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Investigating the Long-Term Relationship between Aerosol Optical Thickness and Land Use/Cover Change in Guangxi Coastal Cities, China

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Abstract

Land Use/Cover Change (LUCC) has an impact on AOD to a certain extent. It is of great significance for ecological environment and public health to pay attention to and explore the response mechanism of AOD to LUCC. Based on remote sensing satellite technology, using landsat8 and MODIS data, this paper analyzes the correlation between different land use types and AOD in Beibu Gulf coastal urban belt under the background of wide-scale region and long time series, and further discusses the difference value and contribution level of each LUCC to AOD. The results show that: 1) there is a positive correlation between PM concentration and cultivated land, urban land, water area and other types of land, and the correlation coefficient increases in turn, R is 0.812, 0.685, 0.627, 0.416, respectively, which indicates that the increase of cultivated land and urban land increases PM concentration to a certain extent; 2) there is a significant negative correlation between PM concentration and forest land, R is −0.924, The results show that the decrease of woodland is an important factor for the increase of atmospheric particulate matter concentration in the study area from 2015 to 2019; 3) through the contribution analysis method, the contribution of cultivated land to AOD is the largest, followed by urban land, and the water area is the smallest in 2015-2019, which indicates that the land use mode is closely related to AOD. It can be helpful to reasonably plan land use types and scientifically optimize land use structure. It can effectively reduce the concentration of air pollution particles.

Keywords

Land Use and Land-Cover Change (LUCC), Modis, Aerosol Optical Depth

(AOD), Correlation Analysis, Contribution Analysis

1. Introduction

Aerosol dispersion system composed of solid or liquid particles in gaseous medium is called aerosol (AOD), and its optical thickness, scattering characteristics, chemical composition and other photophysical characteristics affect global climate, radiation balance and human health [1] [2] [3]. Due to the complex factors affecting aerosol, its spatiotemporal distribution and environmental coupling mechanism are uncertain [4]. Previous studies have shown that the absorption and scattering effects of atmospheric aerosol are related to urban heat island effect, and the intensity of urban heat island effect is enhanced to a certain extent when the aerosol concentration is large [5]. Under high-pressure weather and calm wind, the stable inversion boundary layer structure formed by warm advection and radiant cooling has a positive correlation with the accumulation of pollution aerosols, which further promotes the formation and development of fog and hazes [6] and threatens human health. With the increase of urbanization, the environmental pollution weather caused by high-concentration aerosol has become a prominent atmospheric problem in the development of our socialist economy [7]. Based on this, the study of aerosol thickness influence formation and governance mechanism is conducive to the healthy and stable development of national economy.

In recent years, with the rapid development of land use/cover change (LUCC) in China as whole, man-made structures replace vegetation in large numbers, reducing the ability of the surface to absorb and block particulate matter, and causing a series of air pollution problems [8]. The change of land use/cover structure under industrialization significantly affects the concentration of aerosol. Aerosol pollution originates from the long-term accumulation and deposition of atmospheric particles, and atmospheric meteorological conditions are external factors while underlying surface changes caused by human activities are internal factors [9]. Domestic and foreign scholars have made a lot of achievements in the research of land use/cover change. At present, dynamic LUCC monitoring of multi-source remote sensing data, exploration of LUCC spatial distribution law and change trend, and LUCC coupling mechanism under global climate change are the current research hotspots [10]. At the same time, global academic research is in its optical characteristics of aerosol particle concentration, time and space distribution rule and prediction and simulation of the dynamic monitoring and the response mechanism of global climate change on [11], the particle concentration of access to information from the initial ground site monitoring changes to satellite remote sensing data model inversion [12]. However, there are still few studies on the response relationship of land use/cover change to air solubility, and more attention is paid to specific areas within a short period of time, while there is a lack of studies under long time series.

Under the background of wide-scale area and long time series, the increasingly mature remote sensing satellite monitoring and extraction provides stable and reliable technical support for LUCC and aerosol information. Based on this, this paper selects the coastal city belt of the Beibu Gulf as the research area, conducts atmospheric aerosol inversion by using long-term MODIS data, interprets Landsat data for land use/cover change, and explores the correlation between land use/cover change and aerosol in the five years from 2015 to 2019. To determine the response mechanism of land use/cover change and aerosols, and to provide a decision basis for the development and environmental protection of the Beibu Gulf Economic zone, as well as a theoretical reference for the ecological and environmental security of urban belt.

2. Overview of the Study Area

The coastal area of Beibu Gulf is located between 21˚24'N-22˚43'N, 107˚27'E-109˚52'E, with an east-west length of about 246 km and a north-south length of about 141 km. The total area is about 20,017.25 km^2, as shown in **Figure 1**. The administrative division includes Beihai City, Qinzhou City and Fangchenggang City. The regional climate is South Asian tropical monsoon climate, with the average annual temperature of about 22˚C, the annual rainfall of about 1800 mm, and the average annual sunshine duration of about 1800 h [13].

