Research on eco-efficiency evaluation and influencing factors of Five Urban Agglomerations in China

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Abstract This research uses the SBM-DEA model to measure the economic efficiency and eco-efficiency of the cities in China's five major urban agglomerations of the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration, Middle Reaches of the Yangtze River, the Pearl River Delta urban agglomeration and the Chengdu-Chongqing urban agglomeration in 2007-2016, and further analyzes the factors affecting eco-efficiency by using the Tobit model. The results show that: (1) The economic efficiency of the five urban agglomerations is at a medium to upper level. The economic efficiency among urban agglomerations still shows some differences, but the efficiency gap has shrunk. (2) The eco-efficiency of the five urban agglomerations is slightly lower than the economic efficiency, and the difference of the two efficiencies has significantly expanded after 2011. Eco-efficiency still shows significant regional difference among urban agglomerations. The nuclear density curves of five urban agglomerations show different distribution states and development trends. Environmental pollution is the determining factor for the eco-efficiency of the five urban agglomerations. (3) From the perspective of factors affecting eco-efficiency, economic development, industrial structure, investment in science and technology, environmental regulation, and population size have different effects on the overall and different urban agglomerations.

1. Introduction
Duo to the close economic relationship and the highly integrated spatial organization form, the urban agglomeration has become an important support for China’s new industrialization and new urbanization. With the advantage of superior geographical location and reasonable policy orientation, China has cultivated a number of typical urban agglomerations with high levels of openness and economic development on the main economic development axes along the coast and the river. National New-type Urbanization Plan (2014-2020) positions the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration, the Pearl River Delta urban agglomeration, Middle Reaches of the Yangtze River and the Chengdu-Chongqing urban agglomeration as national-level urban agglomerations. It will play a more important role in the new pattern of urban space in China and is expected to become a new growth pole for China's economic development.

However, as the urban agglomeration covers a wider space and the growing population size in the past development process, the problems of unbalanced economic growth and unsustainable development are becoming increasingly serious. The irrational urban industrial structure and extensive development models have caused the urban environment to deteriorate and pollution emissions to remain at a high level. At the same time, due to the significant spillover effects of the environmental pollution and imperfect regional cooperation mechanisms, pollution in a certain city will become a common environmental risk in other cities within an urban agglomeration, such as the smog pollution
that has occurred in the Beijing-Tianjin-Hebei urban agglomeration recent years. Therefore, the “Environmental Air Quality Standards” and the “13th Five-Year Plan” view the Beijing-Tianjin-Hebei and surrounding areas, the Yangtze River Delta, the Pearl River Delta and other regions as the key monitoring scope, in order to deepen the joint prevention and control of the regional joint defense and establish a normalized regional cooperation mechanism. And the regional organization of urban agglomeration can play a more important role to solve outstanding regional environmental problems.

As a method to measure the coordinated development of economic activity output and environmental impact, eco-efficiency provides an effective tool for assessing the green development level of urban agglomerations and analyzing green development factors. Accordingly, the following arrangements are as follows: the second part is the literature review. The third part introduces the model method and data source used in the article. The fourth part uses the SBM-DEA model to measure the economic efficiency and eco-efficiency of the five major urban agglomerations in China respectively and analyze the regional differences from different perspectives. The fifth part uses the Tobit model to investigate the influencing factors of eco-efficiency from the perspectives of economic development, industrial structure environmental regulation and so on. The six parts are conclusions, and propose policy recommendations to promote eco-efficiency in terms of socio-economic factors such as economic development orientation, environmental policy formulation, opening up, and urban population agglomeration.

2. Literature review

Eco-efficiency can be traced back to the concept of environmental efficiency proposed in around 1970[1]. As an important tool for analyzing sustainable development, eco-efficiency is based on the combined results of economic benefits and environmental impact directly[2,3]. It reveals the empirical relationship between economic activities and environmental impacts or environmental costs[4]. In early studies, eco-efficiency was usually expressed by the ration of value of goods and services to the environmental impacts produced, which exams the level of efficiency of economic activities after integrating ecosystems and environmental impacts[5,6]. The World Business Council for Sustainable Development (WBSCD) points out that the core connotation of eco-efficiency is to provide high-quality goods and services that meet human needs, and to reduce the ecological impact and resource intensity gradually in the production cycle to the same as the Earth's carrying capacity Level[7]. To sum up, eco-efficiency means to create greater market value with minimal resource input and minimum environmental impact, and highlight the quality and efficiency of economic development[8]. Optimizing resource utilization, reducing environmental impact and increasing market value are the three goals pursued by eco-efficiency improvement.

In the quantitative study of eco-efficiency, the use of a single ratio indicator to comprehensively quantify the eco-efficiency of a specific region needs the environmental impact indicator with a high degree of aggregation[9]. However, the existing researches still have no unified conclusion on how to establish the index weight level to reach the aggregation process and measure the regional eco-efficiency including more dimensional indicator system[10]. Data envelopment analysis and Stochastic Frontier Analysis are two common tools for measuring eco-efficiency by objective weighting based on multi-index system using production possibility boundary theory. SFA uses regression analysis to estimate the input-output relationship, but due to the limitation of single output items, it brings a lot of inconvenience to the analysis of multi-output efficiency. The non-parametric DEA model has a series of advantages in measuring eco-efficiency without data dimension processing, no specific function form, no index weight assumption, and has been widely promoted and applied in the multi-index evaluation of eco-efficiency in recent years.

