Research on Evolution Pattern and Spatial Correlation between Economic Development and Environmental Pollution Centers of Gravity

Binbin Du 1,2,3, Qiaoya Zheng 1,2, Xue Bai 3, Longyu Shi 1,2,* and Xian Shen 3

1 Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; bbdu@iue.ac.cn (B.D.); qyzheng@iue.ac.cn (Q.Z.)
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 School of Real Estate, Beijing Normal University Zhuhai Campus, Zhuhai 519085, China; baixue@bnuz.edu.cn (X.B.); sx514347092@126.com (X.S.)

Received: 9 September 2020; Accepted: 27 September 2020; Published: 28 September 2020

Abstract: The coordinated development of environment and economy is an important way to achieve sustainable development. As the Guangdong-Hong Kong-Macao Greater Bay Area has been included in the national agenda, Guangdong province faces a turning point in its economic, social, and environmental development. Taking Guangdong province as an example, this paper analyzes the spatial evolution and correlation of economic development and environmental pollution by means of center of gravity (COG) and geo-information system (GIS). The results show the shift of economic development COGs are smaller than that of environmental pollution. Environmental pollution COGs are negatively correlated with economic scale and quality COGs, whereas it is positively correlated with economic growth COG, which depends on the industrial structure and local policies. The continuous transformation of the industrial structure of the Pearl River Delta Region (PRD) is conducive to improving its environment and promoting economic development of Non-Pearl River Delta Region in Guangdong province (Non-PRD) through bilateral causality. As the receiving place of industrial transfer, eastern Guangdong has obvious effects of environmental pollution transfer from the secondary industries. In this study, the logical spatial evolution path of the economic development and environmental pollution COGs is established. It provides theoretical and practical references for the study of interrelationship between economy and environment.

Keywords: economic development centers of gravity; environmental pollution centers of gravity; evolution pattern; spatial correlation; Guangdong province

1. Introduction

As China’s development enters the new normal stage and regional integration deepens, interregional economic and environmental linkages are producing more profound impact. The coordinated development of environment and economy is an important part of the theory of sustainable development, while environmental deterioration will restrict the progress and quality of economic development. As the forefront of the reform and opening up, Guangdong province’s economy has developed rapidly; however, the ecological environment has deteriorated. The contradiction between the two will restrict sustainable development of the region. At present, Guangdong province, especially the Greater Bay Area, leads the country in overall ecological and environmental quality, but the coordination between economic growth and environmental protection is still far behind that of New
York Bay area, San Francisco Bay area, and Tokyo Bay area [1]. Therefore, it is necessary to explore the evolution pattern and spatial correlation between economic growth and environmental pollution.

Environmental problems cannot be solved simply by relying on technologies or capital investment, as they follow a common evolution pattern with economic and social structures. The center of gravity method offers a perspective for studying spatial evolution by applying the concepts and methods of physics in the field of social science. This method is clear and elaborate, with unique advantages in studying the spatial structure and evolution tracks of regional attributes. It is particularly useful in the structural analysis of the economy and population distribution involving a spatial scope, thus making it possible to discuss the associated forms, trends, and policy effects. The concept of “population center of gravity” was first proposed to analyze the large-scale migration of the population caused by the development of the American West (F. Walker 1874). Later, scholars began to use the method to describe other social attributes to study the evolution track of the world economic center of gravity [2,3]. Aboufadel et al. proposed a method for calculating the population center of gravity to summarize the population distribution and its change in the United States. The method does not rely on any map projection [4]. Grether et al. used this method to study the change in the world economic center of gravity. The results showed that although the world economic center of gravity is still located in Europe, it has started to move toward Asia [5]. Kandogan studied the changes in economic centers of gravity of some countries and the world from 1970 to 2009 to compare the soft power of different parts of the world [6]. Niedomysl et al. based their research on night light intensity and actual population data in Sweden and used the center of gravity method to estimate the distance of human migration, proposing a population model attributable to social trends [7,8]. Breau et al. studied the provincial household income data of Canada from 1926 to 2013, which showed that the fluctuation in the prices of resource commodities is closely related to the historical movement of Canada’s economic center of gravity [9].

