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Analysis of the Carbon Emission Trajectory and Influencing Factors of Agricultural Space Transfer: A Case Study of the Harbin-Changchun Urban Agglomeration, China

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Abstract: The reconstruction of land spatial planning and the increasing severity of carbon emissions pose significant challenges to carbon peak and carbon neutrality strategies. To establish low-carbon and sustainable agricultural spatial planning while achieving dual carbon strategy goals, it is essential to accurately analyze the mechanisms of agricultural spatial transfer and their carbon emission effects, as well as the key factors influencing carbon emissions from agricultural spatial transfer. Therefore, this study, based on land use remote sensing data from 2000 to 2020, proposes a carbon emission accounting system for agricultural space transfer. The carbon emission total from agricultural space transfer in the Harbin-Changchun urban agglomeration over the 20-year period is calculated using the carbon emission coefficient method. Additionally, the spatiotemporal patterns and influencing factors are analyzed using the standard deviation ellipse method and the geographical detector model. The results indicate that: (1) The agricultural space in the Harbin-Changchun urban agglomeration has increased, with a reduction in living space and an expansion of production space. Among land type conversions, the conversion between cultivated land and forest land has been the most intense. (2) The conversion of agricultural space to grassland and built-up land has been the primary source of net carbon emissions. The carbon emission center has shown a migration path characterized by "eastward movement and southward progression," with a high-north to low-south distribution pattern. Significant carbon emission differences were observed at different spatial scales. (3) Natural environmental factors dominate the carbon emissions from agricultural space transfer, while socioeconomic and policy factors act as driving forces. Elevation is the primary factor influencing carbon emissions from agricultural space transfer. Interactions between factors generally exhibit nonlinear enhancement, with the interaction between elevation, annual precipitation, and industrial structure showing a strong explanatory power. Notably, the interactions between elevation, average annual precipitation, and industrial structure demonstrate significant explanatory power. These findings highlight the necessity for government action to balance agricultural spatial use with ecological protection and economic development, thereby providing scientific references for optimizing future land spatial structures and formulating regional carbon balance policies.

Keywords: agricultural spatial transfer; carbon emissions trajectory; spatiotemporal patterns; influencing factors; Harbin-Changchun urban agglomeration

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1. Introduction

The increase in carbon emissions has led to global climate anomalies, which are a focal issue of contemporary society and one of the major challenges in environmental protection today [1,2]. Since the mid-20th century, carbon emissions and other anthropogenic drivers have become the primary causes of intensified global climate anomalies [3]. According to the Fifth Assessment Report by the Intergovernmental

Panel on Climate Change (IPCC), the significant increase in CO_2 concentrations since the pre-industrial era is attributed, on the one hand, to the extensive consumption of fossil fuels such as coal, oil, and natural gas, and, on the other hand, to carbon emissions resulting from the transformation of various land use types within terrestrial space [4]. The evolution of terrestrial space directly affects the carbon sequestration capacity of vegetation and soil, playing a crucial role in the carbon emission effects within terrestrial ecosystems and leading to dynamic changes in carbon emissions [5]. As urbanization progresses, the carbon emission effects resulting from transformations in terrestrial space are particularly pronounced in developing countries. Many regions frequently engage in the "haphazard construction and modification" of land to promote socioeconomic development, leading to extremely low land utilization rates and encroaching upon agricultural space or developing backup land resources. This results in vast areas of high-carbon-density land, such as cropland, forest, and grassland, being converted into low-carbon-density construction land. This behavior significantly increases carbon emissions and poses a severe threat to the sustainable development of regional ecosystems and food security [6,7]. As the largest developing country and the biggest carbon emitter in the world [8], China has explicitly stated in its "Carbon Peaking Action Plan Before 2030", issued in 2021, the need to establish a land space development and protection framework that supports "carbon peaking and carbon neutrality" [9]. Additionally, as a major agricultural nation, carbon emissions from China's agricultural space account for approximately 20% of the country's total carbon emissions [10]. Agricultural space, as an important component of terrestrial space and a key carrier of agricultural land, serves as a significant driving force behind the increase in carbon emissions from terrestrial space due to its spatial transformation. Therefore, ensuring the carbon balance of agricultural land ecosystems while scientifically planning the development of agricultural space will pose a significant challenge for China in safeguarding ecosystem security and agricultural development in the future.

Agricultural space transfer refers to the transformative process of agricultural land over space and time, characterized by the interconversion between carbon sources and carbon sinks in terms of carbon emissions [11]. This process not only affects the structure of agricultural space but also directly relates to the total amount and distribution of regional carbon emissions. Research on agricultural space by scholars mainly focuses on land use type conversion [12], spatiotemporal evolution characteristics [13], spatial structure transformation [14], mechanism efficiency [15], and influencing factors [16], employing methods such as spatial autocorrelation [17], statistical data analysis [18], and spatial econometrics [19]. For example, by analyzing the intrinsic mechanisms behind agricultural space formation, researchers interpret the objective realities of current spatial conditions and develop rational forecasts for future spatial optimization strategies to support high-quality socioeconomic development in the region [20]. With the increasing ecological awareness in the development of civilization, the concept of low carbon has gradually been applied to the theories related to land space transformation. Scholars have begun to identify the carbon source and sink functions of different types of land use from the perspective of land space functionality [21]. Especially since the introduction of the "Three Types of Space" concept in China, extensive research has been conducted on the spatiotemporal characteristics of carbon emissions from land space [22], trend forecasting [23], and related aspects. These studies often employ methods such as carbon emission coefficients [24], Dagum Gini coefficients [25], and scenario simulations for analysis [18]. However, research on carbon emissions from agricultural space transfer is relatively limited, differing from the "Three Types of Space", which emphasizes the functional value of land space at a micro scale [26]. Agricultural space focuses more on the regulatory control of land space use concerning its primary functions, making it more suitable for analysis at a medium to large scale [27]. Early research on the spatiotemporal changes in carbon emissions from land use within terrestrial space has been widely applied in practice; however, these studies have primarily concentrated on the scale and

structure of land use space [28]. Further research is needed to explore the transformation of agricultural space patterns, the intrinsic conversion mechanisms of land, and the changes in carbon emission trajectories.

Accurately identifying the factors driving agricultural space transfer is crucial for optimizing resource allocation and coordinating the development of different land spaces to achieve carbon neutrality. For example, Guo [29] analyzed the impacts of agricultural production efficiency, industrial structure, economic development level, and labor scale on land use carbon emissions in the three northeastern provinces of China. The most commonly used methods for analyzing influencing factors include the LMDI model [30] and the Kaya extended model [31]. The LMDI model focuses solely on the impact of individual factors on carbon emissions, lacking an analysis of interactions among multiple factors. In contrast, the Kaya model addresses the analysis of interaction effects among different influencing factors; however, it assumes that relationships among variables remain stable over long time series, making it ineffective in capturing variations in the contributions of influencing factors across different time scales [32,33]. The geographic detector model can effectively address these challenges, as it considers both the influence of each factor on carbon emissions and the degree of their interactions. Furthermore, it can effectively present the temporal changes of influencing factors over long time series [34]. Additionally, unlike other traditional models, the geographic detector does not require the assumption of linear relationships between variables, allowing for a more flexible analytical framework when examining complex, nonlinear spatial phenomena. Therefore, by utilizing the ranking of influencing factors in the geographic detector, one can scientifically and effectively analyze the reasons for agricultural space transfer and changes in carbon emission trajectories, thus providing a scientifically sound data foundation for subsequent policy recommendations.

