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Spatial and Temporal Evolution of Urban Systems in China during Rapid Urbanization

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Abstract: The structure of urban hierarchy and the role of cities of different sizes have drawn considerable scholarly interests and societal concerns. This paper analyzes the evolution and underlying mechanisms of urban hierarchy in China during the recent period of rapid urbanization. By comparing scale changes of seven types of cities (megacity, large city, Type I big city, Type II big city, medium-sized city, type I small city and type II small city), we find that allometry is the main characteristic of urban hierarchical evolution in China. We also test the validity of Zipf's law and Gibrat's law, which broaden the scope of existing studies by including county-level cities. We find that urban hierarchical distribution is lognormal, rather than Pareto. The result also shows that city size growth rates are constant across cities of different types. For better understanding of the mechanisms of urban hierarchical formation, we measure the optimal city size and resource allocation by the Pareto optimality criterion and non-parametric frontier method. The main findings are as follows: (1) scale efficiency is still at a relatively low level among the seven types of cities; (2) the economic efficiency of megacities and large cities is overestimated when compared to economic-environmental efficiency. Hence, this paper has two policy implications: (1) to correct factor market (land, labor and infrastructure investment) distortions among different types of cities for the improvement of efficiency; (2) to strengthen rural property rights to improve social equity, as well as land use intensity.

Keywords: urban hierarchy; Zipf's law; Gibrat's law; total-factor productivity; China

1. Introduction

The spatial and temporal evolution of urban hierarchy has drawn considerable scholarly interests [1–3] and societal concerns [4–6]. In China, labor and capital have been largely migrating to coastal metropolitan areas since the 1990s [7–9], which has been contributing to serious urban problems, such as traffic congestion, environment pollution and resource limitation, alongside threatening social stability and sustainable development [10,11]. To cope with these challenges and as part of the objectives to encourage rapid and healthy urbanization, the Chinese government has promoted policies to optimize the distribution of urban population. The main policy of the Twelfth Five-Year Plan Guideline [12] aims to support the development of small and medium-sized cities and to further restrict the expansion of megacities.

Although the Chinese government has been making efforts to build a healthy and sustainable urban system, the organization and mechanisms of the Chinese urban system remain less understood [13,14]. It is essential to investigate the spatio-temporal evolution and underlying forces of urban hierarchical structure in China during rapid urbanization. Based on theoretical and empirical analyses, this paper attempts to answer the following questions in the context of China: (1) How does the structure of different types of cities in China change? (2) How is the real distribution of urban hierarchy different from optimal distribution? (3) What is the driving force for megacities to attract such large migration?

2. Literature Review

2.1. City Size Distribution and Chinese Cities

Rank-size and primate distribution are two major kinds of city size distribution, with three types: lognormal, primate and intermediate [15]. For a long time, Zipf's law has been gaining continuous interest for the powerful explanation of the optimal city size distribution based on the Pareto optimality criterion [16] (Zipf's exponent one is taken as the underlying reasonable distribution). It provides a strong empirical support for theoretical models, such as the general equilibrium model of the city system [17] and the city growth model [18]. Combining with Gibrat's law [19], three aspects of both the static and dynamic characteristics of the city system can be interpreted: primacy, size and shape [20,21].

Over the past several decades, plenty of empirical studies about city size distribution have been launched, with a focus on testing the validity of Zipf's law [21–27] and Gibrat's law [20,28,29]. Scholars have found that Zipf's exponent is sensitive to both spatial and temporal factors, such as geographical scale and development level [21,22,24,25]. Rosen and Resnick (1980) [22], for example, find the exponent of Zipf's law to be about 1.13 based on the sample of 44 countries in 1970. Batty (2001) [24] estimates the exponent from 1901 to 1991 and finds it to be between 0.58 and 0.82. Soo (2005) [25] finds the exponent to be between 0.817 and 1.719 based on a cross-national sample analysis of 73 countries. Ye and Xie (2011) [21] analyze and compare the differences of the urban system in China and its six macro-regions from 1960 to 2000 and estimate that the range of Zipf's exponent is from 0.72 to 0.86.

As the biggest developing and transitional country in the world, China is facing a new challenge for building a coordinated and healthy urban system, which also motivates empirical studies focusing on city size distribution and urbanization [4,6,25,30–34]. Most of the existing literature focuses on the trajectory of the city system evolution in China before 2000 [21,25,31]. However, China has undergone rapid urbanization since the late 1990s, and the spatial-temporal evolution of the urban hierarchy covering the rapid urbanization period is still rarely studied. On the other hand, most of the existing studies mainly focus on metropolitan areas and prefecture-level cities in China, while county-level cities are largely ignored [21,31]. The administrative city system in China contains four levels of cities—centrally-administered municipalities, sub-provincial cities, prefecture-level cities and county-level cities [35]. As the main body of the city system in China, the county-level cities cannot be excluded in research. In summary, the existing literature still has some unresolved issues: (1) the evolution of cities of different sizes in China in the era of rapid urbanization; (2) whether or not the rank-size distribution exponent is equal to Pareto exponent one.

Although existing studies have deepened the understanding of the urban hierarchical evolution of China, scholars still disagree over the classification and distribution of cities, and consequently, empirical findings cannot provide strong scientific evidence for policy development. The Chinese government traditionally classified Chinese cities into three categories: large (>500,000), medium-sized (200,000–500,000) and small cities (<200,000). However, due to rapid urbanization and the growth of large cities, many Chinese cities have a population over one million, and some cities, like Shanghai and Beijing, are among the largest cities in the world. Consequently, based on extensive studies and discussion, the Chinese government in 2014 promulgated the classification standard of different types of cities [36]. Based on the number of permanent residents (living more than six months per year) in an urban area, the urban hierarchy in China is divided into seven types: megacity (size $\geqslant$ 10,000,000), large city (5,000,000 ⩽ size < 10,000,000), Type I big city (3,000,000 ⩽ size < 5,000,000), Type II big city (1,000,000 ⩽ size < 3,000,000), medium-sized city (500,000 ⩽ size < 1,000,000), Type I small city (200,000 ⩽ size < 500,000), Type II small city (size < 200,000). Urban area in the classification is defined by municipal district. Permanent resident population in the urban area is defined by residents who have lived in cities for more than six months a year. The official statistics data are announced by the Fifth Census data in 2000 and the Sixth Census data in 2010. This new classification also makes it urgent to investigate the proportion and change among the seven types of cities and to measure the deviation of the real distribution of urban hierarchy in China from the optimal distribution.

