J. Geogr. Sci. 2018, 28(8): 1113-1126
DOI: https://doi.org/10.1007/s11442-018-1545-2

Spatiotemporal patterns in urbanization efficiency within the Yangtze River Economic Belt between 2005 and 2014

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Abstract: The question of how to generate maximum socio-economic benefits while at the same time minimizing input from urban land resources lies at the core of regional ecological civilization construction. We apply stochastic frontier analysis (SFA) in this study to municipal input-output data for the period between 2005 and 2014 to evaluate the urbanization efficiency of 110 cities within the Yangtze River Economic Belt (YREB) and then further assess the spatial association characteristics of these values. The results of this study initially reveal that the urbanization efficiency of the YREB increased from 0.34 to 0.53 between 2005 and 2014, a significant growth at a cumulative rate of 54.07%. Data show that the efficiency growth rate of cities within the upper reaches of the Yangtze River has been faster than that of their counterparts in the middle and lower reaches, and that there is also a great deal of additional potential for growth in urbanization efficiency across the whole area. Secondly, results show that urbanization efficiency conforms to a "bar-like" distribution across the whole area, gradually decreasing from the east to the west. This trend highlights great intra-provincial differences, but also striking inter-provincial variation within the upper, middle, and lower reaches of the Yangtze River. The total urbanization efficiency of cities within the lower reaches of the river has been the highest, followed successively by those within the middle and upper reaches. Finally, values for Moran's *I* within this area remained higher than zero over the study period and have increased annually; this result indicates a positive spatial correlation between the urbanization efficiency of cities and annual increments in agglomeration level. Our use of the local indicators of spatial association (LISA) statistic has enabled us to quantify characteristics of "small agglomeration and large dispersion". Thus, "high- high"

Received: 2018-01-18 **Accepted:** 2018-02-28
Foundation: National Natural Science Foundation of China, No.41501593, No.41601592; National Program on Key Research Project, No.2016YFA0602500
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(H-H) agglomeration areas can be seen to have spread outwards from around Zhejiang Province and the city of Shanghai, while areas characterized by “low-low” (L-L) patterns are mainly concentrated in the north of Anhui Province and in Sichuan Province. The framework and results of this research are of considerable significance to our understanding of both land use sustainability and balanced development.

Keywords: urbanization efficiency; stochastic frontier analysis; spatial autocorrelation analysis; spatiotemporal patterns; Yangtze River Economic Belt

1 Introduction

China has experienced a period of rapid urbanization over recent decades. The ever-increasing area of urban construction land nationally has consumed other kinds of territory (e.g., cultivated and forested land) and has led to enhanced and marked contradictions between the development of built-up areas, the protection of farmland, and ecological conservation (Zuo *et al*., 2014; Fang *et al*., 2017). Extensive urban land-use patterns within cities and towns lead to problems in territorial development including the irrational structuring of construction land as well as the scattered spatial distribution and low efficiency of land use (Fu *et al.*, 2014). As China has both a finite land area and a massive population, improving the efficiency of urbanization has become a critical requirement for promoting both regional sustainable development and national ecological civilization (Li *et al*., 2015). Key documents published by the Chinese government in recent years have noted that inefficient and disorderly urban land use needs to be urgently managed; thus, the “13th Five-year Plan for Land and Resources” (2016–2020) explicitly proposed the use of double-control measures to control both the quantity and intensity of land use as well as to strengthen controls on the utilization of construction land (Jin *et al*., 2015). As a result of rapid urbanization, the question of how to obtain maximum socio-economic benefits with minimum input has gradually developed to become the focus of scientific research and national strategic decision-making. A great deal of recent research on urbanization efficiency is available, concerning multiple spatial scales and utilizing a range of methodologies. Most studies have emphasized the issue of land use efficiency from different perspectives, including the efficiency of construction land and farmland productivity. Associations between land use and urbanization efficiency have also been analyzed (Huang *et al*., 2016; Nguyen *et al*., 2017; Deilmann *et al*., 2018) at all spatial scales (e.g., national and provincial as well as at the level of urban agglomerations, watersheds and individual cities) (Wang *et al*., 2014; Rashidi *et al*., 2015). Previous research has also highlighted the mechanisms underlying changes in urbanization efficiency by analyzing drivers and spillover effects at different spatial scales (Wang *et al.*, 2015); thus, both parametric and non-parametric methods have been utilized in this area (Battese *et al*., 1995; Jin *et al*., 2017), corresponding with the classic data envelopment analysis (DEA) and stochastic frontier analysis (SFA) models, respectively. The first of these two approaches employs the linear programming mathematical process to evaluate the relative efficiency of a decision-making unit within a fixed production frontier, while the latter uses a production function to accurately simulate the absolute efficiency of an object being evaluated while at the same time taking the impact of uncontrollable factors influencing efficiency into account. The latter approach has proven to be more pertinent than the former in the case of certain problems (Ghosh *et al*., 2016; Jin *et al*., 2017). Thus, in general, although the SFA model has been widely applied in technical efficiency calculations involving domestic and foreign economic or enterprise production activities, few empirical studies addressing land use, urbanization, and ecological efficiency within China have so far been performed (Li *et al*., 2017; Jia *et al*., 2017). Current results have also normally been analyzed from economic or management perspectives in order to elaborate on the nature of this phenomenon and to understand underlying mechanisms. An extremely limited number of time-series expressions that encapsulate efficient geospatial morphologies have therefore been undertaken.

