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Research on the Impact of Rural Population Structure Changes on the Net Carbon Sink of Agricultural Production-Take Huan County in the Loess Hilly Region of China as an Example

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People are the fundamental purpose and driving force of agricultural development. The changes in population structure can directly affect social and economic development of rural areas and the entire process of agricultural production. This paper takes Huan County in the Loess Hilly Region of China as the evaluation object, the townships as the evaluation unit, the change of rural population structure as the key point, and the agricultural production as the mediating factor, to study the mechanism of agricultural net carbon sinks. The results show: 1) From 2009 to 2018, the number of rural labor force in Huan County was seriously lost, the quality of the labor force was steadily improved, and the age of the labor force was increased. The number of agricultural employees dropped from 72.6 to 49.4%. The number of people with high school education or above increased from 9.7 to 15.1%. Those over working age who participated in the labor force rose from 5.2 to 8.3%. 2) The Loess Hilly Region in the northwest of Huan County was "grain-trending," and the River Valley and Plain Area in the southeast was "grain-removing." The input structure index both increased first and then decreased. and the Loess Hilly Region was more dependent on the fertilizer. 3) The rural population structure affects the agricultural net carbon sink by affecting the planting structure index and the input structure index. The rural population quantity and quality structure have a significant positive effect on the agricultural net carbon sink, while the population age structure has a significant negative effect on the agricultural net carbon sink. 4) From the mediating effect, the loss of population can cause fluctuations in the agricultural net carbon sink. The improvement of population quality will promote the growth of the agricultural net carbon sink, and the aging of the population will cause the decline of the agricultural net carbon sink. 5) The return of the labor force, the improvement of labor force quality, the improvement of production methods, technological innovation, and skill training are the main ways to increase agricultural net carbon sinks and reduce emissions. This paper can lay a solid foundation for realizing the overall emission reduction target of agricultural production in the Loess Hilly Region.

Keywords: rural population structure, agricultural production, net carbon sink, multiple mediating effects model, Huan County of the Loess Hilly region in China

1 INTRODUCTION

As one of the important development models to achieve carbon emission reduction, low-carbon agriculture has received extensive attention from scholars around the world. In its fourth assessment report, the Intergovernmental Panel on Climate Change (IPCC) pointed out that agriculture is currently the second largest source of greenhouse gases. The greenhouse gas emissions from the agriculture account for about 11% of the total greenhouse gas emissions in China (Tian et al., 2012). Although agriculture has always been an important source of greenhouse gas emissions, crops can absorb CO_2 from the atmosphere through photosynthesis. This makes agricultural land ecosystems a strong carbon sink. In the process of China's urbanization, the non-agricultural employment of labor force has led to the phenomenon of "hollowing" and aging of the rural population (Chen and Shi, 2012). As farmers are the main body of rural social development and land use decision-making, changes in rural population structure will lead to a series of problems such as food production security, imbalanced relationship between man and land, and lack of subjects in new rural construction (Zhou, 2008). Rural issues are the key to the rural revitalization strategy. It is of great practical significance to formulate low-carbon agriculture and rural revitalization policies according to changes in rural population structure.

