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Analysis of spatio-temporal pattern of land-use carbon emission in Chang-Zhu-Tan metropolitan area at the grid scale

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Abstract: *Economic activity patterns and land use patterns greatly affect the carbon emission patterns of a certain region. This article is based on 30 meter precision land use data and energy consumption data of the Changzhutan urban agglomeration, using a grid with a side length of 5 kilometers as the research unit. We inferred the spatiotemporal pattern and changes in carbon emissions in the region from 2000 to 2020. We also explored the evolution process of carbon emission grids, carbon source grids, and carbon sink grids at different intensity levels in the region over the past 20 years. This article uses Geoda software to conduct a comprehensive and local Moran's analysis of regional carbon emissions, to explore the spatial autocorrelation between grids. Research has shown that: the total carbon emissions of the Chang-Zhu-Tan urban agglomeration have gone through three stages: first rapid growth, then slow growth, and finally rapid decline. The carbon emissions in 2010 and 2015 were much higher than those in 2000, 2005, and 2020.In 2010 and 2015, a large number of extremely high intensity grids with annual carbon emissions exceeding 500000 tons appeared in the three urban areas of Changsha, Zhuzhou, and Xiangtan. Subsequently, by 2020, the total carbon emissions had fallen back to close to 2005; The central urban area of the three cities of Changsha, Zhuzhou, and Xiangtan is the region with the largest changes in carbon emission patterns within the study area. It is also a high-value core area for carbon emissions and carbon sources. The high carbon emission grid has become increasingly concentrated in the area. The area along National Highway 106 in Zhuzhou is another area with high carbon emissions and carbon source values. The connection between this area and the core area of the Chang-Zhu-Tan metropolitan area is relatively weak due to the influence of terrain and distance. The mountainous and hilly areas are the main functional carriers of carbon sequestration in the entire research area. Several large mountain ranges within the territory are gathering areas for high-value carbon sequestration grids. The carbon emission grid exhibits low to low aggregation in this area. Regarding the task of achieving dual carbon, this article believes that: We must take into account the transformation of economic models within the built-up area, the rational planning and control of regional land use types, and the protection of existing ecological green spaces, and these three directions must be jointly promoted and implemented.*

Keywords: *Land-use carbon emission; Spatio-temporal pattern; Grid Analysis; Chang-Zhu-Tan metropolitan area*

1. Introduction

The definition of peak carbon dioxide emissions is that at a certain point in time, carbon dioxide emissions no longer increase to their peak value, and then gradually decrease. Carbon peaking is a historical turning point in the increase and decrease of carbon dioxide emissions, aiming to achieve a balance between carbon emissions and economic development[1]. The peaking targets include the year and value of the peak. In the new era of wide industry and the context of dual carbon, reducing emissions is an important issue in China. The Central Committee of the Communist Party of China has put forward the concept of "integrating dual carbon into the overall development of the economy and society, accelerating the formation of a resource and environmental friendly industrial structure, lifestyle, and spatial pattern, and firmly adhering to the path of high volume development with green and low-carbon development", with a focus on promoting the normal operation of carbon reduction work and assisting in the implementation of the policy of energy reduction. As a key area that can reduce emissions, urban agglomerations have put forward certain requirements for low-carbon planning

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in the region. As a typical urban agglomeration in the central and western regions, the Chang-Zhu-Tan Urban Agglomeration bears an important fulcrum and growth pole for accelerating the comprehensive rise of the central region. No matter how large the emission reduction is, it is equally urgent at the same time. The simulation study of carbon emissions is one of the important cornerstones for achieving carbon peak goals and implementing carbon reduction strategies. Research can provide policy makers with a straight reference basis, reasonably layout emission reduction work, and specify feasible emission reduction strategies.

At the same time, the spatial scale of existing carbon emission models is relatively large, and the division of land types between the simulated spatial grids is not clear enough. The relationship between the differences in carbon emissions of land types and the overall grid carbon emissions lacks clarity, which increases the uncertainty of future carbon peaking and carbon reduction plans. In the context of the recent epidemic, the uncertainty and credibility of carbon peaking results based on large-scale spatial grid measurements have increased, and carbon reduction goals have been achieved as scheduled, which has constrained the implementation of emission reduction policies. Therefore, under the dual background of increasing the uncertainty of existing carbon peaking and carbon reduction achievements, as well as implementing the energy reduction plan, increasing the accuracy of land use types within the spatial grid, exploring the influencing factors of spatial differences in carbon emissions, and modeling the future carbon emissions situation and possible time intervals of carbon peaking have significant implications for the effective implementation of the energy reduction plan and the carbon reduction in the urban areas of Changsha, Zhuzhou, and Xiangtan.

Since the end of the last century, many scholars have conducted extensive research and research on the relationship between land use and emissions at different spatial scales, including analyzing the carbon emission mechanism of a single land type[2-3], using various models[4-6], and influencing factors[7-9]. However, most of them are limited to a series of research and exploration at a large scale, such as provincial, municipal, and regional levels. However, there is a lack of direct research on the specific classification of land type carbon emissions and the impact of grid carbon emissions on land factors under high-precision conditions.