The SFA model is introduced in this study alongside a spatial correlation approach to urban studies in order to emphasize urbanization efficiency from the joint perspectives of avoiding uncontrollable factors and inefficiencies in calculations as well as to achieve an appropriate geospatial morphological representation. The urbanization efficiencies of 110 cities within the Yangtze River Economic Belt (YREB) between 2005 and 2014 were therefore calculated and further analyzed in this study in order to enrich available case studies, highlight the spatiotemporal evolution and spatial morphological characteristics of these agglomerations, and to provide additional reference data for optimal land allocation in the context of balanced regional development.

2 Study area

The YREB spans three major regions of China (i.e., Eastern China, Central China, and Western China) and includes nine provinces (i.e., Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Sichuan, Yunnan, and Guizhou) and two municipalities (i.e., Shanghai and Chongqing) (Figure 1). Thus, as the YREB encapsulates a total area of approximately 2,050,000 km^2 and includes a population and gross domestic product (GDP) in excess of 40% of the whole country, this region comprises one of the most important strategic support areas nationally. On the basis of differences in socioeconomic development between regions and large variations in natural resources, the YREB is usually divided into three areas that correspond with the upper, middle, and lower reaches of the river basin. The first of these areas includes 33 cities within Guizhou, Yunnan, and Sichuan provinces as well as the municipality of Chongqing, while the middle reaches encapsulates 36 cities within Hunan, Hubei and Jiangxi provinces. The lower reaches of the YREB includes 41 cities within Anhui, Zhejiang, and Jiangsu provinces as well as the municipality of Shanghai. The overall area of the YREB also includes three major urban agglomerations within the Yangtze River Delta urban agglomeration (i.e., urban agglomerations within the middle reaches of the Yangtze River,

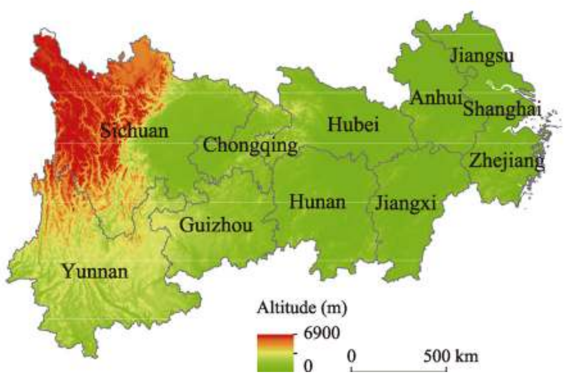

Figure 1 A general overview of the YREB

the Cheng-Yu urban agglomerations and regional urban agglomerations including the Wanjiang urban belt as well as the central Guizhou and central Yunnan urban agglomerations). The "13th Five-year Plan for Economic and Social Development of the People's Republic of China" (2016–2020) has identified YREB policy as one of three major regional development strategies nationally; development within this region is intended to engender an ecological civilization demonstration zone based on advanced ideas with global influence. However, because of the rapid development of urbanization within China, contradictions between ecological preservation, urbanization, and the protection of farmland within the YREB have become increasingly marked. The use of large areas of farmland and ecological land for construction has had a particularly marked negative impact on resources and the environment; coupled with the inefficient utilization of urban land resources, this phenomenon has, to a large extent, restricted regional sustainable development. The YREB is therefore considered in this study as a typical case study region to explore the laws of urbanization efficiency and their spatial differentiation, as well as to provide a scientific basis for the future construction of regional ecological civilization and land-use optimization.

3 Data and methods

3.1 Data sources and processing

Urban construction land, capital stock, and non-agricultural labor were chosen as the input indicators used in this analysis, while non-agricultural output was utilized to comprehensively reflect the level of urban economic development. The use of these variables is based on the classic production functions of labor, capital, and land as three basic input indicators alongside economic output. The use of these indicators is appropriate based on an understanding of urban land use characteristics such that specific variables should adequately reflect the characteristics of non-agricultural production activities (Wang *et al*., 2015; Deilmann *et al*., 2016; Chen *et al*., 2016).