2.2. The Underlying Forces for Urban Hierarchical Formation

City system evolution is driven by two types of opposed forces: market force and government intervention [33,37]. Efficiency and equity are dual goals for building healthy and coordinated urban hierarchy, and balancing market and government is a common principle for policy making [14]. However, China's current urbanization pattern is inefficient, both in size and structure [6]. Different from most urbanization processes in developed countries, China's urbanization is heavily guided by the Chinese government. The rapid urbanization in China is mainly due to large-scale industrial land development, housing construction and public facility construction [13]. In China, market prices do not always play a leading role in factor allocation to achieve effective use of resources. This causes serious problems, such as unsystematic development of urban land and over-investment of infrastructure in megacities, on the one hand, while schools and hospitals in small cities are fewer and have poor quality, on the other. This inefficient urbanization pattern also has a negative influence on social welfare accumulation [6]. Considering the resource limitation in China, this urban development pattern is not sustainable.

In summary, the rapid urbanization in China is largely driven by the accumulation of capital, labor and land. The efficiency of markets is still required to be improved. Questions, such as how to achieve an effective use of scarce resources and what is the optimal way to allocate them among different types of cities, are challenging issues in China's urbanization. By employing the Pareto optimality criterion, the general equilibrium model of the city economy [17] may offer insight for answering these questions from an optimum city size and city system formation perspective. Based on this general equilibrium theory, some empirical studies have explicitly studied city size and growth rates in China [33,38–42]. Li Xun, et al. (2005) [39] use the DEA (data envelope assessment) model to evaluate 202 cities' efficiency from 1990 to 2000 and testify that urban efficiency is relatively low and diminishing from the east to the west. Fang and Guan (2011) [42] estimate and compare the efficiency of 23 urban agglomerations and find that input-output efficiency decreases gradually from the eastern region to the central and western regions of China. By evaluating and comparing five types of prefectural-level cities in China, Wang (2010) [33] argues that the development of megacities led by market forces facilitates economic efficiency and the optimal allocation of resources.

Overall, most literature of urban efficiency focuses on prefectural-level cities [39–41,43], largely excluding county-level cities, which includes most small cities in China, and few study the whole city system. On the other hand, although some studies have discussed different types of cities' efficiency, the classification methods of cities are not different and mainly use the old classification system [38,39]. Furthermore, there is a void of research on factor allocation efficiency among different types of cities under China's rapid urbanization. Hence, this paper estimates and compares input-output efficiency among different types of cities during the rapid urbanization period, according to the new classification standard, to contribute to a better understanding of urban hierarchical evolution and its inherent mechanism in China.

3. Data and Methodology

3.1. Data and Indicators

Resident population data are from the fifth nationwide population census in 2000 and the sixth nationwide population census in 2010 [44]. Annual input and output data are from China City Statistical Yearbook (2000–2010) [35]. The number of residents in the urban area is used for city size classification. In 2000, the total number of cities was 663, including 4 centrally-administrated municipalities, 15 sub-provincial cities, 244 prefecture-level cities and 400 county-level cities. In 2010, the total number of cities was 657: 4 centrally-administrated municipalities, 15 sub-provincial cities, 268 prefecture-level cities and 370 county-level cities.

The input and output indicators are illustrated in Table 1. Based on the general equilibrium theory of city economy [17], the input indicators can be classified into three categories: land, labor and investment. This paper chooses the cumulative area of land used for urban construction, the number of persons employed in districts of cities and the investment in fixed assets for urban construction as input variables. Since current urban construction investment will play a role in the following years, we apply the perpetual inventory method to calculate capital stock: $K_{i,t} = (1 - \delta_{i,t})K_{i,t-1} + I_{i,t}/P_{i,t}$ where $K_{i,t}$ is the gross capital stock of city i in the current year, $K_{i,t-1}$ is the gross capital stock of city i in the last year, $I_{i,t}$ represents investment for urban construction of city i in the current year, $I_{i,t}/P_{i,t}$ represents real investment after price adjustment and $\delta_{i,t}$ represents the depreciation rate of capital stock. For the output indicators, we use gross domestic product as an expected variable and pollution discharge as an unexpected variable.

Table 1. Illustration of the input and output indicators.

Variables	Category	Indicator
Input	Capital	Investment in fixed assets for urban construction
	Labor	Persons employed in districts of cities
	Land	Area of land used for urban construction
Output	Expected Output	Gross domestic product
	Unexpected Output	Pollution discharge

3.2. Methods and Models

The empirical analysis is based on the Pareto exponent estimate and non-parametric frontier methods: DEA models [45–47]. The DEA model framework is composed of three parts: (1) measuring the "economic-environmental" efficiency of different types of cities by a non-radial directed distance function based on the BCC-DEA model; (2) comparing dynamic efficiency change by the sequential DEA-Malmquist index; (3) distinguishing differences between the actual value and the target value by the projected value function.

3.2.1. Estimate of the Pareto Exponent

According to urban residents (s) of the i-th city, the Pareto distribution cumulative function is:

$$\Pr(S_i > s) = \alpha s^{-\beta} \tag{1}$$

The bi-logarithmic equation is:

$$\ln(\Pr(S_i > s)) = \ln\alpha - \beta \ln s \tag{2}$$

$\Pr(S_i > s)$ is of equal value to the rank of the i-th city (R_i). The regression model to estimate the Pareto exponent of "rank-size" distribution is:

$$\ln(R_{it}) = c - \beta \ln S_{it} + \varepsilon_{it} \tag{3}$$

where c is the constant term, β is the estimated Pareto exponent, t is the year and ε_{it} is the disturbance term. When $\hat{\beta}$ is close to one, this means the city system conforms to Zipf's law.