2. Research ideas and data sources:

2.1. Research Area

The research area of this article - Chang-Zhu-Tan Urban Agglomeration(***fig.1***), located in the central eastern part of Hunan Province, People's Republic of China, is an important component of the urban agglomeration in the middle reaches of the Yangtze River and a core growth pole for the economic development of Hunan Province. The urban agglomeration covers an area of 28000 square kilometers, including The municipal jurisdiction of Changsha, The municipal jurisdiction of Zhuzhou, The municipal jurisdiction of Xiangtan, as well as Liuyang City, Ningxiang City, Changsha County, You County, Chaling County, Yanling County, Liling City, Xiangxiang City, Shaoshan City, and Xiangtan County. The three central urban areas of Changsha, Zhuzhou, and Xiangtan are distributed in an "equilateral triangle" along the Xiangjiang River, with a distance of less than 40 kilometers between them and a compact structure.The core area of the urban agglomeration covers an area of 9211.03 square kilometers. In 2020, the per capita GDP of the three cities of Changsha, Zhuzhou, and Xiangtan reached 140000 yuan, and the urbanization level reached over 75%. The electronic information, engineering machinery, transportation equipment manufacturing, and non-ferrous metallurgy industries in this region are relatively developed, making it an important old industrial base in China. The Beijing Guangzhou Railway, Beijing Guangzhou High Speed Railway, Xiangjiang River, Beijing Hong Kong Macao Expressway, Shanghai Kunming Expressway and other major public, rail, and waterway transportation routes cross the territory. In 2007, the Chang-Zhu-Tan Urban Agglomeration was approved as a comprehensive supporting reform pilot zone for the construction of a resource-saving and environmentally friendly society in China.

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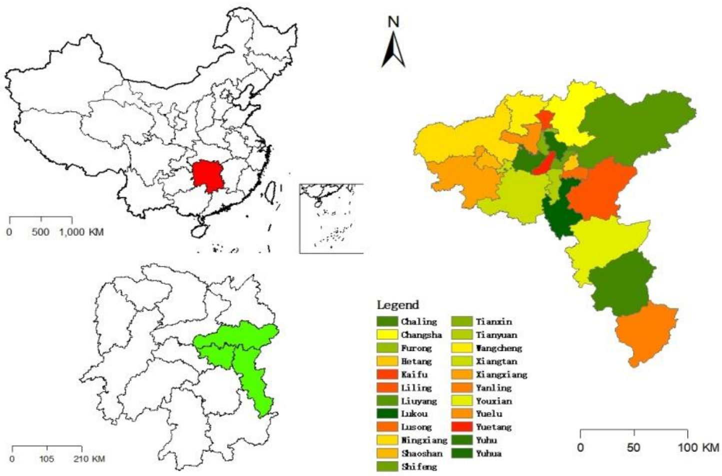

Fig. 1 Changsha Zhuzhou Xiangtan Administrative Division Map

2.2. Research methods

2.2.1. Estimation method for carbon emissions from land use

The calculation of carbon emissions in the research area uses the land area of each land type multiplied by the corresponding carbon emission coefficient, and then summed up.

The calculation formula for carbon emissions is:

$$T_z = \sum t_i = \sum A_i \times \beta_i \tag{1}$$

In***(Eq.(1))***, T_z represents direct carbon emissions; t_i It represents the carbon emissions of various types of land use; A_i and β_i represent the area and carbon emission coefficient of land type *i*, respectively. Determine the carbon emission coefficients of each land use type by referring to the "Estimation of Land Vegetation Carbon Sink in China from 1981 to 2000" [10-13], see (***Table 1***).

Table 1 Emission coefficient of land use type.

Land type	**carbon emission coefficient / (t/hm^2)**	**Reference source**	**Land type**	**carbon emission coefficient / (t/hm^2)**	**Reference source**
cultivated land	0.422	Li Ying et al[10]	Water body	-0.253	DuanXiaonan et al[12]
woodland	-0.644	Fang Jingyun et al[11]	unused land	-0.005	Lai Li et al[13]
grass	-0.022	Fang Jingyun et al[11]			

Calculate the carbon emissions of construction land based on the fossil energy consumption of the Chang-Zhu-Tan urban agglomeration from 2000 to 2020. The calculation of carbon emissions from construction land adopts indirect estimation method. Combining the "China Energy Statistical Yearbook" and the 2006 IPCC "Guidelines for National Greenhouse Gas Emissions Inventory" (***Table 2***). Finally, it is estimated through the consumption of various energy sources and carbon emission coefficients.

Table 2 Conversion coefficient of various energy sources into standard coal and carbon emission coefficient

Energy types	**Standard coal efficiency**	**Carbon emission coefficient**	**Energy types**	**Standard coal efficiency**	**Carbon emission coefficient**
Raw coal	0.7143	0.7559	Diesel oil	1.4571	0.5921
Hard coke	0.9714	0.855	Fuel oil	1.4286	0.6185
Natural gas	1.2143	0.4483	Kerosene	1.4714	0.5714
Crude oil	1.4286	0.5857	Electricity	0.404	0.7935
Gasoline	1.4714	0.5538			

The calculation formula for carbon emissions from construction land:

$$T_j = \sum t_i = \sum E_i \times \mu_i \times \eta_i \tag{2}$$

In ***(Eq.(2))*** , T_j is the carbon emissions from construction land; t_i is the carbon emissions generated by energy *i* consumption, E_i is the consumption of energy*i*; μ_i is the coefficient of converting energy consumption into standard coal;; η_i is the carbon emission coefficient of energy *i*.

