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Reinvestigating China's urbanization through the lens of allometric scaling

Wei Lang [a,b,c,1], Ying Long [d,1], Tingting Chen [a,b,c,1], Xun Li [a,b,c,*]

[a] Department of Urban and Regional Planning, School of Geography and Planning, Sun Yat-sen University, Guangzhou, 510275, China
[b] Urbanization Institute, Sun Yat-sen University, Guangzhou, 510275, China
[c] China Regional Coordinated Development and Rural Construction Institute, Sun Yat-sen University, Guangzhou, 510275, China
[d] School of Architecture and Hang Lung Center for Real Estate, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- Urbanization in China follows allometric scaling law.
- Scaling exponent varies at the different stages neither static state nor isometric.
- Urban system allometric scaling evolves to align with the theoretical assumption.
- Government-led developments deviates the scaling relations for a short term.
- Driving force of complex system shifts leading role at various urbanization stages.

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ABSTRACT

Cities are complex systems; we expect the dynamics of the urbanization process to follow the power law, which alludes to the scaling properties of allometry. Urban scaling as a fundamental theory has drawn abundant attention in geography and urban studies literature over the past few decades; yet, there is uncertainty about its applicability in a global context, especially in a fast-transforming urban environment such as China. More importantly, there have been very few studies on the allometric scaling of Chinese cities. This study intends to show the importance of the concept of dynamic evolution in urban systems. We examined the most significant impacts of urbanization are explicitly manifested by the scaling laws, for which the scaling exponent is the key indicator. We applied the scaling law in examining the hypothesis that the actual scaling exponent is stable at different stages of urbanization compared to the static or isometric state. We found that Chinese government-led developments may upset the power law and scaling relations among urban factors but for a short time only. Despite the driving forces in the different categories of cities alter their effects at different urbanization stages; the exponents of growth processes (urban land use area and its population density) obey the laws and rules of self-similarity and scaling coherence. Analyses of double logarithmic linear regression and quantile regression reveal the actual and observed scaling relation of urban system will always evolve to align with the theoretical assumption ($\beta = 2/3$), which provides implications on future urban development and planning in terms of city size and urban density.

* Correspondence to: D205, Dihuan Dalou, Department of Urban and Regional Planning, Sun Yat-sen University, Haizhu district, Guangzhou, 510275, China.
E-mail address: lixun@mail.sysu.edu.cn (X. Li).

[1] These authors contributed equally to this study and share first authorship.

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1. Introduction

Cities have traditionally been regarded as self-organizational in an evolutionary process. Urban evolution largely involves scaling power law in the physical processes, but the scaling relationships of urban systems are far from being in an equilibrium state [1]. Founded on "the new science" [2] and "the nature of order" [3] for city research, the theory of scaling city size elucidates the allometric relations of growth among different urban factors [4,5], which can also evoke a new kind of beauty of geographic space [6]. From fractal ideas, this allometric scaling has strong spatial correlation with urban factors of complex urban systems in the spatio-temporal evolution process [7,8]. In the real world, the urban population is never stable [1]. However, there is evidence to show that urban systems evolve towards a self-organizing process, and that urban systems are trying to restore the disturbed symmetry of nature [9]. Despite this changing effect, the measurements of scaling in urban systems are relative (change with size) and not absolute [10].

The universal law of scaling has drawn increasing attention across many disciplines. The study on allometric scaling theory was first raised by Thompson D'Arcy Wentworth in 1917 [11], and contemporarily developed in biology since 1980s [12], in which it refers to the changes in the proportion of one component size relative to a second component within the same system [13,14]. As in the case of organisms, the allometric scaling law describes the size differences in the proportions of constituent elements within the urban systems [15–17]. The classic studies involving allometric scaling law include city size and the number of manufacturing establishments [18]; residential areas, urban facilities, and land uses [15]; [19]; urban population density [20]; urban structure and population size [21]; Modeling polycentric cities [22]; temporal urban–rural relationships between urban area and their population [23–28]; the metabolism of cities [27,29] and metabolic rate growth [30], proportional distributed urban growth to their size [31] and reproductive rate and lifespan [32].

In addition to these empirical studies on the urban system in some countries around the word, such as studies on Brazilian cities [33], cities in Australia and New Zealand [34], Indian cities [35], and etc. Researchers also consider a methodological issue, e.g. Cottineau et al. discussed the systematic paradox of urban scaling laws in diverse cities [36]; deconstructed scaling laws in the evolution of British cities [37]; Leitao et al. investigated the existence of β by comparing 5 different models with 15 city datasets from 5 regions and found that β vary dramatically not only depending on the datasets but also on assumptions of the models [38]. Whether scaling relation is linear or nonlinear depending on the fluctuations that can lead to different estimations of β ($= 1$, < 1, or > 1) in double logarithmic plots.

Scaling can be derived from the mathematics of Zip's law, Pareto distribution, and power law distributions in different contexts [39], which theoretically has a mathematical relationship to the hierarchical scaling law [40]. Gibrat proposed a growth model of the exponential type with growth vary in the course of time [31]. According to Gibrat's law, the statistical form of urban hierarchies and inequalities in city sizes are growing faster in real urban systems, from one city to another over short time spans, but long-term growth averages out at the same level for all cities in a given system. In this study, scaling refers to city size, ranging from the largest cities to the smallest cities, in an allometric form of hierarchical distribution. Land use and population are two crucial organs of an urban system for rational allocation of public resources. The allometric scaling research provides some profound implications for addressing the long-standing problem of how to assess the effects of imbalanced growth on cities. These implications can be extended to urban planning and policy with respect to the regulation of the spatial form of urbanization.

With a view to the most stringent studies about Chinese cities [39,41,42], from spatial dimensions, has early characterized urban growth and systematically deciphered the allometric scaling relations of Chinese cities with a particular focus on discussing allometric scaling exponents. Fragkias and Seto demonstrated rank–size distributions of intra-metropolitan urban clusters in China [43]; Seto and Fragkias presented a spatio-temporal pattern of land use change through time series landscape metrics in China [44]. Although urban scaling as a fundamental theory has drawn abundant attention in geography and urban studies literature over the past few decades, the research community is uncertain about its nature in a global context, especially in the rapidly transforming urban environment, e.g. Chinese cities.