Considering that the economic development of developing countries in the process of industrialization is realized by huge energy consumption and pollution emissions, neglecting the negative effects of environmental harmful by-products may lead to deviations in the measurement of eco-efficiency and poor policy effects. Different from traditional economic efficiency measurement, eco-efficiency incorporates environmental impact factors on the basis of original capital, labor, land,
energy and economic output, reflecting the value of products and services, while also focusing on reducing environmental negative effects and improving energy efficiency. As one of the key indicators for examining eco-efficiency, how to integrate environmental factors into the research framework is especially critical for measuring eco-efficiency. There are three different methods for dealing with pollutant emissions in the existing literature: the first one is incorporate environmental pollution indicators as input factors into the measurement model\textsuperscript{[11,13]} The second one converts environmental pollution indicators into expected outputs\textsuperscript{[14,15]}. The third directly treats pollutants as undesired output\textsuperscript{[16,17]}. The first two methods are contrary to the actual production process, causing deviations in the results\textsuperscript{[18]} The SBM-DEA model proposed by Tone can effectively avoid the deviation of the results measured by the traditional DEA model due to the radial and angular problems, and incorporate the undesired output items of environmental pollutants, so as to obtain more reliable eco-efficiency results\textsuperscript{[19,20]}.

Since eco-efficiency provides effective information on both dimensions of economic well-being and environmental impact, scholars can provide quantitative information on comprehensive assessments of economic and environmental change for policy by measuring the eco-efficiency of specific firms\textsuperscript{[21,22]}, industry sectors\textsuperscript{[23,24]}, regions\textsuperscript{[25,26]} or countries\textsuperscript{[27,28]}. By now, many scholars have used different models to examine China’s ecological efficiency from various regional levels. In the provincial perspective, Zhang et al. used the SBM-DEA model to assess the regional eco-efficiency of various provinces in China, and used hierarchical clustering analysis to examine the socio-economic factors of ecological efficiency improvement\textsuperscript{[29]}. Huang et al. used the extended DEA model to find China’s provincial eco-efficiency showed a V-shaped trend, and each region also showed huge differences\textsuperscript{[30]}. In the research of provinces, the spatial pattern of eco-efficiency is similar to the economic spatial pattern, showing a trend of decreasing from the coast to the inland and from the east to the central and western regions\textsuperscript{[31-33]}. However, the uneven development of eco-efficiency in different cities is difficult to reflect in the efficiency measurement at the provincial level. At the city level, scholars have confirmed that the urban eco-efficiency of China shows significant spatial agglomeration characteristics in terms of spatial distribution, regardless of the study of national prefecture-level cities or sub-regions\textsuperscript{[34]}. Chen et al. and Zhou et al. used the super-efficiency model to examine the Yangtze River Economic Belt and the cities of Guangdong Province\textsuperscript{[35,36]}. Other scholars started from a single urban agglomeration to examine the regional distribution and development of urban eco-efficiency within the group\textsuperscript{[37,38]}. The efficiency analysis at the city level has also gradually moved closer to the urban agglomeration.

Based on the existing research, this paper improves and deepens the research from the following aspects. First, we will get rid of the limitations of administrative district, and take multiple urban agglomerations at different stages of development as research objects. Investigate the difference in eco-efficiency of each urban agglomeration as a single entity and the overall effect of the urban agglomeration. Second, this study quantified the economic efficiency and eco-efficiency of urban agglomerations respectively, and compares the numerical results of the two to reveal the specific degree of loss caused by environmental pollution to different urban agglomerations. Third, this study identifies the causes of differences in eco-efficiency from the perspective of input and output, and examines measures and means to improve eco-efficiency from the perspective of socio-economic factors, so as to achieve the best development situation for the urban agglomeration without reducing long-term sustainability.

3. Method and data

3.1. SBM-DEA model

The existing research mainly uses Data Envelopment Analysis (DEA) to measure the eco-efficiency level of different regions by constructing a multi-input and multi-output indicator system. Based on the traditional DEA model, the SBM-DEA model proposed by Tone can effectively avoid the deviation of the results measured by the traditional DEA model due to the radial problems, and incorporate the
undesired output of the ecological environment pollutants to get more reliable eco-efficiency results. The SBM-DEA model can be written as follows:

$$\rho^* = \min \left( \frac{1}{m} \sum_{i=1}^{m} \frac{S^i}{x^i} \right)$$

$$1 + \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{m} \frac{s^g_r}{y^g_r} + \sum_{r=1}^{m} \frac{s^b_r}{y^b_r} \right)$$

s. t. $$x = X \lambda + s_0$$

$$y^g = Y^g \lambda - s^g_0$$

$$y^b = Y^b \lambda + s^b_0$$

$$s^g_0 \geq 0, \quad s^b_0 \geq 0$$

In the SBM-DEA model, $$\rho^*$$ is the objective function and the eco-efficiency. When the value is 1, it indicates that the urban eco-efficiency reaches the level of production front. When the value is less than 1, it indicates that the eco-efficiency of the city still has some space for improvement. M is the number of input factors, $$S^i_1$$ representing expected output, $$S^i_2$$ representing undesired output. $$S^b_0$$ indicating that the city has excessive input, $$s^b_0$$ indicating that city’s undesired output is excessive, $$s^g_0$$ indicating that the city’s expected output is short.