Early explorations of the center of gravity method in China can be found in the works of Li, who analyzed the spatial evolution of China’s population centers of gravity from 1953 to 1982. In terms of research methods, some scholars have combined the center of gravity method with the Kuznets curve and GIS technology [10,11]. Hu et al. pointed out that compared with the traditional formula for calculating the center of gravity, the GIS interval subset method can more accurately reduce errors caused by incompletely randomized spatial data [12]. Guo et al. further explored the calculation method of the center of gravity for complex terrains [13]. All these studies combined the center of gravity method and other visual research methods. In terms of research contents, the existing literature mainly discusses the spatial evolution of the population and economic centers of gravity. In terms of research contents, many studies examine the evolutionary relevance of different attribute centers. Most of the studies are on the relationship between the population and economic centers of gravity [14–16]. In addition to research on China as a whole, there are also studies on different regions. Xu et al. inferred that Xi’an’s population and economic centers of gravity have moved north [17]; Li et al. concluded that the deviation between the economic and population centers of gravity in the Beijing-Tianjin-Hebei region has increased [18]. Huang et al. used night light data to analyze the spatial evolution tracks of the population and economic centers of gravity in Henan province [19]. Since 2005, there have been more studies on the spatial evolution path of other indicators in China. For example, Li et al. found that the center of gravity of China’s railway transportation gradually moved southwest [20]. Tang et al. discussed the spatial correlation between the centers of gravity of the population, economy, and rice planting area in Jiangsu province from 1949 to 2011 [21]. In addition, research on the correlation between economic and environmental centers of gravity has appeared. Ding et al. calculated the evolution path of China’s pollution and economic centers of gravity and found that they had a relatively close spatial relationship with each other [22]. Du et al. discussed the characteristics of the evolution of the economic and pollution centers of gravity in the Shandong Peninsula urban agglomeration [23]. Du et al. discussed the mechanism of economic growth and environmental pollution [24]. Qi used the decoupling model to analyze the fluctuation trend of “expanding and connecting–weak decoupling–strong decoupling” between China’s economic growth and carbon emissions [25]. Han discussed the spatial correlation
between economic agglomeration and environmental pollution in China [26]. At present, scholars mostly use the center of gravity method to study the spatial differences and correlations among regional attributes [27,28]. Some scholars combine the center of gravity method with GIS and statistical analysis to improve the logicality and visibility of such spatial evolution analysis [29–31].

In this paper, COG method was used to study the spatial correlation between economic development and environmental pollution in Guangdong province of China and analyze the internal driving force and evolution pattern, which is beneficial for finding positive measures for the coordination between economic development and pollution reduction. Promoting the coordinated and sustainable development of the environment and economy in Guangdong province will not only have important practical significance for itself but will also have important reference significance for China. Theoretically, this paper deepens the research about the relationship between economy and environment in Guangdong province and expands the theoretical framework of the evolution of regional gravity center. Practically, the exploration of the internal relationship between the economic development and the environmental pollution COGs contributes to the government management and achievements of both high economic quality and sustainable environmental development. Furthermore, its research methods and results support researches on economic development and environmental pollution in Guangdong province and China.

2. Research Method and Data Use

2.1. Concept of the Center of Gravity

The center of gravity (COG), also known as the “spatial mean,” refers to the point at which the force moment of a certain attribute reaches an equilibrium on the spatial plane within a certain time, which is the extension of the sample mean in the two-dimensional space. Suppose a certain region is composed of \( n \) subregions and that the attribute value of each subregion is \( p_i \), for each subregion, the coordinate of the geographical COG is \((X_i, Y_i)\), and the COG is calculated as follows:

\[
X = \frac{\sum_{i=1}^{n} p_i X_i}{\sum_{i=1}^{n} p_i}, \quad Y = \frac{\sum_{i=1}^{n} p_i Y_i}{\sum_{i=1}^{n} p_i}
\]  

(1)

If \( p_i \) in the formula is the total gross domestic product (GDP) of subregion \( i \), taking it as the weight, the economic scale COG is calculated after weighted average. When \( p_i \) is taken as GDP, per capita GDP, GDP growth rate, volume of industrial wastewater, volume of industrial waste gas, or volume of solid waste, the corresponding COG coordinate will be calculated.

The moving direction of COG refers to the spatial plate deflection caused by the changes in the attribute values in the process of spatial evolution. It is calculated as follows:

\[
\theta_{s-k} = \frac{n\pi}{2} + \text{degree} \left\{ \arctan \left( \frac{Y_s - Y_k}{X_s - X_k} \right) \right\}, \quad (n=0,1,2)
\]  

(2)

where \( s \) and \( k \) represent two different years; \( \theta \) represents the interannual moving angle \((-180^\circ < \theta < 180^\circ)\); and \( 0^\circ \) represents the east, showing a positive value for counterclockwise rotation and a negative value for clockwise rotation.

The spatial movement of COGs between different years is calculated as follows:

\[
D_{s-k} = C \left[ (Y_s - Y_k)^2 + (X_s - X_k)^2 \right]^{0.5}
\]  

(3)

where \( D_{s-k} \) represents the distance of COG movement between two different years; \( C \) is a constant, which is the coefficient for the geographic coordinate unit (\(^{\circ}\)) to be converted into a plane distance (km); \( C^*(X_s - X_k) \) and \( C^*(Y_s - Y_k) \) represent the actual distances that the COGs move in longitude and latitude, respectively, from year \( k \) to year \( s \).
From the above formula, the important factors affecting COGs are the geographical locations and certain attribute values of the subregions within the region. The change of COGs is mainly manifested in two aspects: migration direction and migration distance. The migration direction refers to the spatial reflection of the high-slope growth position of a certain attribute value. If COG moves in a certain direction, it indicates that the attribute value grows faster in this direction. The migration distance indicates the imbalance of some attribute values. If COG migration distance is large, the difference of the attribute values is large. To explore the spatial characteristics of economic development and environmental pollution in Guangdong province, this study classifies the economic development COGs and environmental pollution COGs. Economic development COGs include economic scale COG, economic quality COG, and economic growth COG. Environmental pollution COGs are divided into industrial wastewater COG, industrial waste gas COG, and solid waste COG. The classification is shown in Table 1.

