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DRIVING FACTORS OF VEGETATION COVER CHANGE IN BEIBU GULF URBAN AGGLOMERATION

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Abstract

This study was based on remote sensing data from 2010 to 2023, and combined methods such as Geodetector to analyze the spatio-temporal variation characteristics and driving factors of the fractional vegetation cover (FVC) in the Beibu Gulf Urban Agglomeration. The study used the pixel dichotomy model to estimate the FVC, and evaluated the change trends through Theil-Sen trend analysis and Mann-Kendall significance test. The results showed that the FVC increased from 0.74 in 2010 to 0.80 in 2023, with an average annual growth rate of 0.0624/10/years. High-coverage areas are concentrated in Fangchenggang and Qinzhou in Guangxi, while low-coverage areas are mainly distributed in coastal cities such as Haikou and Zhanjiang. The analysis of driving factors shows that the urbanization rate (q-value = 0.6464) and precipitation (q-value = 0.5479) are the main influencing factors, and the interaction between population density and urbanization rate (q-value = 0.965) has the strongest explanatory power for vegetation cover. In the future, the change of vegetation cover will mainly be randomly stable. The persistent areas are mainly distributed in Chongzuo and the southern part of Nanning, while coastal cities such as Haikou and Zhanjiang may face the risk of degradation.

Introduction

In recent years, with the rapid development of the regional economy and the acceleration of the urbanization process, the Beibu Gulf Urban Agglomeration is also facing increasingly severe ecological and environmental pressures (Liu 2020, Qin *et al.* 2023). Vegetation, as an important part of the ecosystem, changes in its coverage not only reflect the health of the regional ecological environment but also have important impacts on climate change, soil and water conservation, and biodiversity protection (Purevdorj *et al.* 1998). Under the dual influence of global climate change and human activities, the change of vegetation cover has become one of the hot issues in global ecological research (Richards and Belcher 2019). Scholars carried out extensive research on the vegetation cover change and its driving factors in different regions through methods such as remote sensing technology, GIS and statistical analysis (Zhou *et al.* 2008, Ali *et al.* 2013, Sing *et al.* 2014, Ahmed *et al.* 2018). Research shows that the change of vegetation cover is jointly affected by natural factors and socio-economic factors. Changes in precipitation directly affect the growth conditions of vegetation, while land development and construction activities during the urbanization process may have a negative impact on vegetation cover (Ma *et al.* 2023, Hu *et al.* 2024). However, the driving factors of vegetation cover change vary significantly in different regions, especially in areas with rapid urbanization and economic development, where the impact of socio-economic factors on vegetation cover is often more significant (Li *et al.* 2005).

The Beibu Gulf Urban Agglomeration has achieved remarkable success in economic development and urbanization in recent years, but at the same time, it also faces environmental problems such as vegetation degradation and the reduction of ecological land. Although some studies have preliminarily explored the vegetation cover change in this region, most of them focus

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on the analysis of a single factor and lack in-depth research on the comprehensive effects of natural and socio-economic factors (Wang *et al.* 2023). In addition, the vegetation cover change in the Beibu Gulf Urban Agglomeration has obvious spatial heterogeneity, and the driving factors in different regions may vary significantly (Long *et al.* 2022). The existing research has not fully revealed these regional differences and the underlying mechanisms. Based on this, this study aims to comprehensively analyze the spatio-temporal variation characteristics and driving factors of vegetation cover in the Beibu Gulf Urban Agglomeration through remote sensing data and methods such as Geodetector, reveal the individual and interactive effects of natural and socio-economic factors on vegetation cover, and provide a scientific basis for regional ecological protection and sustainable development. The research results contribute to a deeper understanding of the mechanism of vegetation cover changes in the Beibu Gulf urban agglomeration and provide reference for the high-quality ecological development of the region.

