# Spatiotemporal Variation Characteristics and Influencing Factors of Agricultural Carbon Emissions in Gansu Province: Postprint

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## Abstract

Investigating the spatiotemporal characteristics and influencing factors of agricultural carbon emissions is an objective requirement for effectively eliminating uncertainties in the accounting process of carbon reduction targets and implementing precise policies to achieve agricultural carbon reduction goals. Based on the estimation of agricultural carbon emissions in Gansu Province from 2014 to 2022, this study employs Moran's I index to analyze the spatiotemporal differentiation characteristics of carbon emissions, applies kernel density estimation to examine the dynamic evolution trend of agricultural carbon emissions, and constructs a Geographically Weighted Regression (GWR) model to dissect the influencing factors of agricultural carbon emissions. The results indicate: (1) From 2014 to 2022, the total agricultural carbon emissions in Gansu Province showed an overall declining trend, while livestock breeding constituted the primary emission source with its carbon emissions exhibiting a growth trend. The regional agricultural carbon emissions, in descending order, were: Hexi Oasis Agricultural Area > Longdong-Longzhong Loess Plateau Dryland Farming Area > Alpine Pastoral Area > Longnan Mountainous Rain-fed Agricultural Area. (2) The spatial agglomeration of total agricultural carbon emissions was weak and concentrated in the Hexi Oasis Agricultural Area, with Jiuquan and Zhangye cities exhibiting high-low agglomeration, Jinchang city in a low-high agglomeration state, and no significant agglomeration in other regions. (3) The carbon emission intensity in all four agricultural zones demonstrated a decreasing trend, with regional disparities narrowing. (4) Per capita gross agricultural output value, agricultural industrial structure, and total population had carbon-reducing effects on agricultural carbon emissions, while rural residents' disposable income, agricultural fertilizer application amount, and total agricultural machinery power had carbon-increasing effects. Accordingly, we propose intensifying carbon reduction efforts in the livestock industry through improved livestock and poultry breeds, implementation of moderate-scale farming, and

precise management across the entire industrial chain, alongside reducing the use of agricultural materials such as chemical fertilizers and plastic films and promoting the application of green technologies to achieve agricultural carbon reduction targets.

## Full Text

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### Spatiotemporal Differentiation Characteristics and Influencing Factors of Agricultural Carbon Emissions in Gansu Province

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**Abstract:** Identifying the spatiotemporal characteristics and influencing factors of agricultural carbon emissions is essential for reducing uncertainty in carbon emission reduction target accounting and implementing precise policies to achieve agricultural carbon reduction objectives. Based on agricultural carbon emission estimates in Gansu Province from 2014 to 2022, this study employed the Moran's I index to analyze the spatiotemporal differentiation characteristics of carbon emissions, applied kernel density estimation to examine dynamic evolution trends, and constructed a geographically weighted regression (GWR) model to identify influencing factors. The results show: (1) From 2014 to 2022, agricultural carbon emissions in Gansu Province generally declined, with livestock breeding identified as the primary emission source showing a growing trend. Regional emissions ranked from highest to lowest as: Hexi Oasis Agricultural Area > Longdong-Longzhong Loess Plateau Dry Farming Area > Alpine Pastoral Area > Longnan Mountain Rain-fed Agricultural Area. (2) The spatial agglomeration of total agricultural carbon emissions was weak and concentrated in the Hexi Oasis Agricultural Area, where Jiuquan and Zhangye showed high-low agglomeration, Jinchang City exhibited low-high agglomeration, and other regions showed no significant agglomeration. (3) Carbon emission intensity in all four agricultural regions showed a decreasing trend, with regional differences gradually narrowing. (4) Per capita gross agricultural product, agricultural industrial structure, and total population had emission reduction effects, while rural residents' disposable income, agricultural fertilizer application, and total power of agricultural machinery had incremental effects. Therefore, we recommend improving livestock and poultry breeds, implementing moderate-scale breeding and full-industrial-chain precision management to strengthen emission reduction efforts in animal husbandry, reducing the use of agricultural materials such as chemical fertilizers and plastic films, and promoting green technology applications to achieve agricultural carbon reduction targets.

**Keywords:** agricultural carbon emissions; agricultural carbon emission coefficient; kernel density estimation; geographical weighted regression; Gansu Province

## Introduction

As global climate change intensifies, carbon emissions have become a focal point of concern. Agriculture serves as both a source of greenhouse gas emissions and a carbon sink, making the exploration of its emission reduction and carbon sequestration potential crucial for achieving the "dual carbon" goals. According to calculations by the Intergovernmental Panel on Climate Change (IPCC), agricultural carbon emissions account for approximately 13.5% of global anthropogenic carbon emissions, ranking as the second-largest greenhouse gas source. China's total carbon emissions rank first globally, with agricultural carbon emissions comprising about 17% of the country's greenhouse gas emissions. In recent years, the "dual carbon" targets have imposed higher requirements on agricultural carbon emissions. However, the extensive agricultural production model that relies heavily on chemical fertilizers and pesticides while neglecting sustainable development has led to low production efficiency, high resource consumption, and environmental pollution that urgently need to be addressed. The "14th Five-Year" National Agricultural Green Development Plan proposes enhancing emission reduction and carbon sequestration capacity and improving agricultural ecosystems. Studying the spatiotemporal characteristics and influencing factors of agricultural carbon emissions to effectively tap the potential for emission reduction and carbon sequestration is of great significance for achieving China's overall carbon reduction targets.