3.2. Tobit mode

Since the urban eco-efficiency value is between 0 and 1, the tobit model can be used to analyze the direction and intensity of the factors affecting urban eco-efficiency. The tobit model is a restricted dependent variable model whose form is as follows:

$$Y = \begin{cases} Y^* = \alpha + \beta X + \varepsilon, & Y^* > a \\ 0, & Y^* \leq a \end{cases}$$

Where X is the independent variable, Y is the truncation dependent variable, and a is the intercept term.

3.3. Study area and data sources

This paper selects five major urban agglomerations that are the Beijing-Tianjin-Hebei urban agglomeration (BTH), the Yangtze River Delta urban agglomeration (YRD), the Pearl River Delta urban agglomeration (PRD), the Middle Reaches of the Yangtze River (MRYR), and the Chengdu-Chongqing urban agglomeration (CC).

This study uses the SBM-DEA model to measure the economic efficiency and eco-efficiency of 92 cities in five major urban agglomerations. The data of the eco-efficiency indicator system and its influencing factors are derived from the 2008-2017 China Urban Statistical Yearbook, the China Urban Construction Statistical Yearbook and the statistical yearbooks of the corresponding provinces and cities. The input and output indicators of eco-efficiency are as follows:

In terms of input indicators, the total investment in fixed assets of the whole society is taken as the capital investment of the city. The number of employees at the end of each year is taken as the indicator of urban labor input, and the area of urban construction land is used as the land input index of the city. The entropy method is used to integrate the whole society’s electricity consumption and total quantity of water supply as the city’s resource input indicators.

In terms of output indicators, the GDP of urban areas is the expected output of the city. Wastewater, sulfur dioxide and soot emissions generated in industrial ecological processes are integrated by
entropy method as an undesired output indicator of the city.

A statistical description of the raw data of input and output indicators is shown in Table 1.

Table 1 Descriptive statistics for the variables

| Category | Variable | Unit | Mean | Std.Dev | Minimum | Maximum |
|----------|----------|------|------|---------|----------|---------|
| Inputs   | Capital  | fixed asset investment | 10^8 yuan | 1750.81 | 1906.58 | 95.03  | 17245.76 |
|          | Labor force | the number of employees at the end of each year | 10^4 person | 82.18 | 123.13 | 7 | 986.87 |
|          | Land resource | construction land | Km^2 | 199.09 | 349.11 | 14 | 2915.56 |
|          | Energy resource | Whole society electricity consumption | 10^8 Kwh | 139.89 | 220.11 | 4.07 | 1486.02 |
|          |          | total quantity of water supply | 10^4 tons | 2.88 | 5.07 | 0.12 | 34.05 |
| Outputs  | Desirable outputs | gross domestic product | 10^8 yuan | 2978.12 | 3917.09 | 158 | 28178.65 |
|          | Undesirable outputs | total volume of industrial SO2 emission | 10^4 tons | 6.35 | 7.01 | 0.19 | 68.29 |
|          |          | industrial soot emissions | 10^4 tons | 3.13 | 4.64 | 0.02 | 53.61 |

Notes: Panel data includes time series data for 92 cities from 2007 to 2016, and the sample observations are 920.

4. Analysis of economic efficiency and eco-efficiency of five urban agglomerations

4.1. Analysis of economic efficiency of urban agglomerations

This study firstly uses the SBM-DEA model to measure the economic efficiency of 92 cities in five urban agglomerations from 2007-2016, and examines the corresponding economic efficiency results of cities with non-expected output. The economic efficiency of urban agglomerations is calculated by the mean efficiency of the city. The data results are shown in Table 2.

Table 2 Economic efficiency of China's five major urban agglomerations

| Regions                          | 2007   | 2008   | 2009   | 2010   | 2011   |
|----------------------------------|--------|--------|--------|--------|--------|
| Full sample, Beijing-Tianjin-Hebei Urban Agglomeration | 0.6711 | 0.6814 | 0.685  | 0.7007 | 0.7074 |
| the Yangtze River Delta urban agglomeration | 0.6597 | 0.687  | 0.6516 | 0.6617 | 0.6868 |
| Middle Reaches of the Yangtze River | 0.7115 | 0.7088 | 0.7186 | 0.7186 | 0.7186 |
| the Pearl River Delta urban agglomeration | 0.578  | 0.6128 | 0.6347 | 0.6495 | 0.6597 |
| the Chengdu-Chongqing Urban Agglomeration | 0.7155 | 0.6983 | 0.6882 | 0.7047 | 0.7268 |
| Regions                          | 2012   | 2013   | 2014   | 2015   | 2016   |
| Full sample, Beijing-Tianjin-Hebei Urban Agglomeration | 0.725  | 0.7402 | 0.7475 | 0.7416 | 0.7826 |
| the Yangtze River Delta urban agglomeration | 0.7046 | 0.7597 | 0.7669 | 0.7219 | 0.7526 |
| Middle Reaches of the Yangtze River | 0.7695 | 0.7523 | 0.7695 | 0.7691 | 0.8065 |
The average traditional economic efficiency of the full sample reached 0.67 or above, which was at the upper-middle level, showing a significant upward trend in time. Except for a small decline in 2015, the economic efficiency increased in other years during the study period. At the end of the study period, the economic efficiency increased by 12% compared with the beginning of the period. The results show that the economic development of major urban agglomerations in China has made great progress without considering environmental impacts.

