INFLUENCE OF URBAN CONSTRUCTION LANDSCAPE PATTERN ON $PM_{2.5}$ POLLUTION: THEORY AND DEMONSTRATION – A CASE OF THE PEARL RIVER DELTA REGION

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Abstract. With the continuous improvement of China's urbanization level, the huge expansion of construction land has a negative impact on urban air quality, especially $PM_{2.5}$ pollution. In this paper, the relationship between the landscape pattern of urban construction land and $PM_{2.5}$ concentration is studied by using spatial exploratory analysis (Moran I) and spatial econometric analysis (SLM/SEM). The results show that: ① From 2000 to 2016, $PM_{2.5}$ pollution in the region of Pearl River Delta rose first and then dropped; In terms of spatial distribution, it showed a trend of high in the middle and low in the peripheral areas. ② The construction land in Pearl River Delta expanded obviously from 2000 to 2016, with the overall increase as high as 75.37%. At the same time, the advantages, integrity and accumulation of construction land patches in Pearl River Delta were strengthened continuously, while the degree of size breakage dropped to some extent. ③ The landscape pattern of the construction land in Pearl River Delta has obvious influences on $PM_{2.5}$ pollution: the construction area (CA) and the proportion of construction land (PLAND) have positive correlations with $PM_{2.5}$ pollution; patch density (PD) and mean nearest distance (MNN) show negative correlations with $PM_{2.5}$ pollution; ④ The increase of economic factors, including road network density (RD), average gross domestic product (AGDP) and the proportion of secondary industry output (IND), all could cause $PM_{2.5}$ pollution to rise. Among the natural factors, increase of precipitation could increase $PM_{2.5}$ pollution, while increase of wind speed could reduce $PM_{2.5}$ pollution.
Keywords: *urbanization, construction land expansion, hazy weather, $PM_{2.5}$ concentration, spatial panel model*

Introduction

As Chinese economy and urbanization keep developing continuously, urban air pollution has become one of the serious environmental problems of China (Yang et al., 2012a). As the major air pollutant and the chief culprit of hazy weather, $PM_{2.5}$ could seriously affected on atmospheric visibility (Hyslop, 2009) and human health (Yang et al., 2012b). According to the data issued by the Ministry of Environmental Protection, the average concentration of $PM_{2.5}$ in cities at prefecture level or above in China was 43 ug/m^3 in 2017, dropping 40.3% compared with 72 μg/m^3 in 2012. However, 338 cities of China at prefecture level or above had 2,311 day-time severe pollution and 802 day-time gross pollution, among which the days when $PM_{2.5}$ was the primary pollutant for severe or more serious pollutions accounted for 74.2%. Therefore, $PM_{2.5}$ pollution has become a serious problem in China. In fast development of urbanization, the land use

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types and landscape patterns of urban land also change greatly (Liu et al., 2003), and the emission source and the emission area of urban landscape play decisive roles in $PM_{2.5}$ pollution; so, changes of land use types and the landscape patterns could reflect directly the spatial differences of the emission source of pollutants (Querol et al., 2004; Li et al., 2011; Zhou et al., 2011). The most remarkable feature of urbanization is continuous increase of impervious landscapes, which could result in increase of urban pollution emissions and decrease of absorptivity, thereby leading to degradation of the ecosystem function. Therefore, the construction land with impervious landscape as the major landscape type as well as the changes of its landscape pattern are related closely with $PM_{2.5}$ pollution. So, to study the influences of landscape patterns of urban construction land on $PM_{2.5}$ pollution (Wu, 2000a; Zhang et al., 2006; Strohbach and Haase, 2012; Kadish and Netusil, 2012; Xie and Wu, 2017) is of great significance to exert the controlling effects of construction land type and its landscape pattern on $PM_{2.5}$ pollution and to promote healthy development of urban land use as well as regional ecological and security construction by optimizing spatial configuration.

Nowadays, scholars have begun to study $PM_{2.5}$ pollution together with land use type (Hankey and Marshall, 2015; Fan et al., 2018; Tian et al., 2018). Research finds that the influences of different land use types on $PM_{2.5}$ pollution differ greatly. For example, Tang et al. (2015) conducted analysis on correlations between $PM_{2.5}$ pollution distribution and land use types of Wuhan in 2013 and concluded that the construction land had significant positive influence on $PM_{2.5}$ pollution and that $PM_{2.5}$ pollution could be reduced by increasing the green area (Tang and Liu, 2015). By studying the influences of changes of urban land use on atmospheric particulate pollution, Cui (2013) concluded that the correlation coefficients between residential land and road traffic land and atmospheric particulate pollution are 0.789 and 0.743, respectively. Some other studies analyze the relations between single land use type and $PM_{2.5}$ pollution, such as urban forest (Wu et al., 2008) and types of vegetation coverage of urban green spaces (Wu, 2007; Li et al., 2014; Chen et al., 2014; Weber et al., 2014; Tang et al., 2015; McCarty et al., 2015). In addition, Vegetation cover types on urban green land and urban morphology and landscape pattern could also affect atmospheric particulate pollution, and the landscape indexes have good indicating effect on atmospheric particulates (Tang and Wang, 2007). For example, research has found that patch density in landscape pattern and landscape shape index show negative correlations with $PM_{2.5}$ pollution, while marginal density and atmospheric particulate pollution have positive correlation (Shao et al., 2004). Some other studies investigate the quantitative relations of the proportions of construction land to road area, walking and parallel index, landscape diversity and other indicators of landscape patterns with $PM_{2.5}$ pollution (Jiao et al., 2015). Generally, most of the existing researches discuss the relations between various land use types and $PM_{2.5}$ pollution from the perspective of land use changes. Though some scholars have noticed that landscape indicators have significant influences on atmospheric particulates, there are still less studies on relations between landscape pattern indexes and $PM_{2.5}$ pollution in terms of construction land systematically. As the major place for human activity and energy consumption, construction land is the most important emission source of particulate matters (Xu et al., 2016). Therefore, it is of great significance to study the influences of landscape pattern of construction land on $PM_{2.5}$ pollution. Moreover, in terms of the methods of empirical study, most of the studies are conducted on the data of time sequence; however, development of different regions is unequal and the environmental condition and land use conditions of one area could affect the neighboring regions. Time

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sequence-based analysis method neglects such spatial effect and has certain disadvantages theoretically. So, based on related theories of spatial metrology, this essay studies the spatial effects of landscape pattern of urban construction land on $PM_{2.5}$ pollution from the perspective of landscape pattern of urban construction land, and puts forward $PM_{2.5}$ governance policies, with the aim to provide theoretical basis for region control of $PM_{2.5}$ pollution.

Materials and Methods

Study area

The region of Pearl River Delta has developed economy, high level of urbanization, and strong regional overall strength. In 2016, its GDP accounted for 9.2% of the total amount of the national economy, with the level of urbanization reaching 69.2%, The details are shown in *Table 1*. However, $PM_{2.5}$ pollution in Pearl River Delta is not promising in the process of fast development of economy and urbanization. In 2016, the days when the air quality exceeds the standard of 9 cities in Pearl River Delta accounted for 10.6%, among which mild pollution covered 9.0%, moderate pollution 1.4% and severe pollution 0.2%, and the average concentration of the cities ranges within 26-38 μg/m³. On February 18, 2019, the Central Committee of the Communist Party of China and the State Council issued officially Outline of the Development Plan for Guangdong, Hong Kong, Macao Great Bay Area, in which the guiding thought and strategic location of Guangdong, Hong Kong, Macao Great Bay Area are made clear, pointing out that it is necessary to promote coordinated development of Pearl River Delta with Hong Kong and Macao so as to improve the economic development level and international competitiveness of the region of Pearl River Delta; meanwhile, the development principles of green development and environmental conservation are also put forward. Therefore, it is of great significance to analyze the correlations between $PM_{2.5}$ pollution and the landscape pattern of urban construction land in the region of Pearl River Delta and to put forward policy recommendations for high-quality development of Pearl River Delta and control of haze pollution.