Socio-economic data was used as the basis of a SFA model implemented to measure efficiency (Shabani *et al*., 2015; Yang *et al*., 2016). Thus, relevant land, capital, and labor force data were extracted for this study from China's Urban Statistical Yearbook (2005–2014), the China's Regional Economic Statistical Yearbook (2005–2014), and the Provincial (Municipalities) Statistical Yearbook (2005–2014), alongside consumer price index (CPI) data provided by the National Bureau of Statistics. Urban non-agricultural output was estimated on a yearly basis using the GDP deflator based on statistical yearbook data, while urban construction land was defined as the sum of this land use type within a city and surrounding suburbs. Our use of capital refers to fiscal expenditure and capital stock; the first of these variables was reduced at the beginning of the study period using the CPI, while capital stock was estimated by adopting the perpetual inventory method (PIM). This approach involves the selection of current investment indicators, a yearly capital stock calculation, the selection of a depreciation rate, and an investment calculation (Guan *et al*., 2015; Lin *et al*., 2017). Our use of the concept of labor force refers to non-agricultural workforce, a unit encompassing practitioners, private, and individual employees. All YREB data were organized into city-level panels encompassing the period between 2005 and 2014.

3.2 Methods

3.2.1 SFA model

The SFA method was proposed in the same year by Aigner *et al.* (1977) and Meeusen *et al.* (1977) and is considered an effective tool to measure efficiency. In later work, Battese and Coelli (1995) proposed the use of an improved model for panel data and added a time-variant coefficient for settings. This approach has subsequently been widely applied (Reinhard *et al.*, 1999), in particular as an econometric method for analyzing multiple inputs and single output. The SFA method can be used to verify its own internal parameters and applicability, effectively distinguish statistical and management errors, and mitigate the influence of uncontrollable factors on inefficiency, all characteristics that make the results of these analyses more realistic.

The input of land elements is reflected in this study in the form of labor force and capital per unit area, while the input-output equation utilized fully incorporates both random impacts and technological inefficiencies. Thus, building on the Cobb-Douglas production function logarithm, the empirical input-output SFA model utilized in this study on the basis of unit area is as follows:

$$\ln(y_{it}) = \beta_{0t} + \beta_{1t}\ln(L_{it}) + \beta_{2t}\ln(K_{it}) + \beta_{3t}\ln(F_{it}) + v_{it} - \mu_{it} \quad (1)$$

where y_{it} denotes the non-agricultural outputs per unit area (10,000 yuan per km^2) of city i in year t, while L_{it} denotes the non-agricultural labor force per unit area (people per km^2), K_{it} denotes the capital stock per unit area (10,000 yuan per km^2), F_{it} refers to financial expenditure per unit area (10,000 yuan per km^2), and β_0 is a constant. Thus, β_1, β_2, and β_3 denote the output elasticity coefficients of labor force, capital stock, and fiscal expenditure, respectively, while v_{it} and μ_{it} are error terms. The term v_{it} is considered to be independent, identically distributed, and normally distributed in this study, an assumption which incorporates unpredictable random impacts (e.g., major natural disasters, extreme weather, and important social events), while μ_{it} is considered to be independent, identically distributed, and subject to nonnegative truncated normal distribution; this latter assumption incorporates the inefficient urbanization component of unit i of time t, and denotes the distance between the unit under evaluation and the production frontier.

Thus, urbanization efficiency was calculated based on formula (1), as follows:

$$UE_{it} = \exp(-\mu_{it}) \quad (2)$$

where UE denotes urbanization efficiency and $\mu_{it} \geq 0$, $0 < \mathrm{UE_{it}} \leqslant 1$.

We further quantified the effect of time on μ_{it}, urbanization inefficiency, as follows:

$$\mu_{it} = \beta(t) \cdot \mu_i \quad (3)$$

$$\beta(t) = \exp\{-\eta \cdot (t - T)\} \quad (4)$$

where η denotes the time-variable coefficient to be estimated, reflecting the rate of change in urbanization efficiency. Thus, if $\eta > 0$, $\beta(t)$ decreases with increase in t, and urbanization efficiency increases, but if $\eta < 0$, then $\beta(t)$ increases with the increase in t, and urbanization efficiency decreases. Similarly, if $\eta = 0$, urbanization efficiency remains unchanged over time.

A final hypothesis test was also performed to assess the feasibility and validity of SFA in this analysis, as follows:

$$\lambda = -2\left[LR\left(H_0\right) - LR\left(H_1\right)\right] \tag{5}$$

where λ denotes the log-likelihood ratio statistic, while $LR(H_0)$ and $LR(H_1)$ refer to the stochastic frontier models given the null hypothesis, H_0 (absence of technical inefficiency) and alternative hypothesis, H_1 (presence of technical inefficiency), respectively. Thus, if the null hypothesis is assumed to be correct, then statistics will conform to a mixed chi-square distribution, as follows:

$$\gamma = \frac{\sigma_\mu^2}{\sigma_\mu^2 + \sigma_\nu^2} \tag{6}$$

where γ is used to quantitatively analyze the structure of the model error term; thus, the closer this value is to 1, the greater the technical inefficiency proportion in terms of the difference between observed and maximum feasible output.

