W., et al. (2018). Contemporary evolution and scaling of 32 major cities in China. *Ecological Applications, 28*(6), 1655–1668. https://doi.org/10.1002/eap.1760

Zünd, D., & Bettencourt, L. M. A. (2019). Growth and development in prefecture-level cities in China. *PloS One, 14*(9), Article e0221017. https://doi.org/10.1371/journal.pone.0221017