Table 1. *Basic situation of cities in the Pearl River Delta region in 2016*

City	Construction land area/hm²	GDP/100 million yuan	The level of urbanization/%	Permanent Population at the Year-end/Ten thousand
Zhaoqing	40148.1	2084.02	46.08	454.4
Guangzhou	141027.3	19547.44	86.06	1404.35
Huizhou	72609.39	3412.17	69.05	477.5
Jiangmen	76120.02	2418.78	65.06	454.4
Shenzhen	87642.45	19492.6	100	1190.84
Dongguan	122226.39	6827.69	89.14	826.14
Zhongshan	49771.62	3202.78	88.2	323
Zhuhai	26507.97	2226.37	88.8	167.53
Foshan	116813.52	11423.23	96.77	1000.73

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Connotation of landscape pattern index of construction land and the mechanism of its action on $PM_{2.5}$ pollution

Landscape pattern index refers to the quantitative index that could reveal different landscape types, quantity and characteristics of spatial arrangement. As the specific manifestation of landscape heterogeneity, specifically, it refers to differences in size, shape and spatial combination of landscape patches that are formed naturally or artificially in spatial arrangement; and it is also comprehensive performance of interactions of various ecological actions in different dimensions (Wu, 2000b). Landscape pattern of urban construction land is usually divided into landscape scale, landscape structure and landscape layout. Landscape scale refers to the quantity of landscapes, landscape structure refers to the proportions of the compositions of each landscape type in the landscape pattern of some region, and landscape layout emphasizes the combination effect of patch types as well as the layout effect of the overall landscape (Beckett et al., 1998). Landscape pattern index has been applied extensively not only in the study of urban morphology and urban landscape, but also in study of the effects of the composition and structure of different land use types on biodiversity and habitats. Because landscape index is highly concentrated, easy to express, and easy to acquire (Zhou et al., 2011; Wu et al., 2015; Sun et al., 2015), it is appropriate and feasible to use the landscape index to study the influences of urban landscape patterns on $PM_{2.5}$. On one hand, differences in the attributes of different landscape structures and landscape patterns could cause local $PM_{2.5}$ to increase or decrease directly; on the other hand, changes of the surface landscape structure could cause local climate to change, which could cause the energy and material to be distributed and transmitted unevenly, thereby affecting spatial distribution of urban atmospheric pollutants (Liu et al., 2015; Tong et al., 2016).

Type, shape, size, quantity and spatial combination of landscape patches are results of interactions of various interfering factors; meanwhile, they could also affect the ecological process and peripheral effects of the region (Wu, 2007). The existing studies mainly quantize landscape patterns from the perspectives of patch level, type level and landscape pattern (Loehle and Wein, 1994). On account of this, in this study, analysis framework of the influence of landscape pattern on $PM_{2.5}$ pollution is constructed from three aspects, including landscape area (scale), landscape composition (structure) and landscape layout (see *Fig. 1*). With the continuous progress of urbanization, the landscape pattern will evolve accordingly and affect the concentration of air pollutants. First of all, progress of urbanization will cause the expansion of urban construction land area (CA), increase the landscape of emission sources of air pollutants, and affect the concentration of air pollutants (Tan, 2009). At the same time, this process will lead to increase of the proportion of construction land (PLAND) and landscape dominance of air pollutant emission sources, as well as decrease of landscape dominance of sinks, which will also have an impact on air pollutant emissions (Wang, 2019). In addition, with gradual improvement of the urbanization level, the compactness and integrity of the landscape patch layout of construction land will continue to strengthen. For example, the patch density (PD) and the mean nearest distance (MNN) will decrease, and the largest patch index (LPI) will increase. The change of the landscape layout of construction land means that the distribution of air pollutant emission sources will be more concentrated and the scale effect will be enhanced, which would in turn affect the concentration of air pollutants (Zhang et al., 2019).

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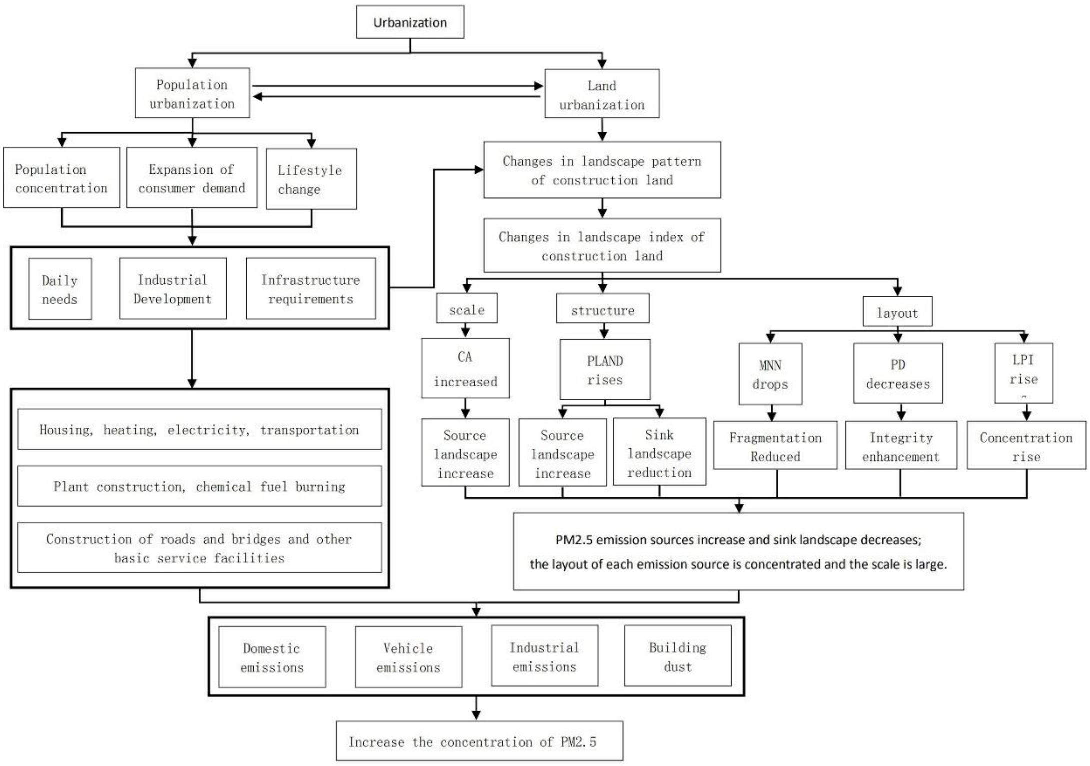

Figure 1. *Analysis framework of the influencing mechanism of landscape pattern index of construction land on $PM_{2.5}$ pollution*

Urbanization is a comprehensive and complex process, which includes mainly land urbanization and population urbanization (Liang et al., 2019). The most direct result of land urbanization is expansion of construction land, which could cause changes of the landscape pattern of urban construction land (Chen et al., 2013). In the process of land urbanization, as the carrier of human survival and development, land could affect population urbanization by attracting the population to gather continuously. Continuous improvement of population urbanization not only could promote population gathering, but also could change the residents' life styles and increase their consumption demands. All these changes could increase demands for capital construction, living needs and requirement for industrial development, resulting in sharply increase of demands for houses, commercial service and industrial lands, which could change the landscape patterns of urban construction land to a large extent. Therefore, it is required synchronous development of land urbanization to meet the survival and development of the population (Fan et al., 2016), that is to say, population urbanization and land urbanization are interactive. Since emission of $PM_{2.5}$ pollution is determined mainly by the emission source and area of urban landscape (Sun, 2017), changes of landscape pattern of urban construction land caused by urbanization could reflect indirectly the changes of $PM_{2.5}$ pollution as well as the spatial differences. Relevant studies show that the changes of the landscape pattern of urban construction land are mainly manifested in three aspects: changes in landscape scale, changes in landscape structure, and changes in landscape layout (Chen et al., 2002). Based on this, this study selects the construction area (CA) to represent the scale of the landscape pattern of urban construction land, the proportion of

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construction land (PLAND) to represent the structure of the landscape pattern of urban construction land, the largest patch index (LPI), patch Density (PD) and mean nearest distance (MNN) to represent the layout of urban construction land. With these five specific quantitative indexes, the law of functions between landscape pattern of urban construction land and $PM_{2.5}$ pollution are studies from different dimensions.

