

Assessment of land use efficiency under carbon emission constraint: An empirical study of Pearl River Delta, China

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Abstract. Land use efficiency (LUE) is the comprehensive reflection of the input and output in the process of land resource utilization. However, carbon emission during this process will lead to a decrease in LUE. It is necessary to evaluate LUE under carbon emission constraint for urban sustainable development. Although the carbon emission and efficiency of land use have been extensively studied, few researches considered the uncertainties in carbon emissions when evaluating LUE. In this study, a comprehensive assessment model of LUE was proposed. Interval parameter is introduced to a super efficiency slack-based measurement (SBM) model, leading to an assessment method of interval LUE, which can analyze the impact of carbon emission on LUE. A case study in Pearl River Delta (PRD) was conducted from 2005 ~2020. Results revealed that the overall carbon emissions of land use in the PRD increased significantly during the study period. Particularly, Zhuhai and Huizhou had a relatively larger increase. In terms of the total amount of carbon emission, it was relatively higher in Guangzhou and Shenzhen than the other cities in the region. Taking the carbon emission into account, the LUE of PRD still improved, especially in Shenzhen, Guangzhou, Foshan, and Jiangmen. However, an opposite trend was found for the LUE of Huizhou and Zhaoqing, changing from effective to ineffective. The LUE of Zhuhai and Zhongshan was always effective, while that of Dongguan was ineffective during the study period. In conclusion, the assessment method of LUE considering carbon emissions should be used to promote the efficient use of land resource. The results of the case study in this research can also provide decision-making reference for PRD and other urban agglomerations to improve LUE.

Keywords: Land use efficiency. Carbon emission. Interval uncertainty. Super efficiency SBM model. Pearl River Delta.

1. Introduction

Land resource is the spatial carrier of urbanization and human social activities [1,2]. With the rapid urbanization, population and economy increases, and urban land greatly expands [3,4]. In this process, great changes have taken place, such as spatial sprawl and inefficient land use [5]. At the same time, carbon emission in land use process increased, which has decreased land use efficiency (LUE) [6,7]. These changes greatly affect the urban sustainable development. Therefore, how to scientifically evaluate LUE considering carbon emission is crucial for the effective use of land resource, generating new land use modes and promoting sustainable development of cities.

In the previous research, many methods were proposed to evaluate land use carbon emissions [8-10]. Among them, the carbon emission factor method combined with IPCC inventory guidelines was commonly used, due to the advantages of small data demand, simple operation, and high effectiveness. In this method, land use carbon emissions were divided into direct and indirect emissions [11]. Specifically, the direct emission is usually calculated according to the carbon emission intensity and land area, while the indirect emission is calculated according to the consumption and carbon emission coefficient of energy [12]. However, there are differences in carbon emission factors in different regions. How to consider the impact of such differences on carbon emission needs further exploration.

Concurrently, many studies have focused on evaluating LUE, which can help plan land use and deal with environmental issues [13-15]. In terms of the research methods, super efficiency slack-based measurement (SBM) model can achieve reasonable evaluation for the problems of non-radial and non-angular because it takes into account the slack in input-output, and further analyzes decision unit with LUE larger than 1 [16,17]. Thus, it is widely used in LUE research [18]. Generally, SBM and its improved models were based on the input-output principle. The input indicators were usually selected from land, capital and labor, while the output indicators were usually selected from benefits of economy, society and ecology [19,20]. Although many valuable research results have been obtained, more researchers concerned the negative environmental impacts in the land use process. Particularly, land use carbon emission remains to be further considered. In addition, there are many uncertainties in the parameters used in the evaluation model of LUE. The impacts of these uncertain parameters on LUE results need to be further explored.

To address the gap of existing researches, we propose the comprehensive assessment model of LUE through introducing interval parameter to super efficiency SBM model to evaluate interval LUE considering carbon emission. The carbon emission factor method was first used to construct assessment method of land use carbon emission. Considering the difference of carbon emission factor in different regions, interval parameter was introduced to the assessment method to evaluate the interval carbon emissions. Then, the evaluation index system of LUE was established. Considering the impact of interval carbon emissions on LUE, we proposed a comprehensive assessment model of LUE through introducing interval carbon emission as an undesirable output to the super efficiency SBM model, to evaluate the interval LUE. The Pearl River Delta (PRD) was selected to conduct the empirical study. The application of the model can provide technical support for improving LUE, and the evaluation results can also help provide decision-making support for the land resource management of PRD and other urban agglomerations.