In recent years, the increase in carbon emissions and environmental problems caused by agricultural production has attracted more and more attention. Scholars mainly focused on the changes in the proportion of agricultural carbon sinks/carbon sources between different countries. For example, ACIL Tasman Pty Ltd. (2009) measured the agricultural carbon emissions in the United States, Canada, India, the European Union, New Zealand, and other countries (Foody et al., 1996; Haxeltine and Prentice, 1996; Paustian et al., 1998; West and Marland, 2002; Wood and Cowie, 2004; US-EPA, 2011). Some scholars also analyzed, calculated and compared the agricultural carbon sinks/carbon sources in different countries and parts of the earth. In addition, they studied the influencing factors of agricultural carbon sinks/carbon sources, the changes in carbon emissions caused by different land use methods, and the changes of carbon emissions direct or indirect caused by different farming methods (conventional farming, precision farming, less tillage, and no-tillage) (Bhat et al., 1994; Neue and Boonjawat, 1998). In my country, since 2000, the level of urbanization has increased rapidly, from 36.2 to 64.72% in 2021. The resident population in rural areas continued to decrease. Labor shortage and aging population have become the main factors restricting rural development. At the same time, it is also an inevitable factor to promote the transformation and development of rural society and economy. With the rapid transformation of agricultural modernization and ecologicalization, it has become a research hotspot to accurately grasp the structural characteristics and change mechanisms of agricultural carbon sinks/sources. On the one hand, more and more scholars have begun to pay attention to issues such as rural labor transfer and agricultural production (Cheng et al., 2015; Huang et al., 2021), rural population aging and agricultural development (Chen et al., 2011; Li and Sun, 2011; Guo, 2013), mainly focusing on labor supply, productivity, modernization process, and labor force Food security issues caused by outflow, utilization of agricultural input factors, etc. On the other hand, scholars have carried out analysis and evaluation on the status quo of carbon sinks/carbon sources at the macro scale. Due to the limitation of existing agricultural economic data, they mainly focus on the provincial, regional and national scales (Zhao, 2004; Zhao and Qin, 2007; Zhang D. D et al., 2012; Chai et al., 2013), and there are relatively few studies on the micro scale. In addition, some scholars have studied the influencing factors of agricultural carbon sinks/carbon sources (Ran et al., 2011; Tian and Zhang, 2013; Wu et al., 2015), mainly from the perspective of agricultural production, such as agricultural economic growth (Li et al., 2011), agricultural development conditions (Wu and Wang, 2017), farming methods (Zhang M. Y et al., 2012). However, "farmers," the decision makers of agricultural production, pay less attention to the impact of agricultural carbon sinks/carbon sources, and the individual's response to economic opportunities is the underlying factor driving changes in agricultural production (Song, 2017). The adjustment of agricultural production is the result of the combined effect of social-economic external driving force and agricultural production decision-making under the change of rural population structure. The interaction of the relationship between man and land is realized through the agricultural production practice of farmers. Farmers are the main body of agricultural production decision-making. The endowment of household labor resources such as the number, quality, and age structure of the rural population has an important impact on agricultural production decision-making (Liao et al., 2021). At the same time, agricultural production directly affects the agricultural ecosystem through the application of chemical fertilizers, the use of agricultural film, and the carbon emission of agricultural machinery. Therefore, it is necessary to explore the changing mechanism and driving mechanism of agricultural carbon effect from the perspective of human beings. In general, although existing studies have made a lot of useful explorations on the issue of agricultural carbon sinks/sources, there are still some problems and weaknesses. First, there are few studies on agricultural carbon sinks, especially net carbon sinks. The existing studies are mainly on the national, provincial and regional scales, and there are few studies on the micro-levels such as counties and townships. This is not conducive to understanding the changes in the pattern of agricultural carbon activities in local areas, and formulating agricultural production emission reduction policies according to local conditions. In addition, the research on the factors of agricultural carbon sinks/carbon sources lacks analysis from the perspective of rural population structure changes.

Based on this, this paper takes Huan County (**Figure 1**) in Gansu Province as the evaluation object, the township as the evaluation unit, based on the panel data from 2009 to 2018, using the multiple mediation effect model, starting from the change of rural population structure, and taking agricultural production as the starting point. Mediating factors to explore the underlying driving mechanism of agricultural net carbon sinks. The main contributions of this paper are as follows: First,