In summary, current academic research primarily focuses on various aspects such as the functional value of different types of land, land space scale, structural transformation, and carbon emissions. However, there is a lack of systematic studies targeting changes in agricultural spatial patterns and analyzing the carbon emission processes in major agricultural production areas that are economically underdeveloped. Furthermore, research combining agricultural space transfer with carbon emissions is exceedingly rare. This scarcity is partly due to the relatively slow pace of agricultural space transfer compared to urban and ecological spaces, and the social implications are more complex. Moreover, current research areas are often concentrated in hotspot regions or economically developed areas, such as the Guangdong-Hong Kong-Macau Greater Bay Area [35] and the Yangtze River Delta [36]. There is little research focusing on the economically underdeveloped northeastern region of China, despite its agricultural resource richness. The northeastern region, as China's largest agricultural production base and a key supplier of commercial grains, accounts for over 16% of the national agricultural space [37]. However, with the rapid expansion of urban space, the structure and scale of agricultural space have undergone significant changes. These changes not only impact the economic development of the region but also exert pressure on the ecological environment. Therefore, analyzing the patterns of agricultural space transfer in the northeastern region and changes in carbon emission effects, along with proposing optimization strategies, is an important practical issue. The Harbin-Changchun urban agglomeration, as the only resource-industrial-ecological complex urban cluster in Northeast China, possesses unique geographical and economic characteristics, serving as a crucial link between Northeast China and the Russian Far East, and is a key component of China's strategy for revitalizing the northeast. In the future, the Harbin-Changchun urban agglomeration will enter a golden period of industrialization, urbanization, and comprehensive economic revival. This transformation will significantly alter agricultural space utilization patterns and ecosystem structures, resulting in increased carbon emissions. Therefore, this study focuses on the Harbin-Changchun urban agglomeration, integrating land spatial governance policies to explore agricultural space transfer and carbon emission

effects within the urban agglomeration and accurately reveal the variations in the contributions of various factors to carbon emissions from agricultural space transfer, thereby providing a scientific basis for optimizing agricultural space structure and promoting high-quality regional development. This contributes to enriching and refining theories of land spatial transfer, facilitating regional carbon neutrality through optimized space utilization, and promoting the sustainable development of the ecological environment in the study area, which holds significant theoretical and practical importance. The specific objectives of this study are as follows: (1) To summarize the spatial-temporal patterns of agricultural space transfer in the Harbin-Changchun urban agglomeration from 2000 to 2020 using remote sensing data on land use; (2) To assess and characterize the carbon emission trajectories caused by agricultural space transfer using carbon emission coefficients, standard deviation ellipses, and other methods, delineating areas of carbon sources and sinks, and identifying the carbon emission effects and spatial-temporal evolution characteristics resulting from changes in land use types due to agricultural space transfer; and (3) To assess the contribution levels of various factors to carbon emissions from agricultural space transfer at different periods using geographic detectors, and to propose carbon neutrality optimization strategies for land spatial governance policies based on these findings. Based on the research objectives, we propose the following hypotheses to guide the study:

H1. *A significant positive correlation exists between agricultural space transfer and carbon emissions.*

H2. *There are significant spatial differences in carbon emissions from agricultural space transfer across different geographical scales.*

H3. *Natural environmental factors are the dominant influences on carbon emissions from agricultural spatial transfer.*

2. Study Area and Date Source

2.1. Study Area

The Harbin-Changchun urban agglomeration is located in the northern part of the Northeast Plain, consisting of 11 cities: Harbin, Daqing, Qiqihar, Suihua, and Mudanjiang in Heilongjiang Province, and Changchun, Jilin, Siping, Liaoyuan, Songyuan, and Yanbian Korean Autonomous Prefecture in Jilin Province (Figure 1). The total land area is 264,000 km^2, with the terrain primarily consisting of plains and mountains. By 2020, the economic output of the Harbin-Changchun urban agglomeration reached 2.12 trillion CNY, with a total population of 42.6 million, accounting for 4.97% of the national population. In land use, arable land has seen rapid growth, while forest land, grassland, and water bodies have declined to varying degrees. The region primarily focuses on agricultural development, with the primary sector accounting for 36.9% of the county-level economy, Agricultural space constitutes approximately 60.7% of the total land area. As the agricultural spatial structure changes, a series of ecological issues have emerged, making carbon sequestration and environmental protection in the Harbin-Changchun urban agglomeration increasingly urgent.

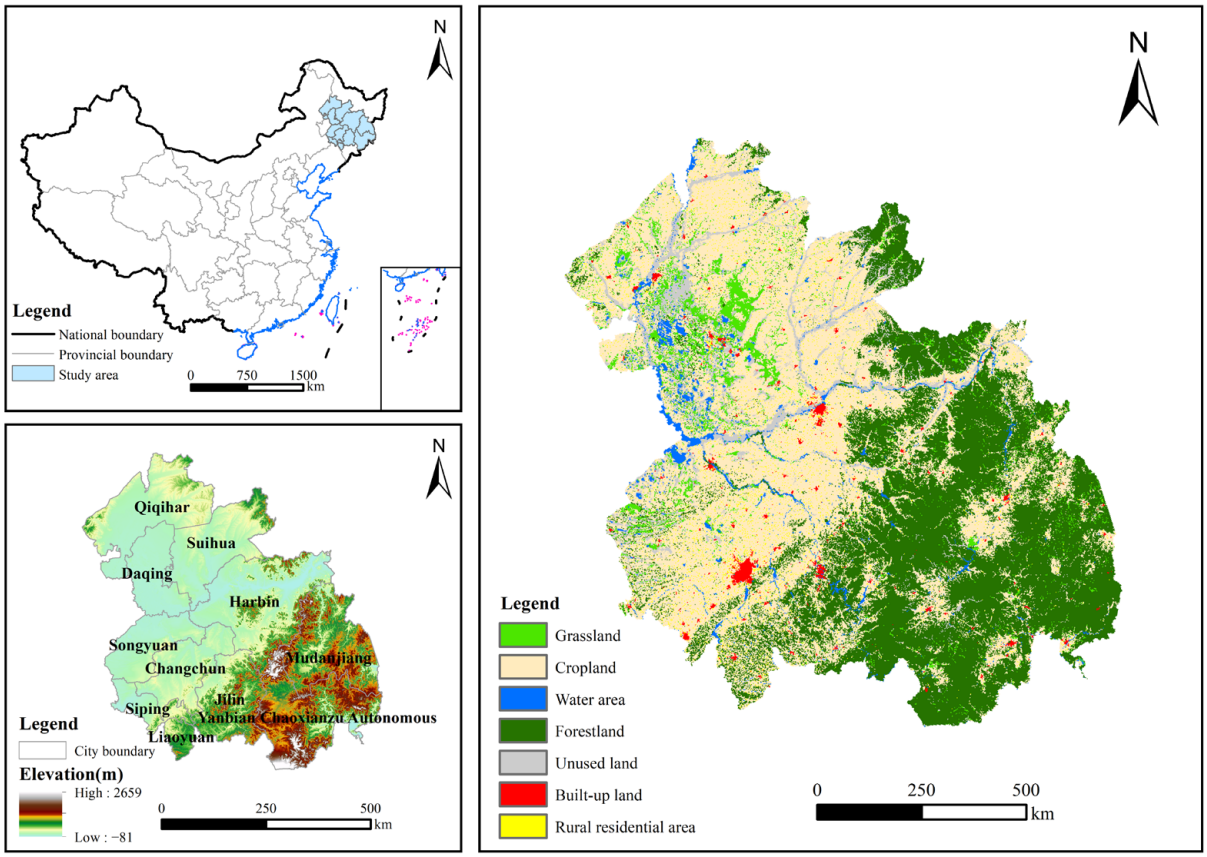


Figure 1. Schematic diagram of the study area.

2.2. Date Source

The data used in this study pertain to the years 2000, 2010, and 2020, focusing primarily on land use remote sensing data, geographic data, meteorological data, and statistical data. The land use remote sensing data, geographic data (elevation, slope), and meteorological data (average annual precipitation, average annual temperature) are sourced from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 12–19 April 2024). The land use remote sensing data are primarily derived from Landsat 8 images, with a spatial resolution of 30 m, employing a Level 2 classification system on 14 April 2024. The geographic data utilize Shuttle Radar Topography Mission (SRTM) data, which are highly reliable, with a spatial resolution of 30 m, accessed on 15 April 2024. The meteorological data are based on daily observation data from over 2400 meteorological stations across the country, generated through spatial interpolation using digital elevation models (DEM) and thin-plate spline smoothing functions, with a spatial resolution of 1 km, accessed on 15 April 2024. The population density data were sourced from WorldPop on 19 April 2024, with a spatial resolution of 1 km. The statistical data (population, GDP, energy consumption, etc.) were derived from the China Energy Statistical Yearbook, China County Statistical Yearbook, Heilongjiang Statistical Yearbook, Jilin Statistical Yearbook, as well as various city statistical yearbooks and bulletins on 20 May 2024, and interpolation methods were employed to fill in any missing data, with all data standardized at the county level.

3. Research Method

3.1. Classification of Agricultural Space

This study builds upon the existing land use classification system, in accordance with the latest requirements for land spatial planning, referencing the spatial classification standards from the National Main Functional Area Zoning and existing research on the

"three zones and three lines" [38,39]. Moreover, based on the actual land conditions of the Harbin-Changchun urban agglomeration, a linkage table between agricultural space and land use types was established (Table 1), guided by unified classification principles [40], to classify urban and ecological spaces, in order to support subsequent research on structural transformation. During the research process, ArcGIS raster calculator, raster reclassification functions, and zonal statistics tools were utilized to directly process land use raster data for each year, extracting information on land use changes [41,42].