The topographic features of the study area include mountains, hills, beaches and shallow seas. The coastline is high in the north and low in the south. Most of the mountains run northeast-to-southwest, with the Shiwan Mountain range in the northwest and the Sixty Thousand Mountain range in the northwest. Rivers

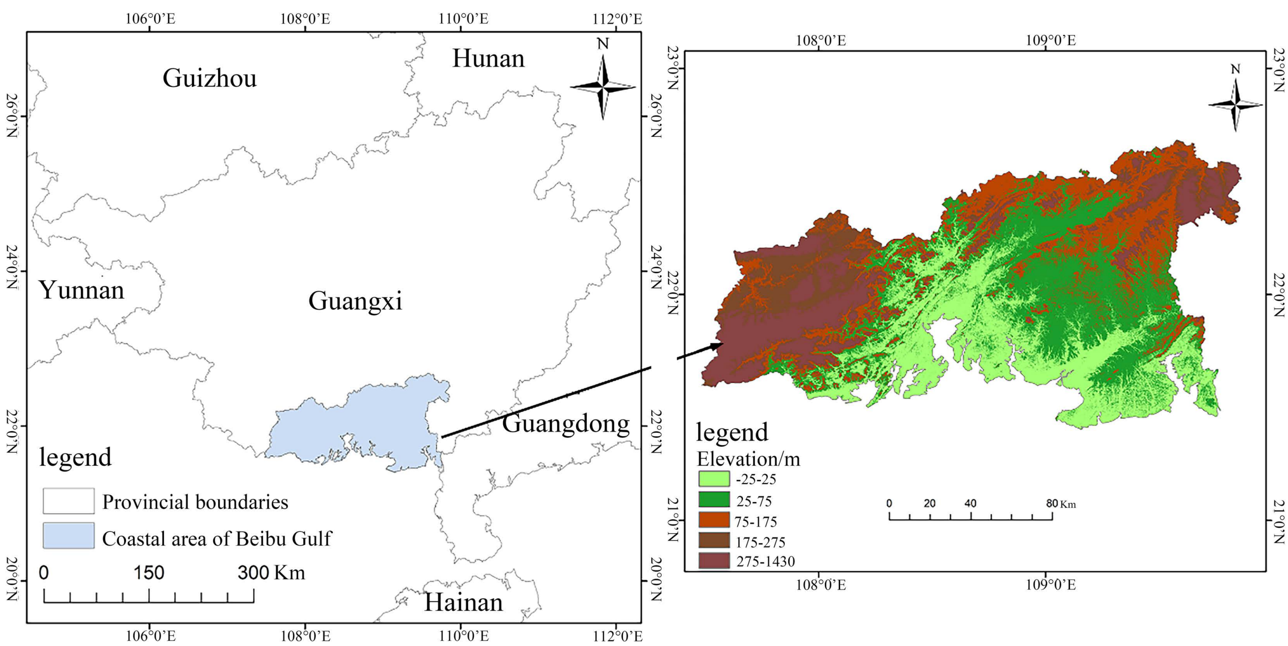


Figure 1. Location of Beibu Gulf coastal urban belt.

running through the study area include Beilun River, Fangcheng River, Maoling River, Qinjiang River, Fengfeng River and Nanliu River. Beibu Gulf is the most convenient and important sea port in southwest China, among which Fangcheng Port is the port with the shortest voyage from mainland China to Southeast Asia, Africa, Europe and Oceania, and it is a good natural deep-water port, which is now navigable with more than 100 countries and regions in the world. The Beibu Gulf area, with its superior geographical position and abundant natural resources, has become the modern port agglomerations under the new layout and new plan in coastal areas in our country, with great development potential.

3. Data Source and Processing

3.1. The Data Source

The remote sensing data in this paper were obtained from the United States Geological Survey (https://www.usgs.gov/). The remote sensing data in 2015, 2016, 2017, 2018 and 2019 were all Landsat8 satellite image data with a resolution of 15 m × 15 m. Aerosol data is derived from NASA's MOD02 1 KM product (https://www.nasa.gov/) using MODIS L1B 1 KM data. MODIS data is widely used in environmental monitoring and climate change, and has the advantages of high quality and short revisit period. Based on MODIS extraction results, NASA provides many standard product services such as reflectance, cloud and aerosol [14]. Considering that the thickness of aerosol in spring and summer in coastal areas is much greater than that in autumn and winter [15], in this paper, 1 KM data of MOD02 in spring and summer of 2015-2019 in Beihai City, Qinzhou City and Fangchenggang City were extracted, and 1 d data were taken with 7-day cycle in the 64 - 235 days of each year, with 24 d in total.

