Spatiotemporal Evolution Characteristics of Carbon Source/Sink Effects from Cropland Use in Xinjiang and Their Contributing Factors: Postprint

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Date: 2025-02-27T00:00:00+00:00

Abstract

To investigate the long-term spatiotemporal variation characteristics of carbon effects from cultivated land use in Xinjiang and accurately assess its potential for carbon sequestration and sink enhancement, this study collected Xinjiang agricultural data from 1991 to 2021, employed the carbon absorption and emission coefficient method to measure and analyze the temporal dynamics of carbon emissions, carbon absorption, and carbon sink amounts during cultivated land use processes in Xinjiang, and utilized Moran' s I, standard deviational ellipse, and gravity center migration to analyze the spatial differentiation, spatial autocorrelation, and evolution characteristics of cultivated land carbon effects, while revealing their main contributing factors. The results indicate that: (1) The carbon absorption amount of cultivated land in Xinjiang far exceeds its carbon emissions, exhibiting a strong carbon sink effect overall, and the carbon sink capacity shows an enhancing trend over time, increasing from 830\$×104*tin*1991*to*3429×\$104 t in 2021. (2) Strong carbon sink regions are mainly distributed in production areas with large cultivated land areas and dominated by the cultivation of maize, wheat, and cotton. (3) At the county scale, the net carbon sink of cultivated land exhibits significant spatial agglomeration characteristics; over the past 30 years, the gravity center of the cultivated land carbon sink has generally shown a migration trend from southwest to northeast, yet remains concentrated in the Aksu region of southern Xinjiang. (4) Chemical fertilizer application, mechanical operations, irrigation, and plastic film are the main sources of carbon emissions, among which, the contributions of chemical fertilizer and plastic film inputs to cultivated land carbon emissions show an increasing trend. Based on the above research findings, it is proposed that measures such as moderately increasing cultivated land area, expanding the planting layout of cotton and grain-oil crops in southern Xinjiang, popularizing relay cropping of maize, soybean, and cotton after wheat according to local conditions to increase the multiple cropping index, and increasing the input of green agricultural materials can enhance the carbon sink effect of cultivated land use in Xinjiang while improving cultivated land productivity to ensure food security.

Full Text

Spatiotemporal Evolution Characteristics and Contributing Factors of Carbon Source/Sink Effects from Cultivated Land Use in Xinjiang

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Abstract

To investigate the long-term spatiotemporal variation characteristics of carbon effects from cultivated land use in Xinjiang and accurately assess its carbon sequestration potential, this study collected agricultural data from Xinjiang spanning 1991-2021. We employed the carbon absorption and emission coefficient method to measure and analyze the temporal dynamics of carbon emissions, carbon absorption, and carbon sink amounts during cultivated land use processes in Xinjiang. We also utilized Moran' s index, standard deviational ellipse, and centroid migration analysis to examine the spatial differentiation, autocorrelation, and evolution characteristics of cultivated land carbon effects, while revealing their main contributing factors. The results indicate: (1) Carbon absorption in Xinjiang' s cultivated land far exceeds carbon emissions, demonstrating a strong net carbon sink effect that has strengthened over time, increasing from 8.30$\times10^{6}$ tons to 34.29$\times10^{6}$ tons. (2) Regions with strong carbon sinks are primarily distributed in production areas with extensive cultivated land and high production of corn, wheat, and cotton. (3) At the county scale, the net carbon sink of cultivated land exhibits significant spatial agglomeration characteristics. Over the past 30 years, the center of gravity has generally shown a migration trend from southwest to northeast, yet remains concentrated in the Aksu region of southern Xinjiang. (4) Cropland carbon sinks are primarily attributed to carbon absorption by cotton, wheat, and corn. Conversely, the main sources of carbon emissions include the application of chemical fertilizers, farmland tillage, irrigation, and the use of agricultural films. Notably, the contribution of chemical fertilizers and agricultural films to carbon emissions is on the rise. Based on these findings, we propose measures including moderately expanding cultivated land area, enlarging the cultivation layout of cotton and grain-oil crops in southern Xinjiang, promoting post-wheat relay cropping of corn, soybeans, and cotton according to local conditions to increase the multiple cropping index, and increasing investment in green agricultural technologies and materials. These measures aim to enhance the carbon sink effect of cultivated land use in Xinjiang while improving production capacity and ensuring food security.