![Economic efficiency of five urban agglomerations](image)

From the perspective of urban inter-group, the economic efficiency among the five major urban agglomerations still show a certain efficiency gap. Among them, the Pearl River Delta urban agglomeration has the highest economic efficiency, followed by the Yangtze River Delta urban agglomeration, the Chengdu-Chongqing urban agglomeration, the Beijing-Tianjin-Hebei urban agglomeration and Middle Reaches of the Yangtze River. In addition, the difference in economic efficiency among urban groups has also narrowed during the study period, from 0.2 in 2007 to 0.12 in 2016. The gap between highly developed urban agglomerations and lagging urban agglomerations is gradually narrowing. The economic efficiency between the underdeveloped urban agglomerations is also roughly the same at the end of the study period. Middle reaches of the Yangtze River has the lowest economic efficiency at the beginning of the period, showing a trend of increasing year by year during the research period, and the gap with other urban agglomerations is shrinking. The other urban agglomerations all showed a rising trend during the study period. The economic efficiency of the Beijing-Tianjin-Hebei urban agglomeration and Middle reaches of the Yangtze River have changed a lot, and the economic efficiency of other urban agglomerations has changed slightly.

### 4.2. Analysis of eco-efficiency of urban agglomerations

| Regions                        | 2007  | 2008  | 2009  | 2010  | 2011  |
|--------------------------------|-------|-------|-------|-------|-------|
| the Pearl River Delta agglomeration | 0.789 | 0.811 | 0.7866| 0.8427| 0.8733|
| the Chengdu-Chongqing agglomeration | 0.7309| 0.751 | 0.7531| 0.7153| 0.758 |
When considering the undesired output of environmental pollution, the average eco-efficiency of the full sample reached 0.63 or more, slightly lower than economic efficiency. However, the difference between eco-efficiency and economic efficiency has significantly increased after 2011, expanding nearly threefold. It can be seen that the environmental pollution discharge in the process of regional development does cause a certain degree of efficiency loss. The traditional economic efficiency measurement without considering the environmental constraints ignores the influence of pollution by-products in the production process, resulting in the deviation of the final measurement results, which cannot be reflected. During the study period, the eco-efficiency of the five major urban

| Regions                        | 2012  | 2013  | 2014  | 2015  | 2016  |
|-------------------------------|-------|-------|-------|-------|-------|
| Full sample                   | 0.6419| 0.6609| 0.6502| 0.6482| 0.6884|
| the Beijing-Tianjin-Hebei Urban Agglomeration | 0.6029| 0.6503| 0.6595| 0.6029| 0.6284|
| the Yangtze River Delta urban agglomeration | 0.7116| 0.6986| 0.682 | 0.6918| 0.7505|
| Middle Reaches of the Yangtze River | 0.559 | 0.5729| 0.5826| 0.5932| 0.6315|
| the Pearl River Delta urban agglomeration | 0.7336| 0.7415| 0.7073| 0.774 | 0.8304|
| the Chengdu-Chongqing Urban Agglomeration | 0.6538| 0.7171| 0.6774| 0.6395| 0.6562|

Figure 2 eco-efficiency of five urban agglomerations
agglomerations did not change much, but at the end of the period, the eco-efficiency increased slightly from the beginning of the period.

The eco-efficiency among urban agglomerations was reduced from 0.26 in 2007 to 0.2 in 2016. In the above, the gap in economic efficiency between urban agglomerations at the end of the study period has been narrowing, and its convergence trend is difficult to reflect the efficiency differences caused by differences in energy utilization levels in the urbanization process of some urban agglomerations. The results of eco-efficiency still show the obvious differentiation trend of environmental benefits when different urban agglomerations create economic output. Among them, the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration and the middle reaches of the Yangtze River is much lower than its economic efficiency, and the average difference is 0.1 and 0.088 respectively. The difference between economic efficiency and eco-efficiency of the Yangtze River Delta, Pearl River Delta and Chengdu-Chongqing urban agglomerations is smaller than the former two, with average differences of 0.045, 0.042, and 0.039, respectively. From the comparison of the above two efficiencies, some urban agglomerations correctly balance the relationship between “long pain” and “short pain” in the one-way thinking of environmental protection restricting economic development, and then achieving both economic growth and environmental protection.