Specific effects of landscape pattern of urban construction land on $PM_{2.5}$ pollution are as follows: ① At the level of scale, with continuous improvement of urbanization, the scale of urban construction land keeps expanding, with increase of impervious surface as well as flying dust and construction dust, which could promote $PM_{2.5}$ pollution. In addition, as the major place for human activities, expansion of construction land has significant gathering effect of population. With the population keeps flowing in and gathering, plenty of demands for electricity, heating, traffic, industrial development and garbage disposal come up one after another, which could cause burning of abundant fossil fuel, resulting in increase of $PM_{2.5}$ pollution, therefore, the increase of urban construction land could cause increase of $PM_{2.5}$ pollution. ② At structural level, increase of the proportion of construction land shows that the land use types of $PM_{2.5}$ sourced landscape which is the carrier of various $PM_{2.5}$ emission sources are increasing, while the land use types of converged landscape represented by greenbelt and forest are decreasing. Significant changes in physical characteristics of the earth surface (roughness, reflectivity, soil water content, etc.), drive changes in climate, soil, hydrology, and landform eco-environmental factors, which in turn could affect regional material energy cycles and eco-chemical process, and affect $PM_{2.5}$. Because of finiteness of land resource, increase of "$PM_{2.5}$-sourced landscape" land use types and decrease of "converged landscape" land use types in the region will inevitably result in rise of $PM_{2.5}$ pollution. So, increase of the proportion of construction land could bring in rise of $PM_{2.5}$ pollution. ③ At the level of layout, larger largest patch index represents stronger integrity of urban construction land patches in the region, and the centralized continuity between the construction land patches is increased, which means that the scale of the city is keeping expanding and enlarging. During this process, the attracting and gathering effects of cities to population and industries are enhanced, which could cause a large increase of domestic emission and industrial waste gas, forming scale effect on $PM_{2.5}$ emission, which could promote $PM_{2.5}$ pollution. The greater the mean nearest distance and the larger the patch density, the worse the agglomeration between patches of the construction land in the area would be, and the stronger the fragmentation would be. Since the distance between the patches of the construction land is large and the construction land of unit area is segmented into small patches artificially or naturally, the scale of such city is relatively smaller and it is hard to form large-scale living quarters, commercial service areas and industrial parks. $PM_{2.5}$ emission sources are distributed in discrete type and it is hard to form large-scale emission of domestic gas and industrial waste gas, resulting in weak urban heat island effect. Therefore, increase of mean nearest distance and patch density could inhibit $PM_{2.5}$ pollution. Based on the above analysis, it could be seen that the stronger integrity of urban construction land and higher aggregation extent could improve $PM_{2.5}$ pollution; otherwise, large fragmentation could inhibit $PM_{2.5}$ pollution.

Data sources

In this paper, the annual average $PM_{2.5}$ concentration of prefecture-level cities in Pearl River Delta from 1998 to 2016 is taken as the explanatory variable, the landscape pattern index of construction land in prefecture-level cities in Pearl River Delta is taken as the

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core explanatory variable, and social and economic factors (road density, population density, per capita GDP, proportion of secondary industry) and natural factors (wind speed, rainfall) are added as the relevant control variables, to explore the impact mechanism of construction land landscape pattern on $PM_{2.5}$ in the Pearl River Delta with spatial analysis method. The specific attributes of each indicator are shown in *Table 2*.

Table 2. *Variable description*

Variables	Level I index	Level II index	Definition of index
Landscape pattern	Landscape area	Construction area (CA)	Total area of construction land, which could reflect the landscape scale of construction land.
	Landscape composition	Proportion of construction land (PLAND)	Proportion of construction area to total land area, which could reflect the landscape dominance of construction
	Landscape layout	Patch density (PD)	Number of patches of construction land in unit area, which could reflect the fragmentation of the construction land.
		Largest patch index (LPI)	Proportion of the area of the largest patch of the construction land to the area of the total construction land, which is used to determine the overall degree of construction land patches.
		Mean nearest distance (MNN)	Sum of the nearest distances between the patches of the construction land divided by total number of the patches, which is used to reflect the aggregation degree of the construction land
Control variables	Road factors	Road density (RD)	Road mileage/total land area, which could reflect the intensity of automobile exhaust emissions
	Population factors	Population density (POPD)	Population/total land area, which could reflect the life emission intensity
	Economical factors	GDP per capita (AGDP)	GDP/total population, which could reflect the intensity of economic energy consumption
	Industrial structure	Proportion of secondary industry (IND)	Yield of secondary industry/GDP, which could reflect the industrial emission intensity.
	Natural factors	Rainfall (RAIN)	Mean annual precipitation, which could reflect the intensity of humidity.
		Wind speed (WIND)	Annual average wind speed, which could reflect the intensity of air flow
Explained variables	$PM_{2.5}$	Average $PM_{2.5}$ concentration ($PM_{2.5}$)	Annual average $PM_{2.5}$ concentration, which could reflect the $PM_{2.5}$ pollution degree

The data sources involved in this paper are as follows:

(1) Land use data: The land use data come from Landsat series remote sensing image data with 30 m × 30 m resolution published by Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences. Based on the availability, time-efficiency and expressivity of data, the image data of 2000, 2005, 2010 and 2016 are adopted as the land use data interpreting map. At the same time, to guarantee the abundance of the expressions of the remote-sensing images as well as the accuracy of the interpreting results, the shooting time of the images is selected to be within the last ten days of May and the middle ten days of June, when the cloudage is less than 10%. Based

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on the above image data, the urban construction land use data of all stages in the research area are sorted, extracted and calculated with Arcgis10.3 and Fragstats4.2 software.

(2) $PM_{2.5}$ data: The data of $PM_{2.5}$ pollution adopted in this essay are acquired based on the global historical $PM_{2.5}$ annual mean raster dataset (http://sedac.ciesin.columbia.edu) from 1998 to 2016 issued by International Earth Science Information Network Center of Columbia University, the aerosol optical depth (AOD) of which is inversed by geographical weighted regression method with various satellite instruments, including NASA MODIS, MISR and Sea-WIFS, to obtain the mean concentration of $PM_{2.5}$ of all cities in the Pearl River Delta. The raster data have the characteristics of wide coverage area (55°S~70°N), long time sequence (19a) and high precision (with the resolution of 1 km × 1 km). Compared with the data of air pollutant obtained based on the ground monitoring point, the global air pollution data retrieved by remote sensing have better spatial continuity, with which the spatial distribution and changes of the pollutants can be detected conveniently for numerical computation. It has been proved that the data can be used to study the relations between landscape pattern and air pollutant (Bechle et al., 2017). In this essay, $PM_{2.5}$ pollution is analyzed from the perspective of landscape pattern index of the construction land, so, emphasis should be laid on the integration with the land use data in model construction. That is why the data of 2000, 2005, 2010 and 2016 are taken as the explained variables in this study.

(3) Socioeconomic data: Based on previous studies (Guo et al., 2018; Han, 2018), this essay adopts road, population, economy and industrial structure as the control variables of socioeconomic attributes, among which GDP per capita, industrial structure and population data come from Statistical Yearbook of Guangdong Province of the corresponding year, and the road mileage comes from China City Statistical Yearbook of the corresponding year. Specific processing methods and attributes of the indexes are shown in *Table 2*.

(4) Natural condition data: Studies have shown that the humidity and flow speed of air have a significant effect on $PM_{2.5}$ (Sun et al., 2020). However, due to the high collinearity of the humidity data in the Pearl River Delta, this essay adopts amount of precipitation and wind speed as the control variables to study the influences of natural weather conditions. The data comes from the annual value of the prefecture-level cities in Pearl River Delta in 2000, 2005, 2010 and 2016 China Meteorological Data Network (http://data.cma.cn/).

Methodology

Landscape pattern index

The landscape pattern indexes are selected from three aspects, landscape area, landscape composition and landscape layout. Fragstats4.2 software is used to calculate the interpreted remote-sensing image of the land utilization to obtain the landscape indexes. Calculation formula of landscape index is as the *Table 3*.

The larger the value of CA, the larger the scale of construction land; the larger the value of PLAND, the higher the proportion of the urban construction land to the total area is; PD could reflect the fragmentation of urban construction land, the bigger the value is, the higher the degree of fragmentation is; LPI could reflect the integrity of urban land, the bigger the value is, the higher the integrity of the urban land is; MNN could reflect the aggregation degree of regional urban land, the smaller the value is, the stronger the cohesiveness of the urban land is.