Gansu Province, located in the upper reaches of the Yellow River, borders Shaanxi to the east, Xinjiang to the west, Qinghai and Sichuan to the south, and Inner Mongolia and Ningxia to the north. It governs 12 prefecture-level cities and 2 autonomous prefectures, encompassing various climate types from humid to arid from southeast to northwest. The terrain slopes from southwest to northeast, with a narrow and diverse topography. The combination of landforms and climate forms multiple agricultural eco-climatic zones. Based on agricultural economic development patterns and regional conditions, Gansu Province's agricultural areas are divided into: (1) Hexi Oasis Agricultural Area (Jiuquan, Zhangye, Wuwei, Jiayuguan, and Jinchang), (2) Longdong-Longzhong Loess Plateau Dry Farming Area (Qingyang, Pingliang, Dingxi, Baiyin, and Lanzhou), (3) Longnan Mountain Rain-fed Agricultural Area (Tianshui and Longnan), and (4) Alpine Pastoral Area (Gannan Tibetan Autonomous Prefecture and Linxia Hui Autonomous Prefecture). Gansu Province has actively explored and promoted agricultural emission reduction and carbon sequestration practices. The Gansu Province Carbon Peak Implementation Plan (2022-2030) emphasizes developing green, low-carbon, circular agriculture, strengthening comprehensive utilization of crop straw and resource utilization of livestock manure, implementing zero-growth actions for chemical fertilizers and pesticides, and establishing a sound farmland fallow and rotation system to enhance farmland carbon sequestration capacity. The Gansu Province “14th Five-Year” Comprehensive Energy Conservation and Emission Reduction Plan proposes strengthening prevention and control of agricultural non-point source pollution, continuously promoting chemical fertilizer reduction and efficiency enhancement and pesticide reduction and harm control, and continuing to carry out resource utilization of agricultural production waste. By 2025, the comprehensive utilization rate of straw is expected to exceed 86%, the utilization rates of chemical fertilizers and pesticides to exceed 43%, and the comprehensive utilization rate of livestock manure to reach over 80%.

Domestic and international scholars have focused on the following aspects: (1) Calculation and structural analysis of agricultural carbon emissions. Scholars have measured agricultural carbon emissions at national and provincial levels from different perspectives. Tian et al. [?] calculated China’s agricultural carbon emissions from 1997-2016 based on five carbon sources including agricultural land use, rice paddies, livestock intestinal fermentation, and manure management, revealing an “increase-decrease-increase” phased change pattern. Li et al. [?] analyzed agricultural carbon emissions from seven aspects including chemical fertilizers and pesticides, dividing regions into high, medium, and low emission zones. Other scholars have predicted agricultural carbon emissions. Wang et al. [?] measured and predicted agricultural carbon emissions in Shanxi Province from 2014-2022. Yang et al. [?] estimated that Gansu Province’s agricultural emissions would peak in 2025. Zhou et al. [?] studied the spatiotemporal evolution of agricultural carbon emissions at the county level in Henan Province, finding significant spatial agglomeration and strengthening trends. (2) Influencing factors of agricultural carbon emissions. Methodologically, Tobit models [?], STIRPAT models [?, ?], and geographically weighted regression (GWR) [?] are widely used. Studies show that agricultural economic development level [?], rural financial agglomeration [?], agricultural industrial structure [?], and urbanization rate [?] are important incremental factors, while energy efficiency improvement and labor transfer are emission reduction factors [?]. Rural residents’ disposable income, total agricultural machinery power, and fiscal education expenditure are key factors causing spatial differentiation in agricultural carbon emissions [?]. Some studies also found agricultural carbon emissions are closely related to extreme climate [?]. (3) Relationship between agricultural carbon emissions and economic growth. Research shows different decoupling relationships across regions [?, ?]. Ning et al. [?] found strong decoupling dominated in China’s major grain-producing provinces. Ma et al. [?] reached similar conclusions for provinces in the Yellow River Basin. Su et al. [?] analyzed the decoupling relationship between agricultural carbon emissions and economic growth in Xinjiang, revealing an evolution from “weak decoupling and expansion connection alternating” to “stable weak decoupling and strong decoupling transition.” Zhang et al. [?] found an inverted U-shaped relationship between agricultural development level and agricultural carbon emissions in Henan Province.