2. Materials and methods

2.1 Calculation of land use carbon emission

Construction land and cropland are considered as the main carbon sources in this research. Concurrently, forest land, water bodies, grassland and unused land are considered as the main carbon sinks. The carbon emissions generated by the activities associated with construction land and cropland, as well as the absorptions of CO₂ from the atmosphere by the four sinks, are calculated through carbon emission factor method. In this process, the interval uncertainties are considered. The overall carbon emissions of land use are the sum of carbon emission and carbon absorption. The formula is given as follows:

$$E_1^{\pm} = \sum_{m=1}^M B_m \times \omega_m \times \mu_m^{\pm} + \theta^{\pm} \times C \quad (1)$$

$$E_2^{\pm} = \sum_{j=1}^J \varphi_j^{\pm} \times A_j \quad (2)$$

where, E_1^{\pm} is the interval carbon emission from carbon sources. B_m is the consumption of energy type m . ω_m is the standard coal conversion coefficient of energy type m . μ_m^{\pm} is the interval carbon emission coefficient of energy type m . It is considered in this research that the carbon emissions of construction land mainly come from energy consumption. θ^{\pm} is the interval carbon emission coefficient of cropland. C is the cropland area. E_2^{\pm} is the interval carbon absorption. j is the land use type of carbon sinks. φ_j^{\pm} is the carbon sink coefficient of land use type j [21]. A_j is the area of land use type j .

2.2 Assessment of land use efficiency

An interval super efficiency SBM model with undesirable output is proposed in this research to evaluate the LUE. An evaluation index system is built first. The input factors are land use area, employment and fixed capital stock of secondary and tertiary industries per area. The desirable output is added value of secondary and tertiary industries per area. In addition, considering the impact of interval carbon emission on LUE, the interval carbon emission was introduced to the super efficiency SBM model as an undesirable output. The general framework of the model is shown as follow.

$$\text{in}\rho = \frac{1 + \frac{1}{e} \sum_{i=1}^e \frac{s_i^-}{x_{io}}}{1 - \frac{1}{r_1 + r_2} (\sum_{r=1}^{r_1} \frac{s_r^+}{y_{ro}} + \sum_{t=1}^{r_2} \frac{s_t^-}{[y_{to}^L, y_{to}^U]})} \#(3)$$

$$\text{s. t. } \sum_{j=1, j \neq o}^u x_{ij} \times \lambda_j - s_i^- \leq x_{io} \#(4)$$

$$\sum_{j=1, j \neq o}^u y_{rj} \times \lambda_j + s_r^+ \geq y_{ro} \#(5)$$

$$\sum_{j=1, j \neq o}^u [y_{tj}^L, y_{tj}^U] \times \lambda_j + s_t^- \leq [y_{to}^L, y_{to}^U] \#(6)$$

$$\lambda, x^-, y^-, y^+ \geq 0 \#(7)$$

$$i = 1, 2, 3, \dots, e. r = 1, 2, 3, \dots, r_1. t = 1, 2, 3, \dots, r_2 \#(8)$$

where s. t. is the set of constraints. λ is the weight vector. x_{io} and y_{ro} are input and desirable output of decision-making units (DMUs) o, respectively. y_{to}^L , and y_{to}^U are upper and lower boundary of undesirable output of DMUs o, respectively. s_i^- , s_r^+ , and s_t^- are the slack of input, desirable output, and undesirable output, respectively. ρ is the value of LUE of DMUs. When $s_i^- = 0$, $s_r^+ = 0$, $s_t^- = 0$, $\rho \geq 1$, DMUs is efficient. e, r_1 , and r_2 are number of factors of input, desirable output, and undesirable output, respectively.

2.3 Study area

The PRD urban agglomeration (21° 17.6 N-23° 55.9 N, 111° 59.7 E-115° 25.3 E) is located in the southern part of Guangdong Province, China (Figure 1). It comprises 9 cities, with Guangzhou and Shenzhen as the core cities. The other seven cities include Dongguan, Foshan, Zhaoqing, Zhuhai, Jiangmen, Zhongshan, and Huizhou. In 2020, the land use area of the PRD reached 54.34×10^5 ha, accounting for 30.11% of the land use area of the Guangdong Province. The feature of land use structure in PRD is dominated by non-construction land, which accounts for 85.11% of the its total land use area. However, the high concentration of socio-economic activities has led to a dramatic change in land use structure, leading to rapid increase in land use carbon emissions. These changes greatly affected the land resource utilization in the PRD. Therefore, the PRD is a typical research area for LUE, which has significant importance for promoting the efficient use of land resources and high-quality development of the region.