3.2.2 Spatial autocorrelation analysis

Spatial autocorrelation analysis is an important index-based approach that can be used to test whether, or not, a value of a certain element is significantly associated with the attribute value of an adjacent spatial point. This class of analyses encompasses global spatial autocorrelation and local indicators of spatial association (LISA) (Anselin, 1995), with the first approach used to analyze the distributional characteristics of a research object in global space. The overall degree of urbanization efficiency global spatial correlation is measured using Moran's *I* statistic (Jin *et al*., 2016), calculated as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{7}$$

where I denotes the global Moran index, while x_i and x_j are the observed values of urbanization efficiency in areas i and j, respectively, $\overline{x}$ is the average urbanization efficiency of the overall study area, and W_{ij} denotes the spatial relationship between urban i and j (i.e., adjacent to 1, not adjacent to zero). A value of Moran's I greater than zero means that attributes between cities are positively spatially correlated; in contrast, if this value is less than zero, then attributes are negatively spatially correlated.

The Moran's I statistic cannot be used to precisely indicate the specific spatial location of an agglomeration or anomaly, however, and so spatial autocorrelation must be applied for further analyses, emphasizing local spatial associations of urbanization efficiency in some localities. The LISA index I_i is therefore introduced in this paper as a partial form of Moran's I that can be used to test agglomeration and dispersion effects within local areas and to reveal spatial autocorrelation between the urbanization efficiency levels of each city and neighboring units. This index was calculated as follows:

$$I_i = \frac{n(x_i - \overline{x})\sum_{j=1}^{n} W_{ij}(x_j - \overline{x})}{\sum_{i}(x_i - \overline{x})^2} \tag{8}$$

4 Results and analysis

4.1 Model estimation and parameter testing

We estimated the urbanization efficiency of 100 cities within the YREB using input-output panel data for the period between 2005 and 2014. As discussed, we applied the SFA model in the form of "per unit area" by formulas (1)–(6). The test results are as follows (Table 1). We assumed that the likelihood ratio test of one-sided effects conforms with a mixed chi-square distribution as well as a technical efficiency term with a significance level of 0.01 and a value of γ of 0.841. Results reveal that technical inefficiencies encompass a large proportion of error terms; the fact that T-test values of parametric coefficients are all above the critical significance level of 0.01 indicates that parameter estimation is accurate at the 99% confidence level. The results of this study therefore demonstrate that it is both appropriate and scientifically valid to introduce a SFA model to estimate urbanization efficiency. In addition, the fact that the η parameter equals 0.061 indicates that the influence of the time factor on $\beta(t)$ decreases at an increasing rate; in other words, urbanization inefficiency components of cities will decrease with time. Calculated output elasticity values for labor, capital, and financial expenditure (i.e., $\beta_1 = 0.171$, $\beta_2 = 0.362$, $\beta_1 = 0.221$) also all suggest that non-agricultural labor force, capital stock, and financial expenditure per unit area will increase by 1%, respectively. These changes will lead to corresponding increases in non-agricultural output per unit area of 0.17%, 0.36%, and 0.22%, respectively.

Table 1 Summary of the SFA production function results

Parameter	Coefficient	Standard deviation	*T*-value
β_0	3.917^{***}	0.282	13.91
β_1	0.171^{***}	0.021	8.25
β_2	0.362^{***}	0.024	15.04
β_3	0.221^{***}	0.016	14.07
σ^2	0.095^{***}	0.011	9.95
γ	0.841^{***}	0.014	62.12
μ	0.566^{***}	0.025	23.03
η	0.061^{***}	0.003	22.39
Log likelihood function	521.31	Likelihood ratio test of one-sided effects	1,494.07

Abbreviations: $*P < 0.1$; $**P < 0.05$; $***P < 0.01$; $\sigma^2 = \sigma_v^2 + \sigma_\mu^2$.

4.2 Urbanization efficiency analysis

We calculated urbanization efficiency values for 110 cities within the YREB between 2005 and 2014 based on our model validity test results. Values for urbanization efficiency were then divided into four categories from high to low (Figure 2) by applying the natural breaks method; this enabled us to analyze the spatiotemporal characteristics of urbanization efficiency within the YREB.

Analytical results show that from a temporal perspective, mean urbanization efficiency values for the YREB in 2005, 2008, 2011, and 2014 were 0.344, 0.407, 0.469, and 0.53, respectively. These data reveal a clear increasing trend at a cumulative rate of 54.07 %. Results also show that four cities had urbanization efficiencies higher than 0.59 (class 1) in 2005, mainly within the Yangtze River Delta region, and that this number had slightly increased to eight in 2008. A total of 19 cities had reached efficiency class 1 by 2009, mainly distributed within the Yangtze River Delta urban agglomeration as well as within the middle reaches of the Yangtze River. Areas characterized by this highest level of efficiency (class 1) increased over time and spread outwards from certain metropolises such as Shanghai and Wuhan; the total number of cities at class 1 in 2014 was 32, 29.09% of the total. However, despite this obvious year-on-year growth rate, many cities still have the potential for upward growth; data show that those characterized by rapid urbanization efficiency growth between 2005 and 2014 were mainly located in Yunnan and Anhui provinces. The cardinality of urbanization efficiency within upper and middle reach cities remained small over the time period of this analysis, further highlighting significant potential for improvement. In contrast, cities characterized by slow urbanization growth efficiency were concentrated in Jiangsu and Zhejiang provinces; indeed, the urbanization efficiency of almost eastern cities has been slower than that of their counterparts elsewhere.