These empirical studies suggest that the scaling relations' dimensions range from 10^0 to 10^7 at city and regional level, e.g., city size, which can be assessed by population [6], and its relation to area in urban systems [8]. From the perspective of rapid urbanization phenomenon in China, an increasing population has moved at an increasing rate from rural to urban areas, resulting in accelerated city growth and expanded urban areas [45–47]. Since China's economic reform began in 1978, comprehensive urbanization resulted in the population of urban areas rising from 19.7% in 1978 to 49.7% in 2010. The urbanization periods of China can be divided into 4 sections: 1978 to 1990; 1990 to 2000; 2000 to 2010 and 2010 to 2014. However, this urbanization process has profoundly disrupted the structure and function of urban systems. More importantly, the difficulty that explains the complex systems involved and provides a comprehensive explanation for the urbanization of China remains unclear and questionable, which extends the underlying scaling theories to embrace the spatially historic evolution of all Chinese cities at prefecture level.

This study aims to extend the underlying scaling theories to embrace the spatially historic evolution of all Chinese cities at prefecture level. Especially, this study has three main objectives: (1) to demonstrate the phenomenon and mechanism of China's urbanization in respect of the allometric scaling relation between land-use and population, (2) to derive presumptive implications from the theory of scaling, in view of the new science of cities and the nature of order, and (3) to provide findings that assist in better developing cities for decision makers.

Here, this study intends to introduce the concept of dynamic evolution to conventional thinking about urban systems. The research contributes to the knowledge and theories of dynamic evolution in: (1) the exploration of characteristics of urbanization in China by examining the interplay between population and land use area by means of both census and official statistics in time series; (2) the relation of allometric scaling growth fits the theoretical assumption of Chinese urban systems; (3) quantile regression (QR) is primarily employed to systematically classify cities with similar properties of allometric scaling into four different categories, which captures the allometric scaling relation better than the conventional administrative classification of city categories; (4) the scaling exponent is at a dynamic equilibrium and adjusts in various ways towards the predictions of theory.

2. Data and methods

As one of the most universally applied formulas, the power law relationship characterizes the scaling structures of a system. The allometric scaling to the body size can be presented as a function:

$$Y = \alpha X^{\beta} \tag{1}$$

The relative growth rate of component Y is proportional to the relative growth rate of another component X, with β being the proportionality factor. The allometric exponent β, known as the scaling factor in biology, describes how Y is scaled in relation to X. When $\beta > 1$, positive allometry implies that Y increases at a faster rate than X and generates superlinear scaling. When $\beta < 1$, negative allometry implies that Y increases at a slower rate. When $\beta = 0$, Y has no scaling relationship with X. When $\beta = 1$, an isometry implies that X and Y increase in a linear proportion. The allometric scaling exponent is a constant growth exponent of the power law function:

$$\beta = \frac{dy}{y} \Big/ \frac{dx}{x} \tag{2}$$

According to the principle in mathematics, x and y in different dimensions should be transformed into the same dimension. If the linear unit is denoted as L, then area A is determined as L^2 and volume V as L^3 such that $V = AL$. Huxley proposed allometric relations of changes in the volume, area or length relative to each other as $A = V^{2/3}$. The area grows at a rate 2/3 of volume growth [48]. The relative growth ratio of area (A) and volumes (V) in a geometric linear model is:

$$A \propto V^{\frac{2}{3}} \tag{3}$$

Similarly, a generalized scaling relation of urban population (N) versus urban area (A) in an urban system can be defined as:

$$A = \alpha N^{\beta} \tag{4}$$

where α is the proportionality coefficient, and β is the scaling factor. Urban population should scale into a three-dimensional space such that $A \sim N^{2/3}$. Nordbeck establishes the first theoretical view on $\beta = 2/3$ in Sweden [24]. Bettencourt claims a universal allometric scaling relation between urban population and area with a theoretically expected assumption at $\beta = \frac{2}{3}$ [49,50]. This β value of $2/3 = 0.667$ should truly represent the scaling relation between urban population and urban land use area [13,14,24]. There are critical ratios in size changes [51], where the observed variability in measuring β is anchored at $2/3 \sim 1$ by worldwide researchers, due to the adoption of inconsistent definitions of city size [52]. The US urban system seems to fit the dynamic similarity with $0.70 < \beta < 1.0$ [52]. The recent studies conducted in the US and UK indicate strong negative allometry but the allometric parameter, after reaching its peak during the 1980s, starts falling from the 1990s to the 2010s [53]. The range given (see Table 1) is a synthesis of these results.

Across time and nations worldwide, all the evidence generally confirms the universal nature of allometric scaling of urban systems. Evidence across urbanization levels shows the consistent scaling relation of the urban systems from the US, UK and Sweden to China. However, the scaling variant is largely changing over time. In order to provide insights, illustrate the allometric scaling relation of China's city size between population and land use, this study compares data from different sources. The best-fit scaling factors in each scaling relation were estimated through ordinary least-squares minimization to the linear relation and quantile regression between logarithmically transformed variables. QR are robust to compute fitted values for multiple quantiles and extreme variable. Quantiles $\tau = (0.25, 0.5, 0.75, 0.9)$ are synthetically used in this study, although it is possible to extract an infinite number of quantiles. Standard linear regression summarizes the average relationship based on the mean function $E(y|x)$, while QR fits specified percentiles of the response and characterizes the entire distribution of y, not only its mean [60,61]. In $Qq(y|x)$, the quantile $\tau \in (0, 1)$ is that y which splits the data into proportions τ below and $1 - \tau$ above: $F(y_\tau) = q$ and $y_\tau = F^{-1}(\tau)$:

$$Q\left(\beta_\tau\right) = \sum_{i:y_i \geq x_i'\beta}^{N} \tau \left|y_i - x_i'\beta_\tau\right| + \sum_{i:y_i \geq x_i'\beta}^{N} (1-\tau)\left|y_i - x_i'\beta_\tau\right| \tag{5}$$

for the median, $\tau = 0.5$. The parameter estimates, the $\beta_i(\tau)$ coefficient are the rate of change of the τth quantile of the dependent variable distribution per unit change in the value of the ith regressor.