Table 1. Description of agricultural space with land use types.

Classification of Land Use Space		Primary Classification	Secondary Classification	Dominant Spatial Function
Primary Land Type	**Secondary Land Type**			
Agricultural Space	Agricultural Production Space Agricultural Living Space	Arable Land	Paddy Fields, Dry Fields Rural Settlements	Ensuring Food Security, Residential, Leisure, and Recreation
Urban Space	—	Construction Land	Urban and Industrial Land	Urban Development Carrier
Ecological Space	—	Forest Land	Forested Land, Shrubland, Sparse Forest, and Other Forested Areas	Ecosystem Provisioning
		Grassland	High Coverage Grassland, Medium Coverage Grassland, and Low Coverage Grassland	
		Water Area	Rivers, Lakes, Reservoirs, Ponds, and Marshes	
		Unused Land	Sandy Land, Saline-Alkali Land, Marsh Land, Bare Land, and Bare Rock and Gravel Land	

3.2. Carbon Emission Estimation

Based on existing land use classification standards [43–45], and in conjunction with the IPCC National Greenhouse Gas Inventory Guidelines, this study categorizes the land use types of the Harbin-Changchun urban agglomeration into six categories: arable land, forest land, grassland, water areas, construction land, and unused land. Among these, forest land, grassland, water areas, and unused land are considered carbon sinks, while arable land and construction land are regarded as carbon sources. The formula is as follows:

$$G_a = \sum t_i = \sum E_i \times c_i \quad (1)$$

In the formula, G_a represents the total carbon emissions, t_i denotes the carbon emissions of the iii-th land use type, E_i indicates the area of the iii-th land use type, and c_i is the carbon emission coefficient for the iii-th land use type. Based on existing research findings [46–48], the carbon emission coefficients for arable land, forest land, grassland, water areas, and unused land are 0.497 t·hm^{-2}, −0.581 t·hm^{-2}, −0.021 t·hm^{-2}, −0.253 t·hm^{-2}, and −0.005 t·hm^{-2}, respectively.

The carbon emissions from construction land are often estimated using indirect methods, typically represented by the carbon emissions derived from energy consumption [49,50]. The formula is as follows:

$$V_m = \sum n_i \times q_i \times y_i \quad (2)$$

In the formula, V_m represents the carbon emissions from construction land, n_i denotes the consumption of the iii-th type of energy, q_i is the conversion factor for the iii-th type of energy, and y_i indicates the carbon emission coefficient for the iii-th type of energy.

According to the IPCC carbon emission calculation guidelines and existing relevant research findings [46], the relevant values are provided (Table 2).

Table 2. Energy type conversion factors and carbon emission factors.

Energy Type	Standard Coal Conversion Factor/tce·t $^{-1}$	Carbon Emission Coefficient/t·t $^{-1}$
Raw Coal	0.7143	0.76
Coke	0.9714	0.855
Crude Oil	1.4286	0.59
Gasoline	1.4714	0.59
Kerosene	1.4714	0.57
Diesel	1.457	0.59
Fuel Oil	1.4286	0.62
Natural Gas	12.143	0.45

3.3. Standard Deviation Ellipse

The standard deviation ellipse can be used to analyze the geographic distribution of carbon emissions in agricultural space from a global perspective. It reflects the direction of agricultural space transfer through the centroid of the ellipse. The components of the ellipse include the center, orientation angle, major axis, and minor axis [51].

3.4. Geographical Detector Model

The geographical detector model is a statistical method used to explore the patterns of spatial differentiation and influencing factors [52]. This study employs the factor detection and interaction detection models of the geographical detector to quantitatively analyze the influencing factors of carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration, as well as the interactions between these factors. Based on relevant research and data availability [53–55], ten influencing indicators were selected across three areas: natural environment, socioeconomic factors, and policy (Table 3). To ensure spatial consistency among the data of various influencing factors, all the data were transformed into a uniform projection coordinate system, specifically into the WGS_1984_UTM_Zone_51N coordinate system. In terms of data processing, the spatial data were uniformly converted to a resolution of 1 km, with specific operations as follows:

Table 3. System of indicators of impact factors.

Factor Type	Impact Factor	Selection Basis	Processing Method
Natural Environment	Elevation (x1)	Elevation influences carbon footprint levels by affecting agricultural production, residential suitability, and ecological conditions.	The data for the Harbin-Changchun urban agglomeration were extracted using the Extract By Mask tool in ArcGIS 10.8.
	Slope (x2)	Steep slopes are prone to soil erosion, complicating production and residential construction, thus affecting carbon footprint trends.	Same as above
	Average Annual Precipitation (x3)	Annual precipitation is a crucial factor for sustainable agricultural development, influencing production structures and promoting carbon footprints.	Same as above

Table 3. *Cont.*

Factor Type	Impact Factor	Selection Basis	Processing Method
	Average Annual Temperature (x4)	Temperature changes affect crop cultivation, agricultural management, and soil organic matter decomposition, indirectly increasing carbon emissions.	Same as above
	Urbanization (x5)	Urbanization has a linear relationship with carbon emissions. Increased urbanization levels lead to population growth, heightened production and consumption, and increased carbon emissions, occupying agricultural space.	Urbanization data for each district were spatialized using the Inverse Distance Weighting method in ArcGIS 10.8.
Socioeconomic	Population Density (x6)	Population density drives the transfer of agricultural space and alters lifestyles and behaviors, thereby affecting carbon footprint levels.	The data for the Harbin-Changchun urban agglomeration were extracted using the Extract By Mask tool in ArcGIS 10.8.
	Per Capita GDP (x7)	Changes in economic development levels trigger shifts in production and consumption patterns, consequently altering carbon footprint levels.	Per capita GDP data for each district were spatialized using the Inverse Distance Weighting method in ArcGIS 10.8.
	Industrial Structure (x8)	The proportion of primary industry output is used to represent agricultural space development, as the generation of production value is accompanied by significant carbon emissions.	Same as above
	Per Capita Grain Output (x9)	As one of the primary functions of agricultural space, the level of per capita grain production significantly influences carbon footprint levels.	Same as above
Policy	Policy Factors (x10)	The government is the primary manager of agricultural space transfer and carbon emissions, and the agricultural policies it formulates significantly drive carbon emissions.	Spatial overlay analysis was conducted using ArcGIS 10.8.

(1) Natural environmental factors: Using the ArcGIS resampling tool, the spatial resolution of 30 m was uniformly converted to a resolution of 1 km, and data were obtained according to 1 km × 1 km grid cells.

(2) Socioeconomic factors (excluding population density) were obtained based on administrative divisions, and spatial interpolation was conducted using the inverse distance weighting (IDW) method in ArcGIS. Subsequently, a 1 km × 1 km fishing grid overlapping

with administrative divisions was established. The weighted average of the regional data for each fishing grid cell was calculated based on the degree of overlap between the grid cells and the different administrative divisions [56]. The calculation formula is as follows:

$$Z_{grid} \frac{\sum_{i=1}^{n}(Z_i \cdot W_i)}{\sum_{i=1}^{n} W_i} \quad (3)$$

In the formula, Z_{grid} represents the weighted average value of the grid cell, Z_i is the data value for the iii-th administrative region, and W_i is the proportion of the overlapping area of the iii-th administrative region to the total area of the grid cell.

(3) Policy factors: Based on the list of major grain-producing counties in China, values were assigned according to the significance of each county unit in grain production. Ordinary counties were assigned a value of 0, while major grain-producing counties were assigned a value of 1. Spatial overlay analysis was performed in ArcGIS to ensure consistency with the spatial format of the geographic data [57].

(1) Factor Detection

Factor detection enables the exploration of the strength of influence that various factors have on carbon emissions from agricultural space transfer. The q value is used to measure the explanatory power of spatial differentiation in carbon emissions resulting from agricultural space transfer.

$$q = 1 - \frac{\sum_{i=1}^{m} N_I \sigma_i^2}{N\sigma^2} \quad (4)$$

In the formula, m represents the stratification of the dependent or independent variable, N_I and σ_i^2 represent the number of units and variance in layer m, respectively, and N and σ^2 represent the total number of units and variance for the study area, respectively.

(2) Two-Factor Interaction Detection

Through two-factor interaction analysis, the interactions between different factors are identified, and the explanatory power of these factors on carbon emissions when acting together is assessed. Based on the [q(X1∩X2)] type, the impact of their combined effect on the explanatory power of spatial differences in carbon emissions is determined to be either increased or diminished.