Keywords: cultivated land use in Xinjiang; carbon source/sink effect; Moran' s index; standard deviation ellipse; center of gravity migration trajectory model; spatio-temporal evolution characteristic

Introduction

Reducing greenhouse gas emissions and addressing climate change are critical global concerns. Farmland, as an important component of terrestrial ecosystems, serves as both a source of carbon emissions and a vital site for carbon sequestration. On the one hand, carbon sequestration can be achieved through crop photosynthesis and soil organic carbon accumulation. On the other hand, farmland management practices such as mechanical operations, fertilization, pesticide application, and irrigation also generate greenhouse gas emissions, with planting activities producing two-thirds of total agricultural emissions. Therefore, farmland systems play a key role in global carbon cycling and climate regulation.

Xinjiang has a land area of 1.66 million km^2, accounting for one-sixth of China' s total territory and ranking fifth nationally. Xinjiang serves as a national reserve grain base and an important production base for agricultural and pastoral products, representing the region with greatest potential for farmland ecosystem carbon sink utilization. Since the 1990s, with the promotion and application of water-saving irrigation technologies, Xinjiang' s agricultural planting scale has continued to grow, with cultivated land area increasing by 2.3676 million hectares and irrigation area increasing by 3.9517 million hectares. According to the Third National Land Survey, Xinjiang currently has 7.0386 million hectares of cultivated land, an increase of 1.901 million hectares compared to the Second National Land Survey, primarily distributed in Tacheng, Changji Hui Autonomous Prefecture, Ili Kazakh Autonomous Prefecture, Aksu, and Kashgar in the northwest.

Previous studies on carbon effects of cultivated land use in Xinjiang have focused on examining impacts from perspectives of different industries or geographical spaces. These studies explored how energy development, industrial structure adjustment, and land use types affect agricultural carbon emissions or absorption, and analyzed the decoupling relationship between agricultural carbon emission characteristics and economic growth. Some studies have measured carbon emissions from different land use types in Xinjiang and their driving factors, but have primarily focused on revealing microscopic soil carbon sequestration mechanisms and carbon emission effects of technology input intensity. The spatiotemporal changes and evolution trends of cultivated land carbon effects in Xinjiang from the 1990s to present remain unclear, and the carbon sink potential and contributing factors during cultivated land use processes are still uncertain.

In view of this, this study collected agricultural data from various prefectures and cities in Xinjiang from 1991 to 2021. We comprehensively analyzed the long-term spatiotemporal variation characteristics of carbon emissions, carbon absorption, and carbon source/sink effects in Xinjiang’ s cultivated land by integrating the carbon effect coefficient method, global and local Moran’ s index methods, standard deviational ellipse, and center of gravity migration trajectory model. The study also identified the main contributing factors and scientifically assessed the carbon sink potential and future trends of cultivated land use in Xinjiang, providing a reference basis for formulating reasonable cultivated land use policies and exploring balanced development pathways between economy and ecology.

1.1 Study Area Overview

Xinjiang is located in northwestern China (73°22 -96°21 E, 34°22 -49°33 N), spanning approximately 22 degrees of longitude and 15 degrees of latitude. The region is vast, with significant differences in climate, geography, and natural resources across different areas. Xinjiang belongs to a typical arid inland climate zone with low precipitation and strong evaporation. The multi-year average precipitation is only 155 mm, dropping below 70 mm in the plains of southern Xinjiang, while water surface evaporation ranges from 1,500 to 3,400 mm. Water resources are extremely unevenly distributed in both time and space.

In terms of cultivated land types, irrigated land accounts for a high proportion while dry land comprises only 3.15%. The region’ s agricultural production is dominated by cotton, wheat, and corn, with these three crops accounting for the majority of the total sown area of crops.

1.2.1 Accounting Method for Carbon Absorption from Cultivated Land Use

To accurately reflect carbon absorption from cultivated land use in Xinjiang, this study selected major crops with large planting areas in Xinjiang as measurement objects based on data availability, including rice, corn, wheat, beans, potatoes, cotton, rapeseed, sunflower, sugar beet, and vegetables. Following the “National

Greenhouse Gas Inventory Guidelines" and existing research, we employed the widely used carbon absorption measurement model [**?**] to calculate the total carbon absorption for each crop. The specific calculation formula is as follows:

$$C_{abs} = \sum_{i=1}^{n} \frac{Y_i \times C_i \times (1 - F_i)}{M_i}$$

where: C_{abs} is the total carbon absorption of cultivated crops (10^4 t); Y_i is the economic total yield of crop i (10^4 t); C_i is the carbon absorption rate of crop i; F_i is the water content of the economic product part of crop i; and M_i is the economic coefficient of crop i, representing the ratio of economic yield to biological yield. The carbon absorption rates and economic coefficients of various crops are shown in Table 2.