| Classification       | Weight  | Indicators                      | Explanation                                                                                           |
|----------------------|---------|---------------------------------|-------------------------------------------------------------------------------------------------------|
| Economic Development | Economic scale COG | GDP                             | It reflects the difference of economic aggregate and economic aggregate growth rate in Guangdong, as well as the difference of overall economic performance among 21 prefecture-level cities in Guangdong province |
|                      | Economic quality COG | Per capital GDP                | It reflects the difference between the growth rate of the quality about economy and life in Guangdong, as well as the difference of the economic quality level among 21 prefecture-level cities in Guangdong province |
|                      | Economic growth COG  | GDP growth rate                 | It reflects the differences of economic growth and economic growth rate in Guangdong, as well as the differences of economic development potential among 21 prefecture-level cities in Guangdong province |
| Environmental Pollut| Industrial wastewater COG | Volume of industrial wastewater | It reflects the overall distribution and dynamic change of total wastewater emission in Guangdong province, as well as the differences of water pollution among 21 prefecture-level cities in Guangdong province |
| Environmental Pollut| Industrial waste gas COG  | Volume of industrial  | It reflects the overall distribution and dynamic change of total waste gas emission in Guangdong province, as well as the difference of air pollution among 21 prefecture-level cities in Guangdong province |
|                      | Solid waste COG        | Volume of solid waste          | It reflects the overall distribution and dynamic change of total solid waste emission in Guangdong province, as well as the difference of soil pollution among 21 prefecture-level cities in Guangdong province |

2.2. Data Resources

The data mainly come from the Statistical Yearbook of Guangdong (2001–2018) and include the indicators of GDP, per capita GDP, GDP growth rate, industrial wastewater emissions, industrial waste gas emissions, and industrial solid waste emissions of 21 prefecture-level cities. The data on environmental pollution in 2017 are missing. All the spatial data come from the 1:4,000,000 database of the National Fundamental Geographic Information System (NFGIS), including the administrative maps and longitude and latitude coordinates of the cities. By taking area as the weight and substituting it into the COG formula, it can be calculated that the geographical center of Guangdong province is located at 113.75 east longitude and 23.0 north latitude in Xinhe Village, Wanjiang District, Dongguan city.

2.3. Hypotheses

Based on attributes such as economic development and environmental pollution, the evolution of the industrial structure and environmental regulations in Guangdong [26,27,31], this paper proposes
several hypotheses on the evolution pattern and spatial correlation of the economic development and environmental pollution COGs.

**Hypothesis 1.** The inverted U-shaped theory, which was put forward by an American economist Jeffery G. Williamson, points out that there is an inverted U-shaped relationship between development stages and spatial differences and that economic growth tends to be balanced in the long run [32]. The PRD has no doubt become the core area of development in Guangdong province, and it has disproportionate power over the Non-PRD in terms of industrial upgrading. However, due to the law of diminishing marginal returns and the gradual stabilization of industrial advantages in the Non-PRD, PRD may not have an advantage in the growth rate of various economic indicators. Therefore, this paper assumes that the economic development COGs are close to the PRD but tend to move away from the PRD with little range.

**Hypothesis 2.** With the upgrading of the industrial structure and the industrial gradient transfer between regions, the environmental pollution level in regions dominated by tertiary industries will gradually decrease, and pollution problem in regions that are home to heavy chemical industrial enterprises may worsen [33]. Therefore, this paper assumes that the environmental pollution COGs are closely related to the spatial transfer of secondary industries, and the environmental impacts brought about by such transfer have a certain time lag.

**Hypothesis 3.** The environmental Kuznets curve (EKC) means that there is an inverted U-shaped relationship between environmental pollution and economic development [34]. The Porter hypothesis notes that effective environmental regulation can stimulate technological innovation and improve the productivity of enterprises, thus offsetting the increase in cost brought about by environmental protection, improving the profitability of enterprises, and in turn, achieving a win–win situation for economic development and environmental protection. Therefore, this paper assumes that the relationship between economic development and environmental pollution in Guangdong has passed the inflection point of the inverted U-shaped curve; there are negative correlations between the evolution paths of economic development and environmental pollution.

3. **Time–Space Evolution of Economic Development and Environmental Pollution Centers of Gravity**

3.1. **Evolution of Economic Development Centers of Gravity**

By calculating the locations, directions, and moving distances of the economic growth, economic scale, and economic quality COGs in Guangdong from 2000 to 2017, we can draw the spatial evolution tracks as shown in Figure 1.

