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RESEARCH ARTICLE

Economic structure and environmental quality and their impact on changing land use efficiency in China

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Abstract Extensive urban land expansion and heavy industrialization have increased energy consumption and caused environmental problems, both of which present serious threats to humans. Consequently, improved land use efficiency and realization of green development are imperative. Based on a detailed analysis of spatial-temporal evolution of urban land use efficiency, this paper analyzes the synergistic effect of industrial structure and city size, as well as the effect of environmental quality, by using panel data from 283 cities at or above prefecture-level in China from 2003 to 2012. It was concluded that 1) environmental quality has an obvious "crowding out effect" on urban land use efficiency and 2) urban land use efficiency shows a significant spatial auto-correlation. The effect of industrial structure is dependent on population size of the city. It has been found that a threshold population size of more than 108.45 (10,000 persons) is needed for an optimized benefit from industrial linkages. The urban population size presents an inverted-U shape against the urban land use efficiency, and the marginal benefit of urban size increases when the industrial structure shifts from secondary industry to tertiary industry. Additionally we found that the actual urban size of 98.2% is less than the cities' optimal sizes.

Keywords agglomeration economies, structure-size synergistic effects, environmental quality, land use efficiency, spatial-temporal evolution

1 Introduction

Urbanization has a predominant influence on land use and cover change (LUCC), which is characterized by urban expansion (Deng et al., 2014). Against the background of global urbanization, both large-scale urban expansion and changes in the spatial economic activities across cities have become important driving forces for urban land use. In fact, since the beginning of this century, land urbanization has become an increasingly obvious feature of economic growth in China. The expansion of large-scale urban construction has required high energy use and resulted in environmental problems (Chen and Chen, 2010; Xia et al.,2014; Deng et al., 2015; Hu et al., 2015) and low land use efficiency (Chen and Zhang, 2014), which in turn poses threats to food security (Chen and Han, 2015) and sustained economic growth. Recent research indicates that the allocation efficiency of land resources in China is currently low and yet there is a greater likelihood for improvement in the level of this indicator than for an improvement in energy efficiency, suggesting a great need for detailed analysis of land use efficiency (Chen and Zhang, 2014). Facing the tight supply of new land released by local governments and China's inefficiently utilized urban land stock, academics and practitioners both agree that the transformation of economic development patterns and economic restructuring is the only way to improve land use efficiency and achieve sustainable development.

At present a large number of research papers focus on identifying the drivers of urban LUCC (Hasselmann et al., 2010; Jiang et al., 2011; Qasim et al., 2013; Li et al., 2013; Deng and Srinivasan, 2016). In recent years, there has been an increased interest from domestic and overseas scholars regarding the changes and factors influencing intensive urban land use from the perspective of the evolution of urban industrial activities. Early studies focused on industrial restructuring as a source of agglomeration economies and determinants of intensive urban land use. These studies included Bobylev (1981), who did a systematic study to find the key determinants and mechanisms that are used to promote non-agricultural

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intensive land use, arguing that upgrading the industry structure affects not only labor and capital density, but also industry productivity per unit of land. Consequently, the optimization of urban land use structure is an important driving factor for intensive land use. Fischer and Sun (2001) revealed that upgrading the industrial structure would improve the share of high-quality knowledge, technology, and services available to the economic structure,, both of which are helpful for improving unit land output. Chen et al. (2016) investigated the processes and mechanisms of urban land expansion in the Nanjing metropolitan area. They found that urban land expansion is highly correlated to increases in the tertiary sector.

Understandings have deepened over time as researchers have increasingly focused on analyzing the relationship between industrial structure and city size and acknowledged that adjustment of urban industrial structure depends on a change in city size. Some representative conclusions and theories include, for example, Capello and Camagni (2000), which was based on the sample of 58 Italian cities and provided empirical evidence to show that urban efficient size change with industrial transformations. Abdel-Rahman and Anas (2004) demonstrated that as the industrial structure of a city changes proportionately with city size, those changes can lead to differences in economic efficiency. Au and Henderson (2006) examined China's efficiency of urban scale economies by using the ratio of value-added in the 2nd to 3rd sector as the indicator of urban industrial structure, and found a variance in scale effects in different size cities with different industrial structures.

Supportive empirical evidence exists for the synergistic effects of industrial structure and city size in Chinese studies. For example, the recent related work of Ke and Zhao (2014) found that as urban population size increases, industrial structure shows an inverted-U shape. They constructed a producer services-manufacturing agglomeration model to analyze the synergistic effect mechanism of industrial structure and city size on productivity of Chinese cities. Previous studies were confined investigation of urban economic efficiency from the perspective of structure-size effect. The exception is the empirical research of Dou and Wang (2010), based on panel data of 234 cities in China, that demonstrated there were noticeable differences in urban land productivity based on the magnitude of the impact and the direction of industrial structure of cities and regions of different size. Our literature review revealed there are some shortcomings in Dou and Wang's research. Specifically, it focused on the output efficiency of urban land from either the perspective of industrial structure or from that of city size. If we separate the effect of urban industrial structure from that of urban size , it is easy to ignore their interaction and the coordination mechanism on urban land use efficiency. As a result, the effect of urban economic restructuring cannot be determined in regard to the process of urbanization. Moreover, the time span of this study (1999 to 2006) cannot truly illustrate the most recent output efficiencies of urban land.