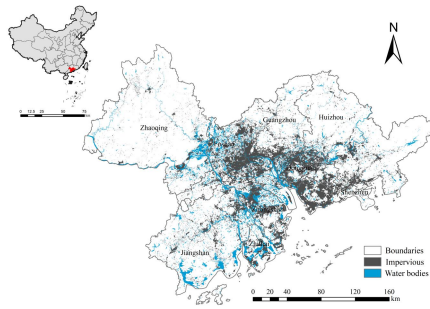


Fig. 1 Geographical location in the study area

2.4 Data sources

The sources of the geographical and social economic data used in this research is shown in Table 1.

Table 1. Data information and sources

Primary category	Secondary category	Year	Source
Geographical data	Land use data	2005, 2010, 2015, 2020	Resources and Environmental Science and Data Center, Chinese Academy of Sciences (30m) (https://www.resdc.cn/)
	Administrative boundary	2020	National geographic information public service platform (https://cloudcenter.tianditu.gov.cn/administrativeDivision/)
Social economic data	Expenditure for energy saving	2005, 2010, 2015, 2020	Shenzhen city statistical yearbook (https://tjj.sz.gov.cn/zwgk/zfxxgkml/tjsj/tjnj/index.html)
	The coefficient of carbon emission		China products carbon footprint factors database (https://lca.cityghg.com/)
	Added value, employment and fixed capital stock of secondary and tertiary industries	2005, 2010, 2015, 2020	Statistical yearbook (http://tjj.sz.gov.cn/zwgk/zfxxgkml/tjsj/tjnj/)

3. Results

3.1 Spatiotemporal characteristic of land use carbon emission

During the study period, the overall carbon emissions of land use in the PRD increased by $[1398.90, 4673.90] \times 10^4$ t, with a growth rate of $[44.67\%, 50.41\%]$ (Figure 2). However, the carbon emission of PRD decreased from $[3736.80, 12728.8] \times 10^4$ t in 2010 to $[3278.70, 12236.00] \times 10^4$ t in 2015. The development actions of energy saving, emission reduction, and low-carbon proposed in 2014 may be the important reason for the reduction of carbon emissions. In terms of the spatial characteristics, Shenzhen and Guangzhou, as the core of the PRD, had a small increase in carbon emission, which was related to the low-carbon development mode. However, the total carbon emissions in these two cities were much higher than the other cities in the region. The cities with the large increases were Zhuhai and Huizhou, which increased by $[70.50, 692.50] \times 10^4$ t and $[1890.20, 3034.40] \times 10^4$ t, respectively. On the contrary, the Dongguan City exhibited greater decrease in total carbon emission, which reached $[140.50, 1915.90] \times 10^4$ t in 2020. This also means that the actions of energy saving and emission reduction of Dongguan made new breakthroughs. In the past decade, the energy structure of Dongguan has been continuously

optimized, and coal consumption has maintained a downward trend, reducing by 40.3%. At the same time, energy consumption per unit of added value of industrial enterprises decreased year by year, with an average annual decline of 7.5%.