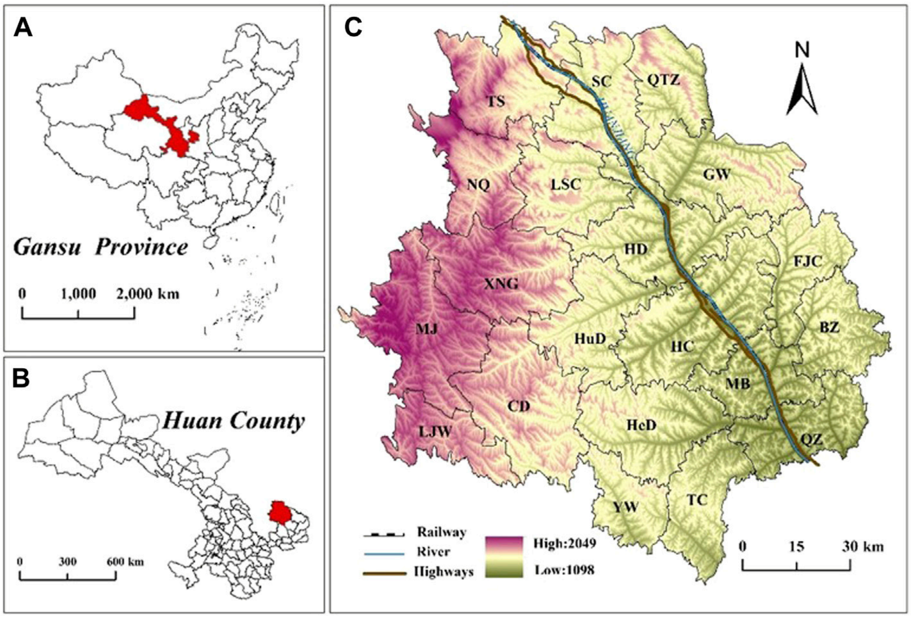

FIGURE 1 | (A) and **(B)** respectively show the location of Gansu Province and the location of Huanxian County, and they are expressed in words in the figure, so there is no repeated expression.

it fills the gap in the research on the impact of farmers on agricultural carbon effects, and uses the mediation effect model to explore the impact of rural population structure on planting structure and input structure, which in turn affects the agricultural net carbon sink. Second, it helps us to further understand and grasp the internal driving mechanism of agricultural net carbon sinks. Third, it expounds how to adjust the rural population structure and promote the low-carbon development of agriculture, which can provide a theoretical reference for the formulation of low-carbon and high-quality agricultural development policies in the Loess Hilly Region or ecologically sensitive areas.

The rest of this paper is organized as follows. In the "*Study Area and Data Sources*" section, we show the natural and social development characteristics and data sources of the study area. The theoretical support for the entire paper is shown in the "*Theoretical Framework*" section. The "*Research Methods*" section covers the selection of variables and model building. The Empirical "*Results*" section discusses the empirical results. The "*Conclusions*" section contains the main conclusions of this paper. The "*Discussion*" section contains discussions on past empirical results and mediating influence mechanisms, as well as specific measures to adjust rural population structure to promote low-carbon agricultural development.

2 STUDY AREA AND DATA SOURCES

2.1 Physical Geography Overview

The Loess Hilly Region is mainly distributed in the middle reaches of the Yellow River and the northern part of the Loess Plateau, involving seven provinces (regions) and an area of 211,800 square kilometers. Huan County is located in Qingyang City, Gansu Province, China, between longitude 106°21′ and 107°44′ east, latitude 36°1′ and 37°9′ north, 124 km from east to west, 127 km from north to south, with a total area of 9,236 km^2, belonging to the Loess Plateau region. The terrain is high in the northwest and low in the southeast, with an altitude of 1,098–2,049 m. The landform is divided into the typical Loess Hilly Area in the northwest, and the River Valley and Plain Area in the southeast (**Figure 1**). Huan County has a significant semi-arid climate in the temperate continental zone in the interior of the continent. The annual average temperature is 9.2°C. The sunshine hours are 2,600 h. The precipitation is 300 mm, and the spatial and temporal distribution is uneven. The precipitation period is in the 3 months of July, August and September. The annual evaporation is 2000 mm. The precipitation gradually decreases from the southeast to the northwest of the region. Rain-fed agriculture is the basic condition of Huan County, and the desert area accounts for 58% of the total land area. These natural characteristics doomed the difficulty of agricultural production in Huan County, and also reflects the current state of agricultural production in the Loess Hilly Region. At the same time, affected by various factors such as topography, landforms, rivers, roads, social economy, and ideology, etc., the spatial distribution of agricultural inputs within the territory is uneven, and the spatial difference of agricultural production is large.

2.2 Socio-Economic Overview

Huan County has 20 townships (Tianshui-TS, Nanqiu-NQ, Luoshanchuan-LSC, Maojing-MJ, Xiaonangou-XNG, Lujiawan-LJW, Chedao-CD, Shancheng-SC, Qintuanzhuang-QTZ, Gengwan-GW, Hongde-HD, Hudong-HuD, Hedao-