3.2.2. Non-Radial Directed Distance Function

The non-radial directed distance function is a linear programming method viewing pollutants as an unexpected output to assess the efficiency of decision making units (DMU) [48]. In the process of production, there are N kinds of inputs, $x = (x_1, \cdots, x_n) \in R_N^+$; M kinds of expected outputs, $y = (y_1, \cdots, y_m) \in R_M^+$; and I kinds of unexpected outputs, $b = (b_1, \cdots, b_I) \in R_I^+$. The input-output vector of region k (k = 1, ... , K) is $(x^{t,k}, y^{t,k}, b^{t,k})$ at time t (t = 1, ... , T).

$$\vec{D}_0(x, y, b; g) = \sup\left\{\left[\beta : (y + \beta g_y; b - \beta g_b; x - \beta g_x)\right] \in P(x)\right\} \tag{4}$$

The envelopment of the k-th DMU at time t is derived by the non-radial directed distance function:

$$\begin{aligned}
&\vec{D}^t(x^{t,k}, y^{t,k}, b^{t,k}; g^t) = Max\eta \\
\text{s.t.}\quad &\sum_{j=1}^{J} z_j^{t,k} Y_{j,m}^{t,k} \geqslant (1+\eta) Y_{j,m}^{t,k}, \quad m = 1, \ldots, M; \\
&\sum_{j=1}^{J} (z_j^{t,k} + u_j^{t,k}) k_{j,n}^{t,k} \leqslant k_{j,n}^{t,k}, \quad n = 1, \ldots, N; \\
&\sum_{j=1}^{J} (z_j^{t,k} + u_j^{t,k}) L_{j,n}^{t,k} \leqslant L_{j,n}^{t,k}, \quad \sum_{j=1}^{J} (z_j^{t,k} + u_j^{t,k}) L_{j,n}^{t,k} \leqslant L_{j,n}^{t,k}; \\
&\sum_{j=1}^{J} z_j^{t,k} b_{j,i}^{t,k} = (1-\eta) b_{j,i}^{t,k}, \quad \sum_{j=1}^{J} (z_j + u_j) = 1, \quad 0 \leqslant \Phi \leqslant 1
\end{aligned} \tag{5}$$

where k represents the capital input, L represents the labor input, E represents the land input, Y represents expected output (GDP), b represents unexpected output (pollutant), Φ represents the subduction factor of the unexpected output and η is the level of redundant inputs. Let $\lambda_j = z_j + u_j$ ($z_j = \Phi\lambda_j, u_j = (1-\Phi)\lambda_j$).

In Figure 1, Point A is set as a datum mark; the production frontier can reach Point C without taking pollutants into consideration and reach to Point B when taking pollutants as the unexpected output on the non-radial directed distance function [49].

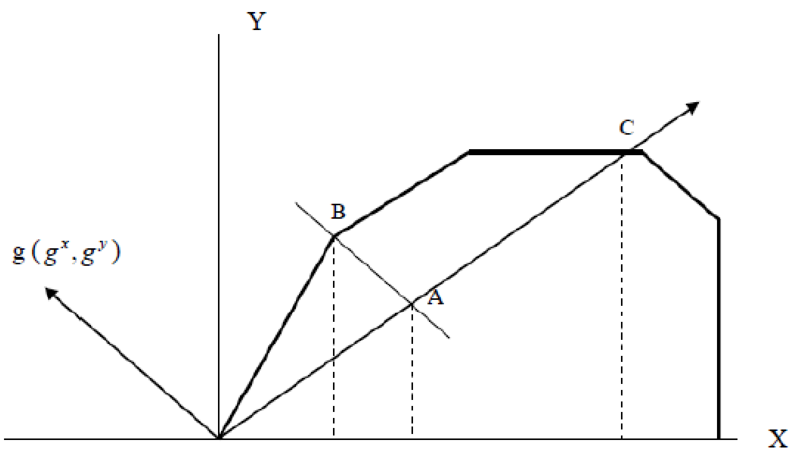

Figure 1. The data envelope assessment (DEA) frontiers of two models.

3.2.3. Sequential Malmquist TFP Index

We use the Malmquist TFP (Total factor productivity) index to measure the efficiency change of different types of cities and then to decompose this efficiency change into technical change and technical efficiency change.

Assuming there are k-th (k = 1, ... ,K) DMU at time t (t = 1, ... ,T), use $x^t_{i,\mathrm{m}}$ inputs of m (m = 1, ... , M) kinds to get n (n = 1, ... , N) kinds of $y^t_{i,\mathrm{n}}$. Technological frontier at the current period (t) is:

$$L^t(y^t|C,S) = \left\{(y^t_k, x^t_k) : y^t_k \leqslant \sum_{k=1}^{K} z^t_k \cdot y^t_k; x^t_{k,m} \geqslant \sum_{k=1}^{K} z^t_k \cdot x^t_{k,m}; z^t_k \geqslant 0\right\} \quad (6)$$

The output-based distance function is:

$$D^t_i(y^t, x^t) = 1/F^t_i(y^t, x^t|C,S) \quad (7)$$

An output-based Malmquist productivity change index at time t is specified by Caves, et al. (1982) [50] as:

$$M^t_i = D^t_i(x^t, y^t)/D^t_i(x^{t+1}, y^{t+1}) \quad (8)$$

Additionally, the Malmquist productivity change index at time t + 1 is:

$$M^{t+1}_i = D^{t+1}_i(x^t, y^t)/D^{t+1}_i(x^{t+1}, y^{t+1}) \quad (9)$$

Using Equations (8) and (9), the DEA Malmquist TFP index from time t to t + 1 is defined as follows:

$$M_o\left(X^{t+1}, Y^{t+1}, X^t, Y^t\right) = \left[\frac{D^{t+1}_o\left(X^{t+1}, Y^{t+1}|CRS\right)}{D^{t+1}_o\left(X^t, Y^t|CRS\right)} \frac{D^t_o\left(X^{t+1}, Y^{t+1}|CRS\right)}{D^t_o\left(X^t, Y^t|CRS\right)}\right]^{\frac{1}{2}} \quad (10)$$

The sequential Malmquist TFP index can be decomposed into technical change and technical efficiency change:

$$M_o\left(X^{t+1}, Y^{t+1}, X^t, Y^t\right) = \left[\frac{D^t_o(X^{t+1},Y^{t+1}|CRS)}{D^{t+1}_o(X^{t+1},Y^{t+1}|CRS)} \frac{D^t_o(X^t,Y^t|CRS)}{D^{t+1}_o(X^t,Y^t|CRS)}\right]^{\frac{1}{2}} \frac{D^{t+1}_o(X^{t+1},Y^{t+1}|CRS)}{D^t_o(X^t,Y^t|CRS)} = TC * EC \quad (11)$$

3.2.4. Projected Value Function

The efficient use of a resource is to minimize the input for the given output. We employ the ratio of target inputs to the actual inputs to reveal the potential savings [49].