Figure 1 shows that the economic development COG is in the south-central part of Guangdong. The economic scale (Figure 1a) and economic quality (Figure 1b) COGs are relatively stable, with small changes and similar moving tracks. They both move steadily toward the northwest and then slightly back to the southeast, which shows that regions with larger economies and regions with higher per capita economic levels are basically the same. They both lie in the PRD, which does not have the incremental advantages of these two indicators. However, economic growth COG has changed contradictory, and the overall shift is mainly to eastern Guangdong (Figure 1c). The driving force is mainly related to Guangdong’s promulgation of a series of plans, such as “Decision on Further Promoting the Revitalization and Development of the Northern, Eastern, and Western Guangdong.” These plans entrust the industrial parks with the important task of leading the revitalization of industries in the Non-PRD.

3.2. **Evolution of Environmental Pollution Centers of Gravity**

By calculating the locations, directions, and moving distances of the industrial wastewater, industrial waste gas, and solid waste COGs in Guangdong from 2000 to 2016, we can draw the spatial evolution tracks as shown in Figure 2.
Figure 1. Spatial evolution of (a) economic scale, (b) economic quality, and (c) economic growth COGs in Guangdong from 2000 to 2017.

Figure 2. Spatial evolution of (a) industrial wastewater pollution, (b) industrial waste gas pollution, and (c) solid waste pollution centers of gravity in Guangdong from 2000 to 2016.
Figure 2 shows that the industrial wastewater pollution (Figure 2a) and industrial waste gas pollution (Figure 2b) COGs are both located at the junction of Guangzhou and Dongguan. The locations of both COGs are relatively stable, with only small changes, and both are generally moving from west to east. The moving path of the solid waste pollution COG spans several cities (Figure 2c), with a great range of movement. According to the emissions of pollutants of the cities in recent years, the solid waste discharge is basically zero except in western Guangdong; therefore, the solid waste pollution COG moves to the west. In recent years, the Non-PRD has taken on part of the secondary industries from the PRD, which has had a serious impact on the atmospheric and water environment.

4. Spatial Correlations between Economic Development and Environmental Pollution Centers of Gravity

4.1. Comprehensive Comparison

The results of placing the coordinates of economic development and environmental pollution COGs in the same coordinate system are shown in Figure 3.

![Figure 3. Spatial track of economic development and environmental pollution COGs in Guangdong.](image)

Figure 3 shows that the economic development and environmental pollution COGs are quite close to each other, falling approximately on the border between Guangzhou and Dongguan, and close to the geographic COG. The changes in the economic development COGs are much smaller than those in the environmental pollution COGs. It indicates that the spatial solidification effect and inertia of the difference in economic development are stronger and that the time lag of the relative change in the difference of the environmental pollution discharge is shorter. Spatial transfers of secondary industries can drive the distribution of environmental pollution discharge within a short time; however, disrupting the existing economic spatial pattern is difficult.

4.2. Spatial Correlation Analysis Based on Longitude

The longitude evolution tracks of the economic development and environmental pollution centers of gravity are shown in Figure 4, and the correlation coefficients are shown in Table 2.
Sustainability 2020, 12, 8020

Figure 4. Longitude of economic development and environmental pollution COGs in Guangdong.

Table 2. Longitude correlation coefficients between economic development and environmental pollution COGs in Guangdong.

| Economic Scale Center of Gravity | Economic Quality Center of Gravity | Economic Growth Center of Gravity | Industrial Wastewater Center of Gravity | Industrial Waste Gas Center of Gravity | Solid Waste Center of Gravity |
|---------------------------------|-----------------------------------|----------------------------------|---------------------------------------|---------------------------------------|-------------------------------|
| Economic scale center of gravity | 1                                 |                                  |                                       |                                       |                               |
| Economic growth center of gravity | -0.460 **                         | -0.545 *                         | 1                                    |                                       |                               |
| Industrial wastewater Center of gravity | -0.830 **                        | -0.903 **                        | 0.696 **                             | 1                                    |                               |
| Industrial waste gas Center of gravity | -0.743 **                        | -0.730 **                        | 0.468                                | 0.654 **                             | 1                             |
| Solid waste center of gravity | -0.316                             | -0.202                           | -0.146                                | 0.012                                | 0.445                         |

**: at the 0.01 level (double-tailed), the correlation is significant; *: at the 0.05 level (double-tailed), the correlation is significant.

Figure 4 and Table 2 show that the economic scale and economic quality COGs basically overlap in longitude and change stably, with little change in the east-west direction. The longitude of the economic growth COG gradually increases, and the economic growth in eastern Guangdong indicates a slight advantage over that in western Guangdong. The evolution trends of industrial wastewater pollution and waste gas pollution COGs are relatively consistent in longitude with the evolution trend of the economic growth center of gravity, mostly falling in eastern Guangdong. The solid waste pollution COG changes significantly in longitude and mainly moves westward. At the 0.01 level, the economic scale COG is positively correlated with the economic quality COG. The industrial wastewater pollution and industrial waste gas pollution COGs are negatively correlated with the economic scale and economic quality COGs. The industrial wastewater pollution COG is positively correlated with the economic growth COG. The industrial waste gas pollution COG is positively correlated with the industrial wastewater pollution COG. At the 0.05 level, the economic quality COG is negatively correlated with the economic growth COG. This finding shows that the PRD, which has the highest production efficiency in China, is far ahead in terms of economic scale and development compared with the Non-PRD. The economic development potential in eastern Guangdong is increasing, but its environmental pollution is gradually becoming serious.