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Table 3. *Calculation formula of landscape index*

Categories	Metrics	Formulas
Landscape scale	Construction land area (CA)	$CA = \sum_{i=1}^{n} a_i$
Landscape composition	Proportion of construction land (PLAND)	$PLAND = \frac{\sum_{i=1}^{n} a_i}{A} \times 100$
Landscape layout	Construction land Patch density (PD)	$PD = \frac{n}{A}$
	Construction land Largest patch index (LPI)	$LPI = \frac{\max_{0<i\le n} a_i}{A}$
	Construction land Mean nearest distance (MNN)	$MNN = \frac{1}{n} \min_{0<i\le n} h_i$

i refers to some patch of urban construction land within the research unit, *n* is the number of the patches of urban construction land within the research unit, and a_i is the area of the *i*-th patch of urban construction land within the research unit (hm^2), *A* is the total area of the research unit (hm^2), h_i is the Euclidean distance of the patch that is the nearest to the *i*-th patch (m)

Spatial econometric model

Spatial autocorrelation refers to potential interdependency between the observed data of some variables within the same distribution area. Tobler (1970) once pointed out "The first law of geography: Everything is related to everything else, but things closer are more relevant than things far away." So, this essay adopts spatial autocorrelation test to measure whether $PM_{2.5}$ pollutions in different regions are interdependent. If the spatial autocorrelation test is passed, a spatial econometric model is adopted for modeling; otherwise, a linear regression model is used for regression analysis. At present, two common indexes for spatial autocorrelation test are Moran's index I and Geary's index C. In this essay, Moran's I index is adopted to conduct spatial test, as shown by formula *Eq.1*:

$$Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sigma^2 \sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}} = \frac{\sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}\left(x_i - \frac{1}{n}\sum_{i=1}^{n} x_i\right)\left(x_j - \frac{1}{n}\sum_{i=1}^{n} x_i\right)}{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \frac{1}{n}\sum_{i=1}^{n} x_i\right)^2 \sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}} \quad \text{(Eq.1)}$$

where, x_i and y_i are the attribute values of regions i and j; $\bar{x}$ is the mean value of the attribute value of the regions ; w_{ij} is the weight matrix of spatial position. when i is adjoined to j, w_{ij}=1; if i is not adjoined to j, w_{ij}=0; σ^2 is the variance of the attribute value; n is the sum of the spatial units.

Environmental pollution has high spatial autocorrelation (Maddision, 2005; Zhu et al., 2010), while high geographical aggregation of construction landscape has strengthened the spatial dependency of environmental pollution, so, spatial correlation should be included in studies on correlations between landscape pattern index of construction land and particle pollution. The premise in the classical econometric model is the premise of strict assumptions of spatial homogeneity and independence of the sample to be studied, and fixed explanatory variables. At the same time, common econometric model ignores

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the spatial correlation of the residual terms when applying ordinary least square for parameter simulation, resulting in large deviation between the estimation result of the model and the actual meaning. Therefore, the spatial econometric model is required to effectively solve the problems of the variables, such as spatial dependence and spatial correlation. While, conducting empirical studies by using spatial measurement method, the model could be divided into two types based on different impact ways of spatial terms, that is, Spatial Lag Model (SLM) and Spatial Error Model (SEM). The SLM and SEM established in this essay are shown by Formula *Eq.2* and Formula *Eq.3*.

$$P_{it} = \rho W_{P_{it}} + \alpha_0 + \alpha_1 CA + \alpha_2 PLAND + \alpha_3 PD + \alpha_4 LPI + \alpha_5 MNN + \alpha_6 X_{it} + \varepsilon_{it} \quad \text{(Eq.2)}$$

where, $\varepsilon_{it} \sim N(0, \sigma_{it}^2)$,
and where, *i* and *t* are the data of the *i*-th prefecture-level city in the region of Pearl River Delta in the *t-th* year. *P* refers to $PM_{2.5}$ pollution, ρ is the spatial regression coefficient, which reflects the spatial dependency between the observed values of the samples, i.e., the direction and strength of the functions of $PM_{2.5}$ pollution value W_P of the neighboring prefecture-level city in Pearl River Delta on the W_P pollution value *P* of the local region. *W* is $n \times n$ spatial weight matrix. In this essay, spatial adjacency weight matrix is adopted, that is, when local prefecture-level city *i* is adjourned to prefecture-level city *j*, *W*=1; if city *i* is not adjourned to city *j*, *W*=0. W_P is the spatial lag dependent variable, which reflects the extent of the influence of spatial distance on $PM_{2.5}$ in prefecture-level cities in the Pearl River Delta. CA is the area of the construction land, PLAND is the proportion of construction land types, PD is the patch density of the construction land, LPI is the largest patch index and MNN is the mean nearest distance between the patches. *X* is the other control variable that could affect environmental pollution, including road density, population density, GDP per capita, proportion of secondary industry, precipitation, and wind speed. ε_{it} is random error term vector.

$$P_{it} = \alpha_0 + \alpha_1 CA + \alpha_2 PLAND + \alpha_3 PD + \alpha_4 LPI + \alpha_5 MNN + \alpha_6 X_{it} + \varepsilon_{it} \quad \text{(Eq.3)}$$

where, $\varepsilon_{it} = \lambda W_{it} + \mu_{it}$, $\mu_{it} \sim N(0, \sigma_{it}^2)$.

In the formula *Eq.3*, parameter λ is spatial error coefficient, which evaluates the spatial dependency of the observed value of the sample, that is, the degree and direction of the influences of $PM_{2.5}$ of the neighboring prefecture-level city in Pearl River Delta on $PM_{2.5}$ pollution of the local region. Different from SLM model, there is error term in the spatial dependency in SEM model, which could measure the influence degree of error impact of dependent variable of the neighboring region on the observed value of the local. μ_{it} is the random error vector in normal distribution.

Results

Spatial-temporal change characteristics of $PM_{2.5}$ pollution in Pearl River Delta

Time change characteristics

It can be seen from *Fig. 2* that $PM_{2.5}$ pollution in the region of Pearl River Delta generally increases first and then decreases, which is mainly divided into three phases:

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① Phase of fast growing: During 2000 to 2005, prefecture-level cities in Pearl River Delta experienced a phase of fast growing, when the annual growth of Guangzhou was 3.84 μg/m^3, the highest growth of all the cities. Zhuhai had the smallest growth, which was 1.86 μg/m^3. ② Phase of slow growing: During 2005 to 2010, the $PM_{2.5}$ pollution values of most cities in Pearl River Delta were rising slowly, among which Zhaoqing had the largest annual growth, which was 0.38 μg/m^3, and Zhongshan had the smallest growth, which was 0.02 μg/m^3. The maximum annual growth was 1/5 of the minimum annual growth of the phase of fast growing. During this period, $PM_{2.5}$ pollution in Guangzhou, Shenzhen and Dongguan showed descending tendency, with the annual descending degree of 0.44 μg/m^3, 0.16 μg/m^3 and 0.18 μg/m^3, respectively. The possible reason could be that the year of 2010 was the year when the Asian Games was held in Guangzhou, when air quality assurance measures were taken on pollution sources of industry, automobile and flying dust in the city of Guangzhou and the surrounding areas, which has inhibited to some degree urban particle pollution; so, $PM_{2.5}$ pollution in Guangzhou as well as Shenzhen and Dongguan (which are display windows to the outside world) were reduced to some degree (Hu et al., 2013). ③ Phase of slow declining: From 2010 to 2016, $PM_{2.5}$ pollution in all the prefecture-level cities in Pearl River Delta declined slowly, among which Zhaoqing had the largest descent degree, with the annual descent value of 1.78 μg/m^3, and Huizhou had the smallest descent degree, with the annual descent value of 0.98 μg/m^3. Compared with the annual growth during the phase of fast growing, the annual descent degree of this phase was low, so, it was the phase of slow declining. However, by 2016, $PM_{2.5}$ pollution of all the prefecture-level cities was higher than that in 2000. The main reason for this change is that industrialization and urbanization in the region of Pearl River Delta was developing rapidly during 2000-2005, which was manifested mainly in rapid development of the secondary and tertiary industries, expansion of construction land area, significant accumulation of population and industries, as well as a series of domestic emissions, industrial waste gas, and automobile exhaust that were generated in large quantities, causing rapid increase of $PM_{2.5}$ pollution (Zhou et al., 2019). During 2005 to 2010, the region of Pearl River Delta began to upgrade and transform it industries for the first time in China, so the proportion of the secondary industry decreased, while the proportion of the tertiary industry represented by high-tech technology and services increased, resulting in significant changes of the industrial structure (Zhao, 2011). Different industrial structures have different influences on environment. Generally speaking, in the three industrial structures, the pollution intensity of the secondary industry is significantly higher than that of the primary and tertiary industries. This is because industrial production of the secondary industry is mostly extensive production with high consumption intensity and high consumption amount, while the tertiary industries are mainly intelligent-intensive enterprises and service industries, whose energy-consuming intensity and emission intensity are far lower than those of the second industry (Zhang, 2009). Therefore, with the optimization and upgrading of the industrial structure in the region of Pearl River Delta, the $PM_{2.5}$ pollution in this region was slowed down also. During the period of 2010-2016, with continuous deepening of government regulations and ecological development concept, the industrial structure of the region of Pearl River Delta had been continuously optimized and upgraded, the popularity rate of clean energy technology was increased continuously, and tasks of energy conservation and emission reduction were introduced, so, $PM_{2.5}$ pollution started to decline (Luo et al., 2018).