2.2.2. Exploratory spatial data analysis (ESDA)

Exploratory spatial data analysis is a basic statistical method for studying the spatial distribution characteristics of regional socio-economic development, with spatial correlation measurement as the core. Through visual analysis of the spatial distribution of a certain thing or phenomenon, its spatial correlation and aggregation can be discovered. Including Global Moran's I and Local Moran's I.

The formula is as follows:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\left(\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \right) \sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{3}$$

$$I_i = \frac{n (x_i - \bar{x}) \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{4}$$

In ***(Eq.(3))*** and***(Eq.(4))***, I is the global Moran index; I_i is the local Moran indexN is the number of research squares with a side length of 5km; w_{ij} is the spatial weight matrix; x_i and x_j represent the land use carbon emissions of the i-th and j-th study grids; $\bar{x}$ represents the average carbon emissions from land use.

2.3. Data source

This article adopts the land use data of China from 2000 to 2020 by the team of Huang Xin and Li Jiayi from Wuhan University[14], with a resolution of 30m.According to the land use classification standards of the Chinese Academy of Sciences, the land use data of each year is divided into six primary types, namely arable land, forest land, grassland, water body, construction land, and unused land. Energy consumption and socio-economic data are sourced from statistical data such as the China Energy Statistical Yearbook, the Statistical Yearbook, and the Hunan Provincial Statistical Yearbook (2000-2020) for the corresponding years. Using the fishing net analysis method of ArcGIS, this article divided the research area into 970 evaluation units based on a grid of 5km * 5km size.Due to the difficulty in obtaining data, this article indirectly calculates the energy consumption data of the Chang-Zhu-Tan urban agglomeration from 2000 to 2020 based on the ratio of the current year's GDP of the three cities in the study area to that of Hunan Province.

3. Result analysis

3.1. Spatial pattern evolution

3.1.1. Spatial pattern evolution of carbon source

In this section, the above formulas and collected data are used to calculate according to various indicators, and the grids with 5km accuracy are used to summarize and divide the grids with different intensities. The spatial pattern of land use carbon source, carbon sink and carbon emission in Changsha-Zhuzhou-Xiangtan urban agglomeration is roughly deduced.

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In the process of urbanization and industrialization, industrial production and residents ' life are the main sources of carbon emissions. In order to more intuitively compare the differences in carbon sources between regions, this section divides the annual carbon source intensity of the Changsha-Zhuzhou-Xiangtan urban agglomeration into six grades : 0t-5000t, 5000t-10000t, 10000t-30000t, 30000t-100000t, 100000t-500000t and 500000t-2000000t. The grid above 5000 t is considered to be a high-value grid.

It can be seen from (***Fig.2***) that the total amount of carbon sources is unevenly distributed, with the central urban areas of the three cities of Changsha, Zhuzhou and Xiangtan and the built-up areas of the cities and counties under their jurisdiction as the core, and the total amount of carbon sources decreases outward. Among them, the total carbon source in the central urban area of Changsha is the largest, followed by the central urban areas of Zhuzhou and Xiangtan, which form the "triangle" type carbon source core of the urban agglomeration. On the east side of the Hengshan Mountains, the central urban area of You County has become a carbon source highland, which may be related to its relatively flat terrain and its role as a hub for many important highways.

From the perspective of temporal and spatial changes, the high-value grids of carbon sources in 2000 were relatively scattered, generally bounded by the remaining veins on the southwest side of the MulianJiushan Mountains, which were divided into two parts: east and west. On the west side, the central urban area of the three cities of Changsha, Zhuzhou and Xiangtan is the core, and the east side is the axis of the national highway 106.By 2005, the intensity of carbon source on the west side was significantly enhanced. The grids with an annual carbon source of more than 5000t began to be contiguous, and the sub-core centered on the central urban area of each county and city began to develop towards the urban area of Changsha-Zhuzhou-Xiangtan. The carbon source intensity on the east side also increased to a certain extent. By 2010, the grid with an annual carbon source of more than 5000 t on the west side of the MulianJiushan Mountains has completely formed a large area of continuous area with the three cities of Changsha, Zhuzhou and Xiangtan as the core, the rest of the counties and cities as the secondary core, and the core is connected with each other. On the east side of the MulianJiushan Mountains, the carbon source intensity along the national highway 106 continues to increase, and the number of grids with an annual carbon source of more than 5000 t in the central urban area and the south side of Liling City has increased to a certain extent. The current situation in 2015 is basically the same as that in 2010, indicating that the urbanization process of the urban agglomeration has reached a certain height. Compared with the period from 2000 to 2010, the speed of urbanization has begun to slow down, and the energy consumption control of construction land has also achieved initial results. By 2020, the grid with an annual carbon source of more than 5000 tons has shrunk, and the extremely high grid with an annual carbon source of more than 100,000 and 500,000 has been significantly reduced. The strategy of regional low-carbon development has achieved remarkable results.