Materials and Methods

The Beibu Gulf Urban Agglomeration is located along the southern coast of China, with a geographical scope of 105°30′-111°30′ E and 18°10′-23°30′ N. The land area of the region is approximately 116,600 square kilometers, with a coastline stretching as long as 4,234 kilometers, and it also includes a vast offshore sea area. This region is in the transitional zone between the tropical and subtropical regions, with a warm and humid climate. The average annual temperature is between 20 and 24°C, and the average annual precipitation is between 1,200 mm and 2,000 mm, with obvious seasonal precipitation. The terrain is mainly composed of plains, hills, and mountains. The coastal plains are suitable for agricultural and urban construction, while the mountainous areas in the central and northern parts are rich in forest resources. The elevation is shown in Fig. 1. There is a wide variety of vegetation types, including tropical rainforests, monsoon forests, evergreen broad-leaved forests, and mangroves, etc., with a complex ecosystem. The land use is mainly composed of cultivated land, forest land, and construction land, and the soil types include lateritic red soil, laterite soil, and paddy soil, etc.

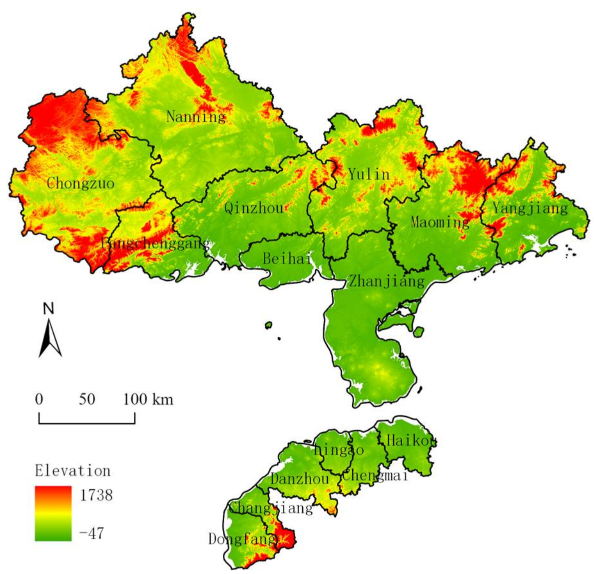

Fig. 1. Elevation of the study areas.

The NDVI (Normalized Difference Vegetation Index) data is sourced from LT5, LT8, and LT8-9 on www.gscloud.cn and obtained through the pixel dichotomy model. There are 14 image data for each year, with a resolution of 30m and a temporal resolution of 16 days. Batch projection transformation of this data is carried out to convert it into WGS 84 coordinates, and pre-processing such as mosaic and masking is performed to obtain the synthesized images for each year. The DEM (Digital Elevation Model) data is acquired from www.gscloud.cn, with a spatial resolution of 30m, which is used to calculate altitude, slope, and aspect. The temperature and precipitation data come from www.geodata.cn, with a spatial resolution of 1 km. The data on land use types and soil types come from http://westdc.westgis.ac.cn/. The data on population density, GDP, and urbanization rate come from the statistical yearbooks of the affiliated provinces and cities. The details can be found in Table 1.

Table 1. Statistics of indicator sources.

Influence category	Specific indicator	Abbreviation	Unit	Data source
Natural factors	Precipitation	Prec	mm	www.geodata.cn
	Temperature	Temp	°C	www.geodata.cn
	Altitude	Alt	m	www.gscloud.cn
	Slope	Slo	°	www.gscloud.cn
	Aspect	Asp	°	www.gscloud.cn
	Soil type	Soil	-	http://westdc.westgis.ac.cn
Social factors	Land use type	Land	-	http://westdc.westgis.ac.cn
	GDP	GDP	Ten Thousand Yuan	Statistical yearbooks
	Population density	Pop	Persons per km²	Statistical yearbooks
	Urbanization rate	Urb	%	Statistical yearbooks

The pixel dichotomy model is a method for estimating the FVC based on remote sensing images (Zhao and Qu 2024). Its core idea is to decompose the information within a pixel into two parts: vegetation and non-vegetation. The model is shown below :

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

FVC is the fractional vegetation cover, with a value range of [0,1]; NDVI is the normalized difference vegetation index of the pixel; $NDVI_{soil}$ is the NDVI value of the pure soil pixel and $NDVI_{veg}$ is the NDVI value of the pure vegetation pixel.