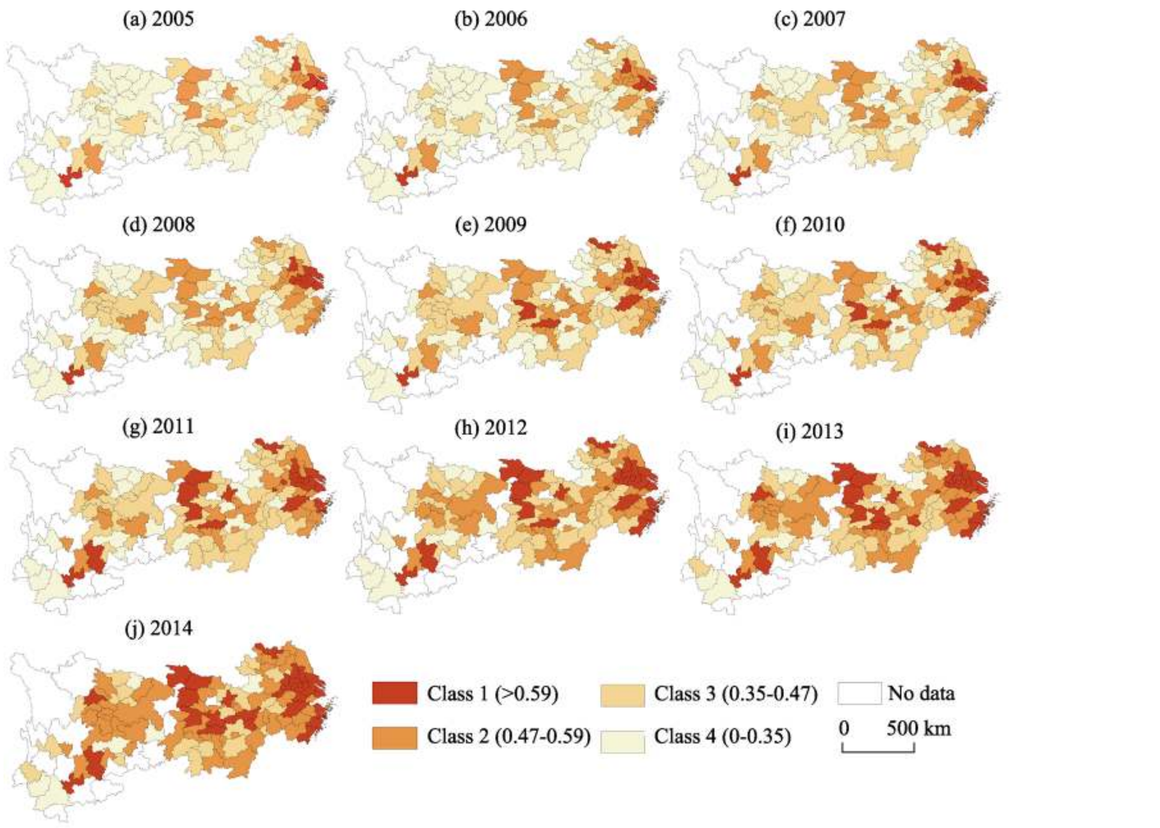

Figure 2 Spatiotemporal patterns of urbanization efficiency in the YREB

Cumulative urbanization efficiency growth rates within the upper, middle, and lower reaches of the YREB between 2005 and 2014 were 65.54%, 56.53% and 45.82%, respectively, a gradual reduction over time. This result is noteworthy because it differs from the conclusions of other recent studies that have addressed the phenomena of economic restructuring and urbanization in China (i.e., increasing regional differences in urbanization efficiency). The indicators (e.g., GDP and urbanization rate) considered in this study suggest that differences in the upper, middle, and lower reaches of the YREB are gradually expanding and while spatial heterogeneity in urbanization efficiency remains significant, distributional differences have tended to widen over time. There are a number of plausible explanations for this trend, including the fact that urbanization efficiency does not include non-observable factors that might influence economic development but rather reflects the inherent contribution due to the investment of land resources in urban development. At the same time, the extensive growth of various kinds of cities has not yet been completely transformational, resulting in a narrowing of discrepancies between the urbanization efficiency values of different agglomerations under sub-optimal conditions despite the effective constraints imposed by geographical conditions and land management policies.