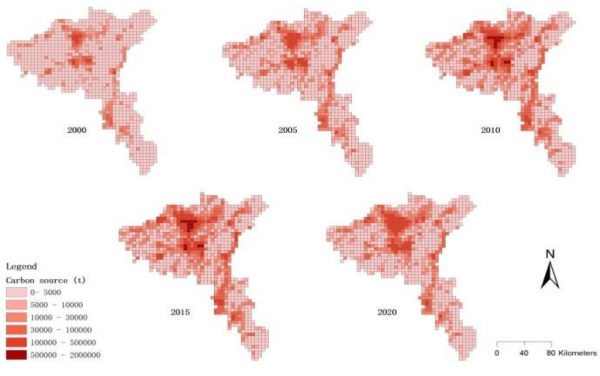

Fig. 2 The Spatial Pattern of Carbon Sources in the Chang-Zhu-Tan Urban Agglomeration

3.1.2. Evolution of the spatial pattern of carbon sink

The carbon sink function is mainly completed by forest grassland and water body. Considering that the Chang-Zhu-Tan urban agglomeration belongs to a typical subtropical monsoon climate zone, is in the evergreen broad-leaved forest belt, and there is no large water body in the territory, the woodland thus undertakes the main carbon sink function of the Chang-Zhu-Tan urban agglomeration. For the convenience of carbon sink research, this section divides the annual carbon sink intensity into six levels, namely 0-300t, 300-600t, 600-900t, 900-1200t, 1200-1600t, and more than 1600t. Among them, a grid with an annual carbon sink of more than 1200t is considered to be a high-value grid. The grid of

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300-1200t is considered to be the median grid.

As can be seen from the figure (***Fig.3***), the high-value grid with a carbon sink of more than 1200t is mainly distributed in the Mulianjiu Mountains and Hengshan Mountains and their surroundings. It is located in the east of the three downtown areas of Chang-Zhu-Tan, in a north-south direction and runs through the east side of the Chang-Zhu-Tan urban agglomeration. It is a veritable natural ecological corridor. In addition, there is also a sporadic distribution of grids with an annual carbon sink of more than 1200t on the southern and west sides of the three urban centers of Chang-Zhu-Tan, most of which rely on mountains. The median grid of 300-1200t of carbon sink is mainly between the mountain and the urban construction land in the Chang-Zhu-Tan urban agglomeration, which is mostly distributed by a mixture of arable land and forest land. On the west side of the Mulianjiu Mountains, there are a large number of distributions on the north side of the Hengshan Mountains.

From the perspective of space-time changes, the smallest change is in the Luoxiao Mountains area in Nansan County (You County, Chaling County, Yanling County) in Zhuzhou City. This area basically maintains a large amount of high carbon sinks of more than 1200t. The regional range of the median grid with a carbon sink of 300-1200t remains largely unchanged, but its overall carbon sink strength has weakened slightly. The area with relatively small changes is around the Moulian Nine Mountains east of the core area of the three cities of Changsha, Zhuzhou, and Xiangtan. The number of high-value grids with an annual carbon sink of more than 1200t has been slightly reduced, mainly distributed in the urban area of Liuyang City and its outer northeast flat area, which is closely related to the economic development and land development of Liuyang City. The biggest change is in the downtown area of Chang-Zhu-Tan and its surrounding areas. The overall number of medium and high-value grids with an annual carbon sink of more than 300t has been greatly reduced, especially in the 2000-2010 period of high-speed urbanization. Its decline rate is relatively fast, and this phenomenon has been alleviated after 2010, which benefits. In the implementation of the ecological protection policy of the country and the Chang-Zhu-Tan urban agglomeration, compared with the adjustment of the economic development model, ecological restoration will go through a longer cycle. Therefore, the recovery process of the number of high-value grids in the carbon sink is still in a relatively preliminary stage by 2020.

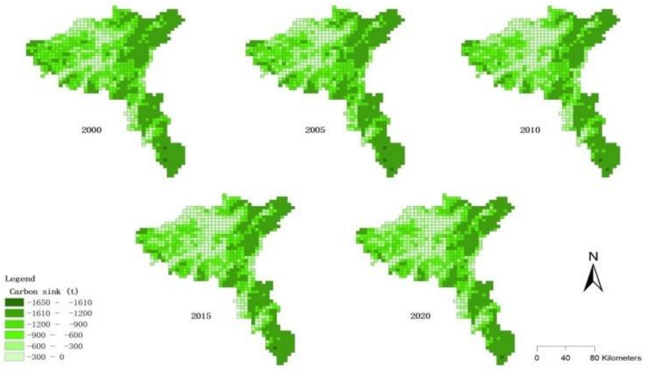

Fig.3. Carbon sink spatial pattern of the Chang-Zhu-Tan urban agglomeration

3.1.3. Spatial pattern evolution of carbon emissions

In order to better express the differences and spatial distribution characteristics of land use carbon emissions in the county of Chang-Zhu-Tan area from 2000 to 2020, this section divides the annual carbon emissions corresponding to each grid into seven levels. They are-1610t-0t, 0t-5000t, 5000t-10000t, 10000t-30000t, 30000t-100000t, 100,000t-500000t, and 500,000t-2000000t respectively. Among them, the grid with annual carbon emissions of 5000 t and above is considered to be a high-value grid, and the grid with 0-5000 t is considered to be a low-value grid. The overall conclusion is shown in (**Fig.4**).