Table 1
Comparison of historical allometric urban development in the USA and UK (Evidence of allometry between area and population size)

Countries	Years	Exponent β	Reference
USA	1940s	0.75	Stewart [54]
	1950s	0.75	Stewart and Warntz [26]
	1960s–1970s	0.8598	Nordbeck [24] and Woldenberg [20]
		0.8621	Boyce [55]
		0.8651	Lee [52]
		0.8803	Nordbeck [24], Woldenberg [20] and Tobler [27]
	1980s	0.8598	Veregin and Tobler [28]
		0.8540	Lee [52]
	1990s	0.65	Sutton et al. [56]
	2000s-2010s	0.63	Paulsen [57]
UK	1950s	0.7502	Stewart and Warntz [26]
	1960s	0.8382	Smith and Jones [58]
	1980s	0.96	Longley et al. [59]
	1990s	0.9587	Batty and Longley [4]
	2000s–2010s	0.7716	Batty [51]

Urban Statistical Yearbook (USY) is used to compare the Census data for 282 urban areas in year 1990 and 2000, and Urban Construction Statistical Yearbook (UCSY) is used for compassion in year 2010 and 2014, with urban built-up area and urban population in year 1990, 2000 from Urban Statistical Yearbook, and urban permanent residents in year 2010, 2014 from UCSY. The National Population Census of China (often referred to as the Chinese Census) is a comprehensive survey of the population within a specific time period across the country, using a unified approach involving a questionnaire and door-to-door registration. The Census data reflects the nature of the urban population's location origins under the Chinese household registration system. It is today the most basic population data collection obtained by scientific method, and is the main source of the national basic demographic data. The Census data is used to derive estimates of population sizes and rates of growth for post-census years prior to the publication of the next census. The National Bureau of Statistics of the People's Republic of China (NBS) is the official source for most national statistics, including censuses every 10 years and major statistical series published in the annual China Statistical Yearbook (CSY). The NBS has traditionally used census data to adjust urban statistics published in the CSY.

Official statistics for actual urbanization in China remain elusive. Chinese cities are extending beyond existing administrative boundaries at an ever-fast pace, leading to a changing definition of the city. The usage of different definitions and delineations also remains as an obstacle to measure city size. Many changes over time in (re) definitions of urban coverage have gone unnoticed. If we are not aware of, the inconsistent data will make conduct analysis difficult. The aspect of changes in the criteria used by the NBS for urban territory definitions is one of the main reasons for inconsistent statistics [8]. Pumain and Swerts [62] and Pumain et al. [63] systematically demonstrated the dynamic urban processes in city delineation of Chinese cities through an international comparison in different countries. Urban delineation is subjected to the local regime of political and institutional recognition. The particular history of cities building has influenced the statistical results and statistical conventions, such as government decision on migrant populations not being taken into account, periodic political adjustment on administrative designations of cities and towns (e.g. merge or split districts, towns, and cities), and explosion of urbanization with the prioritization from the central government and local governments to economy increase and real estate development.

As summaries of national censuses, the UCSY and USY are the major sources of urban data for China. These standardized databases are widely frequent used for comparing urban systems in rapidly growing cities of China, although for some researchers, the delineations of built-up areas are collected from satellite images of the districts, municipalities and counties. For compiling data as constant and unified as possible to interpret closely to actual urban profiles, we have made efforts: for those cities who have administrative boundary adjustment (split or merge), we used the same urban units according to early statistics definition; for those cities who have changed names, we kept data identical on the basis of initial definitions; for population data, we considered urban residents population to avoid the uncertainty of migrants and informal residents; for urban area, we focused on urban built-up area that is more pervasive than administrative region, with references to supplement data accuracy, e.g. remote sensing data to consolidate a few cities' variances. To the existing knowledge, these data are still the most reachable feasible sources for urban studies. Although a number of data issues remain, the availability of data for China has a bright future in future research agenda of city size [64]. China is gradually adopting international standards in the compilation of its statistics. In order to project an accurate profile of the Chinese urban population and land use area, we will compare the official data obtained from the CSY with Census data to produce the scaling relationship for Chinese urbanization (Fig. 1).

3. Results

Fig. 1 compares the linear scaling relationship between USY (black line and dots) and census (red line and dots) data in four representative periods. We plot allometric scaling in log–log regression with base 10 such that log x means $\log_{10}x$. The