1.2.2 Accounting Method for Carbon Emissions from Cultivated Land Use

Carbon emissions from different cultivated land use methods were primarily calculated using the carbon emission coefficient method [**?**]. The total carbon emissions were calculated as the sum of the products of various cultivated land use pathways from the agricultural carbon emission accounting inventory and their corresponding carbon emission coefficients. Based on the actual situation of cultivated land use in Xinjiang, this study selected chemical fertilizers, pesticides, agricultural films, irrigation, and mechanical operations as the main carbon emission sources.

The carbon emissions from each cultivated land use pathway were estimated using Formula (2):

$$E_n = T_n \times \delta_n$$

where: E_n is the total carbon emission from pathway n (10^4 t); T_n is the total consumption of pathway n; and δ_n is the carbon emission coefficient for pathway n. Chemical fertilizer data were based on the year' s pure nutrient application amount, agricultural film data on actual usage, and irrigation data on effective irrigation area. Notably, carbon emissions from agricultural mechanization include both plowing and electricity use, with plowing area based on crop planting area and electricity consumption based on total agricultural machinery power. For ease of calculation and comparison with related research from other provinces, carbon emission coefficients were primarily determined by referencing IPCC assessment reports, FAO, Oak Ridge National Laboratory, and published literature [24-27], as detailed in Table 3.

1.2.3 Accounting Method for Net Carbon Sink and Carbon Sink Intensity from Cultivated Land

Based on the carbon absorption data from crops and carbon emissions from cultivation activities, the net carbon sink of cultivated land was calculated using the subtraction method. The temporal dynamics of carbon absorption and emissions were used to further analyze and clarify the carbon sink effect changes during the process of cultivated land quality change in Xinjiang. The relevant calculation formulas are as follows:

$$C_{net} = C_{abs} - C_{em}$$

where: C_{net} is the carbon sink amount from cultivated land use (10^4 t); C_{abs} and C_{em} are the carbon absorption amount and carbon emission amount, respectively.

To reflect carbon absorption, carbon emissions, and net carbon sink per unit of cultivated land area, the intensity of cultivated land carbon effects was calculated, including carbon absorption intensity, carbon emission intensity, and carbon sink intensity, using the following formulas:

$$C_{intensity} = \frac{C_{total}}{S_{land}}$$

where: $C_{intensity}$ is the carbon effect intensity of cultivated land use ($\mathrm{t} \cdot \mathrm{hm}^{-2}$); C_{total} is the total carbon absorption, emission, or net sink amount (10^4 t); and S_{land} is the cultivated land area of Xinjiang or each prefecture (10^4 hm^2).

1.3 Spatial Characteristic Analysis Method for Cultivated Land Carbon Effects

The global Moran’ s index [**?**] was used to analyze whether spatial correlation exists in the carbon effects of cultivated land use across Xinjiang’ s prefectures and cities. The global Moran’ s index is calculated as:

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

where: I is the global Moran’ s index value; n is the number of study objects; x_i and x_j are the observed values of the target attribute for objects i and j; w_{ij} is the spatial weight between objects i and j; and $\bar{x}$ is the mean of the variable. The Moran’ s index ranges from -1 to 1, with larger absolute values indicating stronger spatial correlation. A positive I value indicates positive spatial correlation and clustering, while a negative I value indicates negative spatial correlation and dispersion. Values closer to 0 indicate weaker spatial correlation.

Based on the analysis of global spatial correlation, local Moran’ s index was further calculated. Local Moran’ s index, first proposed by Anselin [?], is primarily used to reflect whether similar or dissimilar clustering exists in local areas. When local Moran’ s index is positive, the region exhibits spatial clustering; when negative, region i and its neighbors show spatial dispersion.

The center of gravity migration trajectory model (CGMTM) [?] and standard deviational ellipse [?] were combined to reflect the distribution direction and range of geographic elements from a global perspective. These methods are widely applied in research on long-term spatiotemporal pattern evolution of study objects. This study utilized these models to quantitatively analyze the spatial variation characteristics and temporal centroid migration trajectory of cultivated land carbon sinks across Xinjiang’ s prefectures and cities.