4. Results

4.1. Temporal and Spatial Pattern Evolution of Agricultural Space Transfer in the Harbin-Changchun Urban Agglomeration

4.1.1. Changes in the Temporal and Spatial Patterns of Agricultural Space

As shown in Table 4, the agricultural space of the Harbin-Changchun urban agglomeration accounts for approximately 49.76% of the total land area of the urban agglomeration, primarily concentrated in the northern and southern regions. The ratio of production space to living space within this area is approximately 15.78:1. Over the past 20 years, the scale of agricultural space has continuously increased, with the area changing significantly from 15.92 million hm^2 in 2000 to 16.04 million hm^2 in 2020, representing a total increase of 114,300 hm^2. Specifically, agricultural production space increased by 115,800 hm^2, while agricultural living space decreased by 1500 hm^2, resulting in a transformation of the agricultural space. The changes in agricultural space are most pronounced in the urban peripheries and plains, exhibiting temporal variations. From 2000 to 2010, changes in agricultural production space were primarily concentrated in Daqing, Qiqihar, Jilin, and Suihua, while changes in agricultural living space were mainly observed in Qiqihar and Suihua. From 2010 to 2020, agricultural production space changes were primarily noted in Qiqihar, Jilin, Songyuan, and Yanbian Korean Autonomous Prefecture. Agricultural living space changes were mainly concentrated in Jilin, Changchun, and Liaoyuan. The changes in agricultural production space from 2000 to 2020 primarily resulted from

the increase in newly cultivated land, whereas changes in agricultural living space were mainly attributed to the intensified trends of urbanization and population outflow.

Table 4. Spatiotemporal changes in agricultural space in the Harbin-Changchun urban agglomeration in 2000—2020 (10,000 hm^2).

Region	2000			2010			2020		
	Agricultural Production Space	Agricultural Living Space	Agricultural Space	Agricultural Production Space	Agricultural Living Space	Agricultural Space	Agricultural Production Space	Agricultural Living Space	Agricultural Space
Daqing	86.13	6.62	92.75	87.73	6.63	94.36	88.37	6.70	95.07
Harbin	234.87	12.43	247.30	235.54	12.47	248.01	235.31	12.45	247.76
Mudanjiang	97.40	4.20	101.60	96.38	4.22	100.60	96.16	4.22	100.38
Qiqihar	292.75	16.31	309.06	294.90	16.21	311.19	297.53	16.25	313.78
Suihua	207.99	10.54	218.53	209.51	10.42	219.93	209.93	10.39	220.32
Jilin	93.52	8.00	101.52	95.34	7.97	103.31	97.49	6.84	104.33
Liaoyuan	27.89	2.43	30.02	27.77	2.40	30.17	27.11	3.06	30.17
Siping	72.17	5.59	77.76	72.26	5.66	77.92	69.43	5.97	75.40
Songyuan	132.07	8.59	140.66	133.04	8.57	141.61	134.76	8.44	143.20
Yanbian Korean Autonomous Prefecture	55.76	2.29	58.05	55.30	2.35	57.65	59.63	3.06	62.69
Changchun	195.95	18.69	214.64	195.45	18.74	214.19	192.28	18.16	210.44
Total	1495.80	95.69	1592.11	1503.30	95.64	1598.94	1507.38	95.54	1603.54

4.1.2. Changes in Agricultural Space Transfer Structure

This study employs the overlay analysis tool of the ArcGIS platform to analyze the distribution characteristics of agricultural space transformation quantities and the directions of mutual transformation in the Harbin-Changchun urban agglomeration from 2000 to 2020, thereby revealing changes in the structure of agricultural space transfer (Table 5). The results indicate that from 2000 to 2010, agricultural space increased by 207,900 hm^2, with the most intense transformation occurring between agricultural and ecological spaces. Forestland of 70,500 hm^2 was converted to agricultural space, with an entry rate of 34%. The conversion of grassland to agricultural space totaled 66,900 hm^2, with an entry rate of 32%. Additionally, 62,700 hm^2 of unused land transitioned to agricultural space, with an entry rate of 30%. However, agricultural space also experienced an outflow of 129,600 hm^2, with 103,000 hm^2 converted to ecological space, resulting in an outflow rate of 79%. Furthermore, 26,600 hm^2 transitioned to urban space, with an outflow rate of 21%. The mutual transformation between water bodies and agricultural space was the least significant. Overall, the inflow of agricultural space exceeded the outflow, resulting in an increasing trend in agricultural area, with a net increase of 80,100 hm^2, primarily from the conversion of ecological space. From 2010 to 2020, the inflow of agricultural space continued to exceed the outflow, although the increase in agricultural area was reduced, with a net increase of 36,000 hm^2. During this period, the transformation between agricultural and ecological spaces was 3.2 times greater than in the previous phase, with 420,500 hm^2 of forestland converted to agricultural space, yielding an entry rate of 62%. Grassland and unused land contributed 99,100 hm^2 and 86,300 hm^2 to agricultural space, with entry rates of 15% and 13%, respectively. Simultaneously, agricultural space saw an outflow of 640,200 hm^2, with 526,100 hm^2 converted to ecological space, resulting in an outflow rate of 60%. Additionally, 114,100 hm^2 transitioned to urban space, with an outflow rate of 18%. In summary, the inflow of agricultural space was greater than the outflow, maintaining an increasing trend in agricultural area, although the increase was reduced, with a net addition of 36,000 hm^2, primarily from ecological space conversions.

Table 5. Transformation of land transfer of agricultural space in the Harbin-Changchun urban agglomeration in 2000—2020.

Period	Land Type	Other Land Types Converted to Agricultural Space		Agricultural Space Converted to Other Land Types		Change Situation
		Conversion Area (10,000 hm^2)	Entry Rate (%)	Conversion Area (10,000 hm^2)	Outflow Rate (%)	Net Conversion Area (10,000 hm^2)
2000–2010	Forest Land	7.05	33.91	5.15	39.74	1.90
	Grassland	6.69	32.18	3.48	26.85	3.21
	Water Area	0.73	3.51	1.21	9.34	−0.48
	Construction Land	0.05	0.24	2.66	20.52	−2.61
	Unused Land	6.27	30.16	0.46	3.55	5.81
	Total	20.79	100.00	12.96	100.00	7.83
2010–2020	Forest Land	42.05	62.19	38.6	60.29	3.45
	Grassland	9.91	14.66	6.14	9.59	3.77
	Water Area	5.67	8.39	4.79	7.48	0.88
	Construction Land	1.36	2.01	11.41	17.82	−10.05
	Unused Land	8.63	12.76	3.08	4.81	5.55
	Total	67.62	100.00	64.02	100.00	3.60

4.2. Spatiotemporal Evolution Characteristics of Carbon Emissions from Agricultural Space Transfer

4.2.1. Temporal Variation Characteristics of Carbon Emissions from Agricultural Space Transfer

From 2000 to 2020, the carbon emissions resulting from agricultural space transformation in the Harbin-Changchun urban agglomeration amounted to 532,846.2 tons (Table 6), while the carbon absorption was −271,564.6 tons. This indicates that carbon emissions exceeded carbon absorption during the transformation of agricultural space, thus presenting agricultural space transformation primarily as a carbon source. Moreover, this carbon source form aligns with the trend of agricultural space transformation. During the period from 2000 to 2010, the net carbon emissions from agricultural space transformation totaled 86,751.9 tons, with carbon sources at 120,488.5 tons and carbon sinks at −33,736.6 tons, indicating that agricultural space transformation during this period also functioned as a carbon source. The mutual transformation between forest land, grassland, and unused land with agricultural space was the primary source of carbon emissions resulting from changes in agricultural space, generating carbon emissions of 35,082.3 tons, 33,249.3 tons, and 31,161.9 tons, respectively. However, despite forest land being the largest carbon sink, absorbing 29,805.3 tons of carbon emissions and accounting for 88% of the total carbon sink, it still did not offset the carbon emissions produced by the conversion of forest land to agricultural space. From 2010 to 2020, the net carbon emissions from changes in agricultural space amounted to 174,529.7 tons, which is 2.01 times greater than the previous period. This indicates a more intense degree of agricultural space transformation during this period, with a significant increase in the area of mutual transformations, consequently resulting in higher carbon emissions. During this period, the mutual transformations between forest land, construction land, grassland, and unused land with agricultural space were the main sources of carbon emissions from changes in agricultural space, generating carbon emissions of 210,214.9 tons, 80,826.3 tons, 49,588.5 tons, and 43,358.3 tons, respectively. Among these, forest land remained the largest carbon sink, absorbing 224,265.9 tons of carbon emissions, accounting for 94% of the total carbon sink. The increase in mutual transformations between agricultural space and construction land was the primary reason for the rise in net carbon emissions during this period.