3.2. Data Preprocessing

According to the current land use classification standard (GB/T 21010-2017) and land use classification method, combined with the actual situation of land use in the study area, based on ENVI5.3 software, remote sensing data is processed by geometric correction, radiometric calibration, flash atmospheric correction, image Mosaic and image cropping [16]. The support vector machine method was adopted for supervised classification, and the land use types in the study area were divided into five types: urban land, cultivated land, forest land, water area and other types of land, as shown in **Table 1**.

When verifying the classification results, Google Earth was used to extract the satellite topographic map of Beihai City, Qinzhou City and Fangchenggang City, and 25 sample points of urban land, cultivated land, forest land, water area and other types of land with obvious and long-term no change were selected through visual interpretation [17], a total of 125. Envi5.3 was used to evaluate the accuracy of the confusion matrix. The overall accuracy of land use supervision classification results of remote sensing images is greater than 95%, and the Kappa coefficient is greater than 0.93, which meets the research needs. The remote sensing interpretation results are shown in Table 2 and Figure 2.

ENVI5.3 is used for aerosol inversion in the coastal area of Beibu Gulf, including MODIS image (HDF) band synthesis, radiometric correction, geometric correction, cloud detection and aerosol inversion. Aerosol inversion algorithm adopts the classical dark pixel method (DDV), which is mainly used for summer inversion and has poor effect on aerosol inversion in winter. Inversion lookup table is obtained by using IDL and calling 6S radiation model [18]. The aerosol data obtained by inversion can be calculated by using formula (1) and (2) to obtain the quarterly composite and daily AOD data. In the calculation process, invalid pixels and singular values are deleted, and only valid aerosol data is retained (if the number of effective pixels in the image is greater than or equal to

Table 1. Land use classification standard.

Classification standard	Land class merge	Land use status standard (GB/T 21010-2017)
Land use type	Urban land use	Commercial land Industrial and mining storage land Residential land Land for transportation
	Arable land	Paddy field Irrigated land The dry land
	Woodland	Arboreal lands Mangrove forest Other woodland
	Waters	The river of the water The lake water The reservoir of the water
	Other types of land	Land types other than urban land, arable land, forest land and water

Table 2. Classification results of land use in Beibu Gulf Coast.

Land use type	In 2015 Area (km^2)/ Percentage (%)	In 2016 Area (km^2)/ Percentage (%)	In 2017 Area (km^2)/ Percentage (%)	In 2018 Area (km^2)/ Percentage (%)	In 2019 Area (km^2)/ Percentage (%)
Urban land use	1256.22/6.28	1517.35/7.58	1543.13/7.71	1727.42/8.63	1726.53/8.63
Arable land	3334.63/16.66	3690.41/18.44	3297.80/16.47	3372.94/16.85	3503.85/17.50
Woodland	14,557.20/72.72	13,599.05/67.94	14,406.71/71.97	14,219.06/71.03	13,876.31/69.32
Waters	228.96/1.14	294.30/1.47	295.05/1.47	284.23/1.42	261.17/1.30
Other types of land	640.25/3.20	916.04/4.58	474.70/2.37	413.78/2.07	649.25/3.24