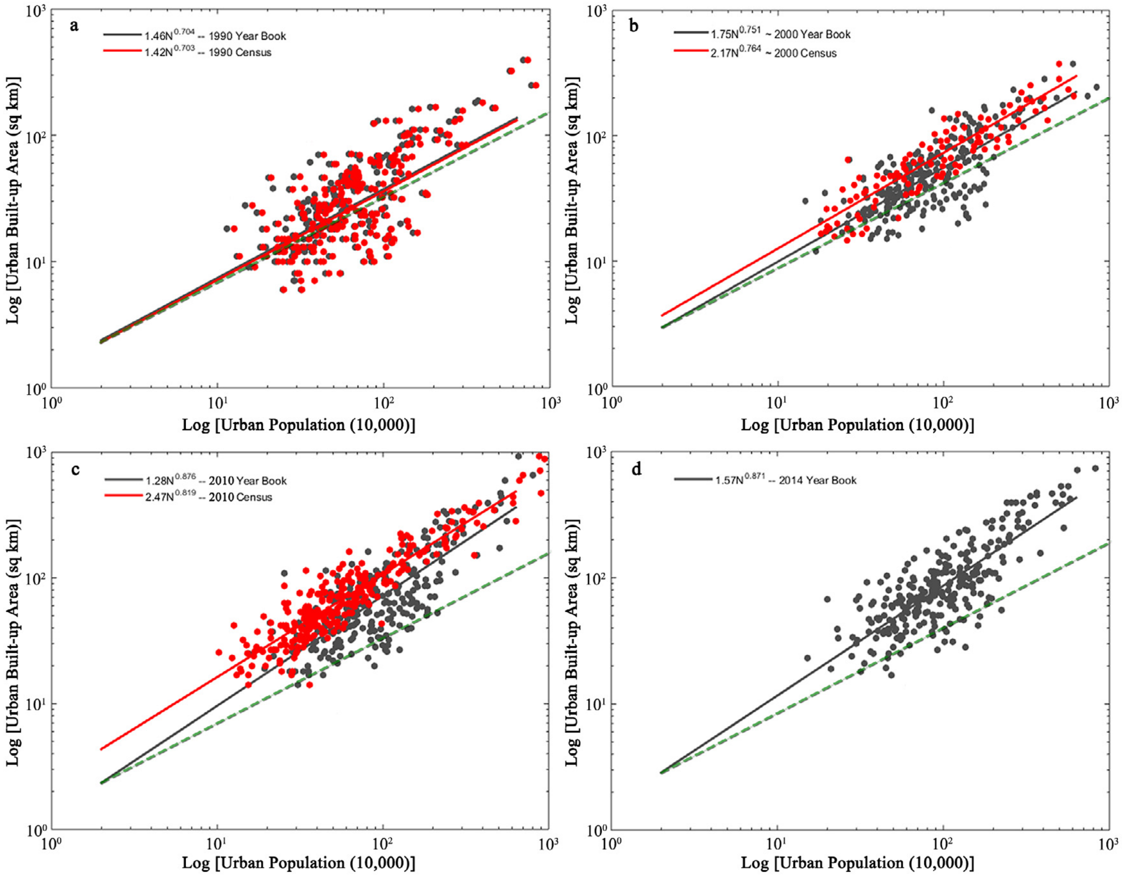

Fig. 1. Double logarithmic plots of the allometric scaling relationship between urban area ∼ urban population of Chinese cities at prefecture level in various years. Fig. 1(a) Lines show the best fit to a scaling relation $A = \alpha N^{\beta}$ in year 1990, Census (red), with $\beta = 0.703$ [95% confidence interval (CI), 0.632∼0.774, $R^2 = 0.60$]; USY (black), with $\beta = 0.704$ [95% confidence interval (CI), 0.588∼0.821, $R^2 = 0.60$]; and the theoretical prediction, $\beta = 2/3$ (green); Fig. 1(b) Lines show the best fit to a scaling relation $A = \alpha N^{\beta}$in year 2000, Census (red), with $\beta = 0.764$ [95% confidence interval (CI), 0.611∼0.916, $R^2 = 0.73$]; USY (black), with $\beta = 0.751$ [95% confidence interval (CI), 0.670∼0.832, $R^2 = 0.65$]; and the theoretical prediction, $\beta = 2/3$ (green); Fig. 1(c) Lines show the best fit to a scaling relation $A = \alpha N^{\beta}$ in year 2010, Census (red), with $\beta = 0.819$ [95% confidence interval (CI), 0.780∼0.858, $R^2 = 0.86$]; UCSY (black), with $\beta = 0.876$ [95% confidence interval (CI), 0.798∼0.953, $R^2 = 0.65$]; and the theoretical prediction, $\beta = 2/3$ (green); Fig. 1(d) Lines show the best fit to a scaling relation $A = \alpha N^{\beta}$in year 2014, UCSY (black), with $\beta = 0.871$ [95% confidence interval (CI), 0.799∼0.944, $R^2 = 0.67$]; and the theoretical prediction, $\beta = 2/3$ (green).

allometric scaling (1980s–2010s) demonstrates that Chinese cities have a proportionately larger land area than population, and β is always greater than 2/3 (Fig. 1). It describes the scaling exponent $\beta = 0.704$ (USY) and 0.703 (census) in year 1990; $\beta = 0.751$ (USY) and 0.770 (census) in year 2000; $\beta = 0.876$ (USY) and 0.819 (census) in year 2010 and $\beta = 0.871$ (USY) in year 2014. This means that if the populations of a city increase by a unit, the city area will increase by less than a population unit as per a sub-linear relation. In other words, the urban area grows proportionally less than the urban population compared to the linear relation. However, to the most researchers, the assumption of scaling factor (exponent β) yields a best fit value to the relation between population and land area. It is known as the theoretical value from scaling model, which justifies the rationale as to population and land area. In this sub-linear scaling relation, when $2/3 < \beta < 1$, that is where land area grows at a faster rate than that of population (positive allometry).

The estimation from both data sources shows a changing scaling relation that accelerates until 2010, then it slightly decreases in the very recent year 2014. All those cities distributions are moving from the left lower to upper right side of the chart, following the same scaling law within one category. Smaller cities are anticipated to grow in the same trajectory going forward as the bigger cities did. There is a distinct change from 2000 to 2010, which was the result of administrative adjustments and major national policies. The most influential national policies include an investment in state infrastructure for west China in 1998; from 2000, land use right transfers in China being allowed only by land auction; China's entry to the WTO in 2003 leading to huge urban transformation in the coastal areas; and in 2005, land finance (land sale finance) being introduced to stimulate urban development. For differentiating the evolution of urbanization, cities are grouped according to the orientation of their trajectories to which they belong, which may be faster or slower than that of the country as a whole. Through QR, cities are systematically classified into different categories according