1.4 Data Sources

The input data on crop planting area, yield, irrigation, chemical fertilizers, machinery, and other factors for Xinjiang were obtained from the Xinjiang Statistical Yearbook, China Rural Statistical Yearbook, and China County Statistical Yearbook. Specific data mainly include crop sown area and yield, crop yield per unit area for some years, chemical fertilizer application amount (in pure nutrients), pesticide usage, agricultural film consumption, total agricultural machinery power, and effective irrigation area. Among these, electricity consumption from agricultural mechanization was based on the year’ s total agricultural machinery power; energy consumption from agricultural mechanization was primarily used for plowing, with plowing area based on the year’ s crop sown area; and energy consumption for irrigation was based on effective irrigation area. The economic coefficients, carbon absorption rates, and water content rates for different crops required for calculating cultivated land carbon absorption were mainly derived from literature [?]; and the carbon emission coefficients for calculating carbon emissions from cultivated land use pathways were primarily obtained from literature data [?].

2.1 Temporal Dynamics of Carbon Effects from Cultivated Land Use in Xinjiang

From 1991 to 2021, both carbon absorption and carbon emissions from cultivated land use in Xinjiang showed continuous growth trends. Carbon absorption increased from 1062$\times10^{4}$ t to 4126$\times10^{4}$ t. Carbon emissions increased from 232$\times10^{4}$ t to 697$\times10^{4}$ t. Since carbon absorption consistently exceeded carbon emissions each year, Xinjiang’ s cultivated land use demonstrated a strong carbon sink effect that strengthened annually, with the net carbon sink increasing from 830$\times10^{4}$ t to 3429$\times10^{4}$ t. Analyzing the decadal growth rates of the three 10-year stages from 1991 to 2021, the period from 2011-2021 showed the fastest growth rates for carbon emissions, absorption, and total carbon sink, with the carbon sink total growth rate far exceeding the other two periods.

To more precisely reveal the carbon effects of cultivated land use activities and eliminate the influence of cultivated land area changes, we measured and analyzed the carbon absorption, emission, and sink intensity per unit area from 1991 to 2021. As shown in Figure 3, over the past 30 years, carbon absorption intensity continued to rise, fluctuating between 4.0–7.9 $\text{t}\cdot\text{hm}^{-2}$. In contrast, carbon emission intensity per unit area decreased annually, ranging between 0.3–0.7 $\text{t}\cdot\text{hm}^{-2}$. Net carbon sink intensity per unit area showed a stable upward trend, increasing from 3.3 $\text{t}\cdot\text{hm}^{-2}$ to 7.5 $\text{t}\cdot\text{hm}^{-2}$, indicating that the carbon sink effect of cultivated land use in Xinjiang has significantly strengthened in recent years. This demonstrates that the carbon sink effect of Xinjiang’ s cultivated land use has been substantially enhanced, with net carbon absorption capacity increasing by more than double.

The temporal dynamics show that the growth in carbon sink amounts is not only related to area expansion but also closely associated with changes in cultivation practices and crop yield improvements brought about by technological inputs.

2.2 Spatial Distribution and Evolution Characteristics of Carbon Sink Effects from Cultivated Land Use in Xinjiang

The spatial distribution of carbon sink effects from cultivated land use in Xinjiang showed significant changes from 1991 to 2021. Except for a brief period where Karamay City exhibited carbon source characteristics, cultivated land across all prefectures and cities in Xinjiang consistently demonstrated significant carbon sink features, with substantial regional differences in spatial distribution, consistent with spatial changes in carbon absorption amounts. The number of prefectures and cities with carbon sinks exceeding 400$×10^{4}$ t increased over time. The Kashgar region, due to its large cultivated land area and dominant cultivation of cotton and grain crops, showed high carbon sink amounts exceeding 600$×10^{4}$ t. Aksu, Ili Kazakh Autonomous Prefecture, Changji Hui Autonomous Prefecture, and Tacheng also exhibited high carbon sink characteristics, with net carbon sink amounts between 400-600$×10^{4}$ t. Karamay City, Urumqi City, Kizilsu Kirghiz Autonomous Prefecture, Turpan City, and Hami City generally had carbon sink amounts below 50$×10^{4}$ t, representing low carbon sink valleys in spatial terms, closely related to the relatively small agricultural scale in these areas.