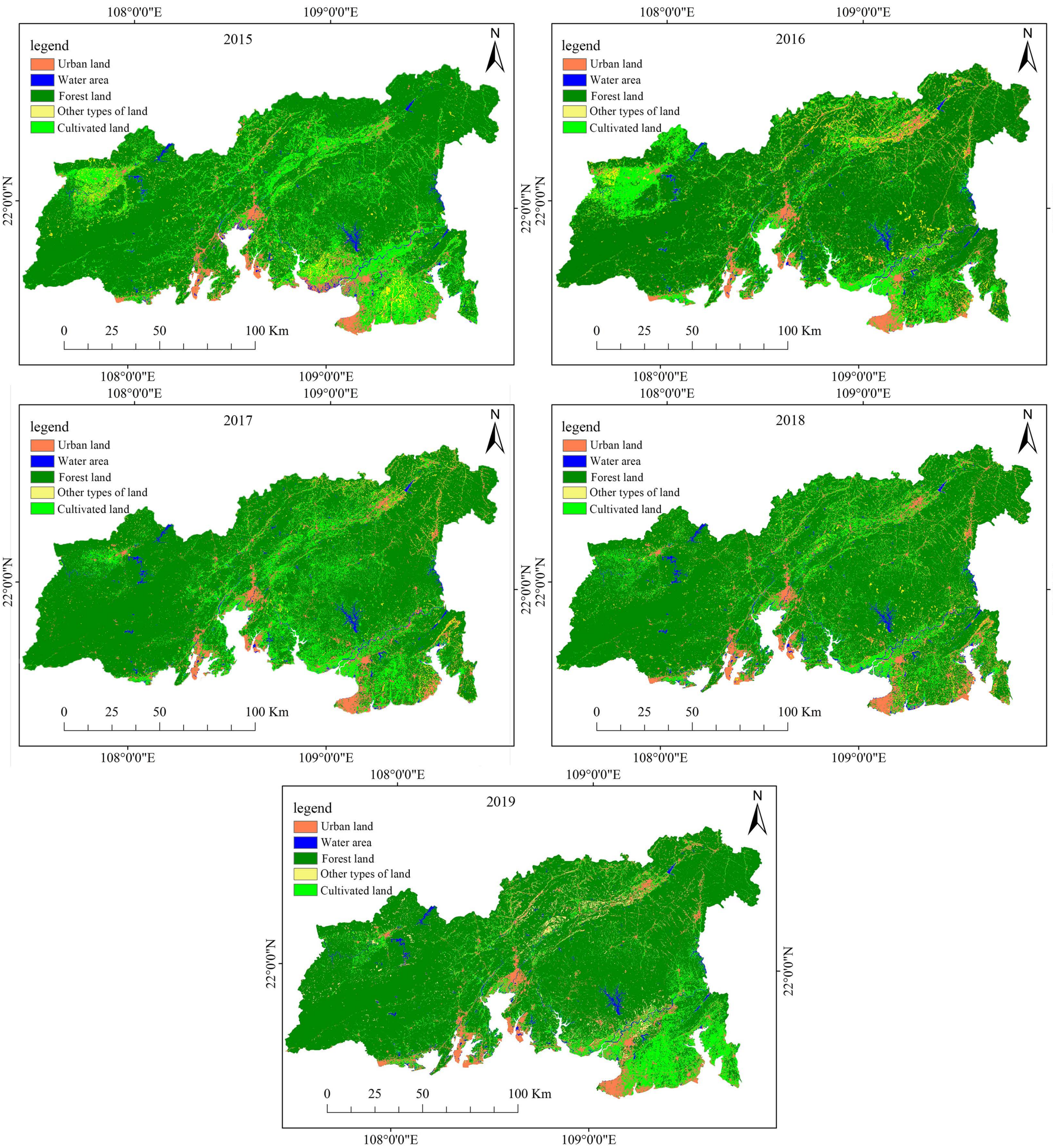


Figure 2. Land use/cover change along the Beibu Gulf coast from 2015 to 2019.

50%, it is regarded as valid data) [19]. The calculation formula is:

$$\text{AOD}_{\text{QS}} = \left[\sum_{M=1}^{M} \left(\text{AOD}_{(s)} \right) \right] \Big/ M \tag{1}$$

$$\text{AOD}_{\text{Avg}} = \left[\sum_{i=1}^{m} \sum_{j=1}^{n} \left(\text{AOD}_{(i,j)} \right) \right] \Big/ N \tag{2}$$

In Equations (1) and (2), AOD_{QS} is the quarterly composite aerosol data, AOD is the effective aerosol data, the total number is M, and s is the S-th amplitude data. AOD_{Avg} refers to the daily AOD value data, $AOD_{(i,j)}$ refers to the pixel value in row i j column in the data, N refers to the total number of effective pixels, wherein $N = m \times n$. Data calculation is carried out in ENVI5.3, and the results of quarterly synthetic AOD data processing are shown in **Figure 3**.

In this paper, the remote sensing interpretation results and AOD inversion results are uniformly projected into the same coordinate system, the coordinate system is WGS-1984, and the pixel sizes of all data are ensured to be consistent in the process of processing.

4. The Research Methods

4.1. Correlation Analysis between Air Pollutants and LUCC

In the correlation analysis between atmospheric pollutants and LUCC, due to the correlation between atmospheric visibility (V) and air pollution [20], V is divided into: when V is above 10 km, there is no pollution and low concentration of particulate matter. When V is at 5 - 10 km, it is slightly polluted and the air quality is slightly poor. When V is between 2.5 - 5 km, it is a moderately polluted day with poor air quality. When V is less than 2.5 km, it is a severely polluted day with poor air quality. According to relevant studies [21], the correlation between V and AOD is proposed as follows:

$$AOD_{TH} = \frac{3.91H}{V} \tag{3}$$

In Formula (3), AOD_{TH} is the threshold of the calculated AOD, H is the elevation (km), and V is the atmospheric visibility.