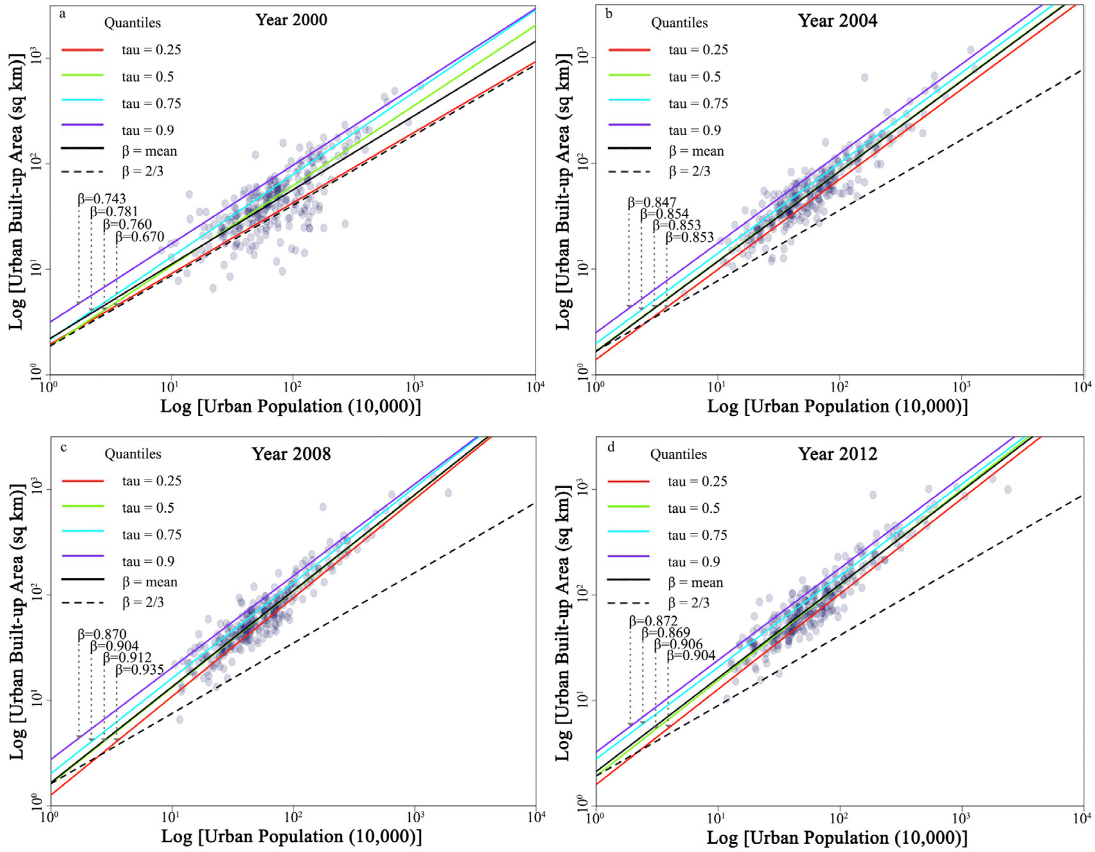

Fig. 2. Quantile regression of double logarithmic plots of the allometric scaling relationship between urban area ∼ urban population of Chinese cities at prefecture level in various years. The black dashed lines represent the theoretical $\beta = 2/3$, and the solid lines in black are the mean regression lines. Data for 282 observed cities (urban built-up area and population of urban permanent residents) were obtained from UCSY. Fig. 2(a) Lines show the best fit to a scaling relation $A = \alpha N^{\beta}$ in a quantile regression (year 2000), quantile: 0.25 (red), with $\beta = 0.670$ [95% confidence interval (CI), 0.469∼0.775, $R^2 = 0.60$]; quantile: 0.5 (green line), with $\beta = 0.760$ [95% confidence interval (CI), 0.662∼0.834, $R^2 = 0.78$]; quantile: 0.75 (cyan), with $\beta = 0.781$ [95% confidence interval (CI), 0.724∼0.814, $R^2 = 0.88$]; quantile: 0.9 (purple), with $\beta = 0.743$ [95% confidence interval (CI), 0.714∼0.772, $R^2 = 0.92$]. Fig. 2(b) Year 2004, quantile: 0.25 (red), with $\beta = 0.853$ [95% confidence interval (CI), 0.813∼0.883, $R^2 = 0.91$]; quantile: 0.5 (green line), with $\beta = 0.853$ [95% confidence interval (CI), 0.824∼0.894, $R^2 = 0.91$]; quantile: 0.75 (cyan), with $\beta = 0.854$ [95% confidence interval (CI), 0.808∼0.902, $R^2 = 0.88$]; quantile: 0.9 (purple), with $\beta = 0.847$ [95% confidence interval (CI), 0.777∼0.892, $R^2 = 0.85$]. Fig. 2(c) Year 2008, quantile: 0.25 (red), with $\beta = 0.935$ [95% confidence interval (CI), 0.903∼0.957, $R^2 = 0.71$]; quantile: 0.5 (green line), with $\beta = 0.912$ [95% confidence interval (CI), 0.864∼0.937, $R^2 = 0.81$]; quantile: 0.75 (cyan), with $\beta = 0.904$ [95% confidence interval (CI), 0.864∼0.939, $R^2 = 0.83$]; quantile: 0.9 (purple), with $\beta = 0.870$ [95% confidence interval (CI), 0.853∼0.922, $R^2 = 0.77$]. Fig. 2(d) Year 2012, quantile: 0.25 (red), with $\beta = 0.904$ [95% confidence interval (CI), 0.858∼0.937, $R^2 = 0.90$]; quantile: 0.5 (green line), with $\beta = 0.906$ [95% confidence interval (CI), 0.865∼0.939, $R^2 = 0.90$]; quantile: 0.75 (cyan), with $\beta = 0.869$ [95% confidence interval (CI), 0.816∼0.924, $R^2 = 0.86$]; quantile: 0.9 (purple), with $\beta = 0.872$ [95% confidence interval (CI), 0.819∼0.942, $R^2 = 0.84$]. Quantiles= 0.25 (red line), 0.5 (green line), 0.75 (cyan line), and 0.9 (purple line).

to individual characteristics of scaling (Fig. 2), which led to four hierarchical city quartiles. with quantile=0.25 (red), quantile=0.5 (green), quantile = 0.75 (cyan), quantile = 0.9 (purple). The theoretical prediction value is $\beta = 2/3$ (dashed line), and the solid lines in black is the mean regression line. The estimated parameters and 95% confidence intervals show all of the parameters are considered significant. The results show the peak growth levels of different quantiles in various years. The median and the mean are close in 2004 and 2008, which indicates that the distribution of urbanization extent is roughly symmetric. In addition, Fig. 3 depict the asymmetric distributions of urban population and land use area in various years, which show a right heavy tail. Growth power moving from upper to lower quantiles signals skewed contribution of population to land use area increases. The median line shifts from the mean left, to overlap the mean, and to the mean right, denotes the shifts of higher ratio of land use area from upper quantile cities to lower quantile cities. For example, the effect of population on land use area is slightly stronger for the upper quantile in 2000.