4.3. Spatial Correlation Analysis Based on Latitude

The latitude evolution tracks of the economic development and environmental pollution COGs are shown in Figure 5, and the correlation coefficients are shown in Table 3.
Figure 5. Latitude of economic development and environmental pollution COGs in Guangdong.

Table 3. Latitude correlation coefficient between economic development and environmental pollution COGs in Guangdong.

|                            | Economic Scale COG | Economic Quality COG | Economic Growth COG | Industrial Wastewater COG | Industrial Waste Gas COG | Solid Waste COG |
|---------------------------|--------------------|----------------------|---------------------|---------------------------|--------------------------|-----------------|
| Economic scale COG        | 0.766 **           | 1                    |                     |                           |                          |                 |
| Economic quality COG      | 0.536 *            | 0.359                | 1                   |                           |                          |                 |
| Industrial wastewater COG | −0.111             | −0.342               | 0.058               | 1                         |                          |                 |
| Industrial waste gas COG  | 0.463              | 0.262                | 0.297               | 0.227                     | 1                        |                 |
| Solid waste COG           | 0.219              | −0.212               | −0.195              | 0.399                     | 0.642 **                 | 1               |

**: at the 0.01 level (double-tailed), the correlation is significant. *: at the 0.05 level (double-tailed), the correlation is significant.

Figure 5 and Table 3 show that the economic scale and economic quality COGs basically overlap in latitude and are stable in the PRD all year round. Different from the change in the longitude, the changes in the economic growth, wastewater pollution, and waste gas pollution COGs on the latitude levels are relatively small. At the 0.01 level, the economic quality COG is positively correlated with the economic scale COG, and the solid waste pollution COG is positively correlated with the industrial waste pollution COG. At the 0.05 level, the economic growth COG is positively related to the economic scale COG. The spatial evolution of the economic development and environmental pollution COGs is relatively small in latitude, indicating that these centers of gravity mainly move in the east-west direction. In the north-south direction, the environmental pollution COGs are weakly correlated with the economic growth COG. It indicates that the acceleration of economic growth in the PRD has not caused significant environmental pollution, and its advantage in the economic growth rate is mainly associated with the rapid development of tertiary industries.

5. Discussion

The verifications of the hypotheses are based on the analysis of the evolution and spatial correlation of the economic development and environmental pollution COGs in Guangdong, and the results are as follows.

Hypothesis 1 holds: the ranges of movement of the economic scale and the economic quality COGs are proven to be small, and the overall moving directions are first toward the west and north and then slightly back toward the southeast. The evolution of the economic growth COG has no fixed direction. It can be seen that the economic aggregate and production efficiency of western and northern
Guangdong have been improved, and the overall economic difference of Guangdong province has been converged.

Hypothesis 2 holds: the foregoing proves that industrial wastewater and industrial waste gas COGs in Guangdong province have similar moving trajectory, which shows a trend of eastward movement. It basically corresponds to the spatial transfer path of Guangdong’s industrial structure. As of 2017, 13 cities in Guangdong province are dominated by tertiary industries, including Guangzhou, Shenzhen, Zhuhai, and Dongguan, and the remaining cities (mainly in eastern Guangdong) are dominated by secondary industries. This is related to the “dual transfer” policy implemented by Guangdong province since 2008. Although the PRD vigorously promotes industrial transformation and upgrading, its environmental pollution is relatively reduced. However, the eastern Guangdong region has undertaken the industrial transfer from the PRD, which mainly includes labor-intensive industries such as textiles and garments, toys, ceramics, and leather. This has a negative impact on the water and atmospheric environment. Therefore, the industrial wastewater and industrial waste gas COGs move eastward.

Hypothesis 3 is not true: it is proved that the economic scale and economic quality COGs generally move to the northwest, whereas industrial wastewater and industrial waste gas COGs generally move to the east. The spatial evolution of the two shows deviation. This indicates that the improvement of economic scale and quality does not all depend on polluters in the central and western regions of Guangdong province. The inflection point of the EKC curve may have passed. However, facing the problem of increasing environmental pollution with rapid economic development, eastern Guangdong is still in the upward stage of EKC curve.