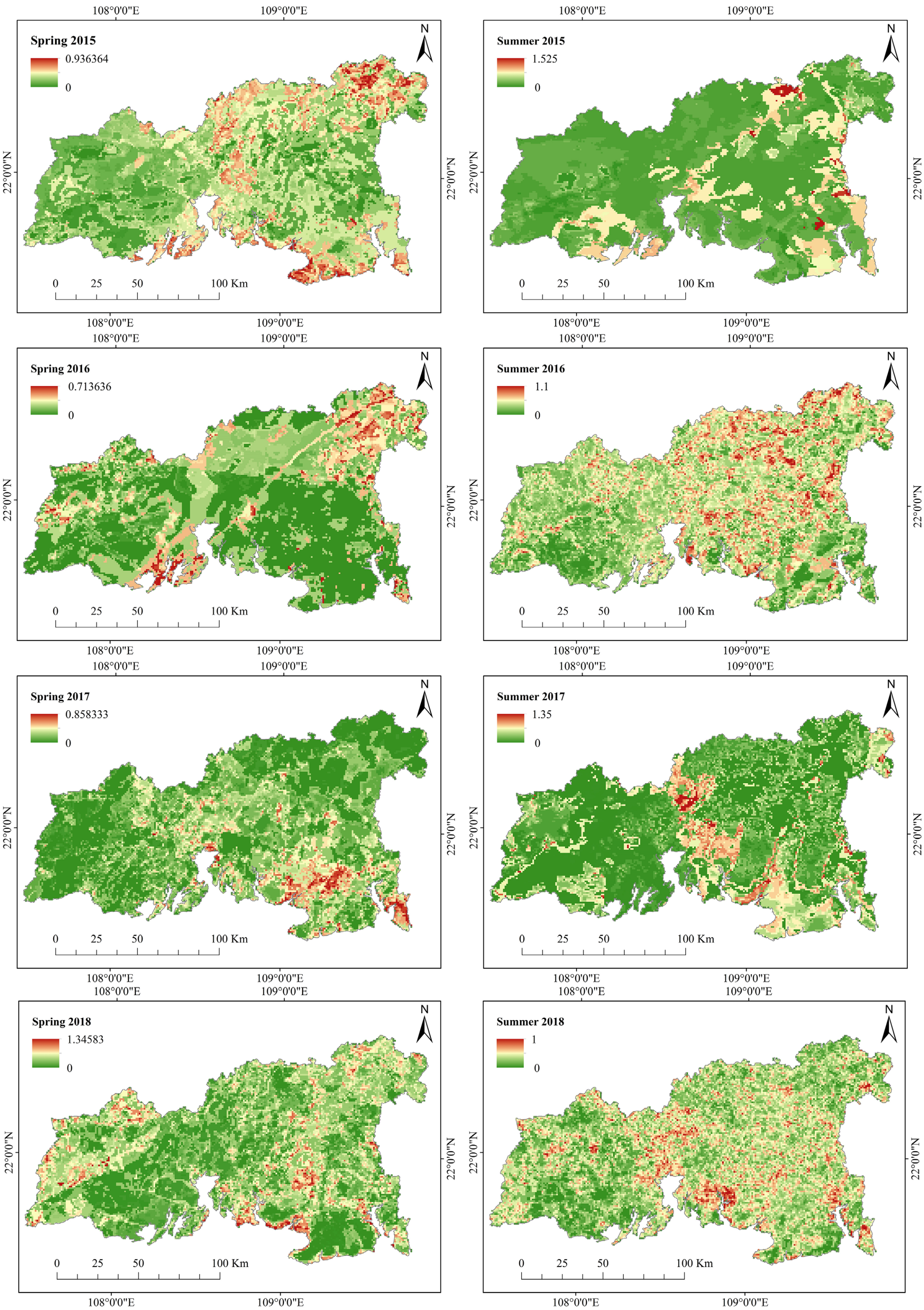
In this paper, the PI's product moment correlation coefficient (PPCC) is used to analyze the correlation between LUCC and V. PPCC has been widely used in various fields and can measure the degree of linear correlation between two random variables. The value range is [−1, 1], and the calculation formula is as follows:

$$R = \frac{\sum_{i=1}^{n}(x_i - x)(y_i - y)}{\sqrt{\sum_{i=1}^{n}(x_i - x)^2 \sum_{i=1}^{n}(y_i - y)^2}} \tag{4}$$

In Equation (4), R is the correlation coefficient of samples, and x and y are random variables.