HeD, Huancheng-HC, Fanjiachuan-FJC, Bazhu-BZ, Quzi-QZ, Mubo-MB, Tianchi-TC, and Yanwu-YW), and 251 administrative villages. Affected by the special geomorphological environment and the advancement of urbanization, the rural labor force has been lost and aged very seriously in Huan County. The change in labor resource leads the left-behind farmers to adjust the input structure and planting structure (Liao et al., 2021). At the end of 2020, the total registered population of the county was 36.32×10^4, of which the agricultural population was 30.35×10^4, accounting for 83.56% of the total population. There were 17.75×10^4 rural employees, including 5.10×10^4 employees working abroad, accounting for 28.73% of the total rural employees. There were 2.95×10^4 people with high school education or above, accounting for 16.62% of the total rural employees. There are 1.65×10^4 people over working age who participated in social labor, accounting for 9.30% of the employees. In 2020, the county's GDP reached 10.964 billion yuan, a year-on-year increase of 6.1%. Among them, the added value of the primary industry was 1.672 billion yuan, a year-on-year increase of 5.4%. The crops are mainly planted crops such as wheat, corn, soybeans, oilseeds, vegetables, and melons. Among them, the planting area of food crops was 1.9402 million mu, with an increase of 3.9%. The rural electricity consumption was 203 million kWh, a year-on-year increase of 2.7%. The amount of agricultural chemical fertilizers used was 65,500 tons, a decrease of 3.1%. The amount of plastic film used was 9,000 tons, a decrease of 0.1%.

2.3 Data Source

The data of this study mainly is from three aspects: 1) Basic maps: including the topographic map of Huan County (1: 100,000) and the vector administrative boundary of Huan County and towns (1:100,000) from the Gansu Provincial Bureau of Surveying and Mapping; 2) DEM data: including the elevation and slope data of Huan County, from the geospatial data cloud through ArcGIS statistics; 3) Statistical data: 2009–2018 Population data of all townships in Huan County and all counties in Gansu province (number of agricultural employees, total number of rural employees, number of people with high school education or above), agricultural input factors (arable land area, scalar volume of chemical fertilizer application, agricultural film usage, total machinery power, and rural production electricity, etc.), the sown area and output of various crops, respectively, from the "Huan County Statistical Yearbook (2010–2019)" and "Gansu Statistical Yearbook (2010–2019)," for individual data Missings are obtained by interpolation, and for very few outliers, corrections are made by the data of adjacent years.

3 THEORETICAL FRAMEWORK

Since China entered the transition period, the rural population structure has undergone tremendous changes. These changes are not only in gender structure and age structure, but also in the quality structure. Changes in rural population structure have also brought changes in socio-economics, labor supply, agricultural production, planting structure, and the associated agricultural carbon emissions. Agriculture is a source of greenhouse gas emissions and the industry most vulnerable to population changes. Agricultural production under the change of rural population structure needs to be studied from two aspects: agricultural input structure and planting structure (**Figure 2**).

First, the change of rural population structure and the configuration of input structure: With the development of urbanization, rural population moved to urban areas. The rural population has been redistributed in space, and the number of agricultural laborers has been decreasing and aging has become increasingly serious (Long and Tu, 2017). This changed the configuration of human capital stock and physical capital in rural areas. To maintain the output of agricultural production, farmers increased the input of agricultural capital such as fertilizers, pesticides, and machinery on unit land. This is an effective way to make up for the shortage and aging of the labor force. According to the principles of economics, there is partial substitution between the input factors in the agricultural production process. When one input factor is reduced, we can increase the one or several corresponding input factors to achieve the same agricultural production goal (Song and Li, 2019).

Second, the change of rural population structure and the adjustment of planting structure. The planting structure is the number and proportion of different types of crops. Crops can be divided into food crops, cash crops and horticultural crops according to their functions. The essence of the adjustment of the planting structure is the readjustment, configuration and combination of production materials, such as labor, land, capital, and technology. This is the process for farmers to pursue economic benefits and maximize production benefits (Liu and Liu, 2009; Wang and Wang, 2013). The adjustment of planting structure is a response to agricultural supply-side reform, changes in market structure and the improvement of consumption levels. On the one hand, the reduction and transfer of the rural labor force has strengthened the constraint of the labor force. The adjustment of the division of labor model within households will tend to plant field crops with low market risk, high degree of social service division, and high government subsidies. On the other hand, the change in the quality of the agricultural labor force will affect farmers' choice of planting structure through the difference in human capital represented by health, learning ability and production experience. The impact of aging labor structure on the planting structure will vary because of the different needs of crops themselves for labor and human capital. In addition, farmers tend to choose crops that are easy to cultivate with high yields and are highly adaptable to mechanization in terms of planting structure (Huang and Li, 2019).