The Theil-Sen trend analysis is a non-parametric slope estimation method that is insensitive to outliers and can effectively reflect the change trend of a time series (Aslam *et al*. 2024). If the change slope $S_{FVC} > 0$, it indicates that the vegetation cover is showing an upward trend; conversely, if $S_{FVC} < 0$, it indicates a downward trend. The calculation of the slope is shown below where FVC_j and FVC_i are the vegetation cover values at time points and respectively. The Mann-Kendall (MK) significance test is used to determine the significance of the change trend. When the absolute value of the MK test statistic is greater than 2.56, the trend is significant at the 0.01 level; when it is greater than 1.96, the trend is significant at the 0.05 level. When it is less than 1.96, the trend is not significant. Combining the results of the S_{FVC} and the MK test, the change trends of the vegetation cover can be classified as follows: low vegetation cover: $0 \leqslant FVC < 0.2$; low-to-medium vegetation cover: $0.2 \leqslant FVC < 0.4$; medium vegetation cover: $0.4 \leqslant FVC < 0.6$; medium-to-high vegetation cover: $0.6 \leqslant FVC < 0.8$ and high vegetation cover: $0.8 \leqslant FVC < 1$.

$$S_{FVC} = \text{median}[\frac{FVC_j - FVC_i}{j-i}]$$

Geodetector is a statistical method used to analyze spatial heterogeneity and its driving factors. It can quantify the influence degree of each driving factor on a certain geographical phenomenon and reveal the interaction between factors. Its core idea is to evaluate the explanatory power of the driving factors by comparing the variances of the sub-regions and the whole region (Tao and Zhou 2024).

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

Where h=1, 2, 3,..., L. L represents the stratification of variables and dependent variables. σ^2 representing the discrete variance of the overall space, N_h representing the discrete variance of a certain layer of space; q represents the explanatory power of the influencing factor variable on the dependent variable of cultivated land transfer, with a larger value indicating a stronger impact.

Compare the relationship among q（A∩B）, q（A） and q（B）to determine the type of interaction, as shown in table 2.

Table 2. Comparison expression and types of interaction.

Comparison expression	Interaction
q（A∩B＜min（q（A, qB））	Nonlinear attenuation
min (q （A), q(B))＜q(A∩B)＜max(q(A), q(B))	Single factor weakening
q(A∩B)＜min(q(A),q(B))	Mutually reinforcing
q(A∩B)=q(A)+q(B)	Mutual independence
q(A∩B)＞q(A)+q(B)	Nonlinear enhancement

Results and Discussion

During the period from 2010 to 2023, the vegetation cover in the Beibu Gulf Urban Agglomeration generally showed an increasing trend. The FVC was 0.74 in 2010 and increased to 0.80 in 2023, with a growth rate of 0.0624 per 10 years, as shown in Fig. 2. The overall vegetation cover in the study area was relatively high. Areas with an average annual FVC was greater than 0.75 accounted for 78.5% of the whole region, mainly distributed in the mountainous areas of Fangchenggang, Qinzhou, and Yulin in Guangxi Zhuang Autonomous Region, as well as Yangjiang and Maoming in Guangdong Province, and Danzhou, Dongfang, Changjiang, Lingao, and Chengmai in Hainan Province. In contrast, areas with relatively low vegetation cover were mainly distributed in coastal cities such as Haikou, Zhanjiang, and Beihai, as shown in Fig. 3A.

The FVC of the Beibu Gulf Urban Agglomeration ranges was found to be between -0.05 and 0.06. The area showing an increasing trend accounts for 77.62%, while the area showing a decreasing trend accounts for only 22.36%. From the results of the significance test of the change trend (Fig. 3 and Table 3), it can be clearly seen that the FVC changes in the Beibu Gulf Urban Agglomeration are mainly concentrated in two types: non-significant improvement and extremely significant improvement, accounting for 46.75 and 28.73%, respectively, while the area of non-significant degradation accounts for approximately 14.43%.