Data show that spatial patterns in urbanization efficiency conform to a “bar-like” distribution, decreasing gradually from the east to the west. These variations do not just encapsulate large intra- and inter-provincial differences, but also occur between the upper, middle, and lower reaches of the YREB. The efficiencies of the eastern cities of Shanghai and Suzhou are the highest within the study area because of the relatively appropriate input of capital and labor allocation within these regions as well as highly intensive land use. The central regions of Wuhan, Changsha, Changde, and Xiangyang are also among the top performers in terms of central region urbanization efficiency; these cities are all regional centers that boast abundant labor, adequate capital, and favorable economic land use benefits. In contrast, the urbanization efficiencies of western cities (i.e., Chengdu and Chongqing) within the YREB lags behind those at the same level in central and eastern regions, suggesting that investment levels for the development of urban stock-building land should be enhanced. The average urbanization efficiencies of all cities across the YREB remain lower than those of the agglomerations within the lower reaches of this river basin, and slightly higher than values for the upper and middle reaches. Similarly, average urbanization efficiency values for cities within the lower reaches of the YREB have always been higher than for their counterparts within the upper and middle reaches; the data in Figure 3 show the results of a coupled

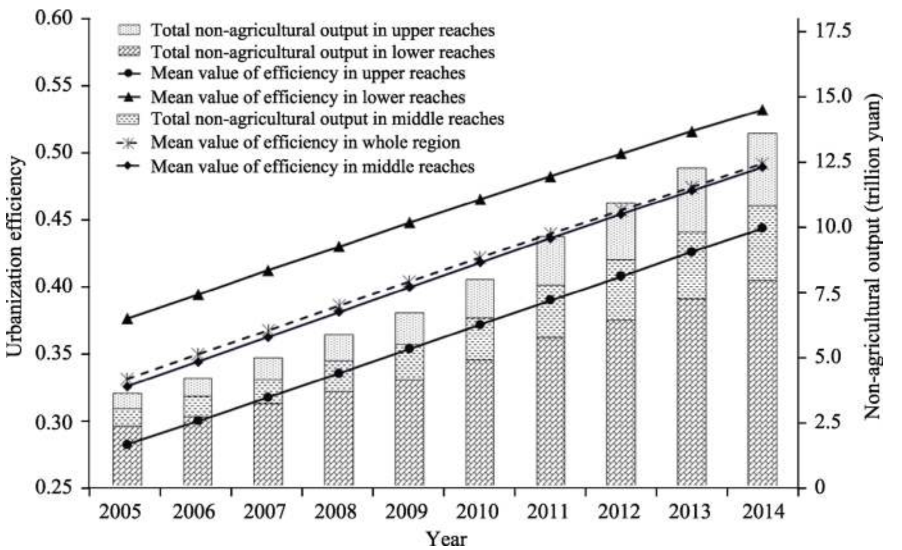

Figure 3 Urbanization efficiency and non-agricultural outputs within the YREB between 2005 and 2014

analysis of the urbanization efficiency and non-agricultural outputs for cities within the upper, middle, and lower reaches of the YREB and show that values are also high for agglomerations with high non-agricultural outputs. Cities at all four levels of efficiency are also seen within the upper and middle reaches of the YREB, a result that reflects poor developmental coordination in these areas. The Yangtze River Delta agglomeration was characterized by the highest level of urbanization efficiency across this region in 2014, attaining a value of 0.624, while those in urban agglomerations of Chengdu and Chongqing ranked second with average values of 0.521. The urban agglomeration within the middle reaches of the Yangtze River had the lowest average efficiency in 2014, just 0.484.

Data reveal a marked overall gap between actual and potential outputs of labor force as well as with capital and construction land inputs in different cities under certain input and technical conditions. This has resulted in spatial differences in urbanization efficiency and the irrational allocation of input elements leading to urban land resource wastage. At the same time, however, it is clear that there is also great potential for improvement in the YREB urbanization efficiency. Future work should further highlight the geospatial morphology of urbanization efficiency as well as its spatial correlation characteristics in order to provide a reference for the construction of a policy system supporting regional development.

4.3 Spatial correlation characteristics of urbanization efficiency

In order to reveal the dominant morphological characteristics of urbanization efficiency within the YREB, we utilized the software GeoDa to reveal spatial patterns within ten years of data and to quantify the relationship between the relative efficiencies of urban units versus their neighbors. A Moran scatterplot for these data is presented in Figure 4; results show that values for Moran's I range between –1 and 1, and that those closer to the former are indicative of stronger negative correlations. Similarly, values closer to 1 indicate a stronger positive correlation, while a value of zero indicates no spatial aggregation. Quadrants I and III in Figure 5 represent "high-high" (H-H) and "low-low" (L-L) agglomerations, respectively, while quadrants II and IV represent "high-low" (H-L) and "low-high" (L-H) outliers. Results show that Moran's I values for urbanization efficiency across the YREB remained above zero and increased year-on-year between 2005 and 2014 indicating a positive spatial correlation between the urbanization efficiency of cities and annual correlation clustering characteristics. Numerous points fall within quadrant I and quadrant III, indicating that the efficiency values of the YREB mainly exhibit H-H and L-L aggregation characteristics. In other words, cities within this region that have similar urbanization efficiencies also have a high probability of spatial clustering. The number of points that fall into quadrant II and quadrant IV is lower than those in the other two, indicating a lower occurrence of significant differences between the urbanization efficiencies of cities and those of their neighbors.