Based on this, we propose a driving mechanism hypothesis for the change in the net carbon sink of agricultural production: changes in rural population structure may indirectly affect agricultural net carbon sinks by affecting agricultural input structure and planting structure. First, the concentration of population in urban areas in the process of urbanization leads to a spatial redistribution of the rural population (Liu and Yang,

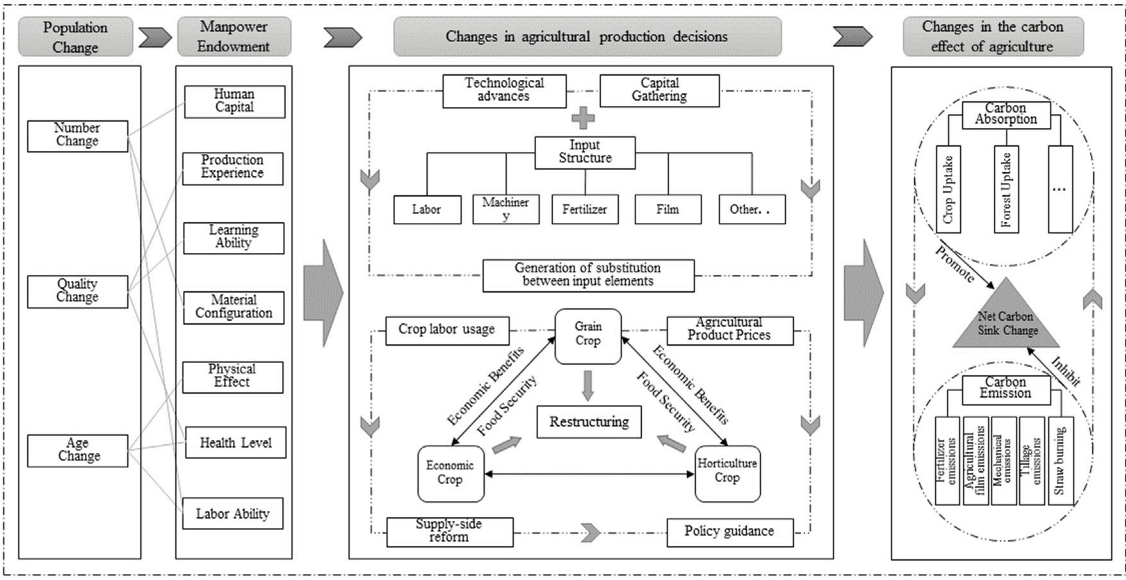

FIGURE 2 | The mechanism of net carbon sink of agricultural production under the change of rural population structure.

2012). The rural population movement and aging have caused shortage of agricultural labor force, forcing farmers to increase the input of fertilizers, agricultural film and other agricultural materials to maintain agricultural income, but at the same time, it will generate a large amount of greenhouse gases and cause environmental pollution. Agriculture is an important source of greenhouse gas emissions (FAO, 2016). 20% of the world's CO_2, 70% of CH_4, and 90% of N_2O come from agriculture and its related processes. Therefore, changes in the input structure will greatly affect agricultural carbon emissions, thus affect the net agricultural carbon sink. Secondly, thecurrent forest carbon sink is the main product in the international carbon sink market, and food crops also have carbon sinks that play an important role in regulating the climate (Li and Ge, 2014). However, because the economic value of crops and their ecological functions are often neglected, especially in the northwest region where the forest area is small, the carbon sink function of food crops becomes more important. Therefore, the adjustment of the planting structure will greatly affect the agricultural carbon absorption and thus affect the agricultural net carbon sink. At the same time, due to the large difference in the straw yield of various crops, the adjustment of the planting structure will also affect the amount of straw produced after the crops are harvested, and then affect a part of agricultural carbon emissions and thus affect the agricultural net carbon sink.

4 RESEARCH METHODS

4.1 Variable Selection

According to the consistency and availability of data, we combine the existing research results and the actual situation of agricultural development in Huanxian County, and select the following variables (**Table 1**) and descriptive statistics of the variables (**Table 2**):

(1) Explained variable: net carbon sink in agricultural production. Net carbon sink refers to difference between the total amount of carbon absorbed by crops through photosynthesis and the total amount of carbon emissions from the burning of crop straws and agricultural inputs in the production process. The relevant estimation models are:

$$C_Z = \sum_i \frac{Y_i \times C_i \times (1 - F_i)}{M_i} \tag{1}$$

where C_Z is the total carbon absorption of agricultural production, which refers to the total amount of carbon dioxide absorbed by photosynthesis during crop growth. Y_i is the harvest amount of the crop; C_i is the carbon absorption rate of crops (Lin and Ge, 2016). F_i is the fruit moisture coefficient of the crop (Lin and Ge, 2016). M_i indicates the economic coefficient of the crop (Lin and Ge, 2016), that is, the ratio of economic yield to biological yield.