Compared with the latitude level, the longitude evolution of economic development and the environmental pollution COGs in Guangdong province is more obvious. It shows that industrial wastewater and industrial waste gas COGs are negatively correlated with economic scale and economic quality COGs, while the correlation between economic development COGs and environmental pollution COGs is not significant at the latitude level. The economic scale and economic quality COGs have been stable in the PRD, which tends to move northwest. The economic growth and the environmental pollution COGs mainly move east. It is mainly affected by the industrial structure, i.e., the industrial structure is more optimized and advanced, and the environmental quality is relatively better in the PRD. On the contrary, secondary industries are more dominant and the environmental quality is poor in eastern Guangdong. Therefore, optimization of the industrial structure is one of the key factors in the spatial evolution of the economic development and environmental pollution COGs. Based on the above findings, the logical path for the spatial evolution of economic development and environmental pollution in Guangdong is shown in Figure 6.

At present, Guangdong is in the stage of economic development driven by both secondary industries and tertiary industries. The PRD is in a postindustrial period currently with a large economic scale and high development quality after the continuous upgrading of its industrial structure. With the increase in production efficiency, the economy has changed from high-speed development to high-quality development. At the same time, the PRD is beginning to attach importance to environmental quality and protection. Environmental pollution has gradually decreased in the process of such economic development. The development status is shown in Cycle 2. However, eastern Guangdong and other peripheral regions still regard economic growth as the top priority, where the industrial structure is starting to upgrade, but it is still at the stage of development of secondary industries. In the process of gradual expansion of economic scale and improvement of production efficiency, environmental pollution also increases. The development status is shown in Cycle 1. However, the current development in eastern Guangdong is in line with the framework of existing experience, i.e., with the continuous improvement of production efficiency, the improvement of production technologies, and the implementation of appropriate environmental regulations, it will gradually but eventually transform from secondary industry-based development to tertiary industry-based development, from Cycle 1 to Cycle 2. The spatial patterns of economic development and environmental pollution will then be more coordinated with fewer
differences, which means that economic development and environmental quality are not antithetical. The potential for coordinated development is a significance aspect of “sustainable development” and the premise of this paper.

Figure 6. Logical path of the spatial pattern of the economic development and environmental pollution COGs in Guangdong.

6. Conclusions and Suggestions

6.1. Conclusions

In this study, Guangdong province is used as a case study for the coordinated development of environment and economy. The results are of great significance for enriching theories of sustainable development, and the research methods and results also provide a reference for China.

The spatial evolution and correlation of the economic development and environmental pollution COGs of Guangdong are discussed, and their driving mechanism and logical path are determined. The results are as follows: (1) The space–time migration tracks of the economic development and environmental pollution COGs are closely related to policies. The PRD has an influence on the location of the economic development COGs. However, according to the growth rates of three economic indicators, the PRD does not have advantages. The economic scale and economic quality COGs generally show a trend of moving toward the northwest and then slightly back toward the southeast, which is related to the diminishing marginal returns of economic factors and the large absolute values in the PRD. In recent years, Guangdong has vigorously promoted the transformation and upgrading of the PRD, thus accelerating the pace of development through two-way causal interaction with the Non-PRD. The industrial wastewater and industrial waste gas COGs mainly move east. (2) There are spatial correlations between the economic development and environmental pollution COGs. The movements of the economic development COGs and environmental pollution COGs are mainly shown in longitude. The industrial wastewater pollution and industrial waste gas pollution COGs are negatively related to the economic scale and economic quality COGs, whereas the industrial wastewater pollution COG is positively related to the economic growth COG. In recent years, eastern Guangdong has a strong economic growth momentum, where the industrial development has a great impact on the spatial pattern of environmental pollution. The changes of economic development COGs and environmental pollution COGs are different overall. The changes in the economic development COGs are relatively stable, moving to the northwest slowly. Meanwhile, the environmental pollution COGs have changed.
greatly, moving from west to east, which is also a new spatial pattern of economic development and environmental pollution in Guangdong. (3) The optimization and upgrading of the industrial structure in the PRD are helping to improve the environment. The industrial wastewater and waste gas pollution COGs generally move to the eastern Guangdong, which are dominated by secondary industries. The economic growth driven by secondary industries is positively related to environmental pollution, i.e., environmental pollution increases with increase in economic growth. This conclusion is consistent with relevant research findings. Liu used the panel data of Guangdong from 2003 to 2013 to study the trend in the changes in the economy and environmental pollution under the “Policy of Dual Transfer of Labor and Industry,” confirming that eastern Guangdong has the strongest pollution transfer effect [33]. This paper also shows that the movements of the environmental pollution COGs toward the eastern Guangdong and the optimization and upgrading of the industrial structure in the PRD are helpful for improving the environment.

The possible innovation of this study is that the description of the shifting paths of the economic development and environmental pollution COGs and the analysis of the correlations between them have been established. The discussions on longitude and latitude levels can facilitate discussions about their spatial overlap and variation consistency and lead to in-depth analysis of the evolution of multifactor interactive coupling relationship patterns from the dynamic space–time perspective. On this basis, the logical paths of spatial evolution of the economic development and environmental pollution COGs are described. Cross-urban environmental management measures under the framework of sustainable development can be constructed in the PRD and the Non-PRD. All these measures can serve as a reference for the coordinated development of the economy and environment in China.