As noted, few studies have analyzed the relationship between industrial structure and city size within the same framework or the impacts of their synergistic effects on urban land use efficiency. However, previous research has provided inspiration, thus we seek to estimate these effects to promote urban land use efficiency. We will investigate the existence of synergistic effects, explore scientific development strategies of urban land use, and then promote the transformation of land use. It is worth pointing out that while land use efficiency is an important indicator of economic output, the influence of environmental quality change on land use efficiency has been neglected in previous literature. As literature on environmental effects concentrated more on the measurement of environmental efficiency (Bian and Yang, 2010), the influence of environmental regulation on total productivity (Lanoie et al., 2008), the relationship between environmental quality and economic growth (Orubu and Omotor, 2011), urban environmental quality change (Liang and Weng, 2011), and the effect of environmental regulation on energy efficiency (Bi et al., 2014), very few studies focused on the effects of environmental quality on land use efficiency. Environmental quality is related to industrial structure (Wang and Mao, 2016). Investigation of the correlation between urban environmental quality and land use efficiency reveals that there is a negative correlation between China's reality of "environment for growth," and the improvement of environmental quality, which is usually at the expense of economic growth. If there is a significant "crowding out effect" between environmental quality and land use efficiency, the magnitude of this effect remains unclear. A clarification of these issues will increase our understanding of the relationship between economic structure, environmental change, and China's urban LUCC law, and will thus contribute to the scientific development of an informed industrial land use policy.

This study contributes to the literature by introducing industrial structure and city size, along with environmental quality into a united analytic frame. The data used in this research are based on panel data of a prefectural or higher level for 283 cities of China, which are able to reflect the characteristics of agglomeration from 2003 to 2012. We examine the synergistic effects on industrial structure and city size on urban land use efficiency. On the basic of this, we estimate the threshold and optimal size of the cities in terms of land marginal benefit from industrial structure upgrading, and the possible magnitude of the effect on industrial structural upgrading to the optimal size of the cities. Further, we study the impacts of environmental quality on urban land use efficiency.

This paper is structured as follows: Section 2 briefly describes the research methodology, study area, and data sources. Methodology includes the spatial autocorrelation analysis method and the panel data model. Section 3 presents a characteristic description of spatial-temporal evolution of land use efficiency, an analysis of the synergistic effects on industrial structure and city size, the environmental quality of urban land use efficiency, and provides a test for robustness. Section 4 draws our conclusions and raises policy and practical implications.

2 Methodology and data

2.1 The spatial autocorrelation analysis

The significance of Global Moran's Index is shown by its effectiveness in revealing spatial characteristics using Exploratory Spatial Data Analysis (ESDA) (Xie et al., 2012). The method has been widely adopted to investigatethe spatial association among variables, and which can be used to measure the level of spatial autocorrelation that reflects characteristics of agglomeration. Global Moran's Index ranges between –1 and 1. Its general specification is formalized as follows:

$$Moran's\ \ I = \frac{m}{\sum_{i=1}^{m}\sum_{j=1}^{m} W_{ij}} \times \frac{\sum_{i=1}^{m}\sum_{j=1}^{m} W_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}, \qquad (1)$$

where $\overline{X} = \frac{1}{m}\sum_{i=1}^{m} X_i$, X_i, X_j represents the observation for the variable in city i and j, m is the total number of cities, and W_{ij} is the spatial weight matrix by row-standardized. Generally speaking, under a given significance level, a positive Moran's Index indicates the spatial agglomeration of the cities with high or low land use efficiency, while a negative Moran's Index indicates the spatial dispersion of the cities in terms of land use efficiency. If the Moran's Index is close to 0, this reflects a stochastic distribution in the area of similar observations. The significance level of Moran's Index is usually tested by standard statistics Z, which is formalized as:

$$Z\left(Moran's\ \ I\right) = \frac{Moran's\ \ I - E(Moran's\ \ I)}{\sqrt{VAR(Moran's\ \ I)}},$$

$$E\left(Moran's\ I\right) = -\frac{1}{m-1}. \qquad (2)$$

With reference to the choice of the spatial weight matrices, this paper applies the same methodology as Roy (2004) or Peng et al. (2014) instead of adopting the traditional binary geographical contiguity matrix as in previous literature. We use a W-based gravity model, which comprehensively considers geographical information and economic distance. It can be mathematically expressed as:

$$W_{ij} = \begin{cases} (\overline{Q}_i \times \overline{Q}_j)/d_{i,j}^2 & , \quad i \neq j \\ 0 & , \quad i = j \end{cases}, \qquad (3)$$

where $\overline{Q}_i$ and $\overline{Q}_j$ denotes the GDP per capita in city i and j, respectively; and d_{ij} denotes the geographical distance between city i and city j, which is calculated according to the longitude and latitude data of administrative units of the prefecture-level city. The latitude and longitude data of the city comes from the National Geometrics Center of China and was published by the National Administration of Surveying, Mapping and Geo information (http://ngcc.sbsm.gov.cn/). We additionally checked Google Maps to complete the missing data. A spatial weight matrix shows the correlation of regional economies positively related to their economic scale and those negatively related to the distance between the two economies, which is consistent with Tobler's First Law of Geography. Finally, we row-normalize the spatial weight matrix so that the sum of each row is equal to one.

Using a spatial autocorrelation analysis, this study presents an analysis and discussion of the characteristics, agglomeration, and dispersion degree of urban land use efficiency in space.

2.2 Model Specification

Based on the agglomeration economies framework, Ciccone and Hall (1996) developed a model in accordance with the externalities theory, confirming that the source of agglomeration effects stem from human economic activities of high density during the process of urbanization. In this section we extend Ciccone and Hall (1996) as well as Ciccone's (2002) models and construct a new theoretical model based on determinants of urban land use efficiency which involves the relationship with industries. A generalized Cobb-Douglas production function form is formalized as:

$$q_i = G_i[(n_i H_i)^{\beta} K_i^{1-\beta}]^{\alpha}(Q_i/A_i)^{(\lambda-1)/\lambda}, \qquad (4)$$

where q_i is the output per area of land in city i; G_i is total factor productivity in city i, which is a Hicks-neutral technology multiplier; $n_i H_i$ is a measure of the efficiency labor in city i, in which n_i denotes the number of workers employed in the city i; H_i is the average level of human capital of workers in city i; and K_i is the physical capital investment per area in city i. The parameters $\beta, 1-\beta$ are the contribution rates of factors in effective labor and capital respectively, and β is between 0 and 1; the parameter α captures returns to labor and capital per area, with a range of values [0, 1], which represents diminishing marginal productivity, and can directly reflect the effect of congestion with element density increase; Q_i and A_i denote the total output and the total area of a city, respectively; Q_i/A_i is output density of the city; the parameter λ is the product of the production elasticity, which measures the effect of agglomeration, and $\lambda > 1$ reflects positive spatial externalities; namely, the contribution made by agglomeration economies to improve city land use efficiency; or alternatively a direct negative effect that would reduce urban land use efficiency.