$$E = \sum (T_i \times \delta_i) \tag{2}$$

where E is the carbon emissions in the agricultural production process. i is the source of agricultural carbon emissions. T represents the characterization data of agricultural carbon emission sources. δ is the carbon emission coefficient of agricultural carbon emission sources (Shu-jie et al., 2018; Bai et al., 2019; Chen et al., 2019; Souza et al., 2019).

$$M = \sum_{i=1}^{n} A_i \times P_i \times F_i \tag{3}$$

TABLE 1 | Variables.

Variable type	Variable name	Symbol	Variable interpretation
Explained variable	Net carbon sink	*NCS*	Total carbon absorption−total carbon emissions
Core explanatory 1	Number structure	*NS*	Number of agricultural employees/total number of rural employees
Core explanatory 2	Quality structure	*QS*	Number of people with high school education or above/total number of rural employees
Core explanatory 3	Age structure	*AS*	The number of people who have exceeded the working age to participate in social labor/total rural labor resources
Mediating variables	Planting structure	*PS*	Sown area of food crops/area sown of non-food crops
	Input structure	*INF*	Nitrogen fertilizer application is in a pure amount/the total area sown to crops
		IPF	Amount of plastic film used/the total area sown to crops
		AML	Total power of agricultural machinery/number of people employed in agriculture
Control variables	Arable land quality	*CLQ*	Cultivated land with a slope of less than 15°/the total area sown to crops
	Irrigation index	*IRRIGA*	Effective irrigation area/total area sown to crops
	Per capita GDP	*PGGDP*	GDP/total number of people

TABLE 2 | Sample Information Description.

Symbol	Township level (200 samples)				County level (860 samples)			
	Mean	Max	Min	S.D	Mean	Max	Min	S.D
NCS	6,127.447	35,164.105	−1,190.661	5,164.967	38,901.274	694,694.308	−23000.130	59,866.030
NS	0.504	0.991	0.161	0.152	0.629	0.929	0.136	0.117
QS	0.133	0.421	0.029	0.081	0.148	0.623	0.012	0.019
AS	0.075	0.241	0.067	0.052	0.054	0.325	0.023	0.076
PS	5.961	17.752	0.639	2.922	2.795	39.831	0.025	4.281
INF	0.134	0.583	0.099	0.101	0.114	2.023	0.043	0.251
IPF	0.052	0.966	0.012	0.124	0.045	1.467	0.009	0.213
AML	4.183	16.976	0.392	3.488	4.667	27.511	0.071	3.88
CLQ	0.582	0.975	0.069	0.177	0.324	0.983	0.012	0.256
IRRIGA	0.035	0.332	0	0.054	0.177	0.983	0	0.256
PGGDP	3,558.845	11,863.539	1,031.331	1,983.126	13,448.579	72,952.096	1,829.678	11,112.242

$$C_{straw} = \sum M \times EF \tag{4}$$

where M is the amount of crop straw burned. A_i is the yield of different crops. P_i is the proportion of straw produced by different crops (Bi and Gao, 2009), that is, the ratio of crop straw yield to crop economic yield. F_i represents the proportion of crop straw burned in the open air (Cao and Zhang, 2006). C_{straw} is the total carbon emissions from crop straw burning. EF is a CO_2 emission factor of 1.515 kg/kg for straw combustion (Shu-jie et al., 2018).

$$C_N = C_Z - C_O \tag{5}$$

where C_N is the net carbon sink, that is, the difference between the total carbon absorption and the total carbon emissions. C_Z is the total carbon absorption of the crop. C_O is the total carbon emissions from the production process and the burning of crop straw.

(2) Core explanatory variables: There are three core explanatory variables in this paper, namely the quantitative structure of the rural population, the quality structure of the rural population, and the age structure of the rural population.
(3) Mediating variables: The mediating variables in this paper are planting structure and input structure. The input structure includes the average amount of fertilizer application per unit areas, the average amount of film usage per unit areas, and the total mechanical power per capita.
(4) Control variables: Agricultural net carbon sinks are affected by many factors. In addition to the population structure, planting structure and input structure, they are also affected by regional natural endowments and socioeconomic levels. According to existing studies, this paper introduces cultivated land quality, irrigation index and per capita GDP.