There are some limitations to this study. First, this paper uses the COG method to show the changes in spatial forces intuitively but weakens the analysis of economic development and environmental quality in terms of specific data. The method of evaluating the space moving track of these COGs can be further explained by the methods of space coupling calculation, gray correlation degree, etc. Second, for the convenience of data acquisition, the data used in this paper are for prefecture-level cities. If county-level statistical indicators are used, the analysis will be more detailed.

6.2. Suggestions

According to the above analysis results, environmental pollution COGs in Guangdong province have a negative correlation with economic scale and economic quality COGs, but positive correlation with economic growth COG. When the economic scale develops to a certain stage, optimization of the industrial structure and improvement of production efficiency can promote economic growth while alleviating environmental pollution. Therefore, it is imperative to balance the relationship between economic development and environmental governance.

First, the industrial structure is to be optimized and technological progresses be promoted. Underdeveloped regions should rationally develop secondary industries without destroying the environment or affecting economic development. Extensive production methods can be combined with new technologies, new models, and new industries. More developed regions should increase the effect of tertiary industries in driving economic growth, actively learn from the economic development experience of developed countries, and increase the potential for absorbing labor. Regional differentiation measures will make Guangdong’s industrial structure more reasonable, leading to greener and healthier economic development.

Second, the environmental and economic pressures are to be alleviated. After the “double transfer” policy, the economic development and environmental protection between the transfer-in and transfer-out areas of Guangdong’s industries cannot be coordinated with each other. Therefore, it is necessary to alleviate the environmental pressure of the transfer-in areas, unleash their growth potential, encourage low-energy, high-efficiency enterprises to settle in local areas, and help high-polluting enterprises to transform their production through policies such as tax cuts, increased investment, and sewage charges. Transfer-out areas should increase investment in ecological environmental
governance, introduce more high-tech, technologically diffusive, and inducible industries, and minimize environmental pollution to the transfer-in areas.

Third, reasonable economic growth targets are to be set. With China’s economic development entering a new normal stage, the government should abandon the “GDP only” performance appraisal mechanism. In the process of economic development in Guangdong, the industrial structure has gradually transformed into a labor-intensive and low-investment service industry. Slow economic growth is normal. Guangdong province should set reasonable economic growth targets and establish a green mechanism that links environmental protection and political performance, so as to achieve a win-win situation for environmental protection and economic development.

Author Contributions: Conceptualization, B.D. and Q.Z.; methodology, X.B.; software, B.D. and X.B.; validation, B.D. and Q.Z.; formal analysis, B.D. and Q.Z.; investigation, B.D.; resources, B.D.; data curation, X.S.; writing—original draft preparation, B.D., Q.Z. and X.B.; writing—review and editing, Q.Z.; visualization, X.B. and X.S.; supervision, L.S.; project administration, L.S.; funding acquisition, L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Project of China (2018YFC0506901), “Strategic Priority Research Program (A)” of the Chinese Academy of Sciences (XDA23030201) and “Teachers’ research ability promotion plan” of Beijing Normal University Zhuhai (201850001).

Acknowledgments: This work was supported by National Key Research and Development Project of China (2018YFC0506901), “Strategic Priority Research Program (A)” of the Chinese Academy of Sciences (XDA23030201) and “Teachers’ research ability promotion plan” of Beijing Normal University Zhuhai (201850001).

Conflicts of Interest: No potential conflicts of interest was reported by the authors.