Technological progress (i.e., development in Total Factor Productivity) is an important driving factor with the potential to affect urban LUCC (Capello and and Camagni, 2000). Based on the previous discussion, this paper sets total factor productivity G as $G = G(S,T)$ and S denotes industrial structure. Apart from industrial structure, more recent studies show that the socio-economic and institutional factors are key variables in determining the total factor productivity of other cities which cannot be ignored; thus, T denotes other variables such as urban size, land marketization level and urban land use structure, etc. Accordingly, we decompose total factor productivity G in detail, as shown in the following equation:

$$G= (S,T) =T_0 e^{S} N^{\rho_1} LM^{\rho_2} JG^{\rho_3}, \tag{5}$$

where S_i is the industrial structure correlation. "The Structural Bonus Hypotheses" revealed that industrial structure upgrading is a key contribution variable that affects total factor productivity (Peneder, 2003; Bun and Makhloufi, 2007). In order to demonstrate the theoretical mechanism, we adopted the exponential form to perform theoretical characterization based on the stochastic frontier production function, which captures the technical efficiency of industrial structure (Chen et al., 2011). We assume N is city size, LM is urban land market level, JG is urban land use structure, and T_0 is other variables that affect the total factor productivity, including natural resources, regional condition, etc. Since Q_i/A_i is output per built-districts area, which is defined as land output efficiency, we substitute Eq. (5) into Eq. (1), and then divide both sides by $(Q_i/A_i)^{(\lambda-1)/\lambda}$. We then obtain:

$$q_i = T_0^{\lambda} e^{\lambda S_i}\, N_i^{\rho_1\lambda} LM_i^{\rho_2\lambda} JG_i^{\rho_3\lambda}\left[(n_i H_i)^{\beta} K_i^{1-\beta}\right]^{\alpha\lambda}. \tag{6}$$

From Eq. (6) we find that urban land use efficiency depends on industrial structure, city size, land market level, capital density, employment density, human capital, and land use structure, etc. Meanwhile, related studies on agglomeration economy and agglomeration diseconomy show that there could be an inverted U-shaped relationship between city size and urban land use efficiency (Dou and Wang, 2010). Therefore, we introduce the quadratic term of city size to accurately reflect the change between land use efficiency owing to interaction in both the agglomeration and deagglomeration economies. Since the main purpose of this paper is to test the synergistic effect of industrial structure and city size in accordance with Ke and Zhao (2014), we introduce the cross term of industrial structure and city size into the extended model, depicting the role of the synergistic effect in land use efficiency. Hence, after taking logarithms on both sides of Eq. (6), the regression equation can be written as follows:

$$\begin{aligned}\ln q_i = {} & m_0 + m_1 \ln N_i + m_2 (\ln N_i)^2 + m_3 S_i + m_4 S_i \\ & \times \ln N_i + m_5 \ln LM_i + m_6 \ln JG_i + m_7 \ln n_i \\ & + m_8 \ln H_i + m_9 \ln K_i + u_i. \end{aligned} \tag{7}$$

2.3 Study area

Our sample consists of 290 cities at/above prefecture-level in Mainland China (including four provincial-level cities), which in this paper is expressed as "cities." Given the lack of data on Chaohu in Anhui, Tongren and Bijie in Guizhou, Longnan in Gansu, Lasang in Tibet, Zhongwei in Ningxia, and Sansha in Hainan, we focus on the remaining 283 cities at/above prefecture level.

2.4 Data and descriptive statistics

Based on Eq. (7), given the availability of statistical data and the reality of China, the variables in this paper are constructed as follows:

1) Urban land use efficiency (q: 100 million CNY/km^2) is computed by real added value of non-agriculture GDP divided by area of built districts and deflated to the constant prices of the base year 2003. It is defined as the comprehensive measure of land use efficiency. 2) Industrial structure (S): as Au and Henderson (2006), apply the ratio of value-added in the 3rd to 2nd industry, which shows the process of optimization and serialization of industrial structure. 3) City size (N: 10,000 persons) is represented by non-agricultural population in districts under city. 4) Land market level (LM: %): as demonstrated in most literature(Li and Qu ,2012), we adopted weight average methodology to calculate the level of land market as a proxy, as shown in Eq. (8) :