4.2. Analysis on the Contribution of Different LUCC to AOD

In order to further analyze the response of different LUCC to AOD, the contribution of different LUCC to air pollution was quantified. Referring to existing studies [22], the average AOD data of the whole study area was calculated first, then the average AOD of each LUCC was calculated (the influence of other LUCCs was not considered when calculating the average AOD of a certain


Spring 2015
0.936364
0
Summer 2015
1.525
0
Spring 2016
0.713636
0
Summer 2016
1.1
0
Spring 2017
0.858333
0
Summer 2017
1.35
0
Spring 2018
1.34583
0
Summer 2018
1
0
N
0 25 50 100 Km
108°0'0"E
109°0'0"E
22°0'0"N

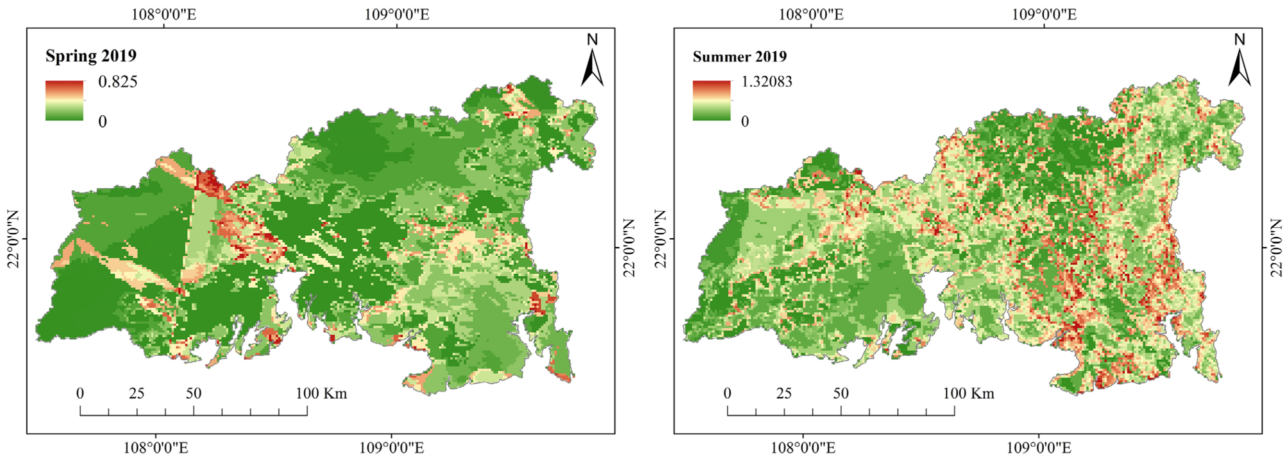


Figure 3. Seasonal variation of AOD in Beibu Gulf coast from 2015 to 2019.

LUCC in the study area), and then the difference between the average AOD of corresponding LUCC and the average AOD of the whole study area was calculated. Then, the contribution levels of different LUCCs to AOD were characterized by the product of the difference value and the proportion of each LUCC area. The calculation formula is:

$$dT_i = \frac{\text{mean}\left(\Delta \text{AOD}_i\right)}{\text{meanAOD}} \quad (5)$$

$$C_i = S_i \times dT_i \quad (6)$$

In Formula (5), dT_i represents the difference between the average AOD of corresponding land use/cover and the average AOD of the whole study area, mean(ΔAOD) is the average AOD of each LUCC, and mean AOD is the average AOD of the whole study area.

In Formula (6), C_i is the contribution level of different LUCC to AOD, and the higher the value, the higher the response degree of different LUCC to AOD. S_i is the area proportion of each land use/cover type, %.

5. Results Analysis

5.1. Response Analysis of LUCC to Atmospheric Pollutants

According to the air quality grade standard converted by formula (3), as shown in Table 3, the daily AOD data were processed in sections according to this standard, the occurrence days of air grade pollution in coastal urban areas of Beibu Gulf were counted, and the corresponding effective percentage was calculated, as shown in Table 4. The number of air pollution days in the coastal city belt of Beibu Gulf from 2015 to 2019 was in the air quality level Ⅰ and ⅠⅠ, the average daily particulate pollution concentration was generally low, and there was no moderate or severe pollution days with average daily aerosol thickness greater than 0.8, but the air quality tended to deteriorate on the whole. In the past five years, the number of effective days of pollution-free weather in the study area decreased from 83.33% to 62.22%, and the number of effective days of lightly polluted weather increased from 16.67% to 37.78%.

Table 4 and the land use classification results of the Beibu Gulf coastal urban belt (see Table 2) were analyzed in SPSS24 for the PI's product moment correlation coefficient (PPCC), and the results are shown in Table 5. During 2015-2019, there was a certain correlation between land use/cover change and air pollutants in the study area. There is a negative correlation between urban land use and class I air quality, and the correlation coefficient R is −0.685. There is a positive correlation between urban land use and class II air quality, and the correlation coefficient R

Table 3. Air quality level standard.