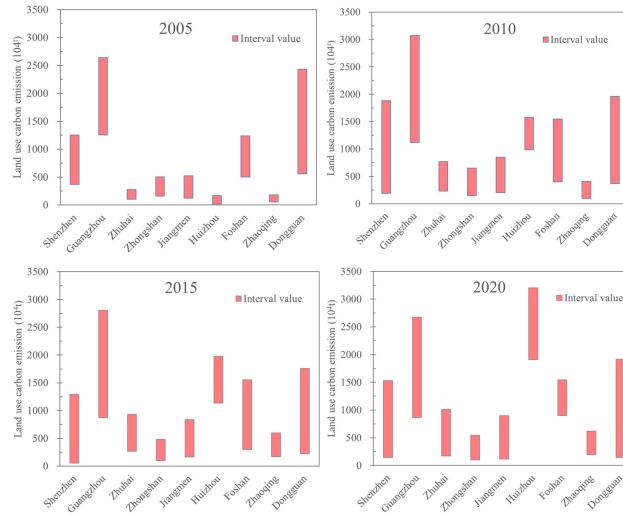


Fig. 2 Interval carbon emissions of different cities in different periods

3.2 Analysis of land use green efficiency

The LUE of PRD improved from ineffective in 2005 to effective in 2020. Meanwhile, there was a significant difference in the changes of LUE among the cities in PRD. Specifically, the LUE of Shenzhen, Guangzhou, Foshan, and Jiangmen greatly improved during the study period. The efficiency values respectively increased from [0.4916, 0.5129], [0.3957, 0.4064], [0.5802, 0.5997], and [0.7968, 0.8195] to [1.2739, 1.2759], [1.0130, 1.0333], [1.0663, 1.0665], and [0.9707, 1.0045] indicating the land use changed from ineffective to effective or basically effective (Figure 3). However, an opposite trend was found for the LUE in Huizhou and Zhaoqing, with the efficiency values decreasing from [1.1574, 1.2218] and [1.0911, 1.0941] to [0.5174, 0.5289] and [0.6343, 0.6603], respectively. In addition, although the LUE of Zhuhai and Zhongshan decreased, the LUE of these cities were still effective in 2020. Only the LUE in Dongguan City was always ineffective during the study period, with the efficiency values of [0.3599, 0.3633], [0.3593, 0.3608], [0.4062, 0.4586], and [0.3896, 0.4252], respectively.

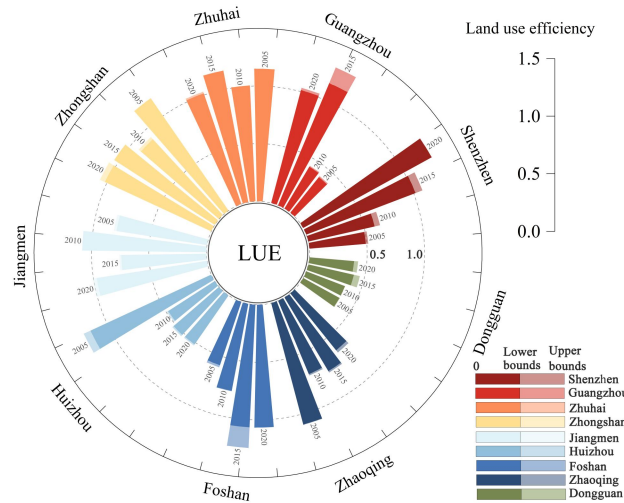


Fig. 3 Land use efficiency of different cities in different periods

4. Conclusions

The inefficient expansion of land has made the improvement of LUE a significant challenge to the high-quality development. Scientific evaluation of LUE helps verify the improvement space of land resource utilization and provide a data base for promoting sustainable urban development. In this study, a comprehensive assessment model of LUE was proposed. In the model, the interval carbon emissions were calculated and introduced to the super efficiency SBM model as the undesirable output. The model was then used to evaluate the interval LUE of PRD in 2005, 2010, 2015, and 2020. The results showed that, during the study period, overall carbon emissions of land use in the PRD increased significantly. The total carbon emission of Guangzhou and Shenzhen were relatively higher than other cities, and there was a small increase during the 15-year study period. The cities with the larger increase in carbon emissions were Zhuhai and Huizhou, while the carbon emissions of Dongguan greatly decreased. Over the study period, the LUE in PRD improved, especially in Shenzhen, Guangzhou, and Foshan. However, the LUE of Dongguan, Huizhou, and Zhaoqing exhibited decreasing trend, achieve ineffective in 2020.

These findings indicated more attention should be paid to the cities with larger increases and total amounts of carbon emissions, such as Huizhou, Zhuhai, Guangzhou and Shenzhen. It is also worth noting that the reasons for the reduction of carbon emissions in Dongguan are worth exploring, which can help analyze the reduction potential of carbon emission and provide the low-carbon development paths of the PRD urban agglomerations. In addition, to enhance overall utilization of land resources of PRD, the LUE of Huizhou, Zhaoqing, and Dongguan Cities should be given priority. These cities have relatively higher potential for improving LUE. Specially, these cities should promote the concept of intensive and economical land use and refer to the development of core cities such as Shenzhen and Guangzhou by learning their experience of improving LUE, while considering the development of the local and the status of land resources.