In summary, existing research focuses on temporal calculations and influencing factors at national and provincial levels, with fewer studies on spatial patterns and dynamic evolution at municipal and county levels. Therefore, this study takes Gansu Province's four agricultural zones as the research area, uses the carbon emission factor method to calculate agricultural carbon emissions, analyzes total trends and structural characteristics, employs Moran's I to analyze spatial correlation and regional differences, uses kernel density estimation to analyze dynamic evolution trends, and finally builds a GWR model to analyze influencing factors, revealing the impact degree of each factor on agricultural carbon emissions in different regions. Based on these findings, effective policy measures are proposed to slow agricultural carbon emission growth and promote sustainable agricultural development.

## 1 Data and Methods

### 1.1 Study Area Overview

Gansu Province is located in the upper reaches of the Yellow River, bordering Shaanxi to the east, Xinjiang to the west, Qinghai and Sichuan to the south, and Inner Mongolia and Ningxia to the north. It governs 12 prefecture-level cities and 2 autonomous prefectures, covering latitudes 32°11 ~42°57 N and longitudes 92°13 ~108°46 E. The province encompasses various climate types from humid to arid from southeast to northwest, with terrain sloping from southwest to northeast, forming a narrow and diverse topography. The combination of landforms and climate creates multiple agricultural eco-climatic zones. Based on agricultural economic development patterns and regional conditions, Gansu Province's agricultural areas are divided into: (1) Hexi Oasis Agricultural Area (Jiuquan, Zhangye, Wuwei, Jiayuguan, and Jinchang), (2) Longdong-Longzhong Loess Plateau Dry Farming Area (Qingyang, Pingliang, Dingxi, Baiyin, and Lanzhou), (3) Longnan Mountain Rain-fed Agricultural Area (Tianshui and Longnan), and (4) Alpine Pastoral Area (Gannan Tibetan Autonomous Prefecture and Linxia Hui Autonomous Prefecture) [Figure 1: see original paper].

**Note:** Based on the standard map from the Ministry of Natural Resources (Approval No. GS(2024)0650), with no modifications to the base map boundaries. The same applies below.

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### 1.2 Data Sources and Processing

Data for this study were obtained from the Gansu Rural Statistical Yearbook, Gansu Development Yearbook, and Statistical Bulletins on National Economic and Social Development of various prefectures and cities from 2014-2022, as well as the Gansu Province Third National Agricultural Census Data Compilation. Crop planting area data were based on actual annual figures, with tillage data substituted by actual annual sown area [?]. Livestock numbers were based on year-end inventory data adjusted by appropriate slaughter rates.

### 1.3 Research Methods

**1.3.1 Agricultural Carbon Emission Calculation** Drawing on existing research and considering Gansu Province's actual conditions and data availability, this study used the emission coefficient method to calculate agricultural carbon emissions from 2014-2022 across three aspects: agricultural materials, land management, and livestock breeding. The specific calculation formula is:

$$C = \sum_{i=1}^{n} T_i \times \delta_i$$

where $C$ represents total agricultural carbon emissions (t), $T_i$ represents the quantity of carbon source $i$, and $\delta_i$ represents the emission coefficient of carbon source $i$. Agricultural materials primarily considered chemical fertilizers, plastic film, diesel fuel, and irrigation, excluding pesticide carbon emissions [?]. Land management carbon emissions mainly resulted from tillage disrupting soil organic carbon pools and carbon-nitrogen cycles [?]. Livestock breeding carbon emissions primarily originated from ruminant intestinal fermentation and manure emissions [?]. Based on Gansu Province's actual livestock breeding conditions, this study estimated emissions from cattle, sheep, pigs, horses, donkeys, and poultry. Due to different livestock breeding cycles, annual average breeding quantities needed adjustment. The adjustment method followed Hu et al. [?]: when the slaughter rate exceeds 100%, the average breeding quantity was calculated as:

$$A_i = \frac{\text{Days\_alive}_i \times B_i}{365}$$

where $A_i$ represents the annual average breeding quantity of livestock type $i$ (heads); $\text{Days\_alive}_i$ represents the average lifespan of livestock type $i$ (with average lifespans of 200 days for pigs and poultry); and $B_i$ represents the annual slaughter quantity of livestock type $i$ (heads). When the slaughter rate is less than 100%, the annual average breeding quantity was represented by the average year-end inventory. Based on relevant studies [?], using conversion coefficients of $1\,\text{t CH}_4 = 6.82\,\text{t C}$ and $1\,\text{t N}_2\text{O} = 81.27\,\text{t C}$, the emissions were converted to carbon emission coefficients and multiplied by each carbon source quantity to obtain total agricultural carbon emissions. The emission coefficients for each carbon source are shown in Table 1 .