The coefficient of variation of the vegetation cover ranges from 0.006 to 4.62, with an average value of 0.07. The Hurst index ranges from 0.07 to 0.96, with an average value of 0.57, indicating that the changes in the vegetation cover in the Beibu Gulf region are mainly characterized by random stability. The area of the anti-persistence region accounts for 19.25%, mainly distributed in the central and northern parts of Nanning and Chongzuo, as well as the coastal areas of Haikou, Fangchenggang, Qinzhou, Beihai, Zhanjiang, and Maoming. The area of the persistence region accounts for 37.48%, concentrated in Chongzuo, the southern part of Nanning, the coastal areas near the sea in Qinzhou, Fangchenggang and Hainan Province, as well as the mountainous areas in the northern parts of Maoming and Yulin, as shown in Fig. 3B.

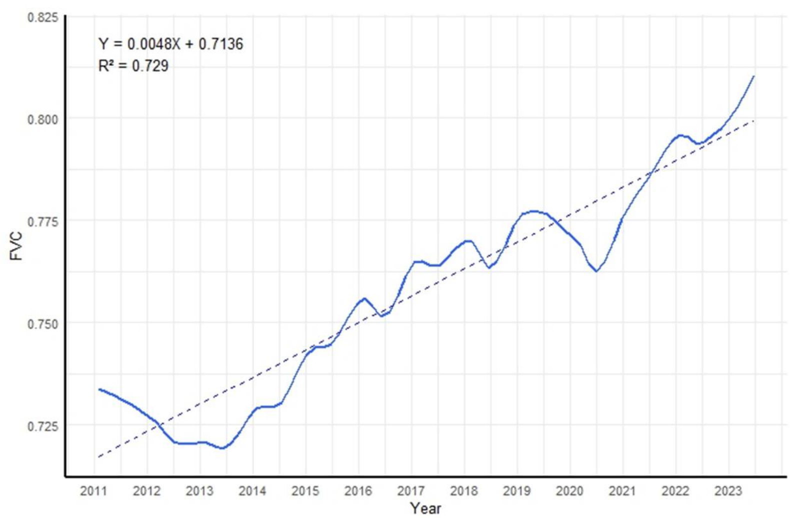

Fig. 2. FVC changes of the Beibu Gulf Urban Agglomeration.

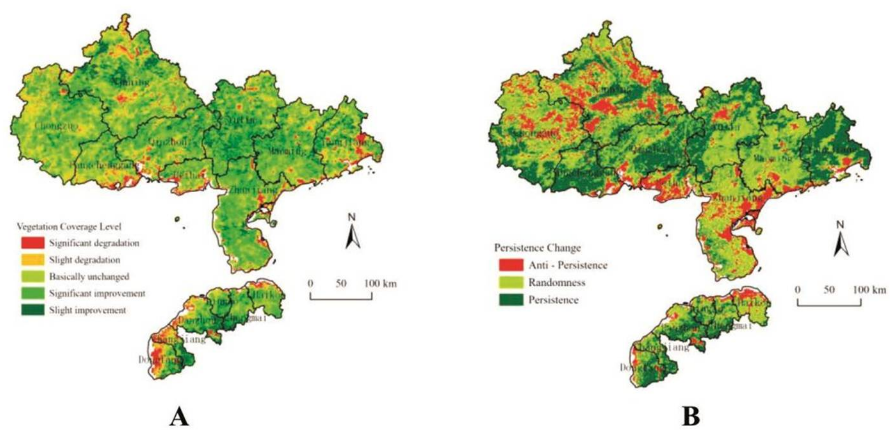

Fig. 3. Spatial distribution of the change trend of FVC (A) and the future trend (B).

The factor detection by the geodetector in Table 4 shows that the independent variables affecting the vegetation cover of the Beibu Gulf Urban Agglomeration are ranked according to the magnitude of their explanatory power (q value) as follows: urbanization rate (0.6464), precipitation (0.5479), soil type (0.4934), population density (0.4258), land use type (0.38687), GDP (0.2847), aspect (0.2481), temperature (0.1972), and slope (0.0202). This indicates that among the many factors influencing the vegetation cover of the Beibu Gulf Urban Agglomeration, the urbanization rate has the highest explanatory power, suggesting that it has the most significant impact on the changes in vegetation cover. This may be because of land development, construction activities, etc. during the urbanization process have changed the vegetation growth environment. In contrast, the slope has the lowest explanatory power and has a relatively small impact on the vegetation cover.