Table 6. Carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration in 2000—2020 (t).

Transformation Type	2000–2010			2010–2020			2000–2020		
	Carbon Source	Carbon Sink	Net Carbon Emissions	Carbon Source	Carbon Sink	Net Carbon Emissions	Carbon Source	Carbon Sink	Net Carbon Emissions
Forest Land	35,082.3	−29921.5	5160.8	210,214.9	−224,265.9	−14051	245,297.2	−254,187	−8890.2
Grassland	33,249.3	−730.8	32,518.5	49,588.5	−1289.4	48,299.1	82,837.8	−2020.2	80,817.6
Water Area	3628.1	−3061.3	566.8	28,369.7	−12,118.7	16,251	31,997.8	−15180	16,817.8
Construction Land	17,366.9	0.0	17,366.9	80,826.3	0.0	80,826.3	98,193.2	0	98,193.2
Unused Land	31,161.9	−23	31,138.9	43,358.3	−154	43,204.3	74,520.2	−177	74,343.2
Total	120,488.5	−33,736.6	86,751.9	412,357.7	−237,828	174,529.7	532,846.2	−271565	261,281.6

4.2.2. Spatial Differentiation Characteristics of Carbon Emissions from Agricultural Space Transfer

This study presents the spatial differentiation pattern of carbon emissions from agricultural space transfer at a grid scale of 1 km × 1 km, categorizing it into four levels: carbon absorption zones, and low, medium, and high carbon emission zones (Figure 2). The analysis reveals that from 2000 to 2020, carbon emissions from agricultural space transfer continuously increased, with changes in agricultural production space identified as the primary driver of this increase. During the period from 2000 to 2010, carbon absorption zones were primarily located in the southern part of Harbin, as well as in Mudanjiang and the northern area of Qiqihar. The carbon emission zones exhibited a spatial distribution pattern characterized by lower values in the center and higher values surrounding it. High and medium value areas were mainly found in the southern parts of Jilin City, southwestern Qiqihar, western Harbin, and southern Changchun, which are predominantly economically developed, densely populated, and agricultural areas. Low carbon emission zones were primarily located at the edges of medium value areas or near water bodies. This pattern is largely due to the adjacency of water edges to forested and grassland areas, which are significant carbon sinks. From 2010 to 2020, carbon emissions were primarily concentrated in the southwestern part of the Harbin-Changchun urban agglomeration. Medium value areas were mainly found at the urban-rural interface of Changchun, largely due to urban expansion resulting in the conversion of other land types to built-up areas. High value areas were predominantly located in the southern part of Yanbian Korean Autonomous Prefecture, primarily due to increased carbon emissions from the conversion of forested land back to agricultural use.

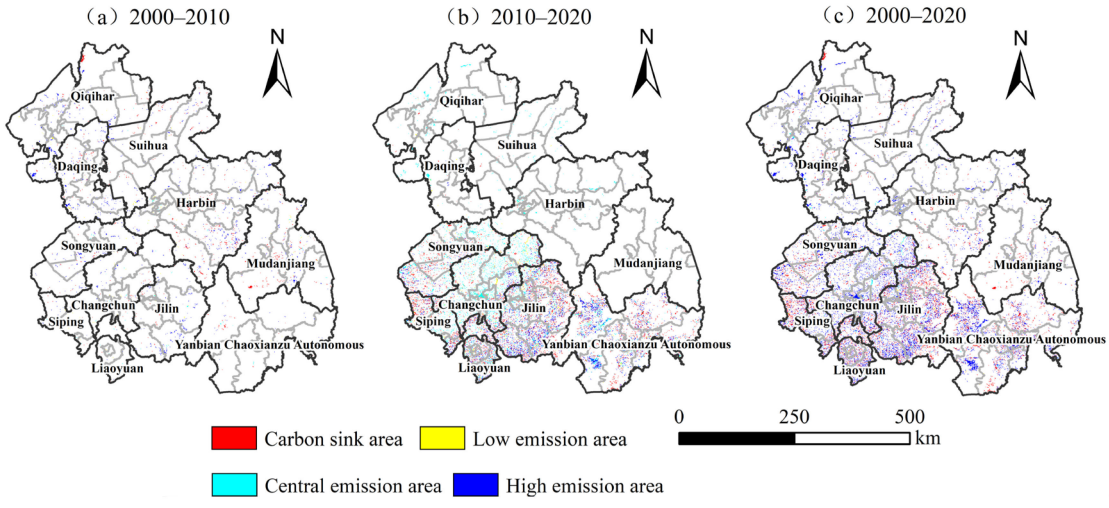


Figure 2. Spatial distribution of carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration in 2000—2020.

4.3. Analysis of Spatial Heterogeneity in Carbon Emissions from Agricultural Space Transfer

To investigate the spatial heterogeneity of carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration, this study employs standard deviation ellipse analysis using ArcGIS 10.8 software for the period from 2000 to 2020 (Figure 3). The analysis reveals that the center of carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration exhibits a migration path characterized by a shift to the east and south. The increase in agricultural space transfer in the southeastern region has led to a shift in the spatial center. An examination of the distribution ellipse for carbon emissions from agricultural space transfer shows a significant reduction in both the major and minor axes, as well as in the area of the ellipse. The concentration of carbon emissions from agricultural space transfer has markedly increased compared to the 2000–2010 period. Notably, agricultural space transfers in the southwestern to southeastern direction have contributed to changes in the carbon emission patterns of the Harbin-Changchun urban agglomeration.

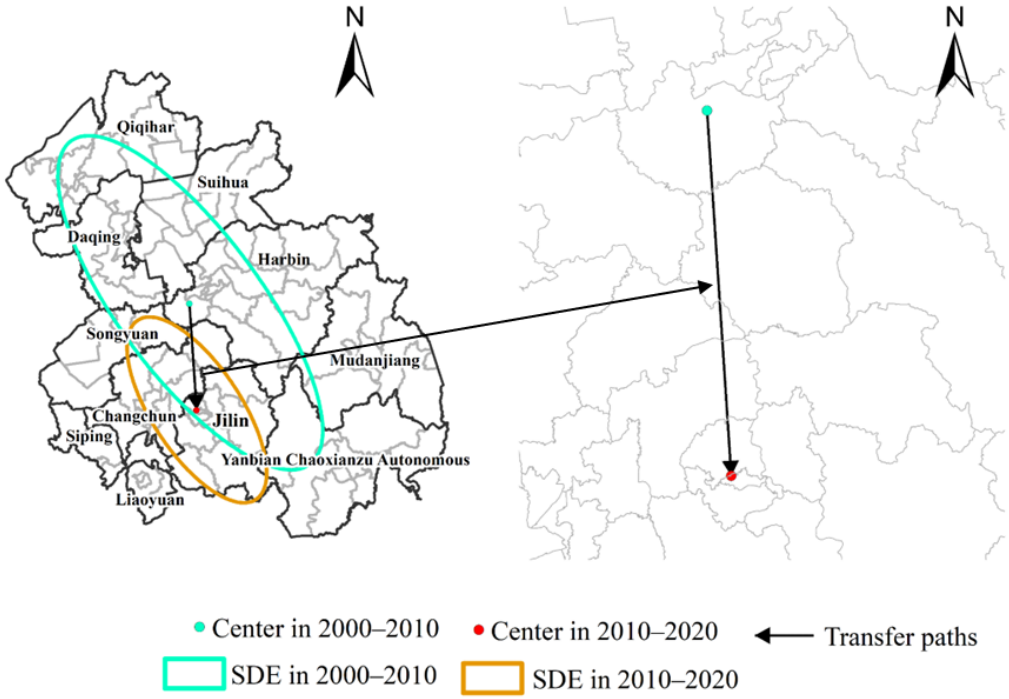


Figure 3. Standard deviation ellipse of carbon emissions from spatial transfer in the Harbin-Changchun urban agglomeration in 2000—2020.

4.4. Investigation of Factors Influencing Carbon Emissions from Agricultural Space Transfer

4.4.1. Factor Detection

The natural breakpoint method is used to discretize and categorize the influencing factors, while the geographic detector model assesses the *q*-values of these factors on the carbon emission patterns of agricultural space transfer during different periods. A higher *q*-value indicates a stronger explanatory power of the factor concerning the spatial differentiation of carbon emissions from agricultural space transfer (Figure 4).