**1.3.2 Spatial Correlation Analysis Methods** To explore the spatial correlation and regional differences in agricultural carbon emissions, this study used global Moran's I to analyze overall regional spatial association and difference degrees [?], and local Moran's I to analyze whether a specific region and its surrounding areas exhibit spatial agglomeration [?]. The global Moran's I calculation formula is:

$$I = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_{i=1}^{N}(X_i - \bar{X})^2}$$

where $N$ represents the number of regions; $X_i$ represents agricultural carbon emissions in region $i$ (t); $\bar{X}$ represents the average agricultural carbon emissions across all regions (t); $X_j$ represents agricultural carbon emissions in region $j$ (t); and $W_{ij}$ represents the spatial weight matrix between cities. The local Moran's I calculation formula is:

$$I_i = \frac{(X_i - \bar{X})\sum_{j=1}^{N} W_{ij}(X_j - \bar{X})}{\sum_{i=1}^{N}(X_i - \bar{X})^2}$$

After variance standardization, Moran's I can assess spatial correlation and regional agglomeration. The Moran's I value ranges from $[-1, 1]$, where $I > 0$ indicates positive spatial correlation; $I < 0$ indicates negative spatial correlation; larger absolute $I$ values indicate more significant spatial correlation. $I_i > 0$ indicates high-high or low-low agglomeration between regions; larger absolute $I_i$ values indicate stronger regional agglomeration; $I_i < 0$ indicates high-low or low-high agglomeration; and $I_i = 0$ indicates no spatial correlation.

**1.3.3 Kernel Density Estimation Method** To investigate the distribution dynamics and evolution characteristics of agricultural carbon emission intensity in Gansu Province and its four agricultural zones, this study used kernel density estimation for analysis. As a non-parametric method, kernel density estimation relies solely on the data itself, effectively avoiding limitations from artificially set conditions, and is widely used in studies of indicator distribution dynamics and evolution characteristics. The kernel density estimation formula is:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{x_i - x}{h}\right)$$

where $f(x)$ represents the kernel density function; $n$ represents the total number of cities (prefectures); $h$ represents the bandwidth; $x_i$ represents the agricultural carbon emission intensity of city (prefecture) $i$ ($\mathrm{t} \cdot \mathrm{hm}^{-2}$); $x$ represents the average agricultural carbon emission intensity ($\mathrm{t} \cdot \mathrm{hm}^{-2}$); and $k(\cdot)$ represents the kernel function.

**1.3.4 GWR Model** To analyze the impact degree of various influencing factors on agricultural carbon emissions in different regions, this study employed the geographically weighted regression (GWR) model for analysis. The GWR model incorporates geographic location information and conducts spatial regression analysis for specific regions using subsamples of adjacent observations, thereby achieving parametric spatial estimation and accurately reflecting actual conditions across different areas. The GWR model calculation formula is:

$$Y_i = \beta_0(v_i, u_i) + \sum_{k=1}^{p} \beta_k(v_i, u_i) X_{ik} + \varepsilon_i$$

where $Y_i$ represents agricultural carbon emissions in city (prefecture) $i$ (t); $\beta_k(v_i, u_i)$ represents the regression coefficient for variable $k$; $(v_i, u_i)$ represents the longitude and latitude coordinates; $X_{ik}$ represents the value of influencing factor $k$ in city (prefecture) $i$; and $\varepsilon_i$ represents the random error term.

Drawing on relevant studies [**?**, **?**] and considering Gansu Province's actual conditions, this study selected six factors: per capita gross agricultural product, total population, rural residents' disposable income, agricultural fertilizer application, total power of agricultural machinery, and agricultural industrial structure. Per capita gross agricultural product represents agricultural economic development status, characterized by the ratio of gross agricultural product to agricultural labor force. Studies show [**?**] that with increasing per capita gross agricultural product, farmers' environmental awareness gradually strengthens, reducing the use of high-carbon agricultural machinery and chemical fertilizers, thereby effectively reducing agricultural carbon emissions. Total population has both incremental and emission reduction effects on agricultural carbon emissions. On one hand, population growth drives increased demand for food and other agricultural products, potentially increasing agricultural carbon emissions. On the other hand, population density creates factor agglomeration effects conducive to economic growth, enhancing social adaptability, strengthening farmers' environmental awareness and sustainable development concepts, changing resource utilization methods and intensity, and promoting widespread application of green technologies in agriculture, thereby reducing agricultural carbon emissions. Agricultural fertilizer application increases directly lead to increased agricultural carbon emissions, and agricultural machinery use consumes large amounts of fossil energy and generates greenhouse gas emissions [**?**]. In agricultural industrial structure, compared with forestry and fisheries, crop cultivation and animal husbandry contribute the main share of agricultural carbon emissions, with larger shares creating more significant incremental effects on carbon emissions [**?**].