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References

- [1] L. Zhang, L. Zhang, et al. Evaluating urban land use efficiency with interacting criteria: An empirical study of cities in Jiangsu China. *Land Use Policy*. 2020. 90(C): 104292-104292
- [2] O. Yifu, B. Zhikang, et al. Land-use carbon emissions and built environment characteristics: A city-level quantitative analysis in emerging economies. *Land Use Policy*. 2024. 137: 107019
- [3] C. Shu, H. Xie, et al. Is Urban Land Development Driven by Economic Development or Fiscal Revenue Stimuli in China? *Land Use Policy*. 2018. 77: 107-115
- [4] K. Wang, Z. Li, et al. Evaluating and simulating the impacts of land use patterns on carbon emissions in coal resource-based regions: A case study of shanxi province, China. *Journal of Cleaner Production*. 2024. 458: 142494
- [5] Y. Fu, T. Zhou, et al. Evaluating efficiency and order of urban land use structure: An empirical study of cities in Jiangsu, China. *Journal of Cleaner Production*. 2021. 283: 124638
- [6] H. Wu, S. Fang, et al. Exploring the impact of urban form on urban land use efficiency under low-carbon emission constraints: A case study in China's Yellow River Basin. *Journal of Environmental Management*. 2022. 311: 114866
- [7] J. Huang, W. Han, et al. The decoupling relationship between land use efficiency and carbon emissions in China: An analysis using the Socio-Ecological Systems (SES) framework. *Land Use Policy*. 2024. 138: 107055

- [8] Y. Fei, Z. Huasheng, et al. The Impact of Multiple Dimensions of Urbanization on CO₂ Emissions: A Spatial and Threshold Analysis of Panel Data on China's Prefecture-Level Cities. *Sustainable Cities and Society*. 2021. 103113
- [9] Y. Yuan, X. Chuai, et al. Carbon emissions from land use in Jiangsu, China, and analysis of the regional interactions. *Environmental Science and Pollution Research*. 2022. 29(29): 1-17
- [10] J. Li, L. Jiao, et al. Spatial disequilibrium and influencing factors of carbon emission intensity of construction land in China. *Journal of Cleaner Production*. 2023. 396: 136464
- [11] Z. Yabo, M. Shifa, et al. Examining the Effects of Land Use on Carbon Emissions: Evidence from Pearl River Delta. *International Journal of Environmental Research and Public Health*. 2021. 18(7): 3623-3623
- [12] W. Cao, X. Yuan. Region-county characteristic of spatial-temporal evolution and influencing factor on land use-related CO₂ emissions in Chongqing of China, 1997–2015. *Journal of Cleaner Production*. 2019. 231: 619-632
- [13] Y. Zhou, Y. Chen, et al. Assessing Efficiency of Urban Land Utilisation under Environmental Constraints in Yangtze River Delta, China. *International Journal of Environmental Research and Public Health*. 2021. 18(23): 12634
- [14] T. Ding, J. Yang, et al. Land use efficiency and technology gaps of urban agglomerations in China: An extended non-radial meta-frontier approach. *Socio-Economic Planning Sciences*. 2022. 79: 101090
- [15] H. Tingting, S. Haipeng. A novel approach to assess the urban land-use efficiency of 767 resource-based cities in China. *Ecological Indicators*. 2023. 151: 110298
- [16] L. Jianfei, C. Songlin. Research on the land-use efficiency and driving factors of urban construction in Fujian province under environmental constraints. *Journal of Natural Resources*. 2020. 35(12): 2862-2874
- [17] L. Qiaowen, L. Huiting. Study on Green Utilization Efficiency of Urban Land in Yangtze River Delta. *Sustainability*. 2021. 13(21): 11907-11907
- [18] H. Jiang. Spatial-temporal differences of industrial land use efficiency and its influencing factors for China's central region: Analyzed by SBM model. *Environmental Technology & Innovation*. 2021. 22: 101489
- [19] X. Zhu, P. Zhang, et al. Measuring the efficiency and driving factors of urban land use based on the DEA method and the PLS-SEM model—A case study of 35 large and medium-sized cities in China. *Sustainable Cities and Society*. 2019. 50: 101646
- [20] Y. Pang, X. Wang. Land-Use Efficiency in Shandong (China): Empirical Analysis Based on a Super-SBM Model. *Sustainability*. 2020. 12(24): 10618
- [21] L. M. A. Bettencourt, J. Gonzales. Science and Practice for Thriving Cities. *Innovations: Technology, Governance, Globalization*. 2016. 11(1-2): 20-30