Target input (K, t) = actual input (K, t) - [radial adjustment (K, t) + non-radial slack adjustment (K, t) (12)

The non-radial slack is defined as the amount of capital, land and labor that can be reduced by using the target projected function. The indices are defined as:

$$\begin{aligned} TFCE_{k,t} &= T\arg et\ Capital_{k,t}/ActualCapital_{k,t} \\ TFEE_{k,t} &= T\arg et\ Land_{k,t}/ActualLand_{k,t} \\ TFLE_{k,t} &= T\arg et\ Labor_{k,t}/ActualLabor_{k,t} \end{aligned} \quad (13)$$

4. Urbanization and Urban Systems in China

Figure 2 shows the trajectory of the urbanization rate in China from 1949 to 2012. Based on the change of government policy and urbanization rate, the whole period can be divided into four stages.

The year 1949 was when the People's Republic of China was founded. In the first stage (1949–1960), the urbanization rate was 10.6% in 1949, and reached the peak at 19.8% in 1960, with about a 0.8% increase per year. In this period, economic recovery and development facilitated the migration from rural areas to cities. In the second stage ending with the launch of economic reforms (1961–1978), the urbanization rate experienced a three-year decline (as Figure 2 shows), falling to 16.8%, and between 1965 and 1978, the urbanization rate was in long-term stagnation. This result could be closely related to economic stagnation in cities due to the Cultural Revolution and the policy of strictly controlling population flow from rural areas to cities that existed at that time.

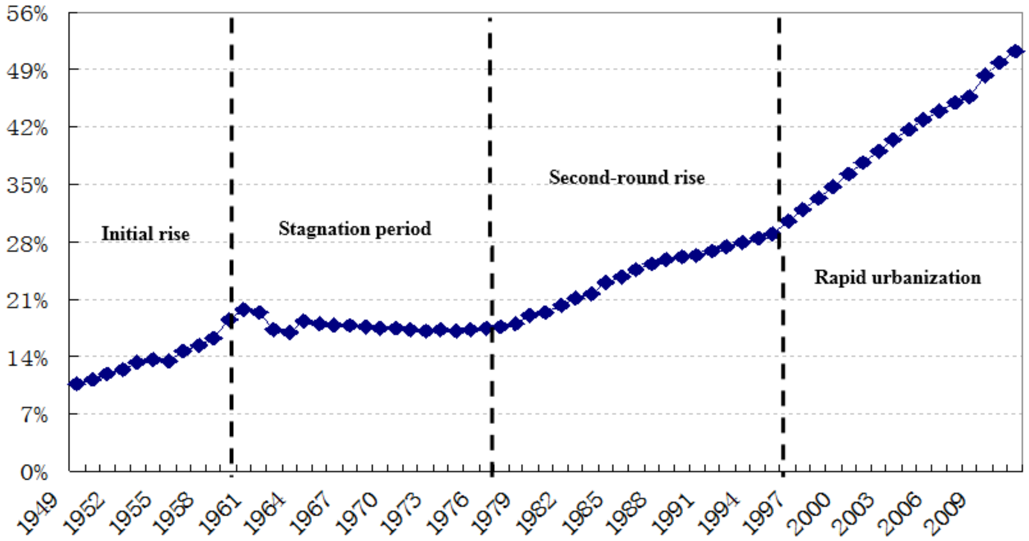

Figure 2. Urbanization rate of China: 1949–2012.

Market reform and urbanization have been the main driving forces after the remarkable economic development of China, often noticed as a symbol of the East Asian Miracle [14]. Since 1978, market reforms had been successfully exceeding the gridlock between rural and urban areas, impeding the movement of labor, capital and goods and further advancing urbanization in China. In the third stage (1979–1997), market-oriented reform resulted in the development of coastal cities much faster than rural areas, which induced a large number of the labor force migrating towards coastal cities. Since 1979, the urbanization rate entered into the second-round rising period, and the year 1997 is the breakpoint for the fourth stage (as Figure 2 shows), since the urbanization rate has been much faster than before, which is a symbol of entering into the rapid urbanization period.

From the perspectives of both theory and experience, urbanization is crucial to economic growth. The Chinese government aims to encourage this rapid urbanization. Relevant policies can be summarized as follows: "To energetically urge urbanization promotion" in the Tenth Five-Year Guideline (2001) [12] and "To promote active and steady urbanization" in the Eleventh Five-Year and Twelfth Five-Year Guideline (2006, 2011) [12]. Besides urbanization speed, the Chinese government also focuses on the quality of the city system. In the Tenth and Eleventh Five-Year Guideline (2001, 2006), the government made a policy on building a coordinated and healthy urban hierarchy of different types of cities. However, in recent years, the overconcentration of population and rapid urban expansion induced city function disorder (traffic congestion, water shortage and air pollution as haze), especially in megacities, like Beijing and Shanghai. A new challenge for the Chinese government is how to achieve rapid and healthy urbanization. One key issue is changing the size and structure of cities to promote efficiency. In the Twelfth Five-Year Guideline (2011) [12], a notable change is that the Chinese government has decided to relax the control on permanent resident permits in small cities. This policy will benefit the regions with a low urbanization rate and a high proportion of small cities.

5. Spatial-Temporal Evolution of Urban Systems

5.1. Spatial-Temporal Evolution of Cities

According to the new classification criteria of seven types of cities in 2014, we analyzed the component and evolution of urban systems in China during the rapid urbanization period. We noticed that, due to population mobility, there is a large difference between resident population and household population, especially in megacities like Beijing and Shanghai. For example, in 2010, the household population of Beijing was 12,554,049; the resident population of the whole city and the urban area was 19,612,368 and 16,858,692, respectively. Therefore, the analysis of the composition and evolution of urban systems in China firstly needs to count the number of residents in urban areas accurately. The Chinese government carries out a national census every ten years, which is the official source for statistics on resident population in urban areas. Based on the Fifth and Sixth Census data, we analyzed the component and evolution of urban systems in China from 2000 to 2010. The results are shown in Table 2.

Table 2. Component and evolution of urban systems in China.

Size of Cities	2000		2010		Change Degree	
	Number of Cities	Population Proportion	Number of Cities	Population Proportion	Number of Cities	Population Proportion
Megacity (Size $\geqslant$ 10,000,000)	3	6.7	6	11.2	3 (+)	4.5
Large City (5,000,000 $\leqslant$ Size < 10,000,000)	7	8.6	15	12.9	8 (+)	4.3
Type I Big City (3,000,000 $\leqslant$ Size < 5,000,000)	19	13.3	29	15.2	10 (+)	1.9
Type II Big City (1,000,000 $\leqslant$ Size < 3,000,000)	135	40.4	167	39.9	32 (+)	−0.5
Medium-sized City (500,000 $\leqslant$ Size < 1,000,000)	92	13.3	94	9.1	2 (+)	−4.2
Type I Small City (200,000 $\leqslant$ Size < 500,000)	212	12.5	229	9.6	17 (+)	−2.9
Type II Small City (Size < 200,000)	195	5.2	113	2.1	82 (−)	−3.1

Source: Fifth Census [51] and Sixth Census [44].