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Figure 2. *Bar graph of time sequential changes of $PM_{2.5}$ concentration in Pearl River Delta*

Evolution of spatial features

Natural breakpoint method is adopted to classify the $PM_{2.5}$ pollution data of four phases of the region of Pearl River Delta into four types, the spatial distribution characteristics of which are shown in *Fig. 3*. It could be seen from *Fig. 3* that $PM_{2.5}$ pollution values in the region of Pearl River Delta generally shows the feature of "high in the middle and low in the surrounding areas". In 2000, the $PM_{2.5}$ pollution value in the region of Pearl River Delta was at a relatively low level. Even Foshan and Zhongshan, which had high $PM_{2.5}$ pollution values in the central region, reached only moderate pollution level, Guangdong, Dongguan, Shenzhen, Zhuhai and Jiangmen were at low pollution levels, and Zhaoqing and Huizhou on both wings of the region were in areas with low $PM_{2.5}$ pollution level. Till 2005, $PM_{2.5}$ pollution value of the region of Pearl River Delta began to rise and the area with high pollution showed expanding tendency in space. Guangzhou, Shenzhen, Foshan and Zhongshan in the middle area had developed into highly $PM_{2.5}$-polluted area, Zhaoqing, Jiangmen, Zhuhai and Shenzhen became highly polluted area from the original low-polluted area or lower polluter area, and Huizhou became moderate polluted area from the original low polluted area. In 2010, the spatial pattern of $PM_{2.5}$ pollution in the region of Pearl River Delta did not change much, with only Shenzhen descending from the original higher polluted area to moderately polluted area; In 2016, compared with the previous period, the $PM_{2.5}$ pollution value in the region of Pearl River Delta had an overall descending trend. Guangzhou, Dongguan, Foshan, and Zhongshan in the middle had lowered from the original highly polluted areas to areas with higher pollution, Zhaoqing and Jiangmen lowered from higher polluted area to moderately polluted area, and Huizhou and Shenzhen descended from moderately polluted area to less polluted area. It could be seen from the four-phase spatial pattern of $PM_{2.5}$ pollution in the region of Pearl River Delta that though it had the rule of rising first and then descending in the sequence of time, it still maintained the spatial pattern of "high in the middle and low in the surrounding area". The major reason for such spatial distribution characteristic is that in middle area of Pearl River Delta, the level of economic development and urbanization are higher, the population size is larger, the secondary and tertiary industries occupy a higher proportion, the industrial waste gas, the domestic discharge and automobile exhaust are more severe, and $PM_{2.5}$-sourced landscape dominance is higher and distributed in concentration. All of these factors are important emission source of particle matters; thereby high-valued aggregation areas of $PM_{2.5}$

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pollution are formed. With relatively low level of economic development and urbanization, the scale effect of the population and the proportion of secondary and tertiary industries in the surrounding areas of Pearl River Delta are relatively low, so, are also relatively less industrial waste gas, domestic discharge and automobile exhaust. In addition, the $PM_{2.5}$ sourced landscape in these areas are scattered and their dominance is low, so the $PM_{2.5}$ pollution value is low (Wang, 2017).

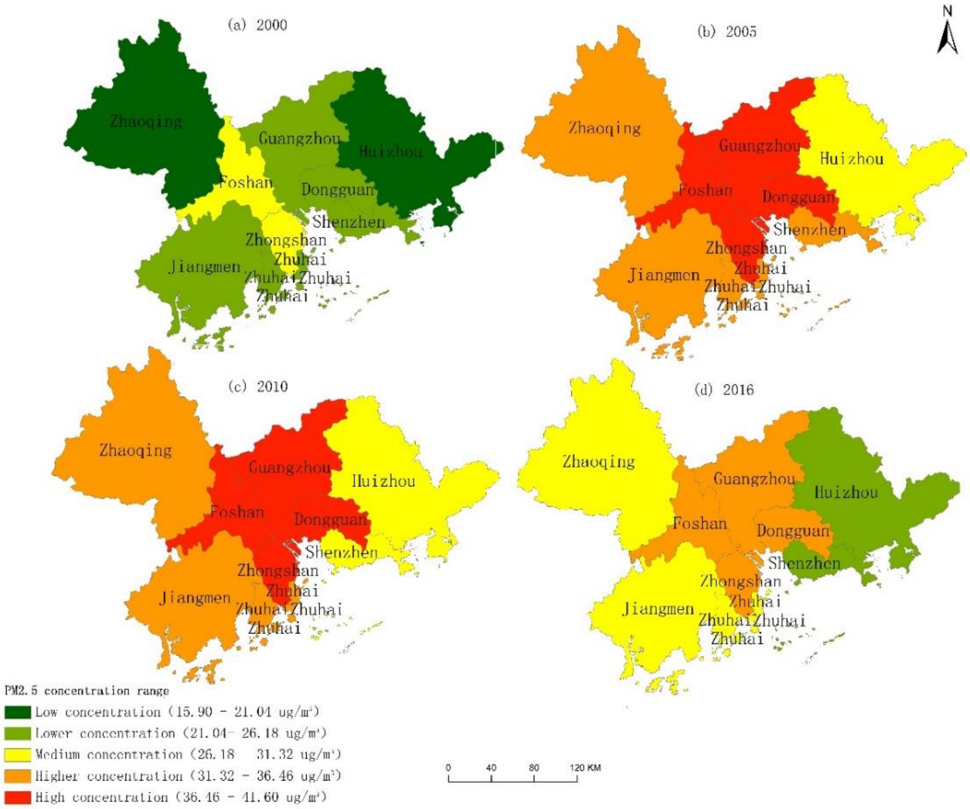

Figure 3. *Spatial changes of $PM_{2.5}$ pollution in the region of Pearl River Delta*

Change characteristics of landscape pattern of urban construction land in the region of Pearl River Delta

Landscape area

As shown in *Fig. 4,* the construction area (CA) shows increasing tendency with years in the cities of Pearl River Delta. Through analysis, it is found that changes of the construction area in the region of Pearl River Delta experience mainly two stages: ① Stage of rapid growth (2000-2005): During this stage, the process of urbanization was accelerated and urban expansion was serious. ② Stage of slow growth (2005-2016): Affected by economic and other factors, the process of urbanization had slowed down, and urban expansion had declined. In addition, with continuous progress of the society, the public began to pay more attention to resource conservation and ecological development, urban intensive and efficient development had gradually become a consensus, and urban expansion contracted further. From 2000 to 2016, Guangzhou was the city where the area of construction land increased the most, rising from 79,904.43 hm^2 to 141,027.30 hm^2, with the percentage gain of 76.49%; while Zhuhai was the region

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where the area of the construction land increased the least, from 18,502.92 hm^2 in 2000 to 26,507.97 hm^2 in 2016, increasing by 8,005.05 hm^2, with the percentage gain of 43.26%. Generally, the total area of construction land in the region of Pearl River Delta was increased obviously. In 2000, the total area was 417,908.61 hm^2, and till 2016, it expanded to 732,866.76 hm^2, increasing 314,958.15 hm^2, with the percentage gain of 75.37%. Thus, it could be seen that the region of Pearl River Delta had experienced a rapid process of urbanization from 2000 to 2016, during which the area of construction land increased significantly.