During the research period, the eco-efficiency levels of the five major urban agglomerations decreased from the Pearl River Delta urban agglomeration, the Yangtze River Delta urban agglomeration, the Chengdu-Chongqing Urban Agglomeration, the Beijing-Tianjin-Hebei Urban Agglomeration and Middle Reaches of the Yangtze River. Except for the Chengdu-Chongqing urban agglomeration, the ecological efficiency of other urban agglomerations showed a rising trend during the study period. At the end of the study period, the ecological efficiency of five urban agglomerations was significantly improved compared with the beginning of the period, indicating that with the further development of the economy and society, people no longer promote economic growth with environmental sacrifice, and pay more attention to environmental issues and the high-quality development of the economy. The eco-efficiency of the Chengdu-Chongqing urban agglomeration has declined during the research period. The reason may be that the Chengdu-Chongqing urban agglomeration is located in the western part of China, and the level of economic development is relatively backward. In order to improve economic output, some developing cities still use a large amount of resources to promote the increase of economic output, and also cause environmental pollution and spread nearby, thus reducing the overall eco-efficiency of the Chengdu-Chongqing urban agglomeration.
b. the Yangtze River Delta urban agglomeration

c. Middle Reaches of the Yangtze River

d. the Pearl River Delta urban agglomeration
Figure 3 Distribution of urban eco-efficiency nuclear density in the five urban agglomerations from 2007 to 2016

Figure 3 shows the nuclear density distribution of urban eco-efficiency in five urban agglomerations in 2007 to 2016. For the Beijing-Tianjin-Hebei urban agglomeration, the eco-efficiency showed an obvious fault distribution of the cities in the early stage of the study, and the number of cities with low efficiency was about twice that of high-efficiency cities. The proportion of inefficient and efficient cities has declined over time, and regional integration has become more balanced. The number of low-efficiency and high-efficiency cities in the Yangtze River Delta urban agglomeration is roughly balanced. At the beginning, there are more low-efficiency cities, and the curve distribution was symmetrical at the end of the study period. The distribution curve of the Middle Reaches of the Yangtze River has a large variation range, and there are more low-efficiency cities. The distribution curve shifts to the right in 2016. The urban eco-efficiency is significantly improved, and the proportion of low-efficiency cities has decreased. The low-efficiency cities and high-efficiency cities in the Pearl River Delta urban agglomeration are symmetrically distributed in the early stage of the study, and the curve fluctuations are moderate. The number of inefficient cities first increased and then declined, while high-efficiency cities were the opposite. At the end of the study period, the number of high-efficiency cities was much higher than that of low-efficiency cities, and the eco-efficiency was significantly improved. The eco-efficiency distribution of the Chengdu-Chongqing urban agglomeration is also symmetric at first. But the curve shows that the proportion of inefficient cities is gradually increasing, and the proportion of high-efficiency cities is decreasing. The curve in 2016 shows that the number of inefficient cities far more than the number of high-efficiency cities.

| Regions                                      | Capital | Labor force | Land resource | Energy resource | Undesirable outputs | Economic outputs |
|----------------------------------------------|---------|-------------|---------------|-----------------|---------------------|------------------|
| Full sample                                  | 12.98   | 17.13       | 26.35         | 36.81           | 41.5                | 0.18             |
| the Beijing-Tianjin-Hebei Urban Agglomeration| 17.94   | 18.08       | 28.43         | 44.51           | 52.01               | 0                |
| the Yangtze River Delta urban agglomeration  | 14.72   | 12.55       | 25.72         | 29.22           | 34.27               | 0.06             |
| Middle Reaches of the Yangtze River          | 16.95   | 23.21       | 30.36         | 49.29           | 52.38               | 0.24             |
| the Pearl River Delta urban agglomeration     | 3.55    | 14.36       | 23.09         | 26.71           | 29.59               | 0                |
| the Chengdu-Chongqing Urban Agglomeration    | 11.73   | 17.46       | 24.14         | 34.29           | 39.25               | 0.62             |
By calculating the redundancy rate of the input and output of each urban agglomeration, we can obtain the redundancy rate of each urban agglomeration. The results are shown in Table 4, we can see that the most important factor determining the eco-efficiency of the five major urban agglomerations during the study period is still the excessive pollution emissions, followed by resource input, land, labor and capital. The above results show that improving resource utilization efficiency and reducing environmental pollution will play a decisive role in improving urban eco-efficiency. It also confirms that the current economic development quality and environmental synergy of major urban agglomerations in China still have a large room for improvement.