Table 2 shows the comparison of the number and population proportion of urban systems in China from 2000 to 2010. From Table 2, we can see that there are two main dynamic characteristics of urban hierarchical evolution. (1) Quick expansion of megacities and large cities: The number of megacities increased from three in 2000 (Shanghai, Beijing, Chongqing) to six in 2010 (Shanghai, Beijing, Chongqing, Guangzhou, Shenzhen, Tianjin). For the same period, the population proportion of megacities increased from 6.7% to 11.2%. The number of large cities increased from seven in 2000 to 15 in 2010. Additionally, the population proportion went up from 8.6% to 12.9%; (2) Population outflow in medium-sized cities, Type I and Type II small cities: For example, the population proportion of Type II small cities decreased from 5.2% down to 2.1%, resulting in stagnation of small cities.

To investigate the changes in the number and proportion of cities of different sizes of China, from Table 2, we can find that Type II big cities, medium-sized cities, Type I and Type II small cities compose the main body of urban systems in China. The population proportion of Type II big cities was close to 40% in 2010, much higher than that of other types of cities, followed by Type I big cities (15.2%), large cities (12.9%) and megacities (11.2%). Although the number of Type I small cities is the largest, the population proportion of these accounts for only 9.6%. The population proportion of

Type II small cities is the lowest, with only 2.1% in 2010. The investigation of the dynamic trends of the urban hierarchical evolution in China revealed that: (1) both the number and population proportion of megacities, large cities and Type I big cities increased from 2000 to 2010; (2) the number of Type II big cities, medium-sized cities and Type I small cities increased, while the population proportion decreased; (3) both the number and population proportion of Type II small cities decreased.

Table 3 compares the 10 largest cities of China in 2000 and 2010 as per the resident population size of urban areas. In 2010, the ten largest cities in China were Shanghai, Beijing, Chongqing, Guangzhou, Shenzhen, Tianjin, Chengdu, Wuhan, Suzhou and Dongguan. In 2010, Suzhou and Dongguan emerged in place of Harbin and Shenyang. In 2010, seven out of the 10 largest cities were from the eastern region; one (Wuhan) out of 10 was located in the central region; and two (Chengdu and Chongqing) in the western region. The fastest growing cities are Suzhou (6.6%) and Dongguan (6.5%); the slowest growing city is Wuhan (1.1%). The above data fully verify the main spatial and temporal evolution trend of the geographic concentration of population to the eastern metropolitan areas during the rapid urbanization period.

Table 3. Ten largest cities in China: 2000 vs. 2010.

2000			2010			2000–2010 Annual Growth Rate (%)
Rank	**City**	**Population Size**	**Rank**	**City**	**Population Size**	
1	Shanghai	14,489,919	1	Shanghai	20,555,098	3.6
2	Beijing	10,522,464	2	Beijing	16,858,692	4.8
3	Chongqing	10,095,512	3	Chongqing	15,295,803	4.2
4	Guangzhou	8,090,976	4	Guangzhou	10,641,408	2.8
5	Tianjin	7,089,812	5	Shenzhen	10,358,381	4.8
6	Wuhan	6,787,482	6	Tianjin	10,277,893	3.8
7	Shenzhen	6,480,340	7	Chengdu	9,237,015	4.5
8	Chengdu	5,967,819	8	Wuhan	7,541,527	1.1
9	Harbin	5,370,174	9	Suzhou	7,329,514	6.6
10	Shenyang	5,066,072	10	Dongguan	7,271,322	6.5

Source: Fifth Census in 2000 and Sixth Census in 2010.

5.2. *Empirical Test on Zipf's Law and Gibrat's Law*

5.2.1. Empirical Test on Zipf's Law

In this context, whether the real distribution of urban hierarchy differs from the optimal distribution becomes an important question, we use Equation (3) to estimate the exponent of the "rank-size" distribution of cities in China in the rapid urbanization period.

Figure 3 compares the distribution frequency of 663 cities in 2000 and 657 cities in 2010, by using histogram stats and the kernel density curve. In 2000, the average value of the logarithmic population size is 5.63; the value of kurtosis is 2.68; the value of skewness is 0.39; and the Jarque-Bera statistic is 18.63. In 2010, the average value of the logarithmic population size is 5.77; the value of kurtosis is 2.46; the value of skewness is 0.35; and the Jarque-Bera statistic is 20.56. According to the statistic test method, the feature of the distribution density curve of the urban hierarchy in China conforms to the lognormal distribution for kurtosis value being less than three; the skewness value tends to be zero; and the J-B statistic passes the significance test. Upon closer inspection, it can be seen that the value of both kurtosis and skewness somewhat declined from 2000 to 2010. The peak position shifts to the right side from 5.2 in 2000 to 5.4 in 2010, which reflects the fact that the number of megacities and large cities grew much faster in urban systems. Although the biased skew somewhat corrects this, the whole density curve still skews to the left side, demonstrating that the proportion of small cities in China is still too high at present.