The graphical representation of QR results allows to observe the different coefficients of different quantiles, where the quantiles are represented on the *x*-axis, the coefficient values are shown on the *y*-axis, the solid lines represent the estimate quantiles, and the dashed line are placed for mean value. This estimation also shows the overall trends of scaling exponent for all quantiles-cities, which started to increase faster at the earlier stage of accelerating urbanizing periods. The exponent peaked in the year 2008∼2009, and has slowed in recent years (Fig. 4). The urbanization driving force has been

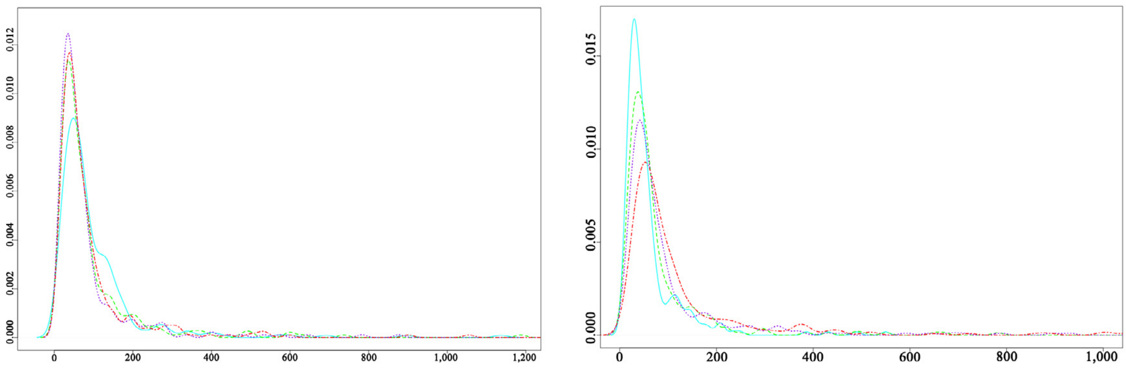

Fig. 3. Observed density plot for the two subsets variable of urban population and urban land use area. The four different lines in each panel represent the densities for observed variable in year 2000 (cyan), year 2004 (green), year 2008 (purple), and year 2012 (red). Fig. 3(a) probability density for *y*-axis and urban population for *x*-axis. Fig. 3(b) probability density for *y*-axis and urban land use area for *x*-axis.

Table 2
Inter-quantile change in the estimated coefficients of quantile regression in various years.

Quantiles	2000	2004	2008	2012
0.25	0.670	0.853	0.935*	0.904*
0.5	0.760*	0.853	0.912*	0.906*
0.75	0.781*	0.854*	0.904	0.869
0.9	0.743*	0.847	0.870	0.872
Mean	0.704	0.853	0.910	0.887

Note: Those coefficients with asterisk indicate the large value change in scaling exponent and the driving force shift of China's urbanization.

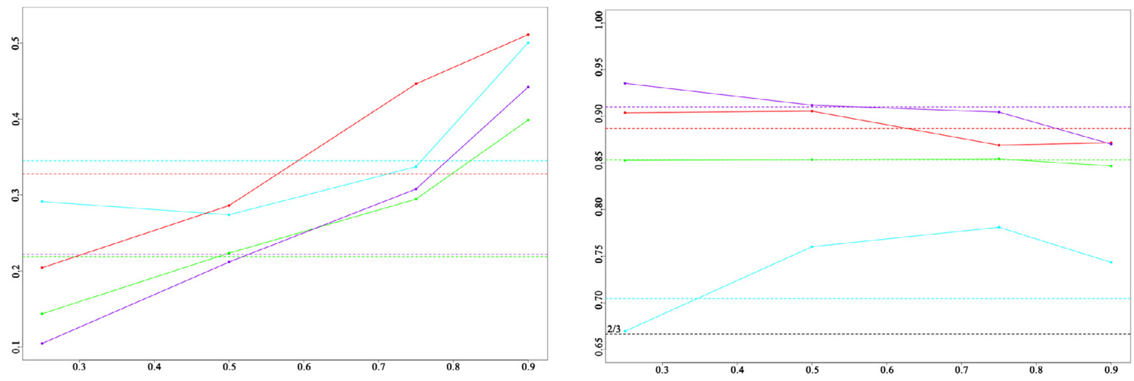

Fig. 4. Graphical representation of quantile regression of intercept change (a) and coefficient change (b) (solid line) among different quantiles in year 2000 (cyan), year 2004 (green), year 2008 (purple), and year 2012 (red). The *x*-axis for quantiles and the *y*-axis for coefficient values, dashed lines for the mean estimates.

shifting in two dimensions from year 2000 to year 2012, along both *x*-axis and *y*-axis (also see Table 2). Longitudinally (y-axis), the ranking of scaling exponents shifts from higher quantile cities to lower quantile cities. Horizontally, the leading driving force of urbanization (larger scaling exponent) changed from low value to high value, and then showed a trend to become low value among the four quantiles of cities. It is apparent that the urbanization tendency has been a shift from mean left in 2000, to mean right in 2012. Essentially, the growth driving force shifts from upper quantiles to lower quantiles.