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## 2 Results and Analysis

### 2.1 Characteristics of Agricultural Carbon Emissions

**2.1.1 Total Agricultural Carbon Emission Characteristics** From 2014 to 2022, total agricultural carbon emissions in Gansu Province generally showed a declining trend, experiencing a “decrease-increase-decrease” trajectory. With the implementation of a new round of the Grain for Green Program in 2014, subsidy intensity increased, crop planting scale decreased, and cultivated land area in 2015 decreased by 955.022$×10^3$ hm$^2$ compared with 2014. Agricultural carbon emissions decreased from 35.601$×10^4$ t in 2014 to 842.806$×10^4$ t in 2015. In 2016, Gansu Province implemented the Gansu Province Waste Agricultural Film Recycling Regulations, promoting waste film recycling and chemical fertilizer and pesticide reduction actions. By 2017, chemical fertilizer application decreased by 30.170$×10^3$ t, and plastic film use decreased by 1.210$×10^3$ t, reducing agricultural carbon emissions. From 2018 to 2020, agricultural carbon emissions increased from 842.806$×10^4$ t to 939.832$×10^4$ t, mainly because the livestock breeding subsidy policy promoted the development of the breeding industry, leading to increased agricultural carbon emissions. By 2020, cattle, sheep, and pig breeding increased by 91.440$×10^4$ heads, 709.661$×10^4$ heads, and 154.301$×10^4$ heads respectively. From 2021 to 2022, agricultural carbon emissions in Jinchang, Jiayuguan, and Wuwei increased, with Jinchang showing the most significant increase at an average annual growth rate of 6.515%. Agricultural carbon emissions decreased in Longnan, Pingliang, and Tianshui, with Longnan showing the most significant decrease at an average annual rate of 4.128% (Table 2 ).

**2.1.2 Agricultural Carbon Emission Intensity Characteristics** Agricultural carbon emission intensity was characterized by the ratio of total agricultural carbon emissions to agricultural land area. From 2014 to 2022, agricultural carbon emission intensity in Gansu Province showed an overall declining trend, decreasing from 0.143 $\mathrm{t \cdot hm^{-2}}$ to 0.084 $\mathrm{t \cdot hm^{-2}}$. Among them, Gannan Prefecture had the highest agricultural carbon emission intensity in Gansu Province, with an average annual intensity of 0.436 $\mathrm{t \cdot hm^{-2}}$, followed by Zhangye, Wuwei, Dingxi, and Linxia Prefecture. Jiayuguan, Lanzhou, and Jinchang ranked in the bottom three, all below the provincial average, indicating significant low-carbon transformation (Table 3 ).

**2.1.3 Agricultural Carbon Emission Structure Characteristics** Livestock breeding carbon emissions reached 5089.046$×10^4$ t, accounting for 62.055% of total agricultural carbon emissions, making it the primary source. Emissions mainly originated from Gannan, Linxia, and Jiayuguan. Carbon emissions from land management processes, including crop planting and tillage, reached 1386.693$×10^4$ t, accounting for 16.909% of total emissions, mainly from Tianshui, Longnan, and Qingyang. Agricultural material carbon emissions reached 1724.738$×10^4$ t, accounting for 21.031% of total emissions, mainly from Jinchang, Lanzhou, and Tianshui (Table 4 ).

### 2.2 Spatial Characteristics of Agricultural Carbon Emissions

To analyze the spatiotemporal differentiation characteristics of agricultural carbon emissions, this study conducted Moran's I analysis (Figure 2 [Figure 2: see original paper]). Agricultural carbon emissions showed significant spatial differentiation across the 14 cities (prefectures) in Gansu Province. Regional emissions ranked from highest to lowest as: Hexi Oasis Agricultural Area > Longdong-Longzhong Loess Plateau Dry Farming Area > Alpine Pastoral Area > Longnan Mountain Rain-fed Agricultural Area. The Hexi Oasis Agricultural Area was the primary source of agricultural carbon emissions in Gansu Province, with high emissions in Wuwei and Zhangye, while Jinchang and Jiayuguan, being small resource-based industrial cities, had lower agricultural carbon emissions. The Longdong-Longzhong Loess Plateau Dry Farming Area showed large variations, with Qingyang's emissions basically stable between 112$×10^4$ t and 96$×10^4$ t, and Lanzhou's between 33$×10^4$ t and 49$×10^4$ t. The Longnan Mountain Rain-fed Agricultural Area showed small differences, with agricultural carbon emissions declining. In the Alpine Pastoral Area, Gannan Prefecture, as a major livestock base, had high agricultural carbon emissions, while Linxia Prefecture had relatively low emissions.

### 2.3 Dynamic Evolution Characteristics of Agricultural Carbon Emission Intensity

This study used global Moran's I to test the spatial correlation of agricultural carbon emissions in Gansu Province (Table 5 ). The Z-scores were all less than -1.96 and $p < 0.05$, indicating significant negative spatial correlation. Additionally, the global Moran's I values were all less than 0, with large absolute values, indicating significant spatial differences. The global Moran's I values remained around -0.4, indicating relatively stable negative spatial correlation.

To further explore regional agglomeration, this study conducted local Moran's I analysis (Figure 3 [Figure 3: see original paper]). The spatial agglomeration of total agricultural carbon emissions was weak and concentrated in the Hexi

Oasis Agricultural Area, where Jiuquan and Zhangye showed high-low agglomeration, Jinchang showed low-high agglomeration, and other regions showed no significant agglomeration.