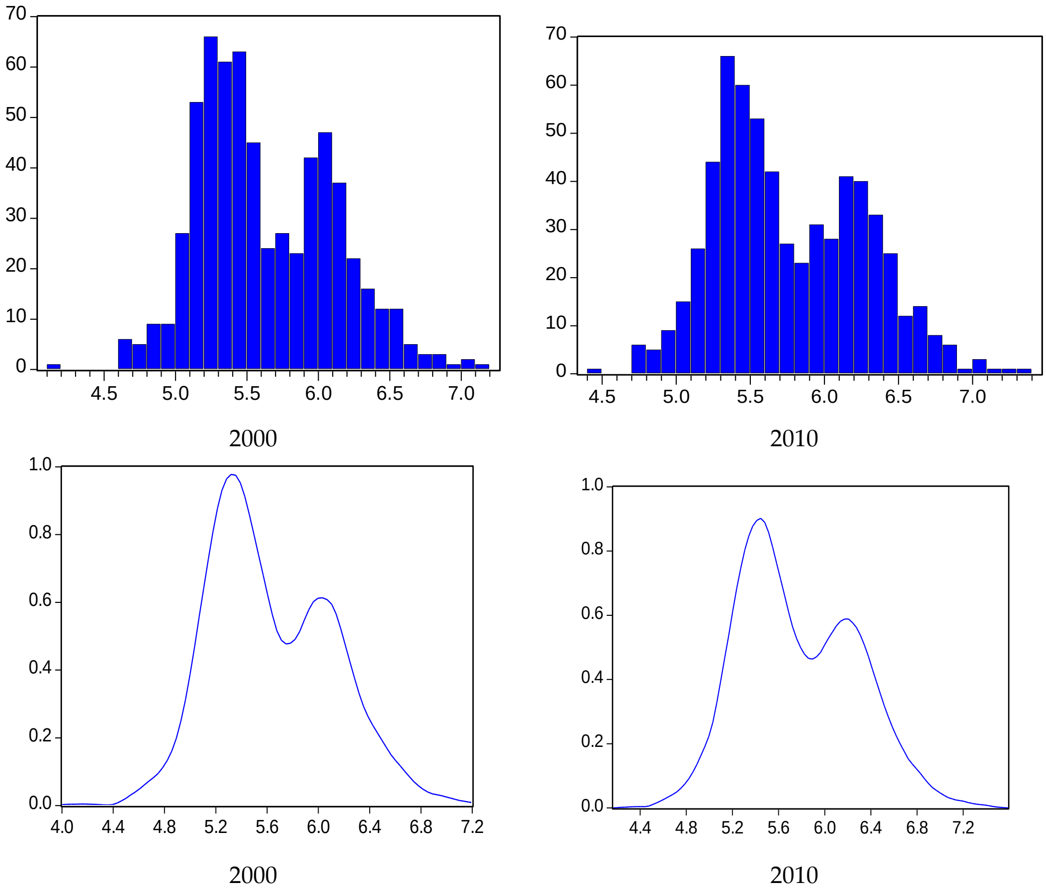

Figure 3. Histogram statistics and kernel density of cities: 2000 vs. 2010.

The regression result of the Pareto exponent in China using Equation (3) is reported in Table 4. Figure 4 illustrates scatter plots of city size against city rank.

Table 4. Regression coefficient of city distribution: 2000–2010.

Year	Number of Sample	Estimation			
		Constant Term ($\hat{c}$)	Pareto Exponent ($\hat{\beta}$)	Deviation (σ)	R^2
2000	663	16.70 ***	0.867 ***	0.997	0.879
2010	657	16.16 ***	0.805 ***	0.997	0.862

Note: *** denotes significant at the 1% level.

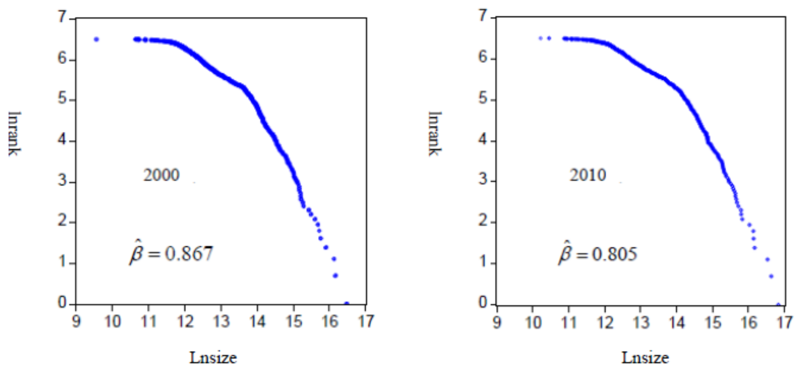

Figure 4. Scatter plot of city size against city rank: 2000 vs. 2010.

According to Table 4, the estimations of Pareto exponents are 0.867 in 2000 and 0.805 in 2010, which cannot be rejected at the 1% significance level. The estimation of the Pareto exponent ($\hat{\beta}$) is less than one, which shows the intensified deviation between the real distribution and the optimal distribution of the urban hierarchy in China.

5.2.2. Empirical Test on Gibrat's Law

For the correlation between city size and city growth rate, existing studies [20,28,29] provided evidence of Gibrat's law on developed countries' samples. Can this finding be extended to developing countries, such as China? This paper examines the correlation between city size and city growth rate for all cities in China from 2000 to 2010. For the administrative division, adjustment causes an incomparable problem. After eliminating the adjusted sample, we got the comparable sample of 622 cities.

Figure 5 illustrates the correlation between city size and growth rate. The horizontal axis is the natural logarithm of city scale. The vertical axis is the expansion ratio from 2000 to 2010. The result supports the hypothesis that the city-size growth rate is constant across cities of different sizes. This result also shows that there is no spontaneous adjustment for the optimal distribution of urban hierarchy in China. Hence, government intervention and policy guidance are needed for urban hierarchical optimization in China.

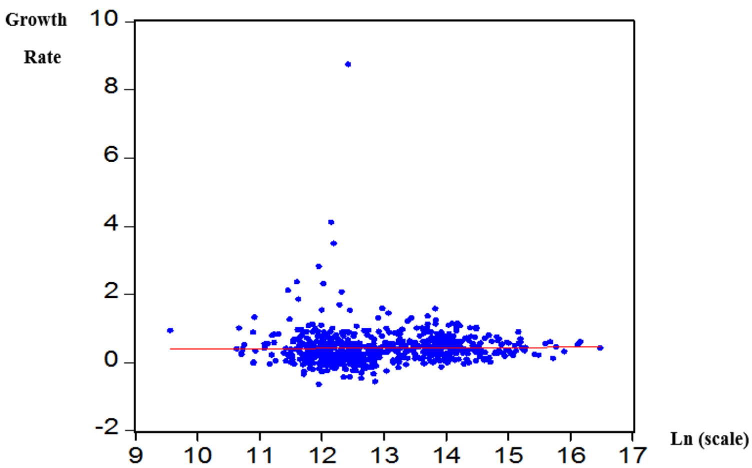

Figure 5. Scatter plot of city size against city growth.

6. Urban Hierarchy and Economic Efficiency

6.1. Comparison of Economic Efficiency and Economic-Environmental Efficiency

During the rapid urbanization period, labor and land used for urban construction in megacities of China increased about 50% and 227.6% respectively, which are 22% and 71% higher than the average level. This phenomenon is caused by a scale effect, which is the driving force for megacities' expansion [52–54]. Big city fever has become more and more serious in recent years and has threatened the sustainable development in China [53,55]. From an economic perspective, sustainable development depends on technological innovation and resource allocation optimization. From the human development perspective, it depends on the transformation from GDP-oriented to environment-friendly development [56,57]. In view of this, this paper estimates and purely compares the economic efficiency and the "economic-environmental" (EE) efficiency of seven types of cities, using the BCC-DEA model and the non-radial directed distance function.