QR provides location, scale, and shape shift information on the distribution of the response variable. In practical terms, the cities of upper quantiles are more likely to expand in the distribution for greater land use area. The effect of changes of urban population-area increases in the central tendency and in the variability of the response variable is defined as a location-scale model [60]. The number of urban population a city is capable to carry has a greater effect for cities with a larger growing power, where one-unit increase of the population leads to an increase in the land use area powered by the scaling exponent. In this regard, Table 3 compared the estimates of different quantiles to mean and observed

Table 3
Regressor at different quantiles and observed value of urban land use area (sq km) for selected sample cities in various years.

Cities	Quantiles	Years			
		2000	2004	2008	2012
1 million population	0.25	67.25	85.42	93.64	90.58
	0.5	76.29	85.57	91.40	0.84
	0.75	78.45	85.73	90.76	87.35
	0.9	74.84	85.07	87.46	87.68
	Mean	70.79	85.53	91.22	89.01
	Observation	36.36	96.81	100.00	114.00
10 million population	0.25	669.88	852.87	935.47	903.93
	0.5	760.48	853.71	912.08	905.83
	0.75	781.42	854.66	904.79	869.46
	0.9	743.87	847.14	870.62	872.22
	Mean	704.82	853.36	910.24	887.15
	Observation	549.58	1,182.30	1,049.42	863.43

values (both in 1 million and 10 million city samples in various years). It is noteworthy that each class of the allometric scaling relations of city size in the four quantiles actually represents a specific group at a particular period of the evolution process, supported by the theory of scaling, i.e., self-similarity of evolution in a complex system. This hierarchical scaling relations accord to a natural law of hierarchical scaling, derived from physical and biological logarithms. All cities consist of a complex urban system as a whole, components (parts) are self-similar to the system (whole), and can generally represent the system's trend.

Based on the above analysis results, Fig. 5 demonstrates a geographical difference in the changing allometric scaling growth of Chinese cities over the past 35 years. This allometric scaling result of land use expansion in relation to urban population growth shows large-scale urban expansion of Chinese cities above prefecture level. The circle size denotes the degree of variance in their scaling factor of actual growth from the theoretical scaling growth over the past 35 years. Blue color indicates a negative scaling factor of actual growth to theory value, whereas red color indicates a positive scaling factor of actual growth to theory value. Most cities have proportionately over used their land, and only a few cities have consumed their land less in the scaling relative to population growth.

The spatial characters of China's urbanization over the past 35 years have considerably different structures compared to cities in North America and Europe in a century span. Western cities traditionally grow outwards with tremendous flows of migrants and large-scale suburbanization. In China, people have more mobility constraints to traveling around cities for decades, which extremely limited location preferences. Furthermore, housing market limits mobility and administrative allocation of inner urban land to state-controlled enterprises at no cost meant that, up until very recently, no economic incentive was given to these firms to relocate to lower-cost suburban sites. Therefore, in the formal urban areas of cities in China, households and firms have been subjected to significant location and mobility constraints absent in North American and European cities.

4. Discussion and conclusion

Urbanization is a self-organizing transition from a rural to an urban system. Theoretically, urbanization, or urban expansion, is closely connected with macro social-economic development in a regional or national context. However, as a populous country, China's rapid urbanization is alternatively led by both top-down urbanization and bottom-up evolution (self-organization). Urbanization has evolved with Chinese economic development since 1978, the start of the reform, which can be divided into four stages: (1) national programming age, (2) starting urbanization movement, (3) dramatic urbanization, and (4) proportionate scaling relation. This process illustrates urbanization dynamics at different stages in accordance with the changing urban planning actions, policies, and political decisions by central government.

Population growth accelerates and then decelerates after reaching its limit. In principle, an increase in urban population and urban land area should be synchronous, but in fact, the growth of urban land area across China has shown distinctive scaling that varies from the theoretical prediction. In the 1990s, an era of the planned economy and the household registration system, land $\sim$population proportional configurations led to balanced urban development. Therefore, at all quantiles, cities are close to the theoretical scaling exponent, most notably the $\frac{1}{4}$ quantile cities scale is almost the same to $\beta = 2/3$ (see Table 2). China experienced accelerating urbanization as a result of the population distribution of urban development following market economy discipline in the late 1990s and China's WTO accession. China's past extensive urban development led to large areas of rural land being converted into urban areas without the equivalent urbanized population corresponding to such land transformation. So, β is greater than 2/3. In addition to real estate investment was one approach to drive China's economy, while at the same time it exacerbated urban expansion. In particular, local governments relied on revenue through land lease, land conversion, and land tax, which stimulated land economy-related development. More seriously, all levels of governments concentrated on the urbanization rate rather than the rationality of evolution within a complex system [65,66], as under the guidance of the current entrepreneurial governments.

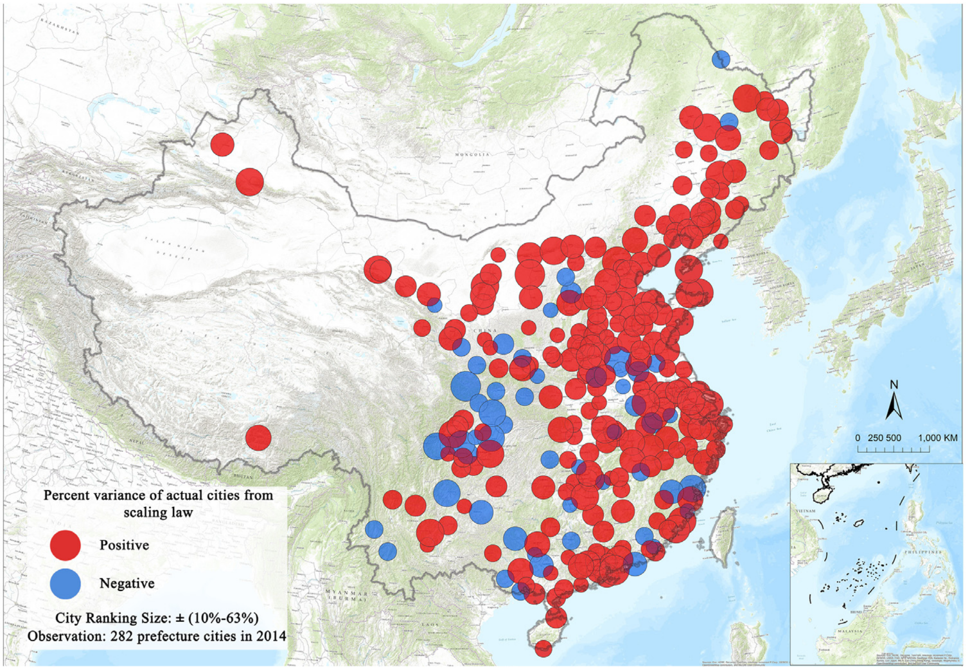

Fig. 5. Changing degree of allometric scaling relation of urban area and urban population in 282 prefecture level cities from 1982 to 2014. Percentage variance of scaling factors of actual value over theoretically expected value, positive (red), negative (blue), and size range: ± (10%—63%)..