1) From 2000 to 2015, the number of grids with annual emissions of more than 5000 t increased significantly, and fell sharply after 2015.In 2000, the grids with annual emissions of more than 5000 tons were scattered in the central urban areas of Changsha, Zhuzhou, Xiangtan and their counties and cities. The spatial continuity between the grids was weak and the distribution of each other was relatively independent. By 2005, the number of grids above 5000t began to increase, and the number of high-value grids with annual emissions of more than 100,000t increased simultaneously, mainly concentrated in the "triangle" shaped zone composed of Changsha, Zhuzhou and Xiangtan central urban areas. The extremely high-value area with annual emissions of more than 500,000t appeared in

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the central urban area of Changsha. The grid with an annual emission of more than 5000 t shows a trend of contiguous development in space. The whole Overall, it is divided into two contiguous areas, with the southwest margin of the Moulian Jiu Mountains and the Hengshan Mountains as the boundary. To the west, there are the central urban areas of Chang-Zhu-Tan, Liuyang, Ningxiang, Shaoshan, and Xiangxiang. The eastern contiguous area is distributed in the central urban areas of Liling City and You County, Chaling County, and Yanling County (Three Southern Counties, Zhuzhou City). The eastern contiguous area is mainly distributed along National Highway 106 and its surrounding areas. By 2010, in the Changsha-Zhuzhou-Xiangtan urban agglomeration, the number of grids in the area with an annual emission of more than 5000 tons has increased significantly, covering a large area on the west side of the MulianJiushan Mountains, the north side of the Hengshan Mountains, and the north-south axis of the Xiangjiang River. In Liling City and Youxian County, Chaling County and Yanling County on the east side of the MulianJiushan Mountains, the overall carbon emission intensity is also significantly enhanced with the national highway 106 as the axis in the high-value contiguous area composed of grids with annual emissions of more than 5000 t. he boundary between the contiguous areas composed of more than 5000 t grids on the east and west sides of the Mulianjiu Mountains is gradually blurred. he extremely high value grids above 500000 t in Changsha, Zhuzhou and Xiangtan increased significantly, and the increase of carbon emission intensity in the central urban areas of the three cities was the most significant. Compared with 2000, by 2010, the contiguous area of the Chang-Zhu-Tan urban agglomeration with an annual emission of more than 5000 tons has achieved rapid growth in area, which is roughly synchronized with the large-scale urbanization process and rapid economic development in China at the same time. By 2015, with the gradual adjustment of national economic construction and the gradual implementation of the two-oriented society in the Changsha-Zhuzhou-Xiangtan urban agglomeration, the rapid growth of carbon emissions in the urban agglomeration was curbed compared with that before 2010, and the spatial pattern of carbon emissions was basically consistent with that in 2010.By 2020, with the further strengthening of the construction of national ecological civilization, the adjustment of China 's economic development model, and the further development and improvement of the two-oriented society in Changsha-Zhuzhou-Xiangtan, the number of high-value grids with an annual emission of more than 5000 tons in the Changsha-Zhuzhou-Xiangtan urban agglomeration has dropped significantly, and the area of the contiguous area has been reduced. The high-value grids of more than 5000 tons are highly concentrated in the central urban areas of the three cities, the central urban areas of each county and city, and along each other's traffic arteries. The grid of 500,000 tons of annual emissions disappeared. The total amount of carbon emissions and the overall spatial pattern in 2020 are close to those in 2005, but the number of high-carbon emission grids in the core areas of Changsha, Zhuzhou and Xiangtan increased significantly and showed a contiguous trend in space, indicating that by 2020, the urbanization process in the central urban areas of Changsha, Zhuzhou and Xiangtan is more successful, and the development trend of Changsha, Zhuzhou and Xiangtan integration is obvious.

2) The spatial pattern and quantity of the annual emissions 0t-5000t grid did not change significantly. Before 2015, the number had been greatly reduced, and by 2020, it had rebounded significantly. This area is mainly cultivated land, which is generally between urban construction land and peripheral green space. From 2000 to 2015, in the area west of Liling City, with the rapid urbanization and economic development of the central urban areas of the three cities of Changsha, Zhuzhou and Xiangtan and the counties and cities under their jurisdiction, the grid of annual carbon emissions of 0t-5000t was gradually eroded by the higher value grid of annual emissions. In 2010, only a small number of grids were scattered in a large area on the west side of the MulianJiushan Mountains. This phenomenon remained until 2015.However, with the gradual strengthening of ecological civilization construction, by 2020, the number of annual emissions of 0t-5000t grids has rebounded significantly in the vast area west of Liling City, and the overall spatial pattern is similar to that in 2005,forming a contiguous situation again. There is a certain degree of expansion in the spatial distribution of the 0t-5000t grid in the area east of the Mulianjiu Mountains-Hengshan Mountains and Liling City. Among them, in the eastern part of ChalingCounty, the surrounding areas of the Luoxiao Mountains, the number of grids has increased significantly, and the new 0t-5000t grid mainly covers the grid with negative annual carbon emissions.

3) The number of grids with negative annual emissions decreased, with a sharp decrease in 2000-201, The sharp decline phenomenon improved from 2010 to 2015, and a slight recovery in 2015-2020.This grid is dominated by forest land and grassland, mainly distributed in the mountainous and hilly areas east of the central urban areas of Changsha, Zhuzhou and Xiangtan.The contiguous areas of negative emissions in 2000 were distributed in a narrow strip from the east of Liuyang City, the west of Liling City, and the east of the three counties (You County, Chaling County, and