$$LM = \left(\sum_{k}^{l} q_k \times f_k \right) / \sum_{k}^{l} q_k, \tag{8}$$

where k denotes the land remising way, which include allocation, agreement, bidding, auction, listing, lease, and other; q_k denotes the number of land plots with remising way k to procure; and f_k denotes the weight of each transaction. Because allocation is configured with administrative transfer means, which is almost free to use, its weight is set as 0. The current average price for leasing land in China is about 20% of that observed in recent years, with a weight of 0.2, while the price of other remising way, such as agreement, bidding, auction, listing, lease and other, has maintained at similar levels to those typically observed, with weights set to 0.2, 1, 1, 1, 0.2, 0.2 respectively. 5) Capital density (*K*: 10^4 CNY/km^2): it is measured as the real fixed capital investment in districts under city divided by area of built districts as the proxy. 6) Employment density (*n*: 10^4 persons/km^2) is measured by the sum of both non-agricultural employment population and self-employed individuals in urban areas, divided by the area of built districts, as the proxy. 7) Human capital density (*H*: 10^4 persons/km^2) is measured by the number of college students enrolled per area of built districts under city as the proxy. 8) Environment quality index (*EQI*): LUCC is an important factor that influences the urban environmental quality, which is closely related to the indexes of the industrial waste water, waste gas, dust emission, and the level of urban greening. Given the availability of data, we selected urban industrial wastewater emission (million tons) of SO_2 (tons), industrial dust emission (tons), and green coverage rate in the built-up-area to demonstrate the urban environmental quality, and developed an environmental quality index (*EQI*) by the method of Generalization Principal Components Analysis (GPCA). The principle and the mathematical model about GPCA are as follows: order $X_b \quad (b = 1, \quad 2, ..., m)$ denotes *m* fundamental variables and $Z_b \quad (b = 1, \quad 2, ..., m)$ denotes *m* principal components. First, on the basis of treatments with the same direction across the fundamental variables data (including forward index and reverse index), the de-mean method (refers to: $x_{bj}/\overline{x_j}$) is adopted to standardize the fundamental variables. Then we plug the processed fundamental variables into the software SPSS19.0, select a covariance matrix to make a Generalization Principal Components Analysis, and determine the first *m* principal components according to the Criterion that the cumulative variance proportion is $\geqslant 85\%$. By Generalization Principal Components Analysis, we obtain the final value function by linear weighting for each coefficient of the principal components and every component's weight (the share corresponding to Eigen-value) in the environmental quality index. As a result, we achieve the synthetic measure for the level of environmental quality in the prefecture-level city. The Eigen-value of the principal component $Z_b \quad (b = 1, 2, ..., m)$ on the j^{th} denotes k_j, so that the value function under Generalization Principal Components Analysis is:

$$Socre = \frac{k_1}{\sum_1^m k_j} \times \frac{Z_1}{\sqrt{k_1}} + \frac{k_2}{\sum_1^m k_j} \times \frac{Z_2}{\sqrt{k_2}} + \cdots + \frac{k_m}{\sum_1^m k_j} \times \frac{Z_m}{\sqrt{k_m}}. \tag{9}$$

9) Land use structure (*JG*: %). Land use structure significantly influences urban land use efficiency. We selected four types of land as a ratio of land area and construction land area, i.e., land use for production, residential, ecological, and land that supports both production and residential living included as a measure of the land use structure. Production land is defined as Industrial Manufacturing land (*IM*), residential land (*R*), ecological land defined as Green Space (*GS*), and land used for both production and residential defined as Municipal Utilities land (*MU*), Road Square Street and Square land (*RSS*).

We collected socio-economic and land data of the 283 cities at/above prefecture-level of China from 2003 to 2012. We categorized the data as follows: 1) economic and socio-economic data for each city were obtained from issues of the China Urban Statistical Yearbook from 2003 to 2012; 2) the land data obtained included area of built district and area of urban construction land obtained from issues of the China Urban Construction Statistical Yearbook from 2003 to 2012 and China Land Resources Statistics Yearbook from 2004 to 2013; and 3) non-agricultural population data from 2011 to 2012 were obtained from issues of the Points Counties and Cities Population Statistics of P.R. China from 2011 to 2012. From the perspective of urban function and considering our research purposes, this paper used data on city districts to research the question. All data regarding monetary values were converted to the constant prices of the base year 2003. The Price Index was obtained from the CSMAR database (www.gtafe.com). The summary of descriptive statistics is shown in Table 1.

3 Results and discussion

3.1 The analysis of urban land use efficiency's spatial-temporal change

Current studies have analyzed changes in spatial features of urban LUCC at different spatial scales. In this paper, the spatial analysis platform ArcGIS 9.2 is adopted to identify the spatial distribution pattern of urban land use efficiency at prefecture level. Figure 1 shows the changes in the spatial distribution of urban land use efficiency in 2003, 2008, and 2012, based on the historical process of spatial agglomeration change in urban land use efficiency over the past ten years. As shown in Fig. 1, panel A, the area of high value of urban land use efficiency is denoted as scattered dot distribution patterns. The specific performances are as follows: 1) Most cities typically experience extensive utilization with low land use efficiency, which coincided with the investment promotion strategy set by the Chinese government since the implementation of the "Tax Sharing System"(TSS) in 1994. 2) The more intensive regions are typically found at higher elevations located throughout the Yangtze River Delta and Pearl River Delta on the east coast, the Economic Zone on the west shore, Beijing-

Table 1 The variables statistics description (2003–2012)

Variable	Symbol	Obs.	Mean	Std	Min	Max
Urban land use efficiency	q	2830	3.81	2.67	0.30	3.39
Industrial structure	S	2830	0.9165	0.5170	0.0943	4.9444
City size	N	2830	84.35	125.30	5.04	1252.22
Capital density	K	2830	22,244.08	14,763.93	814.10	106,924.60
Employment density	n	2830	4015.96	1951.89	412.34	30,169.43
The level of land market	LM	2830	48.94	19.22	2.75	100.00
Human capital density	H	2830	579.92	1069.06	1.81	24,987.40
Environment quality index	EQI	2830	5.55	0.89	0.48	31.58
Residential land	R	2830	31.83	8.09	4.93	73.24
Industrial manufacturing land	IM	2830	12.89	5.12	0.87	58.35
Green space land	GS	2830	20.25	7.96	0.63	61.30
Municipal utilities land	MU	2830	10.52	3.90	0.15	51.42
Road Square Street and Square Land	RSS	2830	10.37	6.65	0.15	55.89