This study plotted kernel density distribution maps of agricultural carbon emission intensity (Figure 4 [Figure 4: see original paper]) to examine dynamic evolution trends in Gansu Province overall and across the four agricultural zones. In terms of distribution location, the main peak of Gansu Province's agricultural carbon emission intensity distribution curve was at a relatively low level, while the secondary peak was at a relatively high level, indicating that most cities (prefectures) had relatively low emission intensity, with only a few having high intensity (Figure 4a). Examining evolution from early to late periods, the spatial pattern of agricultural carbon emission intensity is transitioning from a "one main, one secondary" pattern (2014-2016) to a "one main, multiple secondary" pattern (2020-2022). Overall, the kernel density distribution curve has shifted significantly leftward, with peak width showing a clear narrowing trend, indicating that agricultural carbon emission intensity in Gansu Province shows a significant decreasing trend, with regional differences gradually narrowing.

Regionally, the Hexi Oasis Agricultural Area, Longdong-Longzhong Loess Plateau Dry Farming Area, and Alpine Pastoral Area all showed leftward shifts in their kernel density curves, indicating decreasing agricultural carbon emission intensity. The peak patterns gradually flattened and narrowed, indicating that polarization weakened in the later study period and regional differences in emission intensity gradually narrowed. The Longnan Mountain Rain-fed Agricultural Area showed no obvious dynamic evolution trend, possibly because Tianshui and Longnan showed no significant temporal changes and small differences in total agricultural carbon emissions. Among the four agricultural zones, the Hexi Oasis Agricultural Area's kernel density curve was more concentrated in the low-value region of the horizontal axis, reflecting that this region's agricultural carbon emission intensity was at a relatively low level in the province.

### 2.4 Analysis of Main Influencing Factors of Agricultural Carbon Emissions

The GWR model overall estimation results showed that the adjusted R-squared values were around 0.9, indicating good model fit. Additionally, this study only presents the spatial distribution maps of regression coefficients for even years (2014, 2018, 2022) and the regression coefficient tables for influencing factors to highlight trends.

**2.4.1 Total Power of Agricultural Machinery** Total power of agricultural machinery had a positive impact on agricultural carbon emissions (Table 6 ). In 2014, agricultural machinery total power had the greatest impact on agricultural carbon emissions in Gannan Prefecture, with regression coefficients between 1.265 and 3.376, significantly affecting Zhangye and Qingyang, with regression coefficients between 0.826 and 2.879. The impact on Lanzhou, Jinchang, and Jiayuguan was relatively small, with regression coefficients basically stable between -0.995 and -0.249. This was because these industrial cities focus on suburban vegetable production, with less agricultural machinery use, thus having smaller carbon emissions. By 2018, the impact on Wuwei became more prominent, with regression coefficients between 1.360 and 2.155. By 2022, the impact on Jiuquan, Zhangye, and Wuwei decreased, with regression coefficients dropping to between -0.197 and 0.716. The impact on Zhangye and Qingyang was relatively large, with regression coefficients between 0.174 and 1.330.

**2.4.2 Agricultural Fertilizer Application** Agricultural fertilizer application had a positive impact on agricultural carbon emissions. In 2014, the impact was greatest on Gannan Prefecture, with regression coefficients between 0.611 and 2.224. In 2022, Gannan Prefecture vigorously promoted the "Five Nos Gannan" initiative, comprehensively advancing zero chemical fertilizer use across the region, accelerating the promotion of organic fertilizer application, and agricultural carbon emissions began to decline. The contribution rate of fertilizer application to carbon emissions dropped to 3.24%. The impact of fertilizer application on agricultural carbon emissions was relatively small in Lanzhou, Jinchang, and Jiayuguan.

**2.4.3 Total Population** Total population had a negative impact on agricultural carbon emissions. In 2014, the impact was significant in Jiayuguan, Lanzhou, and Jinchang, with agricultural carbon emissions decreasing by 1.421%-2.062% for each 1% change in total population. From 2018, the number of affected regions increased to 9, with regression coefficients gradually increasing. By 2022, the impact was greatest in Jiayuguan, with agricultural carbon emissions decreasing by 1.833%-2.002% for each 1% change in total population. The negative impact of total population on agricultural carbon emissions may be attributed to: first, accelerated urbanization and rural labor "non-agricultural" transfer, which accelerated land transfer and transformation of management models, increasing green breeding and recycling agriculture, thereby slowing agricultural carbon emissions. As of October 2022, Gansu Province's green breeding and recycling agriculture pilot projects had cumulatively completed 213.33$\times10^3$ hm$^2$, driving the province's organic fertilizer application area to exceed 513.33$\times10^3$ hm$^2$. Second, the application of green agricultural concepts and technologies reduced the use of agricultural materials such as chemical fertilizers and plastic films, effectively curbing agricultural carbon emission growth. By 2022, Gansu Province had built 3 national agricultural science and technology parks and 36 provincial agricultural science and technology parks, with agricultural added value growing at an average annual rate of 7.8%. In 2022, Gansu Province's agricultural machinery power per labor, chemical fertilizer application, and plastic film use decreased by 0.0053 kW, 51.89$\times10^3$ t, and 1.10$\times10^3$ t respectively compared with 2014, effectively curbing agricultural carbon emission growth.