The evolution of carbon sink intensity across Xinjiang’ s prefectures and cities at 10-year intervals shows that the carbon sink intensity of most prefectures and cities did not exceed 5 $\text{t}\cdot\text{hm}^{-2}$ in 1991. By 2001, the carbon sink intensity of Bortala Mongol Autonomous Prefecture (Bozhou) and Aksu region had made breakthroughs. By 2021, the carbon sink intensity of most prefectures and cities had significantly improved, with Changji, Aksu, Bayingolin Mongol Autonomous Prefecture (Bazhou), Ili, Tacheng, and Bozhou maintaining high carbon sink intensity. Overall, Bozhou exhibited prominent carbon sink effects across all periods. In northern Xinjiang, Altay, Urumqi, and Turpan consistently had low carbon sink intensity, while Tacheng showed a significant upward trend. In southern Xinjiang, the ranking of carbon sink intensity in Kashgar and Hotan regions declined over time.

Spatial autocorrelation analysis of total cultivated land carbon sinks in Xinjiang for representative years shows that the global Moran' s index for different years was all greater than 0, passing significance tests at the 0.05 level, indicating that Xinjiang' s cultivated land carbon sinks have positive spatial correlation and exhibit significant spatial agglomeration (Table 4).

Local Moran' s index results (Figure 6) show that high-high carbon sink clusters are mainly located in southern Xinjiang and parts of Ili Prefecture, but their numbers gradually decreased over time. Low-high clusters are slightly more numerous than high-low clusters. Overall, the number of low-high clusters gradually decreased over time. Low-low clusters are mainly located in northern Altay region.

Based on panel data of carbon sinks at three characteristic time nodes for each prefecture and city, standard deviational ellipse and center of gravity migration trajectory were used to map and analyze the spatial distribution and evolution trends of cultivated land carbon sinks in Xinjiang. As shown in Figure 7, Xinjiang' s cultivated land carbon sinks generally exhibit a "southwest-northeast" distribution trend, with the center of gravity concentrated in the Aksu region and the migration trajectory generally moving from southwest to northeast. The migration rate of the carbon sink center of gravity accelerated continuously from 1991 to 2021, with the migration distance reaching 34.9 km from 1991-2001 and 98.4 km from 2001-2011. The migration rate decreased slightly from 2011-2021, with the migration distance dropping to 25.3 km and the center of gravity showing a slight readjustment.

2.3 Contributing Factors to Carbon Sink Effects from Cultivated Land Use

Analysis of the spatiotemporal variation characteristics of carbon effects and their contributing factors reveals that from a temporal perspective, from 1991 to 2021, carbon absorption in Xinjiang' s cultivated land use increased from 1062×10^{4} t to 4126×10^{4} t, while carbon emissions also showed an upward trend but remained substantially lower than crop carbon absorption, thus presenting a strong net carbon sink trend. The carbon absorption is primarily determined by dominant crops such as cotton, wheat, and corn, which collectively contribute 83%-93% to the total carbon absorption. Cotton' s contribution is most prominent, showing an increasing trend; corn' s contribution remains relatively stable; and wheat' s contribution shows a declining trend over time. Other crops contribute relatively small amounts, with a combined contribution of approximately 7%-17%. The contribution evaluation results demonstrate the important role of major crops (corn, wheat, and cotton) in enhancing the carbon sink function of cultivated land, indicating that Xinjiang' s cultivated land use can achieve the dual goals of national food security and carbon sequestration and emission reduction.

Through Formula (2), we calculated the contribution of various cultivated land use activities to total carbon emissions. As shown in Figure 9, fertilizer application, farmland tillage, irrigation, and agricultural film use are the most significant activities affecting total carbon emissions. The proportion of carbon emissions from farmland tillage and irrigation shows a downward trend, while the proportion from fertilizer and agricultural film use has increased, indicating that agricultural chemical inputs remain the major source of carbon emissions from Xinjiang' s cultivated land.