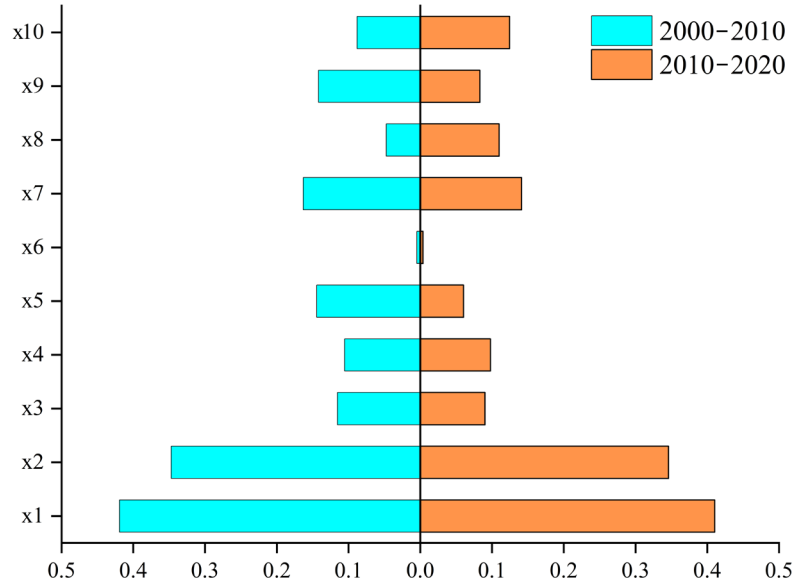


Figure 4. Detection of factors influencing carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration in 2000—2020.

During the 2000–2010 period, the factors influencing carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration, ranked from highest to lowest, are as follows: altitude (0.4192), slope (0.3473), per capita GDP (0.1631), urbanization (0.1443), per capita grain yield (0.1419), annual average precipitation (0.1154), annual average temperature (0.1056), policy (0.0881), industrial structure (0.0473), and population density (0.0048). During this period, carbon emissions from agricultural space transfer were primarily influenced by both the natural environment and socioeconomic factors. Among these, altitude emerged as the dominant factor, while per capita GDP and urbanization also played significant roles. Given that carbon emissions from agricultural space transfer are primarily constrained by natural environmental factors, areas with lower altitude, flat terrain, and favorable economic conditions became prioritized regions for agricultural space transfer. These regions exhibited higher suitability for cultivation and habitation, thereby facilitating agricultural space transfer, which constituted a major cause of carbon emissions during this period.

In the 2010–2020 period, the factors influencing carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration, ranked from highest to lowest, are as follows: altitude (0.4106), slope (0.3459), per capita GDP (0.1413), policy (0.1245), industrial structure (0.1099), annual average temperature (0.0979), annual average precipitation (0.0902), per capita grain yield (0.0831), urbanization (0.0602), and population density (0.0037). During this period, carbon emissions from agricultural space transfer were influenced by the natural environment, socioeconomic factors, and policies. Among these, natural environmental factors had a more substantial impact, with altitude remaining the dominant factor affecting emissions. Compared to the previous period, the explanatory power of the urbanization factor significantly decreased due to the ongoing economic stagnation in the northeast region, which resulted in insufficient economic vitality within the urban agglomeration, exacerbated population loss, and a slowdown in urbanization processes. Against this backdrop, the effects of urban expansion became increasingly fragmented, with urban spatial growth becoming constrained and primarily concentrated in core cities such as Harbin and Changchun, while changes in other districts were relatively minor. This imbalanced development pattern significantly weakened the impact of urban expansion on agricultural space transfer, thereby diminishing the role of urbanization in driving carbon emissions from agricultural space transfer. In contrast, the explanatory power of the policy factor significantly increased, closely related to the adjustment of national policy strategies. During this period, the government prioritized food security,

increasing investments in agricultural development in the Harbin-Changchun region, enhancing agricultural production subsidies, and strengthening infrastructure development. These supportive agricultural policies not only advanced regional agricultural modernization but also prompted local governments and farmers to intensify land reclamation, leading to the large-scale conversion of forest and grassland, as well as unused land into arable land. Furthermore, after 2010, government policies regarding agriculture, ecology, and carbon emissions management gradually tightened, further enhancing the influence of policies on carbon emissions from agricultural space transfer. In summary, the factors driving carbon emissions from agricultural space transfer during this period are more complex, being closely related not only to the natural environment but also increasingly associated with population dynamics, economic conditions, and policy frameworks.

4.4.2. Interaction Detection

The interaction analysis using the geographic detector assesses the combined effects of different factors on the spatial differentiation of carbon emissions from agricultural space transfer. A higher *q*-value indicates a stronger explanatory power of the interaction between the two factors regarding spatial differentiation. As shown in Figure 5, the *q*-values for the interactions between pairs of factors are consistently higher than those for individual factors, exhibiting either enhanced or nonlinear enhancement without any independent or diminishing relationships. This result indicates that carbon emissions from agricultural space transfer are influenced by multiple factors acting in concert, demonstrating strong synergistic effects among different factors. Specifically, during the 2000–2010 period, the interaction between altitude and annual average precipitation (0.4774) was the most significant, indicating that land suitability and water resource availability are the dominant factors influencing carbon emissions during agricultural space transfer. In the 2010–2020 period, the interaction between altitude and industrial structure (0.4740) was the strongest, suggesting that economic factors increasingly explained the spatial differentiation of carbon emissions during agricultural space transfer. Additionally, the interaction between altitude and other factors is notably stronger than the interactions among the other factors. This is because altitude serves as a fundamental basis for agricultural production and living conditions; suitable altitudes are crucial for supporting farmers' livelihoods and agricultural production, resulting in a more pronounced cumulative effect with other influencing factors.

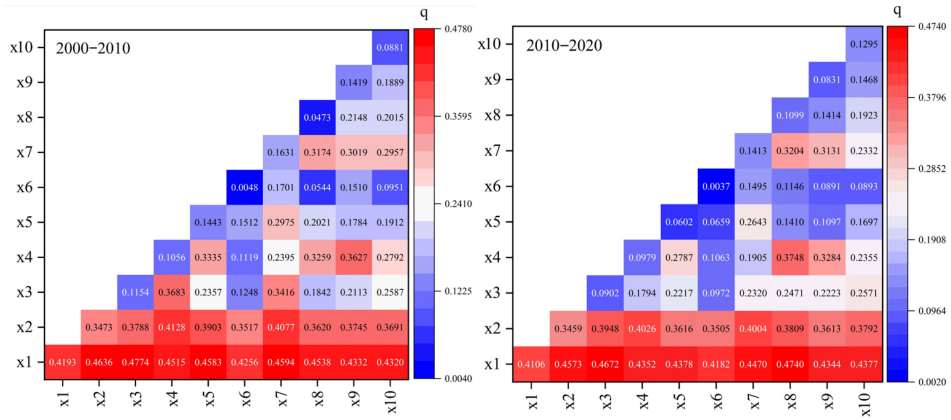


Figure 5. Detection of interactions in carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration in 2000—2020.

A comprehensive analysis indicates that the factors influencing carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration from 2000 to 2020 primarily exhibit nonlinear enhancement. Among these, the interaction between natural environmental factors and socioeconomic factors is stronger than the interactions among the individual socioeconomic factors. Furthermore, natural environmental factors are fundamental conditions for shaping the spatial patterns of carbon emissions from

agricultural space transfer and have a significant impact on regional carbon emissions. Moreover, the interactions between natural environmental factors and per capita GDP, as well as industrial structure, are stronger than those between other factors. Per capita GDP reflects the extent to which socioeconomic factors disrupt agricultural space. As economic levels rise, agricultural space transfer becomes more frequent and complex, leading to more diverse and profound interactions between per capita GDP and other factors. Simultaneously, the influence of industrial structure is also more complex. While the agricultural sector may dominate in certain areas, its scale and structure are closely related to the overall size of agricultural space. However, this does not necessarily imply that agricultural space transfer will occur frequently. A larger share of industrial structure typically correlates with a greater scale of agricultural space, but this expansion does not necessarily lead to a significant increase in the frequency of agricultural land transfer or carbon emissions, as this depends on the specific developmental path of the regional economy and its balance between agricultural and non-agricultural activities. Consequently, the influence of industrial structure on agricultural space transfer may be more indirect in certain areas and should be considered in conjunction with other factors, such as policy and economic vitality.