The Moran's I statistic is a global spatial autocorrelation index that reflects the average degree of association between units and their surrounding counterparts. We used local indicators of spatial association to analyze these patterns in detail to determine the locations of spatial agglomerations or anomalies in urbanization efficiency. A LISA cluster map of urbanization efficiencies at the 0.05 significance level is shown in Figure 5; due to the long time series included in this analysis as well as the increasing degree of spatial correlation of urbanization efficiencies across the YREB, we chose to just evaluate changes in local spatial correlation characteristics between 2005 and 2014.

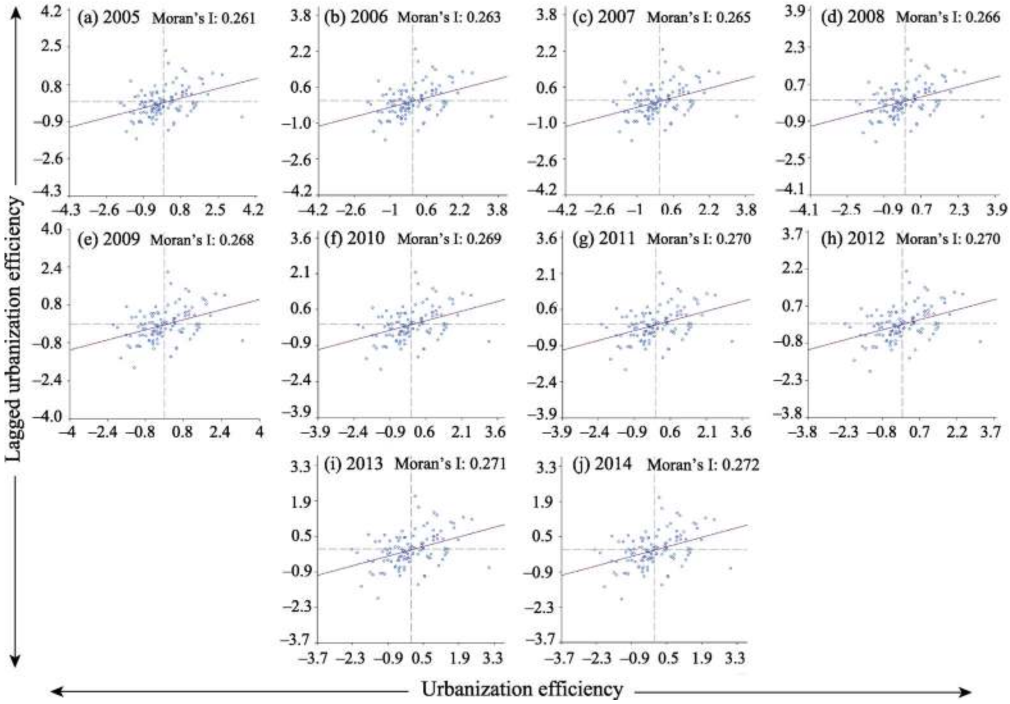

Figure 4 Scatter plot of Moran's *I* values for urbanization efficiency in the YREB between 2005 and 2014

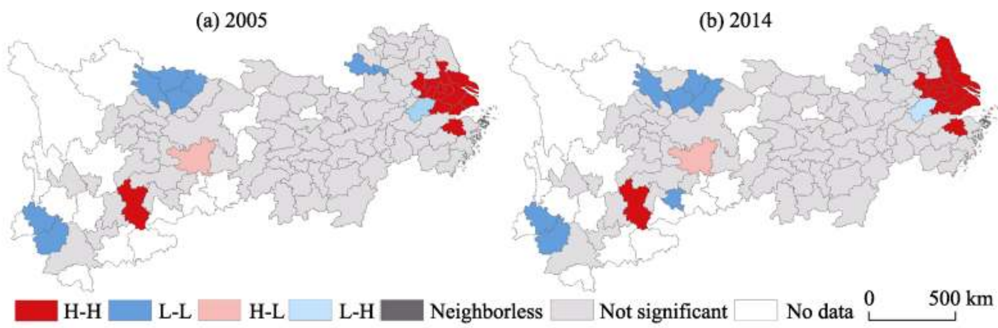

Figure 5 LISA cluster map showing urbanization efficiencies in the YREB between 2005 and 2014