3 Discussion

The increase in net carbon sink from 8.3 million tons to 34.29 million tons in Xinjiang' s cultivated land can be attributed to two main factors. On the one hand, it is due to the continuous increase in cultivated land area in Xinjiang, which aligns with the research findings of Zhang et al. On the other hand, it is closely related to crop planting structure and scale. Cotton, corn, and wheat are the dominant crops in Xinjiang, all belonging to high photosynthetic efficiency and high biomass crops. The planting area of these three major crops in Xinjiang increased from 4.7516 million hectares to 6.885 million hectares, an increase of 2.1334 million hectares. Guo Xia [**?**] pointed out that for every 1 kg of dry matter accumulated in plants, 1.74 kg of CO_2 can be absorbed. Carbon absorption is positively correlated with crop biomass and yield, with annual carbon absorption by crops reaching 4.5 $t \cdot hm^{-2}$. This was also verified by our project' s cotton field CO_2 enrichment experiment (300 ppm), which showed that cotton photosynthetic efficiency and yield increased significantly under low nitrogen conditions [**?**].

It is worth noting that while mechanical power, tillage, irrigation, and fertilizer application in agricultural production activities increase biological yield, they are also important factors triggering carbon emissions. Studies have shown that global cropland is a huge carbon pool. Some research reports that global carbon emissions from irrigation each year amount to 216$×10^{4}$ t, equivalent to [value] of total agricultural emissions.

Inspired by these findings, subsequent research will conduct multi-dimensional modeling from land use scale, economic factors, labor structure, and technological innovation to further demonstrate the carbon sink potential and influencing factors of cultivated land in Xinjiang.

4.1 Conclusions

Based on a comprehensive analysis of the spatiotemporal variation characteristics of carbon absorption, emissions, and net carbon sink effects from cultivated land use in Xinjiang from 1991 to 2021 and their contributing factors, the following conclusions are drawn:

(1) Both carbon absorption and carbon emissions from cultivated land use in Xinjiang showed continuous growth trends, but carbon absorption far exceeded carbon emissions, resulting in a strong net carbon sink effect. The period from 2011-2021 was the fastest growing period.

(2) The carbon sink amount of cultivated land across prefectures and cities showed significant spatial differences, related to regional cultivated land resources, planting structure, and scale. High-high carbon sink clusters at the county scale are mainly located in southern Xinjiang and parts of Ili Prefecture and Bozhou. The carbon sink center of gravity gradually moved from southwest to northeast, but remains in the Aksu region of southern Xinjiang.

(3) Cotton, wheat, and corn contribute 83%-93% of carbon absorption, with these three major crops also being Xinjiang' s main agricultural products. Farmland tillage, irrigation, fertilizer application, and agricultural film use are the main carbon sources in Xinjiang' s cultivated land use, with the contribution of fertilizer and agricultural film inputs to cultivated land carbon emissions continuing to increase.

(4) Although the net carbon sink from cultivated land use in Xinjiang has increased significantly over the past 30 years, there is still considerable potential for improvement compared to regions such as Henan and Shandong [**?**].

4.2 Policy Implications

Based on the research findings and considering Xinjiang' s agricultural realities, the following policy recommendations are proposed to enhance the carbon sink potential of cultivated land use:

(1) Moderately develop saline-alkali land and other reserve cultivated land resources to steadily expand cultivated land area. Simultaneously, adopt measures such as increasing organic fertilizer application, straw return to fields, and conservation tillage to improve soil organic carbon content. By increasing both quantity and quality, the carbon sink potential of Xinjiang' s cultivated land can be tapped.

(2) In response to the decreasing carbon sink intensity in Kashgar and Hotan regions of southern Xinjiang, comprehensive application of land consolidation and development, optimization of planting structure, and irrigation measures can be used to restore and enhance their carbon sink capacity.

For areas in northern Xinjiang with high carbon sink intensity but low total amounts, cultivated land area can be developed according to water resource conditions to increase the number of high-high carbon sink clusters.

(3) Increase the cultivation layout of grain and oil crops in southern Xinjiang, and promote the application of rational cultivation systems, such as wheat relay cropping with corn, cotton, and soybeans, to increase the multiple cropping index, enhance ground cover, and improve carbon absorption by cultivated land.

(4) Implement green and sustainable farmland management measures, such as promoting efficient water-fertilizer integration and photovoltaic pumping technologies to reduce carbon emissions from irrigation energy consumption, and developing and promoting green material inputs such as bio-organic fertilizers and biodegradable films to reduce carbon source emissions.

Acknowledgments

The acquisition of relevant survey data in this paper received strong support from the Xinjiang Uygur Autonomous Region Department of Agriculture and Rural Affairs. The modeling analysis received careful guidance from Dr. Qi Yuchun of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. We express our sincere gratitude here!

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Note: Figure translations are in progress. See original paper for figures.

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