Tianjin-Hebei, the central and southern cities in Liaoning Province, Shandong Peninsula, Harbin-Changchun megalopolis in the northeast, and the Central Plains Economic Region, with additional concentration in provincial capitals. 3) An agglomeration region showing high land use efficiency has been formed in the eastern coastline area of China. In contrast, there was significant change in the spatial agglomeration of land use efficiency during 2008. The spatial distribution pattern formed a core-periphery structure where the east coast is the core and the central and western regions are the periphery. Moreover, the spatial distribution form of urban land use efficiency in China has a "core-peripheral effect" which was more distinct in 2012. During that time, the spatial distribution pattern demonstrated that it mainly focused on agglomeration in groups of cities, from point-like agglomeration to banded agglomeration. More specifically, land use efficiency increased significantly for: 1) the Harbin-Changchun megalopolis with Changchun and Harbin as the core, the central and south cities in Liaoning Province with Shenyang and Dalian as the core, and the east coast regions of the Yangtze River Delta and Pearl River Delta. It is evident that land use efficiency increased more rapidly in these regions than observed in the west and middle regions, where there is obvious strategic coupling of regional and policy. The higher the level of economic development, the stronger the attraction of state-of-the-art facilities and increased capital investment opportunities, such as in labor and technology. As a result, the output effect of land use will increase and land use efficiency will advance. 2) The areas with the highest concentration of land use efficiency formed continuous banding spatial distribution patterns of three vertical structures, found in the following high-level agglomeration regions: 1) Liaoning located in the Bohai Rim region on the east, Beijing-Tianjin-Hebei, and the Yangtze River Delta Pearl River Delta as the first vertical axis, 2) Beijing-Guangzhou and Beijing-Harbin line, including the Harbin-Changchun megalopolis, and the Central Plains and Wuhan economic circles as the second vertical axis, and 3) the Guanzhong-Tianshui and ChengYu economic zones as the third vertical axis. Based on our analysis of the changes in the spatial patterns during the three periods, it is seen that there are spatial geographical agglomeration features in urban land use efficiency. Land use efficiency at different scales exhibits typical spatial correlation and radiation effect.

Based on the spatial agglomeration Moran's I value of urban land use efficiency, we also found that Moran's I has a highly significant positive effect under a given one percent significance level for the three periods. This indicates positive urban land use efficiency for spatial agglomeration since 2003. In addition, it is shown that the agglomeration between areas of high-value on land use efficiency and those of low-value where the level of agglomeration fluctuates narrowly over time indicates that spatial agglomeration tends to be stable. Of course the Z-value decreases each year, which indicates the spatial agglomeration region of urban land use efficiency is expanding.

3.2 The empirical analysis

We conducted an econometric analysis on causality to identify the synergistic effect and the relationship between urban size, and industrial structure. We chose the appropriate panel data model before the econometric estimation. According to the results of the Hausman test with a Chi2-value of 31.88 and P-value of 0.004, we refused the null hypothesis of individual effect under the 1% significance level and took the fixed effect as opposed to the random effect model. We chose short panel data sets of "$T \ll N$"; therefore, we did not consider the problem on

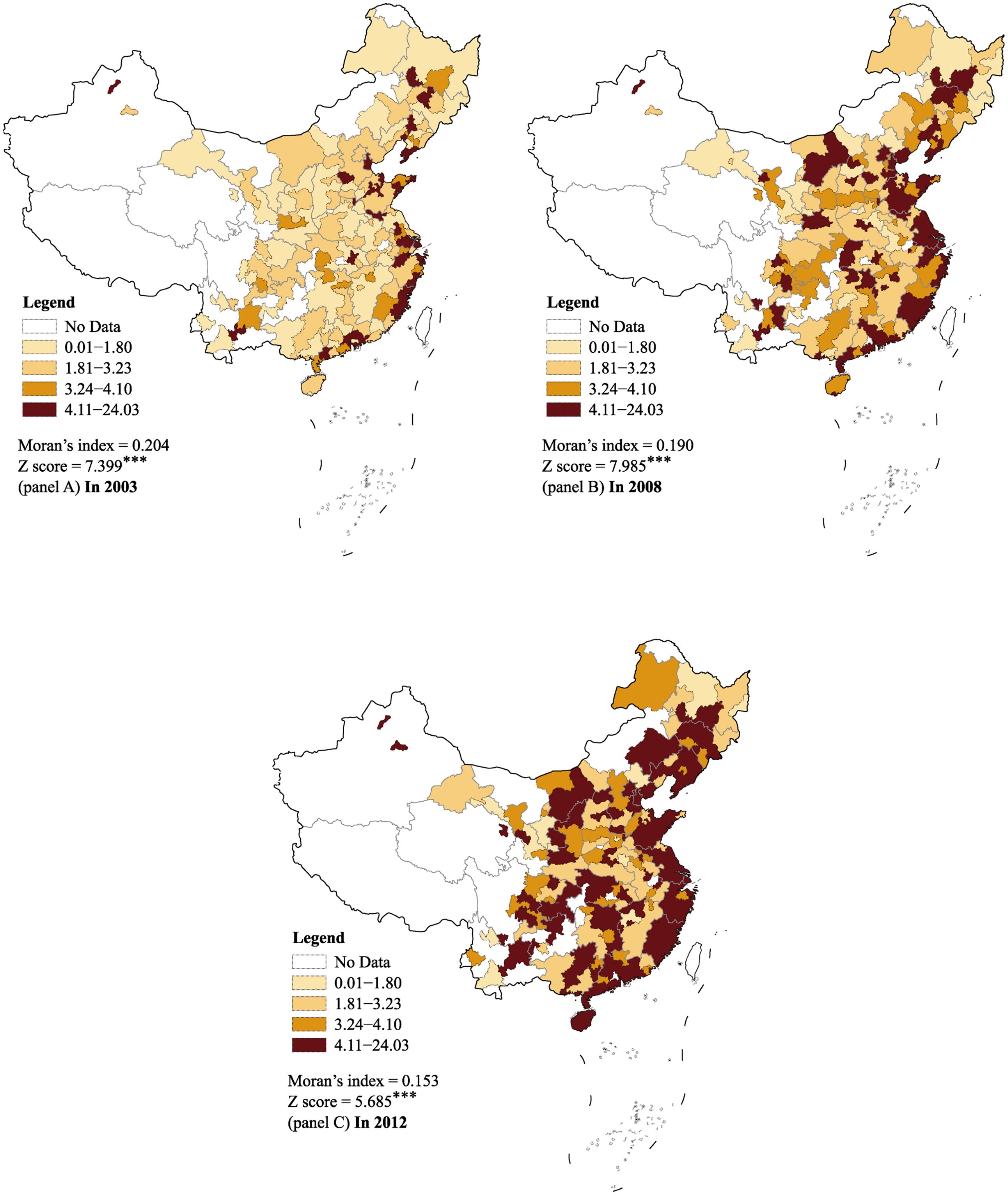

Fig. 1 The changes in the spatial tendency of urban land use efficiency in 2003 (panel A), 2008 (panel B), 2012 (panel C). Note: The map is drawn by the authors using Arigis 10.3.