5. Discussion

5.1. Analysis of Carbon Emission Trajectories from Agricultural Space Transfer

The transfer of agricultural space is, in essence, the evolution of spatial patterns that occurs with the development and changes in society to meet human needs [58]. This paper provides a comprehensive analysis of the spatiotemporal dynamics of agricultural space transfer in the Harbin-Changchun urban agglomeration. The results reveal that the transfer of agricultural space in the Harbin-Changchun urban agglomeration primarily stems from the encroachment of ecological space and the occupation of urban spaces, consistent with previous findings [59,60]. This is also a significant characteristic of the current rapid industrialization and urbanization in China [61,62]. From a temporal perspective, the overall scale of agricultural space in the Harbin-Changchun urban agglomeration has expanded, with an increase in production space and a reduction in living space. The reasons for this are multifaceted and are primarily attributable to the historical development of the city, population migration, and strategic positioning [63]. For example, Qiqihar, with its long development history, primarily focused on agricultural cultivation and industrial raw material processing. As industrial space was restructured, numerous abandoned factories and vacant land were left behind. These abandoned factories were later converted into farmland and other uses, thus expanding agricultural production space. Effective land resource recycling can enhance land use efficiency. However, if this process is not properly regulated, it may exceed the carrying capacity of ecosystems, especially in ecologically fragile areas. This could break through geographical boundaries, leading to ecological degradation. Therefore, ensuring the expansion of agricultural space requires attention not only to its production functions but also to the management of its environmental impacts, thereby achieving sustainable development [64]. In terms of population migration, many rural residents moved to cities, leading to the shrinkage of agricultural living space. Additionally, the reduced demand for housing, services, and living infrastructure due to population outflow led to some land being repurposed for agricultural production or other uses. In addition to economic factors, population migration is closely related to the reallocation of land resources during the urbanization process. This change should also be considered in the context of sustainable development, to avoid excessive reliance on resource-consuming growth models [65]. Furthermore, as an important grain production base in Northeast China, the Harbin-Changchun urban agglomeration bears a significant responsibility for national food security. Some agricultural land has been explicitly designated as production areas, focusing on the cultivation of food crops and cash crops, which has contributed to the expansion of agricultural production space. These factors have ultimately led to changes in both agricultural production and living space.

In the structural changes of agricultural space transfer, the largest conversion occurs between ecological space and agricultural space, followed by urban space. This is because the benefits of ecological space are more latent compared to those of agricultural and urban spaces [66,67]. As a result, people tend to prioritize the encroachment of ecological space to meet their needs and promote social development. This is one of the major issues leading to the global deterioration of the ecological environment [68]. Furthermore, although the conversion of ecological space into agricultural space meets short-term food demands and economic growth, it poses a long-term challenge to sustainable development. Especially in the context of global resource constraints and climate change threats, this phenomenon exacerbates ecosystem degradation [69]. Between 2000 and 2010, the main conversion type of agricultural space in the Harbin-Changchun urban agglomeration was ecological space, with the conversion of forest land being the most significant. This is due to the abundance of forest resources in the region, which has largely contributed to the transformation of ecological space. Terrain also plays a key role in the mutual conversion between agricultural and ecological spaces. For example, Jilin City has shifted agricultural areas with complex terrain to flatter, more fertile ecological areas, thus reducing agricultural development costs and planting difficulties. Between 2010 and 2020, agricultural space transfer gradually shifted towards the southeast. The main conversion type continued to be ecological space; however, the quantity of agricultural space converted into ecological space was much greater than that of ecological space converted into agricultural space. This shift was due to the implementation of China's "Grain-for-Green" policy, which restricted the conversion of agricultural space into ecological space. At the same time, to ensure food security, the development of unused land became the primary contributor to the expansion of agricultural space during this period. However, this transformation differs from that in some developed countries, such as the United States, Australia, and Europe, where further development has been achieved in the land transformation process; in these countries, land transformation involves not only changes in land use but also improvements in land use efficiency and a transformation of agricultural production methods [70,71].

Compared with existing studies [71,72], this study provides a more comprehensive characterization of the carbon emission effects during the agricultural space transfer process, from the perspectives of territorial space and carbon sinks/sources. Over time, carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration show a significant increasing trend. Between 2000 and 2010, the carbon emissions primarily stemmed from the conversion of forest land, grassland, and unused land into agricultural space. Between 2010 and 2020, carbon emissions from agricultural space transfer were 2.01 times higher than those from 2000 to 2010. This significant increase was primarily due to the considerable expansion of cultivated land being converted into built-up land, leading to noticeable differences in carbon emissions. As previously demonstrated [73,74], the expansion of built-up land has contributed to the increase in global carbon emissions. In this context, China's "dual carbon" strategy has had a direct impact on controlling carbon emissions from agricultural space transfer. To achieve the goals of carbon peak and carbon neutrality, the government has gradually promoted green development and strengthened carbon emission management during land transformation [75]. For example, the ecological protection red line policy has been used to restrict further development of ecological space, while promoting ecological restoration and protection [76]. According to the change in the center of gravity of the standard deviation ellipse, the carbon emission center of agricultural space transfer exhibits an "eastward and southward" migration pattern. This is because, compared to the northern region of the Harbin-Changchun urban agglomeration, the southern region has a higher level of economic development and more intense agricultural land conversion. At different spatial scales, carbon emissions from agricultural space transfer at the municipal scale are primarily concentrated at the urban-rural interface, particularly in Changchun and Harbin. As the core cities of the Harbin-Changchun urban agglomeration, the siphoning effect of these cities far exceeds their radiation effect. With the influx of population and economic development, a portion of agricultural space at

the urban-rural interface is converted into urban space, resulting in increased carbon emissions from agricultural space transfer. At the county scale, carbon emissions from agricultural space transfer are primarily concentrated in large grain-producing counties with higher economic development levels, such as Wuchang and Changling. These regions experience frequent agricultural activities and noticeable land use changes, leading to higher carbon emissions. In contrast, for traditional agricultural production areas such as Keshan and Baiquan, slower economic development has limited the demand for large-scale land use changes, resulting in lower carbon emissions from agricultural space transfer. As concluded previously [77], formulating reasonable land use conversion measures is of significant importance in mitigating global climate warming. Against the backdrop of global climate change, ecological civilization construction has become one of the priorities in Chinese government policy. This requires that, when promoting land use conversion, ecological benefits and environmental protection be fully considered [78], in order to ensure food security while mitigating the increase in carbon emissions caused by agricultural space transfer.

5.2. Analysis of Factors Influencing Carbon Emission Trajectories from Agricultural Space Transfer

According to the study, the changes in carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration are primarily driven by socioeconomic development, urban expansion, and policies in the short term. However, over a longer time series, natural environmental factors remain the dominant determinants of carbon emissions from agricultural space transfer [79,80]. Since carbon emissions from agricultural space transfer are primarily constrained by the natural environment, areas with lower elevation, flat terrain, and good economic conditions have become priority regions for agricultural space transfer. These areas have higher suitability for farming and living, making agricultural space transfer more likely, and the changes in carbon emissions within these regions are more pronounced [81]. However, it is important to note that per capita GDP is positively correlated with the expansion of agricultural space but negatively correlated with the agricultural space ecosystem. This suggests that, while pursuing economic growth, it is necessary to appropriately balance the relationship with agricultural ecological space. This is consistent with previous studies [82,83], which suggest that human activities, while pursuing economic development, can disrupt the balance of the original ecosystem. Moreover, the differences in carbon emissions across regions are not only attributed to natural and economic factors but are also closely linked to urbanization, land use patterns, and the strength of policy implementation. For example, the impact of industrial structure on carbon emissions from agricultural space transfer is more complex. While the agricultural industry dominates in certain regions, its scale and structure are indeed closely related to the overall size of agricultural space. However, this does not necessarily mean that agricultural space transfer will occur frequently. The larger the share of the industrial structure, the larger the agricultural space scale tends to be. However, this expansion does not necessarily lead to a significant increase in the frequency of agricultural land transfer or carbon emissions, as it depends on the specific development path of the regional economy and its balance between agricultural and non-agricultural activities. Therefore, the influence of industrial structure on agricultural space transfer may be more indirect in certain regions and should be considered in conjunction with other factors such as policy and economic vitality [84].

In developed countries such as the United States and Australia, it has been observed during land use transformation processes [85–87] that these countries place a greater emphasis on integrating land conservation with agricultural modernization, utilizing more efficient agricultural technologies and low-carbon development models, thus achieving a better balance between urbanization and agricultural development. Through a series of agricultural and environmental policies, such as wetland protection laws, agricultural conservation contracts, and carbon farming programs, these countries have successfully mitigated the negative impacts of agricultural space transfer on ecosystems and limited

the upward trend in carbon emissions. In contrast, the carbon emission characteristics of agricultural space transfer in the Harbin-Changchun urban agglomeration exhibit more complex dynamic changes, reflecting the unique challenges faced by developing countries during rapid industrialization and urbanization. On the one hand, economic growth and urbanization inevitably exert a squeezing effect on agricultural space, leading to the large-scale conversion of agricultural land to non-agricultural uses, which results in a significant increase in carbon emissions [88]. On the other hand, due to relatively low land use efficiency and agricultural technology levels, the challenges in carbon emissions management further exacerbate this situation [89].