AOD_{TH}	Level	Definition
≤0.3	I	V is above 10 km, pollution-free weather, low particulate matter concentration
0.3 - 0.8	II	V is at 5 - 10 km, which is a slightly polluted day with slightly poor air quality
0.8 - 1.5	III	V is 2.5 - 5 km, indicating moderate pollution and poor air quality
>1.5	IV	V less than 2.5 km, for heavy pollution weather, poor air quality

Table 4. Effective percentage of air pollution days along Beibu Gulf Coast in 2015-2019 (%).

Year	Air Quality Level			
	I	II	III	IV
2015	83.33	16.67	0.00	0.00
2016	54.55	45.45	0.00	0.00
2017	75.00	25.00	0.00	0.00
2018	62.50	37.50	0.00	0.00
2019	62.22	37.78	0.00	0.00

Table 5. Correlation analysis between air pollutants and LUCC.

The correlation coefficient	Urban land use	Arable land	Woodland	Waters	Other types of land	I	II
Urban land use	1	0.184	−0.459	0.550	−0.305	−0.685	0.685
Arable land		1	−0.954*	0.300	0.867	−0.812	0.812
Woodland			1	−0.458	−0.701	0.924*	−0.924*
Waters				1	−0.018	−0.627	0.627
Other types of land					1	−0.416	0.416
I						1	−1.000**
II							1

(Note: **Indicates A significant correlation at level 0.01 (double-tailed); *Indicates a significant correlation at level 0.05 (two-tailed).

is 0.685. This indicates that the increase of urban land use will stress the occurrence times of pollution-free weather and contribute to the increase of atmospheric particulate matter concentration. There is also a negative correlation between cultivated land and pollution-free weather, R is −0.812, and a positive correlation with slightly polluted weather, R is 0.812, indicating that the increase of cultivated land can contribute to the increase of slightly polluted weather and stress the occurrence times of pollution-free weather. There was a significant positive correlation between forest land and class I air quality, and a significant negative correlation between forest land and class II air quality, with R values of 0.924 and −0.924, respectively, indicating that forest land significantly affected the concentration of air pollutants in the study area and was beneficial to the occurrence of pollution-free weather. There is a negative correlation between water area and pollution-free weather (R = −0.627), and a positive correlation between water area and lightly polluted weather (R = 0.627). There was also a negative correlation between other types of land use and air quality of class I, and a positive correlation between land use and air quality of class II, with R being −0.416 and 0.416, respectively. Water area and other types of land use will increase the frequency of light pollution weather to some extent and stress the appearance of pollution-free weather. In conclusion, due to geographical factors, the degree of atmospheric particulate pollution is low in the coastal city belt of Beibu Gulf, but the concentration of particulate pollution is generally increasing. The cultivated land, urban land, water area and other types of land had a certain positive correlation with the concentration of particulate matter, and the correlation coefficient increased in turn, and the response degree increased in turn. There was a significant negative correlation between forest land and particulate matter concentration, indicating that the decrease of forest land was an important factor influencing the increase of particulate matter concentration in the study area during 2015-2019.

5.2. Different Contribution Levels of LUCC to AOD

Since the other four types of land except forest land in the study area have a certain positive correlation with atmospheric particulate matter, the influence of land use/cover mode except forest land on atmospheric aerosol is further discussed. In the ArcGIS10.5, the average AOD of each LUCC except forest land and the average AOD of the whole research area during the spring and summer of 2015-2019 were calculated, and the different values of each LUCC except forest land on the urban belt of coastal Beibu Gulf in the spring and summer of the five years were obtained (the results are shown in **Table 6**). In combination with the land use classification results of the Beibu Gulf coastal urban belt (see **Table 2**), the contribution levels of each LUCC except forest land to AOD in spring and summer in the study area in the past five years were obtained by using formula (6), and the results were shown in **Table 7**. The contribution analysis shows that the contribution of arable land to AOD is the largest, followed by

Table 6. AOD difference of each LUCC to Beibu Gulf Coast in spring and summer of 2015-2019.

Differences in values (dT_i)	Urban land use	Arable land	Waters	Other types of land
$dT_{2015spring}$	1.09	1.09	1.15	0.91
$dT_{2015summer}$	1.05	1.02	1.06	0.99
$dT_{2016spring}$	1.05	1.07	1.08	0.96
$dT_{2016summer}$	1.07	1.02	0.98	1.01
dT_{2017}spring	0.96	1.09	1.41	0.96
$dT_{2017summer}$	1.19	1.06	1.27	0.97
dT_{2018}spring	1.00	0.97	1.30	1.06
$dT_{2018summer}$	0.66	1.03	1.15	1.03
dT_{2019}spring	1.11	1.00	1.15	0.89
$dT_{2019summer}$	1.07	0.95	1.03	0.95

Table 7. Contribution level of each LUCC to AOD of Beibu Gulf Coast in spring and summer of 2015-2019.