roots of unity in an empirical analysis. As shown in Table 2, the estimation results of models 1–3 are consistent and highly similar to the expectations from theory. Because this paper adopts the fixed effect estimation model, we used the estimation results of the fixed effect model in the final results reported. At the same time, we took partial derivatives of industrial structure and urban size to analyze their effects on land use efficiency. The analysis of specific effects is as follows:

The estimation results are reported in Table 2. The estimated coefficients are observably positive for capital density (*K*), employment density (*n*), the level of land marketization (*LM*) and the human capital level (*H*), which indicates that these control variables have a significantly positive impact on land use efficiency change with marginal elasticity of 0.395, 0.231, 0.086, and 0.067, respectively. The density of the marginal elasticity of capital density (*K*) is 1.71 times the level of employment density (*n*), which shows its current positive impact on land use efficiency in China. This also reflects that land use in China is still at the capital-intensive land-intensive use stage, consistent with Dou and Wang's (2010) idea. It is worthwhile to reflect on the fact that the environmental quality index has a dominant negative effect on urban land use efficiency; this is closely related to China's ongoing development of heavy-industrialization and its extensive economic growth pattern, matchingits plan for an "environment for growth." The Chinese economy has developed rapidly when measured using the "three-high" growth model; namely, high energy consumption, high investment, and high pollution. At the same time, total land output effect has increased during the past 30 years since the opening-up reform. This has, however, come at the cost of energy, resource, and environmental depletion. In fact, the improvement of environmental quality is a result of stricter environmental regulations. The reverse transmission of environmental regulations has increased the costs of the "three-high" enterprises. When the "cost burden effect" of the environmental regulations policy is higher than the "compensation to innovation effect" (Porter and van der Linde, 1995) it caused, the policy will weaken the production efficiency of the enterprises and reduce the unit land output. This shows that environmental quality has a "crowding-out effect" on the improvement of land use efficiency. The "economic" impacts of land use efficiency are of greater concern in China than the "green" impacts. These conclusions confirm the theory that land use efficiency can be studied from an economic structure adjustment point of view. Accelerating the transformation of economic growth and exerting the improvement effect on the adjustment of economic structure on urban land use efficiency is essential to strike a balance between "green development" and "efficiency promotion." To clearly understand the structure of urban land use in China, it must be known that residential land (*R*), green space land (*GS*), and road square street and square land (*RSS*) do not pass the significance test, and further that industrial manufacturing land (*IM*) and municipal utilities land (*MU*) have a negative influence on urban land use efficiency under the significance level of 1% and 5%. From the estimated coefficient of the type of land use structure on land use efficiency, the effect of intensive land use on urban IM and MU is lower than R, GS, and RSS. It is worth mentioning that the estimated coefficient of IM is –0.035, which is the lowest economic efficiency of all land use types. This corresponds with the facts regarding China's economic and social development to date; that is, China's local government is very motivated to sell industrial land at a low price, thus enlarging the industrial land scale and reducing the quality of capital. This gives enormous impetus to the need for the construction of industrial parks, and not only does this not favor the reasonable agglomeration of industries to release the effect of scale economies, but generates a phenomenon that vast amounts of land are occupied, but not well-developed, which in turn significantly reduces land output efficiency.

We then examined the synergistic effects of both industrial structure and urban size on urban land use efficiency. First, the estimated coefficients of the second model means $\partial(\ln q)/\partial(\ln S) = -0.239 + 0.051\ln N$; therefore, the threshold size of the non-agricultural population in a municipal district that plays a role in urban industrial structure upgrading to land intensive use is about 108.45 (10,000 persons). According to 2012 data from the New Standard Classification of Chinese city size, we found that there are still 223 cities (accounting for 78.80% of total cities) below the minimum threshold size. Therefore, in the second type of city (those with 1–3 million people), and in small- and medium-sized cities (those with less than 1 million people) which are below the threshold size, the higher the level of servitization in the industrial structure, the lower the land use efficiency. The land use efficiency in cities that cross the scale threshold increased when the proportion of tertiary industry increased. In 2012, the average scale of the non-agricultural population was 92.04 (10,000 persons) in a Chinese municipal district; therefore, in average-sized cities, for every 10% increase in tertiary industry to secondary industry, urban land use efficiency will drop by 8.37% (see Table 3). By computation, we found that 78.80% of 223 cities, less than the threshold size of cities in 2012, have lower land use efficiency than those at the national level. In addition, the level of land use efficiency in cities like Guyuan, Suihua, Dingxi, and Heihe is less than half that of the national average, yet the corresponding industrial structure ratio is significantly above the national average. This conclusion provides evidence of the characteristics of industrial development in different sized cities that are undergoing an economic restructuring process. That is to say, since the implementation of the "tax-sharing system" (TSS) reform in 1994,

Table 2 The panel data’s estimation results of urban land use efficiency from 2003 to 2012 (Robust test)