TABLE 3 | Panel model selection results (township level).

		Test value (*p*)	Result
Hausman test	NS	19.524 (0.012)	FE model
	QS	15.615 (0.000)	FE model
	AS	16.425 (0.000)	FE model

TABLE 4 | Panel model selection results (township level).

		Test value (*p*)	Result
Time effect test	NS	36.430 (0.000)	Two-way fixed-effects model
	QS	34.070 (0.000)	Two-way fixed-effects model
	AS	29.283 (0.000)	Two-way fixed-effects model

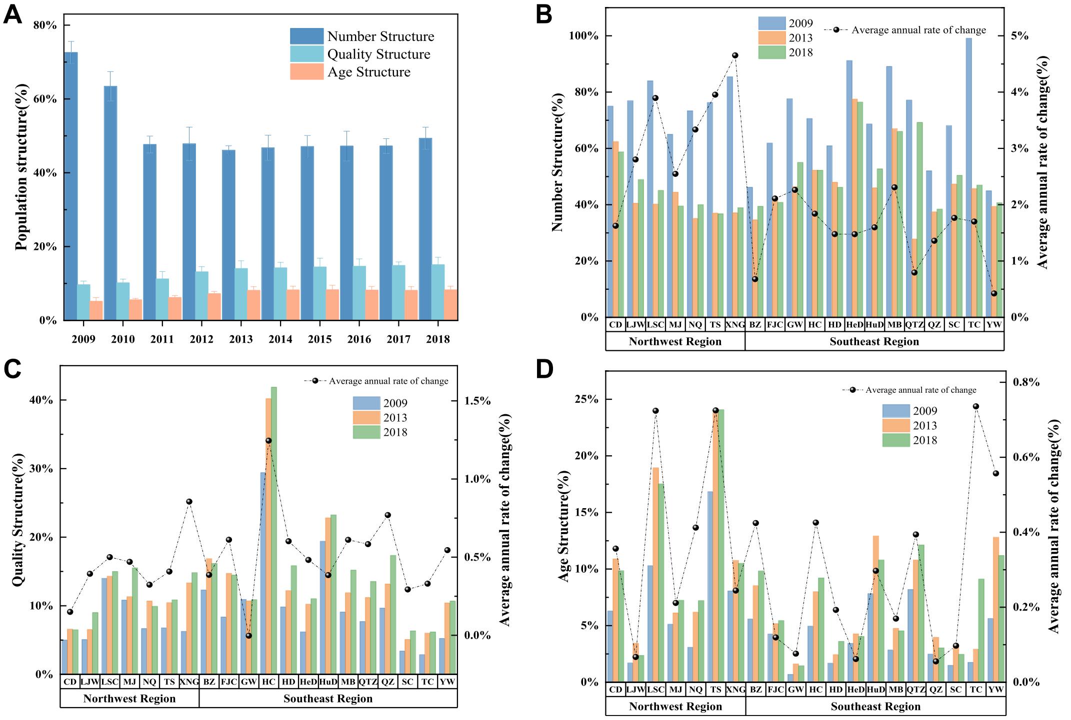

FIGURE 3 | Characteristics of rural population structure change in Huan County. **(A)** Overall changes in Population Structure of Huan County from 2009 to 2018, **(B)** Changes in the Number Structure of population in each township, **(C)** Changes in the Quality Structrue of population in each township, **(D)** Changes in the Age Structrue of the population in each township.

4.2 Model Design

According to the previous research hypothesis, the number, quality, and age of the rural population may affect the agricultural net carbon sink through the intermediary factors of planting structure, average fertilizer application amount, agricultural film usage, and per capita total mechanical power. In order to reduce data variance and narrow the fluctuation range of residuals, all variables in the regression equation are in logarithmic form (Deng and Xue, 2018), and a panel model is used for empirical analysis. Before regression, this paper uses Hausman test to determine whether to choose a fixed effect model (**Table 3**); on the other hand, we tested whether the time effect was significant. First, time dummy variables were generated in stata software, and then the joint significance of these time dummy variables was tested to judge whether to choose a two-way fixed effect model (**Table 4**). From the results in **Tables 3**, **4**, a two-way fixed effect model was finally selected to test the relationship between rural population structure and