Table 3. Significance of changes in FVC.

Change trend	Significant	Change type	%
β<0	P<0.01	Extreme significant decrease	4.12
β<0	0.01≤P<0.05	Significant decrease	7.47
β<0	P≥0.05	Non - significant decrease	14.43
β>0	P≥0.05	Non - significant increase	32.32
β>0	0.01≤P<0.05	Significant increase	12.93
β>0	P<0.01	Extreme significant increase	28.73

Table 4. Ranking of the explanatory power of single factors for FVC.

Independent variable	q value	p value	Ranking of q value	Independent variable	q value	p value	Ranking of q value
Prec	0.5479	0.2494	2	Soil	0.4934	0.1235	3
Temp	0.1972	0.7211	8	Land	0.38687	0.0765	5
Alt	0.1106	0.0925	9	GDP	0.2847	0.0957	6
Slo	0.0202	0.5679	10	Pop	0.4258	0.1543	4
Asp	0.2481	0.5123	7	Urb	0.6463	0.0321	1

FVC is the result of the combined action of multiple factors. The interaction detection function in the geodetector was further adopted to explore the degree of influence of the combined action of two factors on the vegetation cover. The results of the interaction detection are shown in Fig. 4. The interaction effects of pairwise combinations of various factors present diverse situations. Among them, the q value of the combination of Prec and Soil is as high as 0.952, indicating that the interaction between these two factors has a very strong explanatory power for the vegetation cover. As an important water source for vegetation growth, the amount of precipitation directly affects the growth status of vegetation; while the soil type determines the storage and supply capacity of nutrients required for vegetation growth. These two factors interact with each other to jointly shape the growth environment of vegetation, greatly influencing the vegetation cover. In the Beibu Gulf Urban Agglomeration, the interaction detection results of soil type, land use type and slope are all 0.128. This may be because the local topography and geomorphology are relatively stable, so the slope has little influence on the soil type, and there is not much difference in land use patterns under different slopes. In addition, factors such as precipitation and urbanization rate have a more prominent impact on the vegetation cover, weakening the influence of the interaction between these three factors and the slope on the vegetation cover.

The top 7 in the ranking of the interaction of dual factors are Urb∩Pop, Urb∩GDP, Urb∩Soil, Pop∩GDP, Pop∩Prec, GDP∩Land, GDP∩Prec, Land∩Prec, Soil∩Prec, Land∩Prec. According to the frequency of interaction factors greater than 0.85, precipitation in natural factors and GDP, urbanization rate, and population density in social factors are the main influencing factors of FVC in the Beibu Gulf urban agglomeration. Among them, precipitation among the natural factors and GDP, urbanization rate, and population density among the social factors are the main influencing factors of the vegetation cover in the Beibu Gulf Urban Agglomeration. In addition, the soil type among the natural factors and the land use type among the social factors also have a relatively large impact on the vegetation cover, and their explanatory power remains strong after interaction. In the analysis of the influence of single factors, the explanatory power of GDP is very weak, but after the interaction of dual factors, the explanatory power in the dimension of agricultural investment has a very obvious improvement. The geodetector reveals that the geographical and spatial differentiation of the vegetation cover in the Beibu Gulf Urban Agglomeration is the result of the combined action of multiple natural and social factors.

Fig. 4. Interaction force of interaction factors of FVC.

Precipitation is one of the most important natural factors affecting the vegetation cover of the Beibu Gulf Urban Agglomeration. The study shows that the explanatory power (q value) of precipitation is 0.5479, second only to the urbanization rate. Sufficient precipitation provides the necessary water for vegetation growth. Especially under tropical and subtropical climatic conditions, the seasonal variation of precipitation directly affects the growth cycle and coverage of vegetation. In addition, the soil type also has a significant impact on vegetation cover. In particular, under different soil types, there are differences in the growth conditions and nutrient supply capacity of vegetation. Soil types such as red soil and laterite provide a good growth environment for vegetation. Especially in low mountains, hills and coastal areas, the fertility and water retention capacity of the soil play a positive role in improving the vegetation cover.