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YanlingCounty) in Zhuzhou. The negative contiguous areas are generally consistent with the north-south trend of the MulianJiushan Mountains and the Luoxiao Mountains. There are also some negative grid agglomeration distributions on the south side of the central urban area of the three cities of Changsha, Zhuzhou and Xiangtan-the north side of the Hengshan Mountains. There are a small number of negative grids scattered in the hilly area between the downtown area of ningxiang city, the downtown area of shaoshan city and the downtown area of xiangxiang city. With the advancement of urbanization, by 2015, the negative grids around the central urban areas of the three cities of Changsha, Zhuzhou and Xiangtan have been greatly reduced. The reduced grid is distributed on the east side of the central urban area of Chang-Zhu-Tan: within the borders of Liuyang and Liling; To the south of the urban area: Xiangtan County and Lukou District; To the west of the urban area: a vast area within Xiangxiang, Shaoshan, andNingxiang. The negative areas of carbon emissions have decreased significantly, indicating that the urbanization process in the core areas of the three cities of Changsha, Zhuzhou and Xiangtan and their surrounding areas is more significant. Correspondingly, the three counties in the south of Zhuzhou: Youxian, Chaling, Yanling, because they are far away from the core area of the three cities of Changsha, Zhuzhou and Xiangtan, and the negative grid goes deep into the Luoxiao Mountains, the urbanization process in this area is relatively slow. By 2015, the number of negative grids of annual emissions has not changed significantly, and the ecological green space has been better protected. From 2015 to 2020, the overall negative annual emission grid of the urban agglomeration has been restored to a certain extent, which may be closely related to the gradual implementation of the policy of returning farmland to forests in the ecological protection zone of the Chang-Zhu-Tan urban agglomeration.

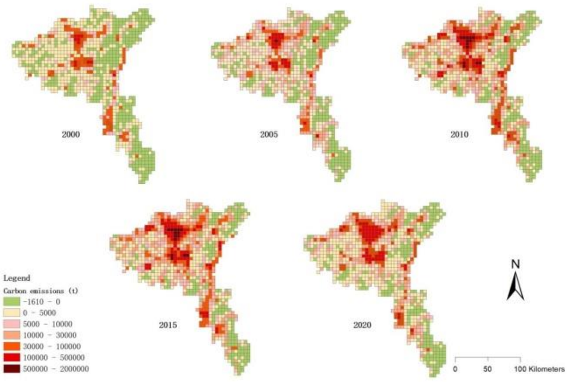

Fig.4. Spatial pattern of carbon emissions in the Chang-Zhu-Tan urban agglomeration

3.2. Changes in total carbon emissions

From the statistical chart (***Fig.5***), we can roughly show the change of the total carbon emissions of Chang-Zhu-Tan urban agglomeration from 2000 to 2020. In 2000, the total carbon emissions in the region were about 5.98 million tons. Compared with 2000, the value showed an upward trend in 2005, and the value increased to about 14.75 million tons. In 2010, it continued to increase significantly compared with 2005, reaching 34.26 million tons, which may be related to China's rapid economic development period and rapid urbanization period. Since the 18th National Congress of the Communist Party of China, the country has paid more and more attention to the low-carbon development model, and the concept of high-quality development has been gradually put forward. At the same time, the construction of Chang-Zhu-Tan's national resource-saving and environment-friendly social construction comprehensive supporting reform pilot zone has gradually matured. From 2010 to 2015, the carbon emission growth rate of Chang-Zhu-Tan urban agglomeration has been significantly reduced. In 2015, the total regional carbon emission was 35.85 million thousand tons, compared with the growth rate of less than 5% in 2010. From 2015 to 2020, regional carbon emissions have been further controlled. By 2020, the total carbon emissions have dropped significantly to 19.58 million tons, roughly falling back to the total level in 2005, indicating that the long-term green and low-carbon transformation strategy has achieved good results.

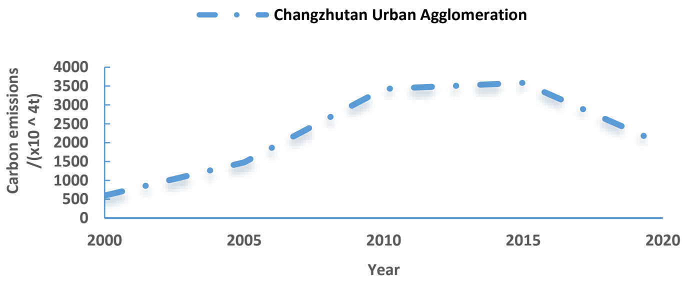

Fig.5. Changes in total carbon emissions of the Chang-Zhu-Tan urban agglomeration

Combined with the 2000-2020 GDP situation of Chang-Zhu-Tan urban agglomeration (***Fig.6***): since the beginning of this century, the GDP of Chang-Zhu-Tan urban agglomeration has maintained a relatively high-speed growth, and the total amount of GDP in the three places will reach 1.7548 trillion yuan by 2020. From 2010 to 2020, after the energy conservation and emission reduction strategy gradually deepened - the total carbon emissions slowed down until it decreased significantly, but the GDP in the region has always maintained a strong growth rate, indicating that the low-carbon development of the Chang-Zhu-Tan urban agglomeration has not come at the expense of economic development. The gross domestic product of the three cities ranks in Hunan respectively. The three cities are ranked first, fifth, and seventh in the province, respectively. The region maintains the status of a service base and an old industrial base in the central region. At the same time, it is making steady progress towards the new goal of high-quality development and building a central economic engine.