Results show that at the 0.05 significance level, H-H regions mainly encompass the city of Shanghai City as well as Jiangsu and Zhejiang provinces within the lower reaches of the Yangtze River. Urbanization efficiency within the Yangtze River Delta has been raised over time because of excellent infrastructural conditions, surplus capital, a more than sufficient non-agricultural labor force, and a high level of economic development. Indeed, urbanization efficiency values for the cities within this delta and across the surrounding area are consistently high with slight differences, illustrating a significant positive influence across the Yangtze River Delta. It is important to note that an H-H agglomeration area has been known to occur within Yunnan Province over the last ten years; this area includes spatial agglomeration features shared between the city of Kunming (with a high urbanization efficiency value) and surrounding agglomerations, a fact that has often been overlooked in previous analyses. There are several possible explanations for the formation of an H-H agglomeration in this region, including the fact that Kunming and surrounding cities are all reasonably endowed with labor and capital sufficient to promote economic capacity close to the production frontier. In addition, as a demonstration case for the construction of mountain cities within China, the development of Kunming and surrounding agglomerations has relied less on the input of construction land but can still guarantee a certain level of economic outputs. Results also show that the H-H agglomeration range of urbanization efficiency has slightly expanded over time within the lower reaches of the YREB, while no obvious changes have occurred in other areas. Similarly, the range of L-L agglomeration has extended slightly; these areas are located around inland cities within Anhui, Sichuan, and Yunnan provinces and tend to be in relatively poor locations characterized by irrational employment structures, poor industrial economic benefits, and low economic outputs per unit of construction land. There is a positive correlation between the urbanization efficiency of cities and their surrounding agglomerations within this region; H-L agglomeration has occurred in the city of Zunyi in Guizhou Province, for example, where a large difference in efficiency was present between this higher-level agglomeration and its surrounding lower-level counterparts. Similarly, L-H agglomeration has occurred within the city of Xuancheng in Anhui Province, indicating that this region has low urbanization efficiency while surrounding areas have higher values. Data also show that the range of H-L and L-H aggregations have not changed significantly over the last ten years (2005–2014); in general, local correlations in urbanization efficiency within the YREB tend to conform with the phenomenon of “small agglomeration and large dispersion”. This result means that a balanced level of development within the middle and lower reaches of this economic region needs to be further strengthened, and areas of newly-added urban construction land should be strictly controlled in the follow-up YREB development plan to alter the current “sharing the pie” approach. Administrators should also act to positively excavate land for urban stock construction, enhance coordinated development amongst cities, and demonstrate the leading role played by these agglomerations in promoting effective and coordinated YREB development.

5 Discussion and conclusions

We constructed a SFA model in this study that is based on the “per unit area” form and calculated the urbanization efficiency of the YREB over one decade, between 2005 and 2014. Our approach was based on the comprehensive consideration of stochastic impacts and urbanization inefficiencies in order to establish a spatial correlation model to make long-term geospatial morphological representation of urbanization efficiency, present new findings, and enrich current empirical studies of this process within the YREB.

The results of this analysis clearly demonstrate that our SFA approach can be validated by testing both its parameters and the overall model, proving the feasibility of our research methodology. Indeed, compared with the use of non-parametric models, the effects of random impact (ν_{it}) and technical inefficiency (μ_{it}) are fully considered in our approach to reduce estimation errors and to enable an absolute value of urbanization efficiency to be calculated which is both more objective and inter-regionally comparable. Second, results show that the urbanization efficiencies of 110 Chinese cities within the YREB increased year-on-year between 2005 and 2014 at a cumulative average rate of 54.07%. A great deal of potential room for improvement nevertheless remains as cities with lower urbanization efficiencies tend to also have faster growth rates. We also show that urbanization efficiency gradually decreases from east to west and that this trend possesses “bar-like” morphological characteristics. Significant differences are also present between the upper and lower reaches of the YREB in terms of both intra- and inter-provincial urbanization efficiencies. Third, we show that Moran’s *I* values for urbanization efficiency are spatially correlated and that clustering characteristics have increased year-on-year. The LISA cluster map generated as part of this analysis reveals “small agglomeration and large dispersion” morphological characteristics; the degree of overall agglomeration amongst cities remains low while local characteristics have not changed significantly from a temporal perspective.

Data show that overall differences in urbanization efficiency have been gradually shrinking within the YREB over the last ten years (2005–2014). This conclusion is important because it is different from the findings of previous studies that have addressed Chinese economic restructuring and urbanization. It is clear that China has experienced marked differences in urbanization efficiency over recent years; indeed, from the perspective of economic indicators (e.g., GDP), discrepancies within the upper, middle, and lower reaches of the YREB have been gradually expanding. Although the spatial heterogeneity of urbanization efficiency remains significant, distributional differences have not been widened further under basic geographical conditions and land management policy constraints. Similarly, the phenomena of H-H aggregation in Kunming and its surrounding cities, which have high urbanization efficiency in Yunnan Province for a long time, also has not been noted previously. In addition to a significant optimized labor force and high allocation of capital, the city of Kunming and surrounds (the main “town mountain” areas of southwestern China) tend to have higher outputs per unit area compared to other regions, factors that have all promoted the formation of H-H agglomeration areas alongside limited urban expansion.

The YREB has key theoretical and practical research value as it is the first and most important example of an innovation-driven region within China that comprises a belt of coordinated development for national ecological civilization construction. We have therefore attempted to scientifically evaluate levels of urbanization efficiency within this region and reveal their geospatial morphological characteristics over the decade between 2005 and 2014. The efficiency of urban construction land, ecological elements, and the productivity of cultivated land are all essential contents of regional coordinated development in this context, in addition to urbanization efficiency. The research results and related conclusions presented in this paper highlight the trade-offs between these three types of efficiency and have enabled us to clarify the mechanisms that underlie their spatiotemporal couplings. This research therefore presents a comprehensive reference analysis that will facilitate future land use decision-making, optimal allocation, and balanced regional development.

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