The urbanization rate is the most significant socio-economic factor affecting the vegetation cover of the Beibu Gulf Urban Agglomeration, with its explanatory power (q value) as high as 0.6464. With the acceleration of the urbanization process, measures such as urban greening construction, ecological corridor planning and industrial structure optimization have directly promoted the improvement of vegetation cover. Especially in urban planning, the concept of giving priority to ecology has been implemented. A large amount of green space has been reserved during the urban expansion process, increasing the urban vegetation cover area. In addition, the growth of GDP has also provided financial support for ecological construction. The government and enterprises have increased their investment in greening projects and ecological restoration, further promoting the improvement of vegetation cover. The increase in population density also has a positive impact on vegetation cover. With the growth of the population, the consumption demand has promoted the ecological transformation of agriculture. Farmers have adopted efficient planting methods such as three-dimensional agriculture, which not only increases the output of agricultural products but also increases the vegetation cover. At the same time, the requirements for the quality of the living environment in areas with high population density have prompted the government to increase the efforts in urban greening construction, further improving the vegetation cover.

The change of vegetation cover is the result of the combined action of multiple natural and socio-economic factors. Through the interaction detection function of the geodetector, the study found that the interaction between population density and urbanization rate has the strongest explanatory power for vegetation cover, with a q value as high as 0.965, indicating that the increase in population density and the advancement of the urbanization process jointly have a significant positive impact on vegetation cover. With the increase of the urbanization rate, the consumption demand and enhanced ecological awareness brought about by the increase in population density have prompted the strengthening of urban greening construction and ecological protection measures, thus promoting the improvement of vegetation cover. In addition, the interaction between precipitation and soil type also has a very strong explanatory power for vegetation cover, with a q value of 0.952. As an important water source for vegetation growth, precipitation, together with the nutrient supply capacity of the soil type, jointly shapes the growth environment of vegetation. In areas with sufficient precipitation and suitable soil types, the vegetation growth conditions are superior, and the coverage is significantly higher. The interactions of other socio-economic factors also show significant impacts. For example, the interaction between the urbanization rate and GDP has a q value of 0.896, indicating that the synergistic effect of economic development and the urbanization process further promotes the improvement of vegetation cover. In general, the change of vegetation cover is the result of the combined action of multiple natural and socio-economic factors. These interactions reveal the complex mechanisms behind the changes in vegetation cover, providing an important scientific basis for regional ecological protection and sustainable development.

The study also found that the changes in the vegetation cover of the Beibu Gulf Urban Agglomeration are mainly randomly stable, with an average Hurst index of 0.57, indicating that the future change trend of vegetation cover will maintain a certain degree of continuity. The continuous areas are mainly distributed in Chongzuo, the southern part of Nanning and the coastal areas near Hainan Province. The vegetation cover in these areas is expected to continue to increase in the future. The anti-continuous areas are mainly distributed in coastal cities, such as Haikou, Zhanjiang, etc. The vegetation cover in these areas may face a certain risk of degradation. Although the increase in the urbanization rate and population density has a positive effect on vegetation cover as a whole, in these coastal cities, the expansion of construction land is rapid, and a large amount of ecological land is occupied, resulting in a decrease in vegetation cover. The economic development model in coastal areas is highly dependent on land resources, further exacerbating the risk of vegetation degradation. Therefore, in the future, ecological planning in these areas should be strengthened to balance the relationship between urbanization and ecological protection and ensure the sustainable development of vegetation cover.

From 2010 to 2023, the vegetation cover in the Beibu Gulf urban agglomeration increased from 0.74 to 0.80. Areas of high vegetation cover were concentrated in mountainous regions, while low-cover areas were primarily in coastal cities. The improvement was primarily driven by socio-economic factors. Urbanization rate was the single most influential factor, but its interaction with population density had the strongest overall explanatory power, indicating that concentrated development and greening efforts significantly boost vegetation cover. The combination of precipitation and soil type was the key natural driver.

Looking forward, the trend of vegetation cover is generally stable and likely to persist. However, coastal cities like Haikou and Zhanjiang face a risk of future degradation due to pressures from rapid urbanization.

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