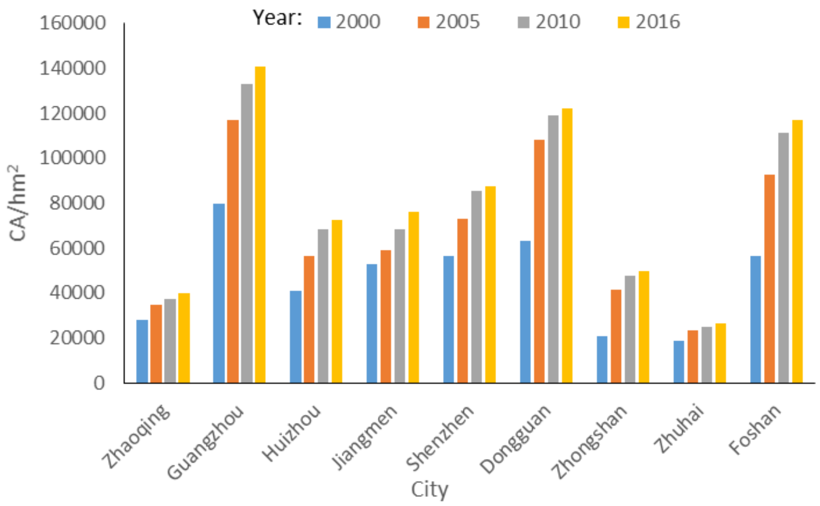

Figure 4. *Pearl River Delta Region Urban Construction Land Area (CA) Change Chart*

Landscape composition

It could be seen from *Fig. 5* that the proportion of construction land (PLAND) of the cities in the region of Pearl River Delta from 2000 to 2016 is basically similar in the changing law of the construction land area (CA), showing increasing tendency with years. Through comparison, it is found that the proportion of construction land (PLAND) in the Pearl River Delta experienced a period of rapid growth from 2000 to 2005; during 2005-2010, the growth slowed down; and till 2010-2016, the growing speed declined further, tending to steady slow growth. The possible reason might be that from 2000 to 2005, Chinese economy grew rapidly, and the process of urbanization was accelerated. As one of the economic development centers of China, it is inevitable that the region of Pearl River Delta would have more demands for construction land, resulting in rapid increase of the proportion of construction land (PLAND). Till 2005-2010, affected by market environment, economic crisis and other factors, the process of urbanization began to slow down and the demands for construction land were reduced also. During 2010-2016, Pearl River Delta had stricter requirements for resource conservation and green development, the concept of urban development transformed from extensive type to descending, digging and other vertical development, and the expansion rate of construction land began to slow down further. By 2016, the proportion of construction land (PLAND) of Dongguan increased the most, increasing 24.57%, while that of Zhaoqing increased the least, increasing 0.80%. Generally, PLAND in the region of Pearl River Delta was increased obviously, averaging 10.58%.

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Figure 5. *Pearl River Delta Region Proportion of Construction Land (PLAND) Change Chart*

Landscape layout

Landscape layout emphasizes the combined effect of patch types in space as well as the layout effect of the entire landscape (Peng et al., 2006). The characterization factors are mainly divided into three aspects: fragmentation, integrity and cohesiveness. So, in this essay, patch density, largest patch index and mean nearest distance are adopted to assess the characteristics of landscape layout of the construction land in the region of Pearl River Delta.

Fragmentation is mainly expressed by patch density (PD) of the landscape. The changing laws (*Fig. 6*) of patch density in the cities are mainly classified into two types: one is U-shaped trend, that is, the patch density decreases first and then increase; and the other is increase by year. Regions that show U-shaped trend include Dongguan, Foshan, Guangzhou, Shenzhen, Zhongshan, and Zhuhai; regions where PD increases by year include Huizhou, Jiangmen and Zhaoqing. Through further analysis, it could be found that regions showing U-shaped trend are mainly cities with higher economic development level, while Huizhou, Jiangmen and Zhaoqing showing the trend of increase by year have relatively lower economic development level. The possible reason could be that with continuous development of economy and urbanization, the city size is keep increasing, the concentration of urban construction land is strengthened and the patch density is lowered. When the level of urbanization is increased further, population, resources, and ecological capacity of the central city reach their limits. To alleviate the pressure on the downtown, development of new urban areas would become an inevitable choice, and so the patch density begins to increase gradually again. Due to relatively lower economic and urbanization levels as well as weak agglomeration effects, Huizhou, Jiangmen, and Zhaoqing have not formed large-scale central cities. The urban layout is relatively scattered and the patch density is high. Compare with 2000, the patch density of Dongguan in 2016 descended the most, dropping 0.14, and PD of Zhuhai descended the least, dropping only 0.01. Zhaoqing, Huizhou and Jiangmen showed increasing trend, rising 0.01. Generally, the patch density (PD) of urban construction land in Pearl River Delta decreased 0.24, indicating that the degree of breakage of the urban construction land in Pearl River Delta decreased.

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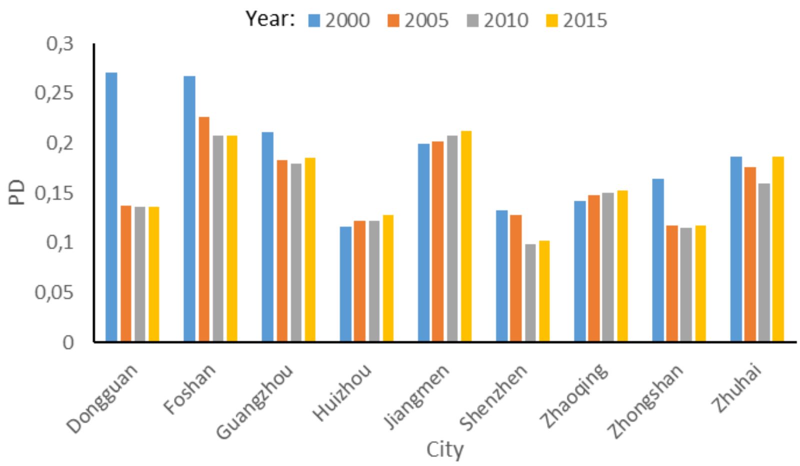

Figure 6. *Pearl River Delta Region Urban Construction Land Patch Density (PD) Change Chart*

Integrity is represented by the area of the largest patch. During 2000-2016, the largest patch index (LPI) in the region of Pearl River Delta showed the trend of increase by year (*Fig. 7*), among which, during 2000-2005, the increasing tendency was the most obvious while during 2005 to 2016, the integrity grew slowly. The main reason is that during the period of rapid development of economy, the level of urbanization in various cities increases significantly, large-scale urban districts have begun to form, the collaboration and integrity of cities are improved significantly, and the largest patch index also increases rapidly; with the slowdown of economic development and urbanization, the expansion of large-scale cities begins to decrease, and the growth rate of the largest patch index is slowed. By 2016, the largest patch index of Dongguan increased the most, increasing 26.3698, while that of Zhaoqing increased the least, increasing 0.05. On the whole, during 2000 to 2016, the largest patch index increased by an average of 7.17 in the region of Pearl River Delta, indicating that the integrity of urban construction land in the region of Pearl River Delta is strengthened.

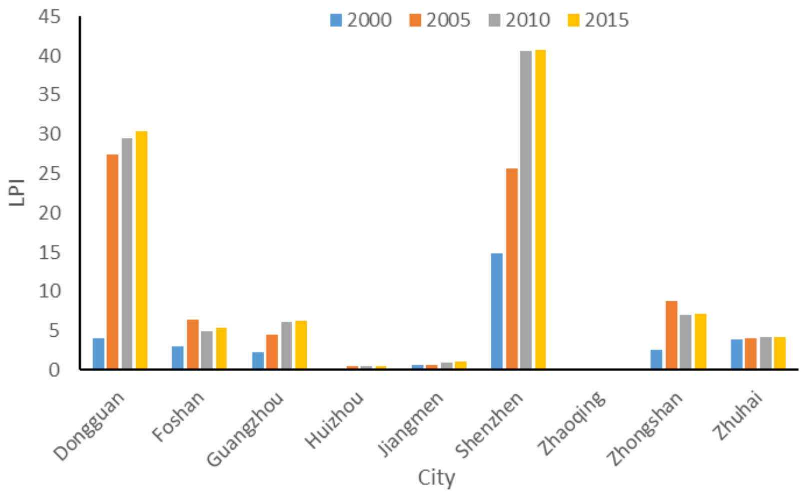

Figure 7. *Pearl River Delta Region Urban Construction Land Largest Patch Index (LPI) Change Chart*

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Cohesiveness is represented by the distance between the patches of the landscape. The mean nearest distance (MNN) of the construction land in the region of Pearl River Delta generally show U-shaped variation (*Fig. 8*), i.e., decreasing first and then rising. The reason is that the aggregation effect and driving effect caused by continuous increase of urbanization, expansion of urban scale and large-scale cities are enhanced continuously, the construction lands develop gradually into concentrated areas, and the average nearest distance keeps decreasing. After the scale of the city reaches certain level, the potential of urban development begins to decline, the government begins to plan construction of sub-central cities and satellite cities, therefore, concentration of the construction land begins to decline, and the average nearest distance increased. During 2000 to 2016, the city where the mean nearest distance of construction land in Pearl River Delta declined the most was Shenzhen, dropping by 95.8791 m, while the city with the smallest decline was Guangzhou, dropping by 1.40 m. Generally, the mean nearest distance of the construction land in the region of Pearl River Delta decreased 42.66 m, indicating that the cohesiveness of the urban construction land of the region of Pearl River Delta from 2000 to 2016 was increased.