The estimated result in Table 5 shows a positive correlation between city productivity and urban scale. When taking the negative externality of environment into consideration, the gap of productivity among different types of cities is reduced significantly. For example, in 2000, the pure economic efficiency of Type II small cities is 0.505, which rises to 0.892 for "economic-environmental" efficiency. The most efficient type of city also changes from megacity and large city to medium-sized city and Type I small city.

Table 5. Comparison of economic efficiency and economic-environmental (EE) efficiency.

Category	Economic Efficiency			"Economic-Environmental" Efficiency		
	2000	2005	2010	2000	2005	2010
Megacity	0.936	0.872	1	0.989	0.977	0.974
Large City	1	1	1	1	1	0.980
Type I Big City	0.892	0.784	0.876	0.954	0.981	0.988
Type II Big City	0.868	0.754	0.801	0.961	0.996	0.995
Medium-sized City	0.738	0.775	0.752	1	1	1
Type I Small City	0.702	0.685	0.724	0.971	1	1
Type II Small City	0.505	0.701	0.722	0.892	0.881	0.922
Mean value	0.806	0.796	0.839	0.967	0.976	0.980

Figure 6 presents the comparison between economic efficiency and economic-environmental efficiency among seven types of cities. Pure GDP-oriented judgment causes seriously overestimated efficiency of megacities and large cities. It also reflects that megacities and large cities will face more challenges for sustainable development in the future.

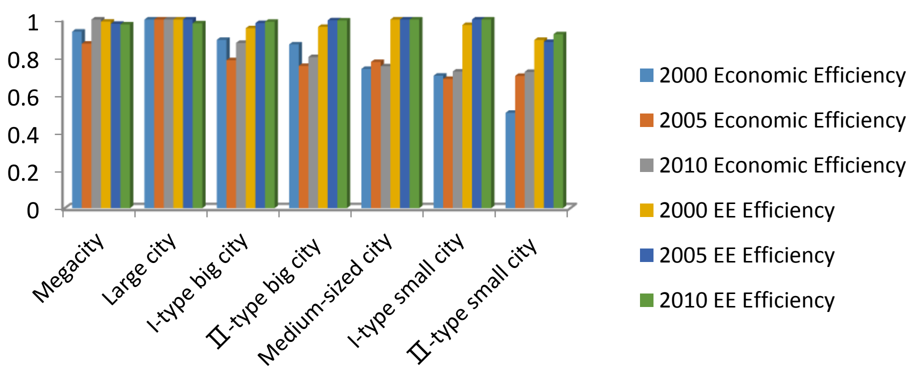

Figure 6. Comparison of economic efficiency and EE efficiency.

6.2. Total-Factor Efficiency Change and Decomposition

We used the DEA-Malmquist index to measure the efficiency change among seven types of cities of China from 2000 to 2010 and then decomposed it into technical change and scale efficiency change. The result is reported in Table 6.

In Table 6, the average estimated TFP of cities in China over the period 2000–2010 is 1.349. The TFP indices of megacity, large city and Type I big city are 1.475, 1.64 and 1.411, higher than other types of cities. The decomposition result shows that: (1) the "growth effect", generated by technical progress, plays the role of the first order driving force for city efficiency improvement in China. There is a positive correlation between city size and technical progress. The average estimated index is 1.280, and the index of large cities and megacities is 1.640 and 1.3, the highest of all types of cities; (2) The "allocation effect", generated by scale allocation, encumbers the efficiency promotion of the city system in China. The average estimated index is 1.049, less than the index of technical change, which strongly reveals factor allocation to be inefficient among cities of China in the rapid urbanization period. The lowest estimated indexes are 0.99 and 0.96 for Type I and Type II small cities, which shows that factor allocation inefficiency is very serious for these two types of city.

Table 6. Total-factor efficiency change and decomposition.

Period	Category	Effch	Techch	Pech	Sech	Tfpch
2000–2010	Megacity	1.175	1.300	0.968	1.207	1.475
	Large City	1.000	1.640	1.000	1.000	1.640
	Type I Big City	1.127	1.284	1.064	1.063	1.411
	Type II Big City	1.017	1.233	1.003	1.014	1.250
	Medium-sized City	1.105	1.133	1.000	1.105	1.238
	Type I Small City	1.069	1.201	1.079	0.990	1.269
	Type II Small City	0.992	1.166	1.030	0.962	1.157
	Mean value	**1.069**	**1.280**	**1.021**	**1.049**	**1.349**
2000–2005	Megacity	1.074	1.260	0.937	1.138	1.334
	Large City	1.000	1.740	1.000	1.000	1.740
	Type I Big City	1.013	1.401	1.006	1.007	1.413
	Type II Big City	1.162	1.203	1.000	1.162	1.365
	Medium-sized City	1.031	1.078	1.051	0.980	1.109
	Type I Small City	1.030	1.218	1.056	0.975	1.248
	Type II Small City	0.935	1.288	1.002	0.933	1.222
	Mean value	**1.035**	**1.312**	**1.007**	**1.028**	**1.347**
2006–2010	Megacity	1.276	1.341	1	1.276	1.617
	Large City	1	1.54	1	1	1.54
	Type I Big City	1.241	1.168	1.121	1.12	1.409
	Type II Big City	1.1	1.178	1.004	1.096	1.278
	Medium-sized City	1.048	1.064	1	1.048	1.112
	Type I Small City	1.107	1.183	1.102	1.005	1.29
	Type II Small City	0.953	1.253	1.009	0.944	1.206
	Mean Value	**1.104**	**1.247**	**1.034**	**1.070**	**1.350**

Note: Effch: technical efficiency change; Techch: technological change; Pech: pure technical efficiency change; Sech: scale efficiency change; Tfpch: total factor productivity change.

On further inspection of the two sub-periods, we found that: (1) the average estimated index of technical change is 1.247 for the second sub-period, much lower than the first sub-period. This reflects that technology progress for efficiency improvement has been weakening sharply in recent years; (2) The average estimated index of scale efficiency is 1.028 for 2000–2005 and rises to 1.070 for 2006–2010, but is still much lower than the technical change index. This result demonstrates that although technical efficiency change significantly contributes to enhancing the TFP of Chinese cities in recent years, the scale efficiency is still at a relatively low level. Therefore, the allocation efficiency improvement among cities is a key issue for the total-factor efficiency improvement of cities in China.