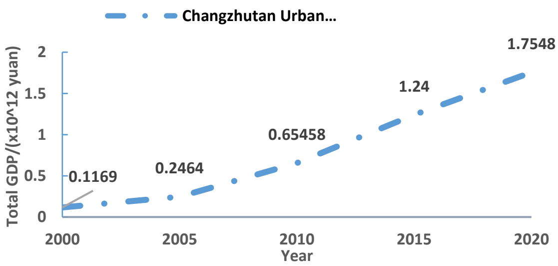

Fig.6 Changes in Gross Domestic Product of Chang-Zhu-Tan Urban Agglomeration

3.3. Spatial autocorrelation analysis of carbon emissions

By utilizing the Moran's analysis tool in *GEODA* software, the Moran's index and various indicators of land use carbon emissions in the Chang-Zhu-Tan urban agglomeration from 2000 to 2020 were obtained (***Fig.7***).

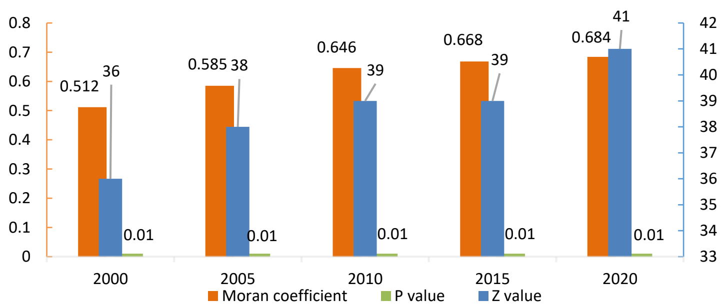

Fig.7 Carbon emission autocorrelation test

From (***Fig .7***), it can be seen that the Moran index of land use carbon emissions in the Chang-Zhu-Tan urban agglomeration from 2000 to 2020 remained generally stable at 0.5 to 0.7, showing a positive correlation, and this positive correlation became stronger over time, indicating that the spatial clustering characteristics of grids with the same level of carbon emission intensity are becoming more and more obvious. The p-value always remains at 0.01, and the z-value is much greater than 0.258. These three types of values have passed the significance level test, indicating that the confidence level of this positive correlation is extremely high in each year.

In order to further explore the spatial interrelationships of annual carbon emissions in the Chang-Zhu-Tan urban agglomeration, this section uses the Geoda software univariate local Moran's analysis tool to conduct local spatial autocorrelation analysis of the region. The results (***Fig .8***) indicate that from 2000 to 2020, except for a few grids showing low - high (mainly distributed between high - high grids and insignificant grids), the correlation attributes of the vast majority of grids are high- high, low - low, and insignificant. The high-high grid is concentrated in the urban built-up areas, especially in the core gathering areas enclosed by the three central urban areas of Changsha, Zhuzhou, and Xiangtan. Here, the population is concentrated, transportation is convenient, and economic vitality is strong. In Ningxiang City, Liling City, and You County, there are also a small number of high - high scattered distributions .The low-low aggregation grid is mainly distributed in mountainous and hilly areas, mainly relying on the northern foothills of the Hengshan Mountains, the western foothills of the Mulianjiu Mountains, and the western foothills of the Luoxiao Mountains.

From the perspective of temporal and spatial evolution, the high-high clustering grid was concentrated in the central urban areas of Changsha, Zhuzhou, and Xiangtan in 2000. Among them, the high-high clustering phenomenon in the central urban areas of Changsha was the most significant, followed by the central urban areas of Xiangtan and Zhuzhou. Due to the fact that the shortest straight-line distance between the central urban areas of Xiangtan and Zhuzhou does not exceed 10 kilometers, both of which are built on the Xiangjiang River. In 2000, the high grid of the two central urban areas had been continuously distributed with each other.

From 2000 to 2010, there was no significant change in the number and spatial distribution of high-high grids in the central urban areas of Xiangtan and Zhuzhou. Based on its strong economic vitality and ongoing Hexi development strategy, Changsha's high-high grid area is showing a trend of outward expansion, especially westward expansion. Yuelu District and Wangcheng District of Changsha City achieved rapid development during this period.

By 2015, the integration of the three cities of Changsha, Zhuzhou, and Xiangtan, led by Changsha City, had begun to take shape. The high-high grid area in the urban area of the three cities of Changsha, Zhuzhou, and Xiangtan had successfully extended south-north through the Xiangjiang Economic Belt, becoming a contiguous area.

By 2020, the high-high grid areas of Yuelu District and Wangcheng District in Hexi District of Changsha City have further expanded outward, which may be related to the economic stimulus effect of the establishment and improvement of the Xiangjiang National New Area. In the eastern part of the river, the area filled with high-high grids in Changsha County has also significantly expanded.

From 2000 to 2020, there was no significant change in the spatial distribution of the low low grid. However, what is worth mentioning is that within the hilly area enclosed by the southern side of Ningxiang City, the northern side of Shaoshan City, and the western side of Xiangshan in Ningxiang City, the area composed of low - low grid has expanded to a certain extent. This area includes important agricultural areas in the river valleys and plains along the Weishui River, The implementation of the strategy of returning farmland to forests in this region is relatively high, and carbon emissions from agricultural land have been controlled to a certain extent.