**2.4.4 Per Capita Gross Agricultural Product** Per capita gross agricultural product had a negative impact on agricultural carbon emissions. From 2014-2022, Jiayuguan, Jinchang, and Lanzhou were most affected by this factor, with regression coefficients between -2.504 and -1.659. The impact on Tianshui and Linxia was relatively small, with regression coefficients between -0.692 and -0.162. The impact on Wuwei, Zhangye, and Qingyang was relatively large, with regression coefficients between -1.833 and -0.967, indicating that this factor had a stable impact on these regions. As per capita gross agricultural product increased, agricultural production reduced the use of high-carbon agricultural machinery and chemical fertilizers, effectively reducing agricultural carbon emissions.

**2.4.5 Rural Residents' Disposable Income** Rural residents' disposable income had a positive impact on agricultural carbon emissions. From 2014-2022, Jiuquan, Wuwei, and Zhangye were most affected by this factor, with regression coefficients between 0.777 and 2.185. The impact increased over time, with agricultural carbon emissions increasing by 0.894%-1.947% for each increase in rural residents' disposable income. The positive impact may be because as farmers' income increases, they tend to plant high-value-added but high-carbon-emission crops or breed high-energy-consumption livestock varieties, leading to increased agricultural carbon emissions. Statistics show that in 2022, Gansu Province's corn seed production area reached 10.512$×10^3$ hm$^2$, with corn seed output increasing annually. Cattle, sheep, and pig breeding also increased by 91.440$×10^4$ heads, 709.661$×10^4$ heads, and 154.301$×10^4$ heads respectively, leading to increased agricultural carbon emissions.

**2.4.6 Agricultural Industrial Structure** Agricultural industrial structure had a negative impact on agricultural carbon emissions. In the agricultural industrial structure, crop cultivation and animal husbandry contributed the main share of agricultural carbon emissions, with larger shares creating more significant incremental effects on carbon emissions. As shown in Table 4, carbon emissions from land management processes (crop planting and tillage) and livestock breeding in Gansu Province reached 16.909% and 62.055% respectively, leading to high energy consumption and greenhouse gas emissions. However, as the agricultural industrial structure continuously optimized, low-carbon agricultural technology promotion, and reduced use of high-pollution pesticides and chemical fertilizers, agricultural carbon emissions were effectively controlled. From 2014-2022, Gannan, Zhangye, and Wuwei were significantly affected by this factor, with regression coefficients between -2.179 and -1.015, indicating that a 1% improvement in industrial structure would reduce agricultural carbon emissions by 1.015%-2.179%. The impact on Jinchang and Lanzhou became prominent from 2018, with regression coefficients between -2.318 and -1.244. The impact on Tianshui was relatively large and stable, with regression coefficients between -1.833 and -0.967.

# 3 Discussion

## 3.1 Agricultural Carbon Emission Structure and Regional Differences

Agricultural carbon emissions in Gansu Province mainly originated from livestock breeding, accounting for 62.055% of total emissions, followed by agricultural materials (21.031%) and land management (16.909%). This structure differs from other provinces. In Jiangxi Province, rice planting is the largest carbon source [?], while in Sichuan Province, livestock breeding and crop planting are the two main sources, accounting for 42.51% and 37.77% respectively [?]. These differences are mainly due to agricultural resource endowments, production methods, and planting structures. The study results show significant differences in agricultural carbon emissions among the four agricultural zones, with the Hexi Oasis Agricultural Area having the highest emissions and the Longnan Mountain Rain-fed Agricultural Area the lowest. Moreover, Jinchang and Jiayuguan in the Hexi Oasis Agricultural Area had the lowest emissions, possibly due to faster industrialization and urbanization, dense populations, and reduced cultivated land area. In contrast, Lanzhou in the Longdong-Longzhong Loess Plateau Dry Farming Area has reduced total agricultural carbon emissions in recent years due to accelerated agricultural transformation and development of green ecological recycling agriculture. Gannan Prefecture in the Alpine Pastoral Area is a major livestock base in Gansu Province, with rapid livestock development and high agricultural carbon emissions. Therefore, agricultural carbon reduction measures need to be differentiated according to regional characteristics. Gannan Prefecture should strengthen emission reduction efforts in animal husbandry by improving livestock and poultry breeds, implementing moderate-scale breeding, and full-industrial-chain precision management to reduce carbon emissions from intestinal fermentation and manure management.