Variable	Model 1: OLS	Model 2: FE	Model 3: RE
S	–0.225***	–0.239***	–0.214***
	(–5.42)	(–4.53)	(–4.31)
$\ln N$	0.126***	1.514***	0.595***
	(2.74)	(9.59)	(6.43)
$(\ln N)^2$	–0.001	–0.123***	–0.045***
	(–0.21)	(–6.68)	(–4.17)
$S*\ln N$	0.027**	0.051***	0.038***
	(2.53)	(3.61)	(2.93)
$\ln K$	0.531***	0.395***	0.436***
	(49.48)	(46.07)	(53.19)
$\ln n$	0.350***	0.231***	0.240***
	(21.05)	(15.28)	(16.10)
$\ln LM$	0.016	0.086***	0.092***
	(1.13)	(8.65)	(9.33)
$\ln H$	–0.008	0.067***	0.054***
	(–1.14)	(8.65)	(7.30)
$\ln EQI$	0.059**	–0.071***	–0.063**
	(2.00)	(–2.68)	(–2.38)
	Variable of land use structure		
$\ln R$	–0.101***	–0.004	–0.010
	(–3.62)	(–0.20)	(–0.48)
$\ln MU$	–0.077***	–0.026**	–0.032*
	(–4.67)	(–1.97)	(–2.42)
$\ln IM$	0.028	–0.035***	–0.029**
	(1.85)	(–3.16)	(–2.65)
$\ln RSS$	–0.009	0.009	0.009
	(–0.68)	(0.80)	(0.85)
$\ln GS$	–0.003	–0.008	–0.004
	(–0.26)	(–1.10)	(–0.54)
N	2830	2830	2830
R^2	0.745	0.727	0.718
F	633.586	482.07	

Note: The statistical value is shown in parenthesis, *** indicates a < 1% significance level, ** indicates a < 5% significance level, * indicates a < 10% significance level.

Table 3 The changes of land use efficiency in cities under structure-scale agglomeration

The Ratio of Tertiary-Secondary Industry	Scale threshold of non-agricultural population in municipal district /(10,000 persons)	Land use efficiency in the scale threshold /($\mathrm{CNY \cdot km^{-2}}$)	Average non-agricultural population in 2012 /(10,000 persons)	Optimal scale of non-agricultural population in municipal district/(10,000 persons)	Optimal efficiency of urban land use /($\mathrm{CNY \cdot km^{-2}}$)
Average $S = 0.886$	108.45	5.64 hundred million	92.04	565.75	8.91 hundred million
S improves 0.1			–8.37%	8.42%	

Notes: The average of variables S, $\ln K$, $\ln n$, $\ln lm$, $\ln LM$, $\ln H$, $\ln EQ$, $\ln R$, $\ln MU$, $\ln IM$, $\ln RSS$, and $\ln GS$ is 0.886, 10.291, 8.242, 3.977, 5.968, 1.704, 3.442, 2.441, 2.752, 2.316, and 2.211 in 2012, respectively.

local government officials, tempted by political promotion and financial incentives, paid more attention to the scale than the quality of investments for economic development in their jurisdiction. A strategy was adopted to reduce investment quality by lowering the price for land transfer and expanding the scale. Despite the positive benefits of "land investment," such as relieved financial pressure on local governments and increased employment and economic growth, it also seriously interferes with land market system operations and introduces low-end industries and redundant construction investments. As a result, land use efficiency decreased and healthy economic development suffered long-term damage. On the other hand, local governments in medium- and small-sized cities did not take full advantage, but rather sought industrial diversity and servitization in industrial pattern in an uninformed manner. This contributed significantly to the demonstrated continuously-low efficiency in land use. First, Chinese medium- and small-sized cities lack both economic aggregate and human resources. They would be better off to concentrate their limited resources and use their regional comparative advantage to play a role in agglomeration externality made possible by specialized production. But in fact, a diversified industrial pattern seriously deviates from the law of economic development, demonstrating intensification of resource competition between different industries. This drives comparative advantage in diversification and does not achieve organic integration of population, land, or industry. Secondly, for cities under the threshold, even those with a high share of service industry, they still cannot support the industrial agglomeration because of their small urban size, outdated manufacturing industries, and low value-added services. As a result, their land use efficiency is low. It is difficult for medium- and small-sized cities to meet the high value-added production sector's demand, thus their integral efficiency of land use is at a lower level. Given these conditions, a service economy will generate unlimited land sprawl and lower land use efficiency. These are the most critical issues facing local governments in their plight for future economic restructuring.

Secondly, with regard to the influence of urban size on land use efficiency, the parameter estimation in the second model is $\partial(\ln q)/\partial(\ln N) = 1.514 - 0.246\ln N + 0.051S$. Obviously, marginal gain of urban sprawl is not only influenced by size, but is also closely associated with industrial structure (S). The higher the cities' value-added ratio of tertiary to secondary industry (S), the higher the marginal gain of the land intensive use effect that is caused by urban size sprawl. The average ratio of tertiary industry to secondary industry (S) in 2012 is 0.886. This can be put into the former formula, and then used to calculate that the urban size in cities has an average ratio of industrial structure that can maximize land use efficiency, which is 565.75(10,000 persons). The size shows that it is 6.15 times greater than the average scale of a non-agricultural population in a prefecture-level municipal district, which is 92.04 (10,000 persons). In the meantime, 283 prefecture-level cities, other than Shanghai, Beijing, Chongqing, Guangzhou, and Tianjin, were all under optimal urban size at the end of 2012, which means there is great potential for promoting optimization of China's urban land use efficiency to satisfy the land demand of urbanization and for China's urban land efficiency use to improve (Chen and Zhang, 2014). Hence, China's main focus should be on facilitating the adjustment of the economic structure to promote urbanization in the "new normal" during the process of agricultural population citizenization over a long period. Population and industry agglomeration should be promoted in the medium- and small-sized cities to generate the effect of the co-agglomeration between population and industry, and not only make these cities exceed the scale threshold, but also focus on urban size matching up with industrial structure, which can in turn optimize urban size.

We can quantitatively estimate the effects of structure-scale agglomeration based on the results shown in Table 2 and the sample average of each variable in 2012. Given the average S, the land use efficiency in cities will improve 57.98% under the effects of agglomeration economies and scale economies even when other variables do not change. In addition, every 10% of ratio S will bring 8.42% improvement of marginal efficiency of land use under optimal city scale.