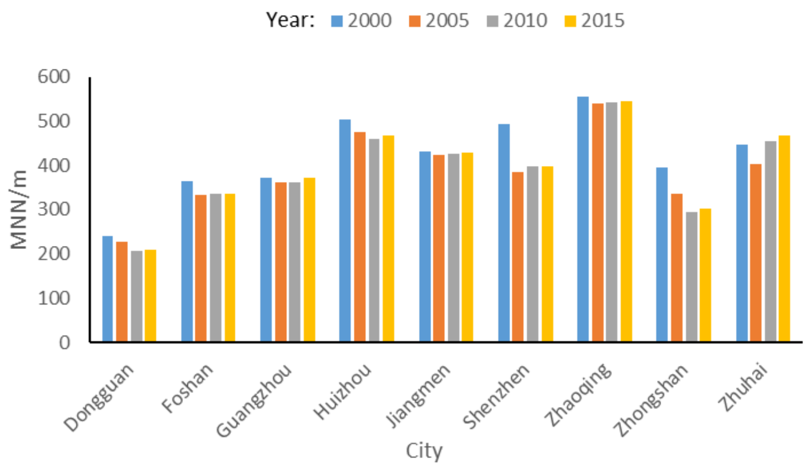

Figure 8. *Pearl River Delta Region Urban Construction land Mean Nearest Distance (MNN) Change Chart*

Spatial panel econometric analysis of the influences of landscape pattern of urban construction land on $PM_{2.5}$ pollution

Spatial autocorrelation test

Moran's I statistic is adopted in this essay to conduct spatial autocorrelation test on $PM_{2.5}$ pollution of four phases in 9 cities in the region of Pearl River Delta. If the spatial autocorrelation test is passed, spatial econometric model would be used to conduct regression analysis on $PM_{2.5}$ pollution in the region of Pearl River Delta, the landscape pattern of urban construction land and relevant control variables; otherwise, OLS method would be adopted to conduct modeling analysis. According to the results of the spatial autocorrelation test shown in *Table 4*, there is a significant spatial correlation between $PM_{2.5}$ pollution in 9 cities in the region of Pearl River Delta. Moran's I values of these four phases are 0.496, 0.411, 0.333 and 0.483, respectively, all passing the significance test at 5% significance level, indicating that $PM_{2.5}$ pollution in the region of Pearl River

Delta has significant positive spatial correlation. Therefore, when studying the correlation between $PM_{2.5}$ pollution in the region of Pearl River Delta and landscape pattern of urban construction land, it is necessary to take spatial correlation into consideration.

Table 4. *Spatial autocorrelation test of $PM_{2.5}$ pollution in the region of Pearl River Delta*

Years	Moran's I		
2000	Statistics	Z	P-value
	0.496	2.701	0.0070
2005	Statistics	Z	P-value
	0.411	2.22	0.026
2010	Statistics	Z	P-value
	0.3330	1.9890	0.047
2016	Statistics	Z	P-value
	0.483	2.511	0.0120

Analysis of spatial panel econometric results

Based on the results of the spatial autocorrelation test mentioned above, two classical models for spatial econometrics are adopted in this essay, spatial lagging model (SLM) and spatial error model (SEM), to analyze the correlations between $PM_{2.5}$ pollution and the landscape pattern of urban construction land as well as the related control variables in the region of Pearl River Delta. According to the results of LM test and Hausman test, it is determined which model is better among SLM / SEM model, fixed effect model/random effect model. According to the LM test results reported in *Table 4*, it could be seen that LM (lag) statistics is larger than LM (errow) and more significant, and based on the principle of LM test (Burridge, 1980), it could be determined that SLM model adopted in this essay is better. The results of Hausman test rejected the null hypothesis of random effects at the significance level of 1%, that is, fixed effect is more suitable in this essay. So, the regression results of the fixed effect model of SLM model as the optimal fitting results are adopted in this essay for analysis and discussion. Specific fitting results see *Table 5*.

According to the optimal fitting results in *Table 5*, it can be seen that the landscape pattern index of each construction land has different influence mechanisms on $PM_{2.5}$ pollution. ① Landscape scale: The construction area (CA) has positive effects on $PM_{2.5}$ pollution, with the regression coefficient of 0.298, and it is significant at 10% level, which accords with the theoretical expectation, indicating that increase of the area of urban construction land could improve $PM_{2.5}$ pollution of the region. ② Landscape composition: Proportion of construction land (PLAND) also has positive effects on $PM_{2.5}$ pollution, with the regression coefficient of 3.299, and passes the significance test at 5% level. This result coincides with the theoretical analysis mentioned above, indicating that expansion of landscape pattern of urban construction land could cause rise of $PM_{2.5}$ pollution. ③ Landscape layout: The regression coefficient of the largest patch index (LPI) is 0.037, however, it fails the significance test, indicating that though increase of LPI of construction land could promote $PM_{2.5}$ pollution, the promoting effect is still weak and has not been displayed fully. The possible reason is that increase of the largest patch index of construction land is the result of the enhancement of urban integrity, which could bring about scale effect of $PM_{2.5}$ emissions; however, since the region of Pearl River Delta has

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higher economic development level, especially in large-scale cities with higher integrity, with continuous optimization and upgrading of the industrial structure as well as the development of scientific technology, the proportion of the tertiary industry, the clean energy technology and waste gas treatment technology are all at higher level; therefore, the scale effect of $PM_{2.5}$ emission in large-scale cities weakens, and the promoting effect of largest patch index of construction land on $PM_{2.5}$ pollution also decreases, resulting in non-significant state finally. Patch density (PD) and mean nearest distance (MNN) have negative inhibiting effect on $PM_{2.5}$ pollution, which accords with the theoretical expectation. The inhibiting effect of patch density (PD) on $PM_{2.5}$ pollution is most obvious, with the regression coefficient of -40.672, and it is significant at 5% level, indicating that with the increase of the fragmentation degree of construction land in the region of Pearl River Delta, $PM_{2.5}$ pollution decreases obviously. The regression coefficient of the mean nearest distance (MNN) is -2.278 and is significant at 5% level, indicating that $PM_{2.5}$ pollution decreases with the increase of the mean nearest distance. Increase of MNN means that the aggregation of the patches of the construction land decreases. $PM_{2.5}$ emission sources are distributed in scatter and the scale effect decreases, which could result in decrease of $PM_{2.5}$ pollution.

Table 5. *Spatial analysis results of landscape pattern of construction land on $PM_{2.5}$ pollution*

Index type	Index name	Model			
		SLM		SEM	
		fe	re	fe	re
Landscape area	CA	0.298* （-1.86）	0.088** （-2.46）	0.383** （-2.51）	0.090** （-2.45）
Landscape composition	PLAND	3.229** (-2.25)	0.053 （-0.19）	-5.116*** (-3.25)	0.028 （-0.11）
Landscape layout	PD	-40.672** (-2.03)	-5.169* (-1.85)	-67.216*** (-2.92)	-5.327** (-2.08)
	LPI	0.037 （-1.2）	-0.006 (-0.17)	0.043 -1.44	-0.008 (-0.25)
	MNN	-2.278** (-2.37)	0.208 （-0.84）	-3.645*** (-3.38)	0.181 (-0.73)
Social-economic factors	RD	0.358** （-2.56）	0.302** （-2.05）	0.245 （-1.59）	0.332** (-2.26)
	POPD	-0.555 (-1.59)	-0.255** (-2.08)	-0.33 (-0.84)	-0.241** (-2.04)
	AGDP	0.183** （-1.97）	-0.002 (-0.07)	0.144 （-1.5）	0.006 (-0.17)
	IND	4.725*** （-2.8）	3.633*** （-2.62）	2.365 （-1.28）	4.077*** (-2.93)
natural factors	RAIN	0.619** （-2.05）	0.034 （-0.12）	1.001*** （-3.27)	-0.029 (-0.10)
	WIND	-1.080*** (-3.95)	-0.788*** (-3.36)	-0.884*** (-3.32)	-0.820*** (-3.55)
LM test	LM(lag) R-LM(lag) LM(errow) R-LM(errow)	3.168* 2.995* 2.293 2.121			
Hausman test	chi2(6) Prob>chi2	114.39 0		83 0	