5.3. Strategies for Optimizing Agricultural Space Carbon Emissions Under Low-Carbon Goals

The Harbin-Changchun urban agglomeration, representing the old industrial base in Northeast China, has been designated as both a pilot area for institutional innovation and a green ecological urban agglomeration. To better adapt to future development needs, this urban agglomeration must not only consolidate existing ecological protection achievements but also promote comprehensive innovation and reform across various aspects such as land spatial planning, technological development, and agricultural transformation. Particularly in the context of addressing climate change and advancing carbon neutrality, the construction of land space in urban agglomerations should focus on low-carbon development and efficient resource utilization.

(1) Reform of Land Spatial Planning and Ecological Space Protection. In the future, the active promotion of land spatial planning reform should be prioritized, alongside the deepening of the ecological civilization construction strategy. Efforts should focus on strengthening the protection of natural ecosystems and guiding spatial planning. The occupation of high-carbon emission areas over low-carbon emission and high-carbon sink areas should be reduced, with a particular emphasis on the protection of ecological spaces such as forests and grasslands. This can be achieved by implementing policies like nature reserves and ecological redlines to strictly control unreasonable development activities. In addition, an emphasis should be placed on forest management, enhancing afforestation efforts, and improving the carbon sequestration function of ecological spaces to ensure the stability and sustainability of these areas. Traditional urban planning often prioritizes the speed of urbanization and economic value, which can easily lead to the compression and destruction of agricultural and ecological spaces. Therefore, future spatial planning should emphasize a balance between economic, social, and ecological values. The total area of urban construction land should be strictly controlled to avoid blind expansion. Additionally, sufficient green space should be ensured in new construction areas to support green and low-carbon development. Furthermore, national land use master planning and cultivated land protection policies will provide policy guarantees for the future agricultural space transformation in the Harbin-Changchun urban agglomeration. These policies aim to prevent the excessive occupation of arable land, while promoting resource recycling, ecological restoration, and reducing resource consumption and waste emissions.

(2) Strengthening Technological Innovation to Promote Low-Carbon Development. Technological innovation is a crucial engine for the transformative development of the Harbin-Changchun urban agglomeration. By leveraging technology, particularly the application of digital technologies, new momentum can be injected into the construction of low-carbon spaces. The integration of technologies such as artificial intelligence, big data, and cloud computing can enable refined management of carbon emissions in agricultural spaces. For instance, smart monitoring systems can provide real-time oversight and adjustments of carbon emission sources, while big data analysis can optimize decision-making support for low-carbon development. It is crucial to promote low-carbon production technologies in traditional high-carbon emission sectors such as agriculture and industry. Circular agricultural technologies, such as straw return and crop rotation, not only reduce carbon emissions but also enhance the carbon storage capacity of soils, thereby promoting the development of a circular economy in agriculture. Furthermore, the recycling of

water resources and the reutilization of waste are key factors in achieving the low-carbon transformation of agriculture. In the transportation sector, promoting water transport as a substitute for rail transport and expanding the coverage of public transportation systems are effective ways to reduce carbon emissions. In certain scenarios, relying solely on emission reduction technologies may be insufficient to achieve carbon neutrality goals. Therefore, ecological compensation projects, such as afforestation and wetland restoration, should be regarded as necessary measures to enhance the overall carbon sink capacity of the region and ultimately achieve carbon balance.

(3) Green Transformation of Agricultural Space. To ensure the carbon sink capacity of regional ecosystems, a strict ecological protection red line system should be implemented for agricultural land. The implementation of this system can effectively prevent agricultural land from being encroached upon by non-agricultural construction, thereby maintaining the stability of agricultural ecosystems. To promote the green transformation of agriculture, green agricultural subsidy policies can be implemented to encourage farmers to adopt low-carbon technologies and organic farming practices. This approach not only enhances soil carbon storage capacity but also promotes the recycling of agricultural waste. By promoting these technologies, the Harbin-Changchun urban agglomeration can not only reduce carbon emissions during agricultural production but also contribute to the overall carbon neutrality goal by enhancing soil carbon absorption capacity. Reasonable planning and management of agricultural space can further enhance carbon sink functions. To achieve a low-carbon transformation in the agricultural sector, the government should improve the relevant policy framework, encourage farmers to adopt low-carbon technologies, protect arable land resources, and promote ecological restoration projects. Additionally, the mechanisms for supervising and evaluating policy implementation must be enhanced to ensure the effective execution of policies. This approach aligns with China's Agricultural Green Development Action Plan and the carbon emissions trading system, further promoting the application of a green circular economy in both agricultural and urban development. From a global perspective, future strategies for addressing carbon emissions from agricultural space transfer should place greater emphasis on regional differences. For rapidly developing regions such as the Harbin-Changchun urban agglomeration, optimizing agricultural spatial planning, improving land use efficiency, and promoting green technological innovation will be important policy directions. Simultaneously, drawing on the experiences of developed countries, promoting low-carbon agricultural technologies, strengthening ecological space protection, and appropriately guiding urban expansion are key pathways for managing agricultural space carbon emissions.

5.4. Limitations and Research Prospects

Overall, this paper provides important insights for ecological security, land spatial optimization, and coordinated emission reduction in the Harbin-Changchun urban agglomeration. However, there are some limitations that warrant attention in future research. First, the accuracy of the land use remote sensing data used in this study is insufficient, which may affect the assessment of agricultural space and carbon emissions. The resolution of the land use remote sensing dataset employed in this research is 1 km. Although this accuracy meets the scientific standards for regional-scale studies, it may still affect the precision of land classification and the prediction of policy impacts. For example, including rural residential areas as farmland or forest land may lead to an underestimation of carbon emissions. Furthermore, this paper primarily relies on the carbon emission coefficients from the IPCC and empirical coefficients from existing studies, which may also affect the accuracy of carbon emission estimates to some extent. Second, this paper assumes that the carbon emission effects after agricultural space transfer occur immediately, overlooking the possibility that it may take a considerable amount of time for agricultural space to transition to a new equilibrium. In analyzing the effects of agricultural space transfer on carbon emissions, the factors chosen in this paper are insufficient and lack consideration of technological development and land planning aspects.

In future research, it is necessary to incorporate relevant technological and spatial planning factors to achieve a deeper understanding of changes in agricultural space and carbon emissions. Additionally, further exploration is needed regarding the spatiotemporal relationships between multi-spatial ecosystem services, natural factors, and environmental policies in the study area.

6. Conclusions

(1) During the study period, the agricultural space scale in the Harbin-Changchun urban agglomeration showed a continuous upward trend, with the agricultural production space increasing and the agricultural living space decreasing. The conversion between agricultural space and land types such as forests, grasslands, and unused land occurred frequently, exhibiting a fluctuating pattern of land use transfer. Simultaneously, the expansion of agricultural space influenced the regional carbon emission levels. During the study period, carbon emissions from agricultural space transfer increased continuously, demonstrating clear carbon source characteristics. The trend of carbon emissions from agricultural space transfer was consistent with the trend of agricultural space transfer itself; the more intense the agricultural space transfer, the greater the resulting carbon emissions.

(2) During the study period, the spatial equilibrium of carbon emissions from agricultural space transfer in the Harbin-Changchun urban agglomeration gradually declined, exhibiting a spatial pattern characterized by lower emissions in the north and higher emissions in the south, as well as higher emissions in the west and lower emissions in the east. The carbon emission center displayed a migration path of "eastward and southward", with significant differences at various spatial scales. At the city scale, carbon emissions from agricultural space transfer were mainly concentrated at the urban-rural interface; at the county scale, they were primarily concentrated in major grain-producing counties with higher economic development levels.

(3) Among the factors influencing carbon emissions from agricultural space transfer, the elevation factor consistently remained dominant, while the explanatory power of policy factors gradually increased. Among the interactive factors, the interactions between each factor exhibited an enhancing effect, predominantly characterized by nonlinear enhancement. Among these, the interaction between elevation and average annual precipitation and industrial structure was the strongest. Overall, the interaction between natural environmental factors and socioeconomic factors was more significant than the effects among internal factors considered individually.

Therefore, future efforts should prioritize balancing agricultural expansion with ecological protection, especially in areas where land use changes result in high carbon emissions. Furthermore, a comprehensive monitoring system that integrates environmental and socioeconomic factors should be strengthened to effectively manage the long-term impacts of agricultural spatial transfer on carbon emissions.

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