From the comparison between urban agglomerations, the middle reaches of the Yangtze River and the Beijing-Tianjin-Hebei urban agglomeration are the areas with the most serious environmental pollution. The resource input and environmental pollution output redundancy rates are 44% and 52% respectively, higher than other urban agglomerations. The Beijing-Tianjin-Hebei urban agglomeration is located in the place of heavy industry in China. The pollution caused by industrial production is very serious, especially the severe PM2.5 pollution that broke out in North China in 2013 made it necessary to deal with smog pollution and improve air quality in China’s environmental protection issues in recent years. Due to its relatively backward economic development level and the incompatibility between cities, the urban agglomeration of the middle reaches of the Yangtze River, consisting of the Wuhan City Circle, the Changzhutan City Group and the Poyang Lake City Group, still has a significant improvement in its eco-efficiency, especially to improve the efficiency of resource allocation and the improvement of green production technology. The Chengdu-Chongqing urban agglomeration is located in the western part of China. Except for the two national central cities of Chengdu and Chongqing, the development of other cities some cities have a high ecological environment because they do not have heavy industry. Therefore, the redundancy of its resource input and environmental output is better than that of the Beijing-Tianjin-Hebei urban agglomeration and middle reaches of the Yangtze River. The Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration are located on the southeast coast of China and have a higher quality of economic development. Most of the various policy implementations and economic reforms are carried out here. Therefore, the dual goals of balancing economic growth and environmental protection are also increasingly emphasized. Most of the various policy implementations and economic reforms have been carried out here. Therefore, the local government pays more attention to the dual goals of economic growth and environmental protection.

From another point of view, although the urban agglomeration has cities with high efficiency and low efficiency, the urban agglomerations such as the Pearl River Delta urban agglomeration and the Yangtze River Delta urban agglomeration have a more coordinated economic and social development due to the larger proportion of high efficiency cities. On the contrary, due to the serious industrial pollution in many cities within the region, the eco-efficiency of the entire region of the Beijing-Tianjin-Hebei urban agglomeration reduced. The results also confirm that the city's "unilateral" pollution control efforts are particularly inadequate in dealing with the environmental pollution problems. Only by controlling the joint prevention and control of pollution control with urban agglomeration as the “carrier” can we better promote the improvement of environmental conditions in the region.

5. Analysis of factors affecting eco-efficiency

5.1. variable description and model selection

Combined with the analysis above, we use the Tobit model to study the factors affecting eco-efficiency from the perspective of socio-economic factors. The specific model form is as follows:

\[ EE_{it} = \alpha_0 + \alpha_1 \ln GRP + \alpha_2 IND + \alpha_3 TEC + \alpha_4 REG + \alpha_5 POP + \alpha_6 FDI + \varepsilon \]

EE is the urban eco-efficiency, i and t represent city and year respectively, and the explanatory variables include economic development, industrial structure, research and scientific expenditure, environmental regulation intensity, population concentration and foreign direct investment. The
specific explanatory variables are defined as follows:

1. The level of economic development. There is a correlation between environmental quality, pollution emissions and regional economic development levels. At the same time, the improvement of the economic development will also help people to enhance their environmental awareness. This paper measures the economic development of the city in the log of the per capita GDP.

2. Industrial structure. As the industrial production process is accompanied by energy consumption and the generation of environmental pollutants, the industrial structure of the city, especially the development of the secondary industry, must have an important impact on the regional eco-efficiency.

3. Research and scientific input. Technological progress is one of the important driving forces for promoting regional eco-efficiency. The proportion of scientific and technological expenditures to fiscal expenditures is used to measure the city's scientific and technological research and development investment.

4. Environmental regulation. Existing research has confirmed the significant impact of environmental regulation on ecological efficiency. Scholars mainly measure the intensity of regional environmental regulation from two aspects, use pollution control, abatement costs or sewage charges to evaluate from the perspective of input, or construct environmental regulations from the perspective of output. Studies have shown that environmental regulation can be more accurately measured from the perspective of output. Therefore, we use the pollution emission to construct index measuring urban environmental regulation. The calculation method is shown in the appendix.

5. The degree of population concentration. The impact of population expansion on the environment is mainly due to the expansion of energy consumption and the increase of pollution emissions caused by the accumulation of human production activities, which put more pressure on urban resource systems and environmental carrying capacity. This paper uses the total population at the end of the year to measure the population concentration of the city.

6. Foreign direct investment. The impact of foreign investment on the ecological environment has been tested by many empirical researches. Although the results of the research on the impact of eco-efficiency have not yet reached a unified conclusion, it can be confirmed that foreign direct investment situation will definitely change the eco-efficiency level of the local city.

This study uses the proportion of the actual use of foreign direct investment in GDP as a substitute.

5.2. empirical analysis
The Tobit model was used to investigate the influencing factors of eco-efficiency. The results are shown in Tables 5 and 6:

| Variables                  | Coefficient       |
|----------------------------|-------------------|
| economic development       | LnGRP -0.0076 (-0.36) |
| Industrial structure       | IND -0.0055*** (-3.6) |
| Research and scientific input | TEC 0.0056 (0.71) |
| Environmental regulation   | REG 0.4061*** (12.35) |
| population concentration   | POP -0.0411** (-2.42) |
| Foreign direct investment  | FDI -0.0224*** (-6.02) |
| Constant                   | c 1.1436*** (4.5) |
During the study period, there was a negative relationship between the economic development and the urban eco-efficiency of the five urban agglomerations. However, from the perspective of sub-regions, the economic development of the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration is positive for eco-efficiency, and the former two are statistically significant. While the improvement of economic development reduces the eco-efficiency in Middle Reaches of the Yangtze River and the Chengdu-Chongqing urban agglomeration. It can be seen that the former three urban agglomerations are located in the coastal areas where China’s economy is developing at a high speed. The overall economic development quality of the city is significantly higher than that of other regions. The enhancement of people’s awareness of environmental protection and the improvement of their quality of life have forced the public to have stricter requirements for a healthy living environment, which has driven local governments to pay more attention to the improvement of economic quality rather than the increase in economic output. On the contrary, Middle Reaches of the Yangtze River and the Chengdu-Chongqing urban agglomerations are located in the inland of central and western China, and the economic development is relatively backward. Most of the economic growth stems from energy consumption and environmental pollution, which has a negative impact on the ecological environment.