Contribution level (C_i)	Urban land use	Arable land	Waters	Other types of land
$C_{2015spring}$	0.07	0.18	0.01	0.03
$C_{2016spring}$	0.08	0.20	0.02	0.04
$C_{2017spring}$	0.07	0.18	0.02	0.02
$C_{2018spring}$	0.09	0.16	0.02	0.02
$C_{2019spring}$	0.10	0.18	0.02	0.03
$C_{2015summer}$	0.07	0.17	0.01	0.03
$C_{2016summer}$	0.08	0.19	0.01	0.05
$C_{2017summer}$	0.09	0.17	0.02	0.02
$C_{2018summer}$	0.06	0.17	0.02	0.02
$C_{2019summer}$	0.09	0.17	0.01	0.03

urban land, and the water area is the least, which indicates that the land use mode is related to AOD to a certain extent. The contribution of cultivated land to AOD fluctuated between 2015 and 2019, and AOD in spring was higher than that in summer on the whole, which was caused by the cultivation of different crops in spring and summer and the fluctuation of cultivated land area during this period. The contribution of urban land to AOD was on the rise from 2015 to 2019, and there was little difference in AOD between spring and summer, which was caused by the continuous increase of urban land in the study area from 2015 to 2019. Other types of land and water area also have a certain contribution to

AOD, which fluctuates.

6. Conclusions

In this study, based on remote sensing satellite technology, the coastal urban belt of the Beibu Gulf was selected as the research area under the background of a wide-scale region and a long time series. The atmospheric aerosol inversion was carried out with the MODIS data of a long time series, and the land use/cover change interpretation was carried out on the Landsat data. The correlation between land use/cover change and aerosol in the five years from 2015 to 2019 was discussed, and the response mechanism between land use/cover change and aerosol was determined. The contribution analysis method was used to further explore the difference value and contribution level of each LUCC to AOD, and the following conclusions were drawn:

1) Cultivated land, urban land, water area and other types of land had a certain positive correlation with particulate matter concentration, and the correlation coefficient increased in turn, and the response degree increased in turn, R was 0.812, 0.685, 0.627, 0.416, indicating that the increase of cultivated land and urban land increased the concentration of particulate matter to a certain extent.

2) There was a significant negative correlation between forest land and particulate matter concentration ($R = -0.924$), indicating that the decrease of forest land was an important factor affecting the increase of particulate matter concentration in the study area during 2015-2019.

3) According to the contribution analysis method, the contribution of cultivated land to AOD was the largest from 2015 to 2019, and it fluctuated between 2015 and 2019. Overall, AOD in spring was higher than that in summer. Secondly, the contribution of urban land to AOD was on the rise from 2015 to 2019, and there was little difference in AOD between spring and summer. Other types of land use and water area also have a certain contribution to AOD, which fluctuates. The results show that the land use pattern is closely related to AOD. Reasonable planning of land use type and scientific optimization of land use structure can effectively reduce the concentration of air pollution particles.

7. Discussion

This paper combines correlation analysis and contribution analysis to discuss the response of atmospheric aerosols to land use/cover change in coastal cities in Beibu Gulf, and the effect of land cover type change on atmospheric aerosol optical thickness (AOD) is significant. Forest land has obvious negative effects on AOD concentration, because forest land has the ability to adsorb and filter particulate matter in the air, which is better for mitigating air pollution. As the main contributor of AOD, the change of cultivated land is the main reason for the increase in the concentration of air pollution particles, which may be that the vegetation cover on the cultivated land is relatively small, and the exposed soil is easily blown by the wind, resulting in particulate matter suspended in the air, resulting in an increase in AOD concentration, in addition, the process of crop residue combustion and fertilization in cultivated land may also lead to particulate matter emissions, further increasing AOD concentration. The increasing impact of urban land on air pollution indicates that human activities in cities and towns produce large amounts of particulate matter and other pollutants, which in turn lead to higher AOD concentrations. Water bodies and other types of land use have less impact and contribution to AOD.

The research conclusion shows that land use/cover change is of great significance to AOD, and can provide reference for regional development and planning and construction to a certain extent. At the same time, this paper still exists drawbacks: 1) in different LUCC and response relation of AOD, as a result of the limitation of data and technology, this article only choose several kind of main land types, in fact there are many subdivision of land types, the future work can be further subdivided land use types in the perfect response to AOD relations; 2) Although the influence of seasonal factors on AOD was taken into account during the study, due to the limitation of relevant data, this paper only considered the variation of AOD concentration in spring and summer, and failed to fully analyze the correlation between the two under four seasons. Future work can further construct and explore the response mechanism under four seasons.

Data Availability Statement: Data source: https://www.usgs.gov/ and https://www.nasa.gov/.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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