3.3 Robust test

Based on Peng et al. (2014), we further calculate a composite index of urban land use efficiency at/above prefecture-level in China of 283 cities from 2003 to 2012 as a proxy to test the robustness of the synergistic effect mechanism of industrial structure, city size, and environmental quality on land use efficiency by using the methods of Generalization Principal Component Analysis (GPCA). The robust estimation results are shown in Table 4. For the Hausman test, the Chi2-value is 868.43 and the P-value is 0.000, and the fixed effect should be used instead of the random effect model. It is shown that after comprehensive consideration of economic, social, and environmental benefits of land use, the magnitude, sign and significance of the core variable parameter estimation are nearly equivalent to the results shown in Table 2. In addition, the estimation results of the control variables are similar, indicating that the results reported in this paper are robust (see Table 4). The estimated results show that the minimum threshold size of the non-agricultural population in a municipal district playing a role in urban industrial structure to upgrade land intensive use is approximately 20.66 (10,000 persons), which is far below 92.04 (10,000 persons) (Table 3). This is due to the fact that a smaller city size is required to improve land use efficiency after comprehensive consideration of economic, social, and

Table 4 The panel data’s estimation results of urban land use efficiency from 2003 to 2012

Variable	Model 4: OLS	Model 5: FE	Model 6: RE
S	–0.0504	–0.1608***	–0.1253***
	(–1.56)	(–4.15)	(–3.42)
$\ln N$	0.3476***	1.4111***	0.7236***
	(9.67)	(12.16)	(9.96)
$(\ln N)^2$	–0.0217***	–0.1204***	–0.0611***
	(–5.14)	(–8.92)	(–7.14)
$S*\ln N$	0.0205***	0.0531***	0.0435***
	(2.44)	(5.16)	(4.49)
$\ln K$	0.4904***	0.4374***	0.4601***
	(58.57)	(69.36)	(76.83)
$\ln n$	0.0894***	0.0418***	0.0415***
	(6.90)	(3.76)	(3.79)
$\ln LM$	0.0770***	0.0835***	0.0912***
	(6.87)	(11.46)	(12.65)
$\ln H$	0.0236***	0.0182***	0.0204***
	(4.37)	(3.21)	(3.74)
$\ln EQI$	0.0598*	–0.0352*	–0.0285
	(2.61)	(–1.80)	(–1.48)
N	2830	2830	2830
R^2	0.7777	0.8257	0.8205

Note: The statistical value is shown in parenthesis, *** indicates > 1% significance level, ** indicates > 5% significance level, and * indicates > 10% significance level. This information only includes estimated results of the main variables, and to avoid multicollinearity, the structure of land use is eliminated to the construction of the land use efficiency index in the robustness test.

environmental benefit of land use. An urban size of 433.01 (10,000 persons), with an average ratio of industrial structure, can maximize land use efficiency which is slightly lower than 565.75 (10,000 persons), shown in Table 3.

4 Conclusions and policy implications

By building an urban land productivity model, which include industrial structure and city size, and based on the spatial-temporal evolution of urban land use efficiency, we have investigated the synergistic effect mechanism of industrial structure and city size, as well as environmental quality on land use efficiency. We used panel data relating to 283 cities at/above prefecture-level in China from 2003 to 2012, and estimated the optimal size of cities for a given industrial structure and marginal benefit of industrial upgrading under a constraint of urban scale. The foremost conclusions of this study are: 1) the “crowding out effect” of environmental quality negatively impacts urban land use efficiency; and 2) the influence of industrial structure on urban land use efficiency depends on city size. The threshold size of land use efficiency increases from industrial restructuring, reaching 108.45 (10,000 persons) of a non-agricultural population in municipal districts. Cities below the threshold size remain unable to persuade the relative upstream and downstream industries of the advantages of agglomeration economies; at the same time, the growth of the proportion of tertiary industry goes against the notion of land use efficiency. Cities that cross the threshold size can promote intensive land use from the transformation of service economy. 78.80% of the cities at/above prefecture-level are lower than the current threshold size; therefore, using the average urban size, the added value ratio of the tertiary industry-second industry each increased by 0.1 and land use efficiency fell by 8.37%; 3) land use efficiency and increased city size presents an inverted-U shaped relationship. The land use efficiencyincreases along with the economy transfers to service-oriented economy. Using the average of the ratio of value-added in tertiary industry and secondary industry (S) as a benchmark in 2012, the optimal scale of the cities that achieves maximum land use efficiency is 565.75 (10,000 persons); however, we found that the actual size of 98.2% of the cities in China is smaller than their optimal sizes.

The above conclusions provide Chinese urban land managers with an important basis on how to improve the efficiency of urban land utilization and to promote change in land utilization pattern.

Overall, to implement a sustainable urbanization strategy, it is essential for local governments to accelerate the transformation of economic development and readjust the economic structure to reduce both energy consumption and waste of land resources. Moreover, the land managers and policy advisors should adapt land uses to the local conditions. Specifically, from the character of spatial-temporal evolution at present, urban land use efficiency is based on the distribution of urban agglomeration. Therefore, it would be beneficial to encourage the surplus labor from industrial and agricultural sectors to move into small cities and the surrounding areas with the goal of developing urban system structure based on city groups as the core element. As a result, land use efficiency could be promoted by coordinating the urban form and the function of land use. Second, given industrial transformation and advancement are the main factors influencing urban land use efficiency, with a variance in benefits based on urban size, megalopolis and large cities should develop a modern service industry, make full use of the land resources released from the industrial transformation, and actively nurture a productive service industry that benefits from the development of high, value-added manufacturing. The large cities should eliminate the older, standardized industries that are unable to benefit from the structure of agglomeration economies (Ke and Zhao, 2014). In contrast, medium- and small-sized cities should place an emphasis on developing modern, advanced manufacturing industry and promoting the agglomeration of population, as this is the most important way to increase land use efficiency during the urbanization process. Third, as the industrial structure and urban size jointly have a synergistic effect on the efficiency of urban land use, less developed areas must focus on promoting the agglomeration of population and industry, and medium- and small-sized cities should actively undertake mature metropolitan manufacturing in order to cross the threshold size faster. Developed areas, on the other hand, should transfer mature manufacturing industry from megalopolis to large-, medium-, and small-sized cities, especially those large- and medium-sized cities that have sufficient carrying capacity of environmental resources, but haven't yet reached optimal size.

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