The t values ***, ** and * represent significant at the 1%, 5%, and 10% levels

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Social-economic factors that have positive influences on $PM_{2.5}$ pollution include road density (RD), average GDP (AGDP), proportion of the output of the secondary industry (IND), the regression coefficients of which are respectively 0.358, 0.183 and 4.725. RD and AGDP) are significant at 5% level, and IND is significant at 1% level. This result shows that the positive influence of IND on $PM_{2.5}$ pollution is the most significant of all the social-economic factors. The major reason is that the secondary industries are mostly chemical industry, manufacturing and other industries which could generate more waste gases, so increase of IND will inevitably bring in increase of $PM_{2.5}$ pollution, with significant influences. The increase of per capita income is based on the increase of the yields of primary, secondary and tertiary industries; therefore, the increase of AGDP can also promote $PM_{2.5}$ pollution. However, with continuous optimization and adjustment of the industrial structure as well as continuous increase of the proportion of the tertiary industry, AGDP has the smallest positive influencing coefficient on $PM_{2.5}$ pollution. Increase of RD means increase of vehicles. At present, most vehicles in China are fuel vehicles and the exhaust emission of the fuel vehicles will inevitably cause increase of $PM_{2.5}$ pollution. The regression coefficient of population density (POPD) is -0.555, indicating increase of population density could lower $PM_{2.5}$ pollution; however, this index fails the significance test. The reason for such result may be that with continuous increase of population density, regional land use efficiency keeps increasing and the public transport is developed; meanwhile, the municipal departments are more active in environmental governance with higher efficiency (Hu, 2019; Chang and Zhao, 2019). A series of such measures could reduce emission of automobile exhaust and industrial gas as well as unlimited sprawl of construction land, which could in turn reduce $PM_{2.5}$ pollution to some degree; however, the significance of the effects is still poor, which cannot improve regional $PM_{2.5}$ pollution obviously.

Natural factors: Rainfall (RAIN) has positive effect on $PM_{2.5}$ pollution, with the regression coefficient of 0.619, passing the significance test at 5% level. The main reason is that the increase of rainfall will increase relative humidity in the air, and the diameter of $PM_{2.5}$ particles is small, which mainly grows by moisture absorption and aggregation to cause rise in pollution; meanwhile, to improve the electric property of particulate matters is more beneficial to aggregation of $PM_{2.5}$ particles, which could increase $PM_{2.5}$ pollution (Tang et al., 2013). Wind speed (WIND) has significant negative effect on $PM_{2.5}$ pollution, with the regression coefficient of -1.080, and is significant at 1% level, indicating that increase of wind speed could reduce $PM_{2.5}$ pollution. This is mainly because wind has good diffusing and purifying effects. The region of Pearl River Delta is in the coastal strip. Especially in summer, the wind blows from the southeast ocean and the clean air brought by it could dilute and purify the air inland, thereby reducing $PM_{2.5}$ pollution (Zhou and Liang, 2013).

Discussion

According to the analysis results of spatial-temporal evolution of $PM_{2.5}$ concentration and landscape pattern index of the construction land in the Pearl River Delta, and the spatial econometric analysis results of the impact of the landscape pattern of construction land on $PM_{2.5}$, some suggestions are put forward on rational utilization of construction land in the Pearl River Delta, with the hope to exert the controlling effect of construction land in $PM_{2.5}$ pollution control and improve the air quality level of the Pearl River Delta. The details are as follows:

(1) From the influencing results of landscape scale of construction land on $PM_{2.5}$ pollution, it could be seen that expansion of construction land could significantly improve $PM_{2.5}$ pollution in the region of Pearl River Delta. So, in the process of urban development: **a.** The area of construction land should be increased rationally and orderly to avoid urban sprawl in urban development; **b.** Emphasis should be laid on improvement of land utilization efficiency and shift towards three-dimensional urban development model; **c.** Reform of the industrial structure should be promoted further, backward industries with high pollution, high consumption and more land capital input should be weeded out gradually, and the proportion of intelligence-intensive high-tech industries should be increased, so as to improve the level of intensive land use in the region of Pearl River Delta.

(2) From the influencing results of landscape composition of construction land on $PM_{2.5}$ pollution, it could be seen that increase of the proportion of construction land has significant positive effect on $PM_{2.5}$ pollution in the region of Pearl River Delta. So, in the process of urban planning, not only the expansion of construction land should be controlled, it is also necessary to increase the proportions of road greening, park green space and urban forests in the design of urban landscapes. In the premise of guaranteeing healthy development of the city, the proportion of $PM_{2.5}$ converged landscape should be improved rationally to exert the dust reducing effect of land use and control efficiently $PM_{2.5}$ pollution.

(3) From the influencing results of landscape layout of construction land on $PM_{2.5}$ pollution, it could be seen that increase of the integrity and aggregation of construction land could improve significantly $PM_{2.5}$ pollution in the region of Pearl River Delta. Since mononuclear city has low efficiency in spatial allocation of the resource factors and that the social resources cannot be integrated effectively, excessive expansion of urban scale could result in increase of traffic cost and reduce of energy utilization efficiency; therefore, when selecting the pattern of urban development, it is necessary to adopt multi-core urban development policy of satellite town, that is, to develop sub-center city and multi-center city so as to avoid severe $PM_{2.5}$ pollution caused by high aggregation of the city.

Conclusion

In this essay, remote sensing is used to revert $PM_{2.5}$ pollution data as the explained variable, the CA, PLAND, PD, LPI, and MNN landscape indexes of the construction land are calculated based on the data of land use as the core explanatory variable, and the social-economic factors and natural factors are taken as the control variables, based on which the spatial-temporal variation rules of $PM_{2.5}$ pollution in the region of Pearl River Delta from 2000 to 2016 as well as the variation law of landscape pattern of the construction land are analyzed, and the correlations between $PM_{2.5}$ pollution and the landscape index of construction land are also analyzed with spatial econometric model. The major conclusions are as follows:

(1) During 2000 to 2016, $PM_{2.5}$ pollution in the region of Pearl River Delta rose first and then decreased, however, by 2016, $PM_{2.5}$ pollution in all regions of Pearl River Delta was higher than that in 2000. Spatially, $PM_{2.5}$ pollution in the region of Pearl River Delta shows the spatial distribution law of high in the middle and low in the surrounding area. The regions with higher value are focused mainly cities neighboring Guangzhou, while regions with low value are mainly Zhaoqing and Huizhou in the east and west wings of Pearl River Delta.

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(2) Construction land area (CA) in the region of Pearl River Delta expanded obviously during 2000 to 2016, with an overall increase of 75.37%. Patch density (PD) and mean nearest distance (MNN) of the construction land decreased to varying degree, indicating that fragmentation of landscape of the construction land in Pearl River Delta decreased while the aggregation increased. Proportion of construction land (PLAND) and largest patch index (LPI) showed the tendency of increasing, indicating that the dominance and integrity of landscapes of the construction land in the region of Pearl River Delta kept increasing.

(3) The landscape pattern index of construction land mainly affects $PM_{2.5}$ pollution from three aspects, landscape scale, landscape structure, and landscape layout. **a.** Landscape scale: Construction area (CA) has positive correlation with $PM_{2.5}$ pollution. **b.** Landscape composition: Proportion of construction land (PLAND) also has positive correlation with $PM_{2.5}$ pollution. **c.** Landscape layout: Patch density (PD) and mean nearest distance (MNN) has negative correlation with $PM_{2.5}$ pollution, i.e., increase of PD and MNN could reduce $PM_{2.5}$ pollution. Though the largest patch index (LPI) shows positive correlation with $PM_{2.5}$ pollution, but it is not significant.

(4) Economic factors and natural factors also have great influences on $PM_{2.5}$ pollution. **a.** Increase of road density (RD), average GDP (AGDP) and the proportion of the output of the secondary industry (IND) could cause rise of $PM_{2.5}$ pollution. Population density (POPD) has negative correlation with $PM_{2.5}$ pollution, but not significant. **b.** In the natural factors, rainfall could increase $PM_{2.5}$ pollution, while wind speed could lower $PM_{2.5}$ pollution.

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