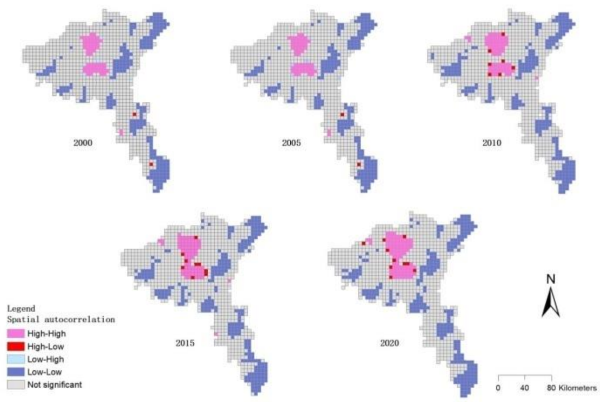

Fig.8 Carbon emissions LISA aggregation chart

4. Discussion

Although this article calculates and summarizes the carbon emissions from land use in various grids through high-precision land use data, and displays the quantitative changes and spatiotemporal pattern evolution of carbon emissions from land use in each grid, there are still some limitations that need further improvement. Firstly, the calculation of land use carbon emissions in this article mostly draws on the carbon emissions and carbon sink coefficients of various land types in existing research, without fully explaining other influencing factors in the study area, such as land quality, land type changes, human factors, etc., which affect the carbon emissions of the study area; Secondly, in this study, land use data with a precision of 30m * 30m and a 5km * 5km grid were used for calculation and summary. However, the relevant research at this precision is not yet saturated, and there is a lack of existing research results for comparison, making it difficult to compare and reference from the side to improve the accuracy of calculation results and conclusions. At the same time, the research scale of this article is single, but due to the complex scale effects accompanying ecological and geographical processes, the evolution of land use carbon emissions also needs to be studied from multiple scales, and the research results at each scale should be summarized and integrated with emphasis. Future research will strengthen research and analysis at different scales in the region. Finally, due to limitations in data collection, this article adopts the indirect GDP estimation method for the carbon emissions of built-up areas. This ignores the impact of industrial production and daily life on carbon emissions, resulting in errors in the calculation results, but does not affect subsequent spatiotemporal analysis. Therefore, in the future, it is necessary to find less restrictive calculation methods.

5. Conclusion

The carbon emissions of land use in Chang-Zhu-Tan urban agglomeration from 2000 to 2020 have experienced a process of growth first and then decline. It can be judged that 2000-2010 was generally in a period of rapid growth, while the rapid growth trend in 2010-2015 was stagnant. From 2015 to 2020, regional carbon emissions finally fell. The total regional land use carbon emissions in 2020 are roughly the same as those in 2005. From 2000 to 2020, the carbon emission spatial pattern of the "triangle"-shaped core area and its adjacent areas formed by the three downtown areas of Chang-Zhu-Tan have changed the most drastically. With the economic growth of each city and the promotion of the integration strategy led by Changsha, the high-value carbon emission grid of the three central urban areas has finally expanded and it can be connected. On the periphery of the central urban area of Chang-Zhu-Tan, the spatial scope of the high value contiguous areaarea has been reduced to a certain extent after 2015, and the carbon emission intensity of the three central urban areas has experienced a significant process of "strengthening first and then weakening". The spatial connection between the three counties in the south of Zhuzhouand other regions is weak, and it is less affected by the integration of Chang-Zhu-Tan. The change of the carbon emission pattern in its territory is not obvious. At the same time, the economy of the three southern counties in Zhuzhou has maintained rapid development, the urbanization process has been continuously improved, and the regional control of carbon emissions has achieved certain results with remarkable results. The high value of the carbon source of the urban agglomeration is concentrated in the core area of the Chang-Zhu-Tan metropolitan area and along National Highway 106. The carbon sink mainly relies on the distribution of the Mulianjiu Mountains, Hengshan Mountains and Luoxiao Mountains. The carbon emission grid of different intensity presents a high positive correlation in the space within the scope of the study. The main correlation is divided into two categories: high-high aggregation and low-low aggregation, which roughly overlaps with the high-value area of carbon source and the high-value area of carbon sink respectively.

The study believes that in order to achieve the goal of carbon peak and carbon neutrality, on the one hand, it is necessary to strengthen the optimization and adjustment of the industrial areas of Changsha, Zhuzhou and Xiangtan, which are the industrial and commercial centers. In view of this traditional industrial base with construction machinery manufacturing and non-ferrous metal processing as important pillars, it is necessary to systematically ban rough, high-pollution and high-energy-consuming enterprises, assist traditional industrial enterprises to upgrade, and realize the joint promotion of double-carbon strategy and economic development. On the other hand, in the process of integrating the Chang-Zhu-Tan metropolitan area relying on the Xiangjiang Economic Belt, it is necessary to strengthen the control of urban disorderly spread, reasonably plan urban construction land, coordinate the number and distribution of different types of land, so that the functional activities of various types of land do not interfere with each other, and pay special attention to and limit urban construction land. The encroachment of residential land and industrial land on arable land, as well as the disorderly expansion of agricultural land to ecological green space. Finally, the protection of ecological green spaces and water bodies is indispensable .there are a large number of natural mountains in the Chang-Zhu-Tan urban agglomeration. These mountains contain rich carbon sink resources. Most of these types of land are subordinate to the counties and cities under the jurisdiction of the urban agglomeration.

Therefore, while carrying out their own economic activities in each county and city and strengthening economic connections with the core areas of the metropolitan area, we should pay more attention to the protection of the local ecological green space, which not only maintains the local ecological resources, but also contributes to the overall goal of carbon neutrality and carbon peaking in the Zhutan urban agglomeration.

Acknowledgments

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