6.3. Input Savings Potential

To use minimal inputs for a target output is a principle for factor allocation among different types of cities [45,58]. Table 7 shows the potential savings of each type of city given by the sum of radial and non-radial slack adjustment, as in Equation (12). Then, we used the projected value function to measure the real inputs against optimal targets, as in Equation (13). The results are reported in Table 7.

Megacities and large cities are efficient DMU on the production frontier. The result in Table 7 shows that: (1) the inefficient use of infrastructure investment is the most serious problem of Type I and Type II big cities, with redundancy degrees of 19.3% and 17.9%, respectively; (2) inefficient uses of land and labor are the primary problems in medium-sized city; with the redundancy degree reaching 9.9% and 8.3%, respectively, much higher than the inefficiency use of capital; (3) there is a large number of inefficient uses of urban land and labor in Type I and Type II small cities, with the redundancy degree of land reaching 29.9% and 29.0%, respectively, and the redundancy degree of labor reaching 14.2% and 26.0%, respectively.

Table 7. Redundancy percentage of real inputs vs. optimal targets.

City Category	2000–2005			2006–2010			2000–2010		
	Labor	Capital	Land	Labor	Capital	Land	Labor	Capital	Land
Type I Big City	0	0.232	0.012	0	0.153	0.007	0	0.193	0.010
Type II Big City	0.017	0.147	0.04	0.007	0.210	0.021	0.012	0.179	0.031
Medium-sized City	0.072	0.009	0.085	0.094	0.026	0.113	0.083	0.018	0.099
Type I Small City	0.128	0.145	0.369	0.156	0.152	0.228	0.142	0.149	0.299
Type II Small City	0.283	0.137	0.273	0.237	0.009	0.306	0.260	0.073	0.290

Note: Redundancy percentage = 1− real input/target value.

7. Conclusions

The speed and scale of China's ongoing urbanization is unprecedented [5]. In this paper, the spatial-temporal evolution and underlying mechanisms of urban hierarchy are unfolded. Focusing on the rapid urbanization period of China, we compared the demographic change of seven types of cities (megacity, large city, Type I big city, Type II big city, medium-sized city, Type I small city, Type II small city) from 2000 to 2010 and tested the validity of Zipf's law and Gibrat's law. To investigate the underlying mechanisms of urban hierarchy formation in China, we also investigated the optimal city size and efficient resource allocation by the Pareto optimality criterion and non-parametric frontier methods.

The results and conclusions are summarized as follows. First, allometry—the quick expansion of megacities and recession of small cities—is the main characteristic of the urban hierarchical evolution of China in the rapid urbanization period. Although urban hierarchical inequality mitigated somewhat during the study period, mainly due to the increase of big cities, for a coordinated and healthy city system of China, it is still required that more big cities emerge. This can ease the population pressure of current megacities, like Beijing and Shanghai. Second, the comparison of economic efficiency and economic-environmental efficiency shows that traditional measurement driven by GDP is overestimated in megacities and large cities. Third, scale efficiency among seven types of cities is still at a relatively low level: (1) inefficient use of infrastructure investment of Type I and Type II big cities is 19.3% and 17.9%, respectively; (2) inefficient use of land and labor in medium-sized cities is 9.9% and 8.3%; (3) there is a huge number of inefficient uses of urban land and labor in Type I and Type II small cities, with the redundancy degree of land reaching 29.9% and 29.0%, respectively, and the redundancy degree of labor reaching 14.2% and 26.0%, respectively.

These findings have profound practical and theoretical contributions. First, this paper distinguishes the exact period of rapid urbanization based on the trajectory of the urbanization rate of China and investigates the spatial and temporal evolution of urban hierarchy during this rapid urbanization period. Second, this paper firstly uses the official and uniform classification standard of cities (megacity, large city, Type I big city, Type II big city, medium-sized city, Type I small city, Type II small city), which enhances the practical contribution of the empirical results for the Chinese government.

From a policy perspective, this paper also has some significant implications. In recent years, the Chinese government has made policies to optimize the city system [33,59,60], and city size [30–33,61,62], by strictly controlling registered population growth in megacities and loosening the regulation in small cities [12]. However, we should notice that government intervention cannot control the floating population, which makes up about 40% of the total permanent population in Beijing and Shanghai [44]. The attractiveness of megacities lies in higher wages, more job opportunities and more public goods (such as hospitals, schools and entertainments) for a better life [63]. However, megacities' expansion in China has sharply increased residents' commuting cost and local government's infrastructure investment in suburban areas, which saps city productivity, as well as residents' quality of life [37,63]. Especially in recent years, the sharp increase of commuting distance has caused the problem of city function disorder. The Chinese government dominates urbanization development, both in size and scale, via land planning and infrastructure investment. The urbanization pattern in China is guided and quite different from that of many developing countries, which is largely market driven, but often leads to over-urbanization and the formation of slums. Government intervention plays an important role in urban boundary control and urban structure formation in megacities. To solve big cities' problem, the Chinese government should take two main measures: (1) effectively control megacities' boundary to prevent urban sprawl; (2) form and strengthen the polycentric urban structure, instead of the current monocentric urban structure. These two measures have proven to be relatively effective in other countries, including the United States. We also notice that government intervention should not be mandatory and should consider market forces and equitable resource allocation. For example, an effective way to guide population transfer from megacities to small and medium-sized cities and from megacities' central areas to sub-central areas is by improving the quantity and quality of public resources and facilities, which should contribute to both productivity and the equity of city systems.

In addition, manufacturing industrial clusters are over-concentrated in the big cities of China, which causes environmental and resource problems. To solve this problem, it is necessary to guide manufacturing industrial clusters to transfer from big cities to less developed areas, which can alleviate the pressure on the resources and environment of megacities and can also create opportunities for the development of lagging areas. With the increase of the production cost in coastal cities, some industrial location away from coastal megacities can be observed, but industrial upgrading remains slow.

Lastly, distortions in the factor market among different types of cities should be corrected to improve efficiency. The Chinese government makes a huge profit by land expropriation [64,65], which is an incentive for the overconsumption of land and urban sprawl in big cities. Steps should be taken to strengthen rural property rights [66], which will effectively intensify urban land use efficiency and reduce the spatial expansion of urban land.

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