References
1. Peng, F.M. Economic Spatial Connection and Spatial Structure of Guangdong-Hong Kong-Macao Greater Bay and the Surrounding Area Cities—An Empirical Analysis Based on Improved Gravity Model and Social Network Analysis. Econ. Geogr. 2017, 12, 54–57. (In Chinese)
2. Anonymous. Greentech Media Inc.; Global PV market’s center of gravity shifting to North America. Sci. Lett. 2008.
3. Anonymous. Center of gravity shifts for energy consumption. ASHRAE J. 2009, 51, 6.
4. Aboufadel, E.; Austin, D. A new method for computing the mean center of population of the United States. Prof. Geogr. 2006, 58, 65–69. [CrossRef]
5. Grether, J.M.; Mathys, N.A. Is the world’s economic centre of gravity already in Asia? Area 2010, 42, 47–50. [CrossRef]
6. Kandogan, Y. Globalization and shifting economic centers of gravity. Thunderbird Int. Bus. Rev. 2014, 56, 261–271. [CrossRef]
7. Niedomysl, T.; Hall, O.; Archila, B.M.F.; Ernstson, U. Using satellite data on nighttime lights intensity to estimate contemporary human migration distances. Annals Am. Assoc. Geogr. 2017, 107, 591–605. [CrossRef]
8. Ernstson, U.; Niedomysl, T. Mean center of population for Sweden, 1810–2010. Environ. Plan. 2015, 47, 1595–1596. [CrossRef]
9. Breau, S.; Toy, B.; Brown, M.; Macdonald, R.; Coomes, O.T. In the footsteps of Mackintosh and Innis: Tracking Canada’s economic centre of gravity since the Great Depression. Can. Public Policy 2018, 44, 356–367. [CrossRef]
10. Wang, J.F. Method of mass centre to analyze social and economic spatial structure of a region. J. Gansu Sci. 1992, 3, 1–5.
11. Huang, H.F. A Study of Coordinative Development between Environment and Economy and Application of GIS in the Pearl River Delta. Ph.D. Thesis, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangdong, China, 2006.
12. Hu, H.; Zheng, C.; Zhang, Q. Discussion of calculation method of focus based on GIS. Guangdong Agric. Sci. 2011, 38, 198–200.
13. Guo, B.; Tao, H.; Liu, B.; Jiang, L. Research on acquisition method of economic gravity centre based on GIS and Delaunay in complicated terrain area. Geo-Inf. Sci. 2012, 28, 55–59.
14. Lian, X. Analysis on the space evolvement track of population gravity center, employment gravity center and economic gravity center. J. Popul. 2007, 3, 23–28.
15. Lian, Y. Comparative Analysis on the Variation Track of the Economy Gravity Center and the Population-Employment Gravity Center in China. Master’s Thesis, Jilin University, Jilin, China, 2007.
16. Ge, M.; Feng, Z. Population distribution of China based on GIS: Classification of population densities and curve of population gravity centers. Acta Geogr. Sin. 2009, 64, 202–210.
17. Xu, S.; Tang, N.; Wei, D.; Li, J. The evolution of population gravity center and economy gravity center in Xi’an based on GIS. J. Northwest Univ. (Nat. Sci. Ed.) 2013, 43, 987–991.
18. Li, G.; Luo, X. Coordinated development between population and economy in the Beijing-Tianjin-Hebei region. Prog. Geogr. 2017, 36, 25–33.
19. Huang, X.; Zhao, J.; Meng, Q.; Hao, J.; Sun, Z. Study on urban expansion and gravity evolution in rapid urbanization areas based on nighttime light data—Taking Henan Province as an example. World Reg. Stud. 2019, 28, 79–89.
20. Li, Q.; Ren, Z.; Zhang, L. Space evolvement track of railway transportation gravity center in recent 30 years in China. Arid Land Geogr. 2009, 32, 119–124.
21. Tang, H.; Bao, P. Space Gravity changes of Jiangsu rice acreage and yield based on GIS. J. Nanjing Agric. Univ. (Soc. Sci. Ed.) 2014, 14, 118–124.
22. Ding, H.; Li, P. The variation contrastive analysis of economic gravity centre and regional pollution gravity centre of China: 1986–2006. Econ. Geogr. 2009, 29, 1629–1633.
23. Du, G.; Ma, M.; Liang, Z. Variation analysis of economic gravity center and pollution gravity of Shandong Peninsula Urban Agglomeration. China Popul. Resour. Environ. 2014, 24, 114–117.
24. Du, W.; Zhang, P. Research on the mechanism of economic growth and environmental pollution under new normal of economy. Soft Sci. 2017, 31, 1–4.
25. Qi, Y. Decoupling effect and gravity center trajectory of regional economic growth and carbon emissions in China. J. Tianjin Univ. Financ. Econ. 2018, 38, 17–29.
26. Han, Y. The Spatial Evolution and Correlation Analysis of Population, Economic Aggregation and Environmental Pollution in China. Master’s Thesis, Capital University of Economics and Business, Beijing, China, 2018.
27. Luo, C. A Study on the Spatial Evolution Pattern of Industrial Structure Development Level and Its Influencing Factors in Guangdong Province. Master’s Thesis, Jinan University, Guangdong, China, 2017.
28. Zheng, X. Research on the Effects of Environmental Regulation on Economic Growth in Guangdong Province. Master’s Thesis, Guangdong University of Finance & Economics, Guangdong, China, 2016.
29. Wu, Y.H. Evolvement and Comparative Analysis of Population Gravity Center and Economic Gravity Center in Qinhuangdao City Based on GIS. Adv. Mater. Res. Trans. Tech. Public Ltd. 2014, 955, 3819–3823. [CrossRef]
30. Quah, D. The global economy’s shifting centre of gravity. Glob. Policy 2011, 2, 3–9. [CrossRef]
31. Klein, L.R. Measurement of a shift in the world’s center of economic gravity. J. Policy Modeling 2009, 31, 489–492. [CrossRef]
32. Williamson, J.G. Regional inequality and the process of national development. Econ. Dev. Cult. Chang. 1965, 13, 3–45. [CrossRef]
33. Liu, Y. Industrial resettlement and environmental pollution in Guangdong Province: An empirical study on twenty-one prefecture-level cities by DID. Rev. Ind. Econ. 2016, 4, 9.
34. Grossman, G.M.; Krueger, A.B. Economic growth and the environment. Q. J. Econ. 1995, 110, 353–377. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).