The industrial structure of the five major urban agglomerations has a significant negative effect on ecological efficiency. Except for the Pearl River Delta urban agglomeration, the coefficient of industrial structure of other urban agglomerations is negative. The results show that during the research period, China’s major urban agglomerations are still in an extensive development mode of high resource consumption and high environmental pollution. Economic growth has relied on heavy industry production and expanding pollution emissions in a long time. In recent years, thanks to the idea of the new economic norm and the implementation of government-led economic transformation and structural reforms, The impact of industrial production on the environment is weakening. However, the government still has a long way to go to take into account the development path of economic growth and environmental protection.

In general, expenditure in science and technology can positively promote the improvement of urban eco-efficiency, but in different regions, the results are not the same. The investment in R&D investment in the Yangtze River Delta urban agglomeration, Middle Reaches of the Yangtze River and

| Table 6 Tobit model regression results of subregion |
|-----------------------------------------------|
| Variables          | BTH          | YRD          | MRYR         | PRD          | CC           |
| economic development |             |              |              |              |              |
| LnGR P             | 0.0766*      | 0.1023**     | -0.0682*     | 0.0714       | -0.0675      |
| Industrial structure |             |              |              |              |              |
| IND                | -0.0027      | -0.0105**    | -0.0045      | 0.001        | -0.0075      |
| Research and scientific input |             |              |              |              |              |
| TEC                | 0.0679*      | -0.0231*     | -0.0194      | 0.092**      | -0.0378      |
| Environmental regulation |             |              |              |              |              |
| REG                | 0.5844***    | 0.1596**     | 0.5816***    | 0.2562**     | 0.3718***    |
| population concentration |             |              |              |              |              |
| POP                | -0.0069      | 0.0553       | -0.0702*     | 0.2128*      | -0.2746**    |
| Foreign direct investment |             |              |              |              |              |
| FDI                | -0.0476**    | 0.0016       | -0.0235**    | -0.0318*     | -0.0014      |
| Constant           | -0.2302      | -0.1832      | 1.8268***    | -1.6102      | 3.4161***    |

Note: ***, **, and * indicate significant at 1%, 5%, and 10%, respectively.
the Chengdu-Chongqing urban agglomerations has a negative impact, while in the Beijing-Tianjin-Hebei urban agglomeration and the Pearl River Delta urban agglomeration it can significantly promote regional eco-efficiency. The reason may be that technological advances can be divided into two categories that are beneficial to productivity improvement or beneficial to the environment and emission reduction activities, depending on the bias in the actual production process. The former may even increase pollution for economic benefits.

The impact of environmental regulation intensity on eco-efficiency has a significant positive effect on both full sample and individual urban agglomerations. During the study period, the environmental regulation of the five major urban agglomerations remained at a relatively low level compared to the western developed countries, especially in the Beijing-Tianjin-Hebei urban agglomeration where environmental pollution is more serious and the central and western regions with backward economic development. At the same time, the economic growth of the city mainly depends on the heavy industry with high energy consumption and high pollution. Therefore, the intensity of environmental regulation with a small scale change can have a significant positive effect on the local ecological environment, and will also reduce the environmental impact of production through high-pollution and high-emission enterprises within the city.

The impact of population agglomeration on eco-efficiency is negative and statistically significant for five urban agglomerations. From the perspective of the sub-regions, the expansion of urban population in the Beijing-Tianjin-Hebei urban agglomeration, Middle Reaches of the Yangtze River and the Chengdu-Chongqing urban agglomeration have a negative impact on urban eco-efficiency, while in the Yangtze River Delta and the Pearl River Delta urban agglomeration it can promote local eco-efficiency. Population expansion can affect urban eco-efficiency from the scale effect and the agglomeration effect. In terms of scale effect, the expansion of population will consume more energy and generate more pollution emissions. The deeper reason may be that the growth of urban population does not match the existing system, technology and management level, thereby limiting the overall carrying capacity and development potential of the urban agglomeration, resulting in its negative impact on ecological efficiency. On the other hand, the increase in the degree of agglomeration can also promote eco-efficiency and reducing environmental impact by sharing pollution reduction facilities and reducing production costs, and thus the pollution level per unit of GDP will be reduced.

Foreign direct investment has a significant negative impact on urban eco-efficiency. Except for the Yangtze River Delta urban agglomeration, foreign direct investment in other urban agglomerations also negatively affects local eco-efficiency. The reason may be that foreign capital chooses China as an investment area to increase its profit level due to the low degree of environmental regulation. Although it has promoted local economic development to some extent, it has become a polluting paradise for foreign capital.