A new development period started to emerge, when the *National New-type Urbanization Plan (2014)* and the *China Central Urban Work Conference (2015)* were enacted, to influence planning and development policies across China. Under the determination to turn extensive urban development (driven by land consumption and real estate investment) into intensive urban development (appropriate city size and rural land reservation), both central government and local government have started to implement planning policies to regulate new development and optimize existing urban areas. Urban expansion has ceased or slowed down in most cities across China. Infill development became the priority option for new growth. This, combined with a new urbanizing population entering into existing urbanized areas will increase urban density. Therefore, we can expect the scaling factors to approximate theoretical values again in the near future.

Although in recent years, there is a large surplus of urban land, in the long run, according to the allometric relations of people, land use must return to a reasonable state. Urban systems characterized by allometric scaling are constantly evolving into an optimal state of environmental, social, and economic efficiency. This allometric urbanizing process infers that all urban systems corresponding to urban land use area and its population density, are in dynamic equilibrium or in a tendency to approach a steady optimal state. Therefore, a steady state of an open system is equivalent to an equilibrium state of a closed system [67]. Such interpretation from the allometric perspective is consistent with the nature of growth that a system adjusts towards an optimal form. This is well described by the observed scaling factors (exponents) that are embedded in the novel theory of scaling coherence in the concepts of fractal and complexity. In previous studies, Mandelbrot recognized coherent properties of self-similarity and scaling in fractals [68], and Jiang and Sui stated such coherence in scaling — that every scale is part of some larger scale, and that every scale is essential to form scaling hierarchy or whole system [6].

Size-dependent change implies new potentiality [69], and allometry implies change of size with development or growth, which has been adopted in the general sense. Area-to-volume relationships is regarded as the elaboration of evolutionary structure. The impetuses for changes are not restricted to consequences of decreasing area-to-volume ratios. The emphasis is upon the method of measuring increase of one part against that of another morphological dimension rather than against time in its Newtonian absolute sense. Urban systems, like organisms, usually conform to the law of allometric growth; likewise, urban systems in China follow the scaling law in a broad sense during the urbanization process. The allometric exponent presented in this study supports the hypothesis of dynamic changing values for urban systems rather than a fixed and stable value. It was found that the actual scaling factor increased or decreased with time variable and gave the perception of urbanization processes. The formation of city size and urban expansion is linked with historical urbanization processes. It is important to demonstrate the trajectories of urban evolution over time and mark the major historical turning points. Nonetheless, the theoretical assumption is that scaling exponents are independent of time [50]. All of the above arguments provide concepts that add to the literature of scaling, and hence give support to implications arising from the theory of fractals and complexity.

We contend for planning and development that: (1) urban density is an effective measurement to evaluate and maintain a rational scaling relation from population to land use, economic development, infrastructures etc.; (2) decision makers need to devote more attention to population urbanization than land area urbanization; and (3) infill development is a desirable approach to achieve new-type urbanization and help to rebalance the scaling relation of Chinese urban systems. The statistics of standard deviations can apply the process of urban scaling to all urban systems. Efficient urbanization should be gauged from the perspective of urban planning for allocation of land. There are prevailing inefficient development patterns during the rapid urbanization and industrialization process in past three to four decades, which draws more attention and brings about more effort on improving: (1) mal-functioning of planning practice, policies and institutions; (2) strong incentives in promoting economic growth through land development by local government; (3) less farmland protection. If a city, at a certain stage of urbanization, fails to follow this law, the city destroys the relation of people to land use, due to factors such as the inefficient use of urban land. That is the essence of scaling to the nature of order [4], which is a universal truth in physics, biology, and the natural environment.

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Wei Lang, is an Associate Professor of urban planning in the Department of Urban and Regional Planning at Sun Yat-sen University. He completed his Ph.D. in urban planning and spatial analysis, Master degree in urban planning and policy design, and Bachelor degree in urban planning. The areas of his academic interest include: urban structure and morphology, regional planning, spatial analysis, network analysis, big data modeling, complex system, and fractal cities.

Ying Long, is an Associate Professor of at Tsinghua University, and an interdisciplinary scholar with a global vision and substantive planning experiences in China. He obtained his Ph.D. degree at Tsinghua University. His research focuses on urban planning, quantitative urban studies, big data application, and applied urban modeling. Dr. Long is also the founder of Beijing City Lab (BCL), an open research network for quantitative urban studies.

Tingting Chen, is an Assistant Professor of urban planning and urban geography in the Department of Urban and Regional Planning at Sun Yat-sen University. She obtained her Ph.D. degree at Hong Kong Polytechnic University, Master degree at University of Hong Kong, and Bachelor degree at Sun Yat-sen University. Her research focuses on urbanization, travel behavior, the built environment to movement, and the formation of urban areas in China.

Xun Li, is a Professor of economic geography in the Department of Urban and Regional Planning and Dean of Urbanization Institute at Sun Yat-sen University. His main research emphasizes on aspects of economic geography, population growth and urbanization in China, and scaling. He has conducted three National Natural Science Foundation of China (NSFC) research projects as principle investigator, which are related to allometric scaling of city development and shrinking cities, with a number of articles published in this area.