## 3.2 Influencing Factors of Agricultural Carbon Emissions and Their Regional Differentiation

Unlike previous studies [?, ?, ?], this study considered spatial location effects when analyzing influencing factors, revealing the spatiotemporal differentiation of each factor through specific analysis of regression coefficients. Studies show that total power of agricultural machinery has a positive impact on agricultural carbon emissions, consistent with conclusions from Fan et al. [?] and Shi et al. [?]. Total population has both direct incremental effects and indirect emission reduction effects on agricultural carbon emissions. Yang et al. [?] showed that population growth's rigid demand for agricultural products increases energy input in agricultural production, leading to increased agricultural carbon emissions. Sun et al. [?] found that population density creates factor agglomeration effects conducive to economic growth, enhancing social adaptability, changing resource utilization methods, and promoting green technology application, thereby reducing agricultural carbon emissions. Ning et al. [?] also found that accelerated urbanization and rural labor “non-agricultural” transfer increase agricultural machinery input, improve agricultural production efficiency, and reduce carbon emissions from chemical fertilizers and plastic films. This study shows that total population has a negative impact on agricultural carbon emissions, consistent with conclusions from Sun et al. and Ning et al., indicating that Gansu Province's total population's direct incremental effect is smaller than its indirect emission reduction effect. Per capita gross agricultural product has a negative impact on agricultural carbon emissions, consistent with Fan et al. [?]. As per capita gross agricultural product increases, people become more environmentally conscious, reducing the use of high-carbon agricultural machinery and chemicals, effectively reducing agricultural carbon emissions. Regionally, agricultural industrial structure has more significant emission reduction effects in Gannan, Zhangye, and Wuwei, so industrial structure should be further optimized and low-carbon agricultural technologies promoted. Total power of agricultural machinery has more significant incremental effects in Gannan, Zhangye, and Qingyang, so the use of high-carbon agricultural machinery and chemicals should be reduced. Total population has more significant emission reduction effects in Jiayuguan, Jinchang, and Lanzhou, so farmers' low-carbon awareness should be enhanced, green technologies promoted to improve agricultural production efficiency, and the use of agricultural materials such as chemical fertilizers and plastic films further reduced to promote transformation toward environmentally friendly, low-carbon agricultural production.

### 3.3 Future Research Outlook

Due to limitations in municipal-level data availability, tillage data were substituted by actual crop sown area, and agricultural carbon emission calculations did not include carbon emissions from pesticide use or straw burning. Additionally, when using the emission coefficient method, the accuracy and applicability of coefficients may be affected by regional, climatic, and production method factors. Future research will focus on: (1) Comprehensive research on full-industrial-chain agricultural carbon emissions. Current studies mainly focus on carbon emissions during agricultural production, not including those from agricultural product processing, distribution, and consumption. Future research should expand to the entire industrial chain process. (2) Continued focus on carbon source-sink balance research. Based on full life-cycle analysis of carbon budget balance, exploring ways to reduce carbon sources and increase carbon sinks, and examining carbon sink driving mechanisms, sink enhancement technologies, and potential assessments. (3) Future emphasis on research regarding farmers' low-carbon production behaviors. Current studies mainly examine agricultural carbon emissions at the macro level, but agricultural emission reduction and carbon sequestration policies must ultimately be implemented by farmers. Future research will explore the mechanisms influencing farmers' production carbon emissions and low-carbon behaviors.

## 4 Conclusion

This study analyzed the spatiotemporal differentiation characteristics and influencing factors of agricultural carbon emissions in Gansu Province from 2014-2022. The main conclusions are:

(1) From 2014-2022, total agricultural carbon emissions in Gansu Province generally declined, experiencing a "decrease-increase-decrease" trajectory. From the perspective of emission intensity, agricultural carbon emission intensity in Gansu Province showed an overall decreasing trend, with Gannan Prefecture having the highest intensity in the province. From the perspective of emission structure, livestock breeding was the main emission source, with its carbon emissions showing an increasing trend.

(2) From the spatial dimension, agricultural carbon emissions in Gansu Province showed significant spatial differentiation. Jinchang and Jiayuguan in the Hexi Oasis Agricultural Area had low carbon emissions, while Gannan Prefecture in the Alpine Pastoral Area had high emissions. The spatial agglomeration of total agricultural carbon emissions was weak and concentrated in the Hexi Oasis Agricultural Area, where Jiuquan and Zhangye showed high-low agglomeration, Jinchang showed low-high agglomeration, and other regions showed no significant agglomeration. The dynamic evolution trend of agricultural carbon emission intensity was obvious, with all four agricultural zones showing decreasing emission intensity and narrowing regional differences.

(3) Per capita gross agricultural product, agricultural industrial structure, and total population had emission reduction effects on agricultural carbon emissions, with the most significant impacts on Jiayuguan, Jinchang, and Lanzhou. Agricultural fertilizer application and total power of agricultural machinery had incremental effects, with the most significant impacts on Gannan, Zhangye, Wuwei, and Qingyang. Rural residents' disposable income also had incremental effects, with the most significant impacts on Jiuquan, Wuwei, and Zhangye.

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