6. Conclusions and recommendations
This study uses the SBM-DEA model to examine the economic efficiency and eco-efficiency of cities in China’s five major urban agglomerations from 2007 to 2016, and uses the Tobit model to analyze the socio-economic factors affecting eco-efficiency. The conclusions are as follows:

The economic efficiency of the five major urban agglomerations is at a medium-to-high level, and the economic efficiency has steadily increased from the time trend, indicating that the economic development of the current urban agglomerations has made great progress. From the perspective of comparison among urban agglomerations, the economic efficiency still has a certain gap, but the difference has narrowed during the study period. The economic efficiency gap between economically backward urban agglomerations and developed urban agglomerations, and the gap between relatively backward urban agglomerations are all decreasing.

The eco-efficiency of the five major urban agglomerations is slightly lower than its economic efficiency, but its difference has significantly increased after 2011, confirming that environmental pollution does cause a certain degree of efficiency loss. The eco-efficiency gap among urban agglomerations has narrowed in time trends, but still shows significant regional differences. The
degree of efficiency loss caused by environmental pollution in the Chengdu-Chongqing urban agglomeration, the Pearl River Delta urban agglomeration, the Yangtze River Delta urban agglomeration, Middle Reaches of the Yangtze River and the Beijing-Tianjin-Hebei urban agglomeration has gradually expanded. In terms of time trend, except for the Chengdu-Chongqing urban agglomeration, the eco-efficiency of other urban agglomerations showed a rising trend during the research period. The nuclear density curve of the ecological efficiency of each city group shows a different distribution state and development trend. From the perspective of the redundancy rate of various urban agglomerations, excessive pollution emissions are still the determining factor of the eco-efficiency for the five major urban agglomerations, followed by resources, land, labor and capital.

From the perspective of factors affecting eco-efficiency, economic development generally has a negative impact on eco-efficiency. But the economic growth of the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration contributes to the improvement of eco-efficiency. While the Chengdu-Chongqing urban agglomeration and Middle Reaches of the Yangtze River has a negative impact. Except for the Pearl River Delta urban agglomeration, the industrial structure of the whole sample and other urban agglomerations has a negative effect on eco-efficiency, and it still has a long way to go to take into account the dual development goals of economic growth and environmental protection. Due to the different orientations of technological progress, the investment in science and technology can promote eco-efficiency of the full sample, the Beijing-Tianjin-Hebei urban agglomeration and the Pearl River Delta urban agglomerations, but it has a negative impact on eco-efficiency of the Yangtze River Delta urban agglomeration, Middle Reaches of the Yangtze River and the Chengdu-Chongqing urban agglomerations. Environmental regulation has a significant positive effect on ecological efficiency, both in the full sample and individual urban agglomerations. Population expansion affects urban eco-efficiency from scale effect and agglomeration effect. The population size of the Beijing-Tianjin-Hebei urban agglomeration, Middle Reaches of the Yangtze River and the Chengdu-Chongqing urban agglomerations with relatively low efficiency has a negative impact, while the Yangtze River Delta and the Pearl River Delta urban agglomeration with high eco-efficiency has a positive impact. Except for the Yangtze River Delta urban agglomeration, foreign direct investment has a negative impact on eco-efficiency in other regions.

To sum up, in order to improve the eco-efficiency of China’s urban agglomerations and promote the coordinated development of regional economy, resources, environment and society, the following suggestions are proposed: The government should transforming the economic development mode and break through the constraints of traditional development models, maintain rapid economic growth. Coastal urban agglomerations should increase investment in science and technology research, improve environmental benefits with technological output, expand the spillover effects of environmental technology. Inland urban agglomerations should take care to ensure the simultaneous migration of pollution in the process of undertaking industrial transfer. Local governments need to formulate reasonable regulatory policies according to local conditions to promote environmental regulation to play a proper role in environmental improvement, it is necessary to strengthen pollution prevention and control between cities in order to effectively control the negative externalities of environmental pollution. The local government continues to expand the degree of openness, enhance the entry barriers for foreign investment and the quality of foreign investment, and promote the role of foreign capital in economic transformation and innovation. Foreign investment should be guided to low-pollution and high-tech industries, avoid becoming a “pollution shelter” in developing countries. High efficiency areas should enhance the population concentration to exert the agglomeration effect brought about by the expansion of population size. Inefficient areas should alleviate the scale effect of the population and raise people’s awareness of environmental protection in order to realize the important role of the people in the process of ecological protection and environmental supervision.

7. Appendix
The calculation of environment regulation consists of three steps.
\[
P_{ijt} = \frac{T_{ijt}}{Y_{it}} \sum_{j=1}^{k} \frac{T_{jkt}}{Y_{ikt}} K
\]

\[
P_t = \sum_{j=1}^{V} P_{ijt}
\]

\[
ER_{1t} = 1/P_{t1}
\]

We first calculate the relative intensity of environmental pollution in different cities. \(T\) represents the amount of pollution emissions, \(Y\) is the total industrial output of the city, \(j\) represents the type of pollutant emissions, \(i\) and \(j\) represent the city and time respectively. Then we calculate the comprehensive index of relative intensity of environmental pollution. Finally, we can obtain the intensity of environmental regulation of each city.

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