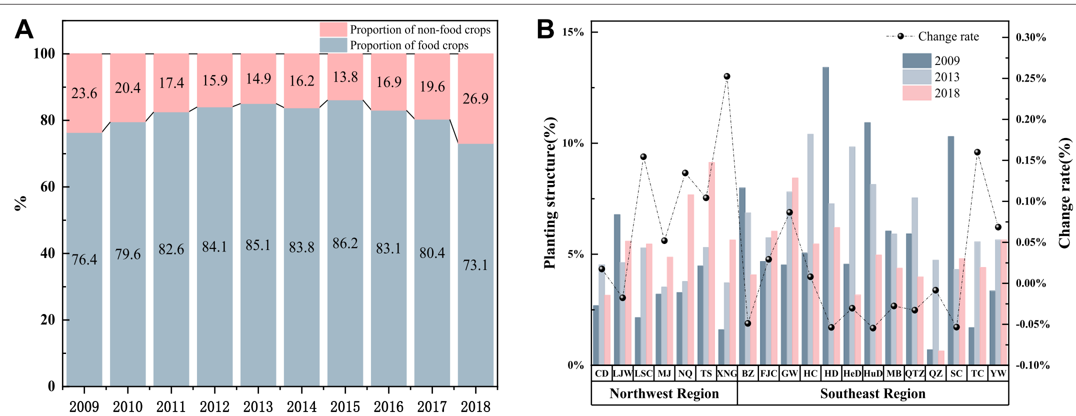

FIGURE 4 | Characteristics of Planting Structure change in Huan County. **(A)** Temporal changes in Planting Structure in Huan County from 2009 to 2018, **(B)** Changes in Planting Structure and rate of change in each township.

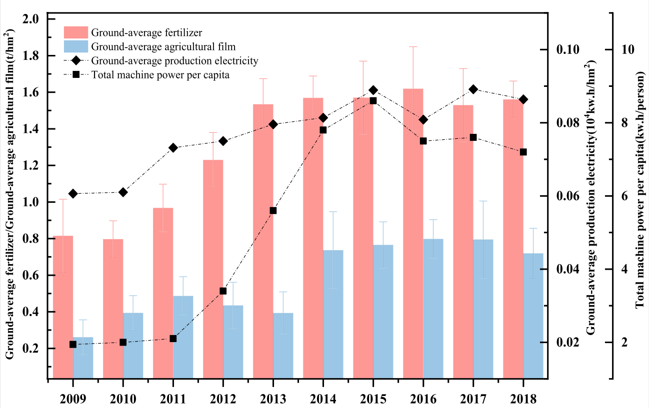

FIGURE 5 | Temporal changes in the input structure of Huan County from 2009 to 2018.

agricultural net carbon sinks. At the same time, drawing on the mediation effect method of (Kristopher and Preacher, 2008). (Preacher and Hayes, 2008), a multiple mediation effect model is constructed:

$$\text{Model I}: lnNCS_{it} = \alpha_0 + \alpha_1 lnNS_{it} + \alpha_2 lnControl_{it} + f_t + u_i + \varepsilon_{it}$$

$$\text{Model II}: lnPS_{it} = \beta_0 + \beta_1 lnNS_{it} + \beta_2 lnControl_{it} + f_t + u_i + \varepsilon_{it}$$

$$\text{Model III}: lnIS_{it} = \delta_0 + \delta_1 lnNS_{it} + \delta_2 lnControl_{it} + f_t + u_i + \varepsilon_{it}$$

$$\text{Model IV}: lnNCS_{it} = \lambda_0 + \lambda_1 lnNS_{it} + \lambda_2 lnPS_{it} + \lambda_3 lnIS_{it} + \lambda_4 lnControl_{it} + f_t + u_i + \varepsilon_{it}$$

where NCS_{it} represents the net carbon sink of agricultural production in the t period of Huan township I. NS_{it} represents the proportion of agricultural employees in the t period of i township. IS_{it} represents the change of input structure in the t period of i township (including the average amount of fertilizer application per unit area, the average amount of film usage per unit area, and total mechanical power per capita). $Control_{it}$ is the control variable that may affect the agricultural net carbon sink and intermediary factors, f_t is the unestimable time fixed effect, u_i is the unobservable individual

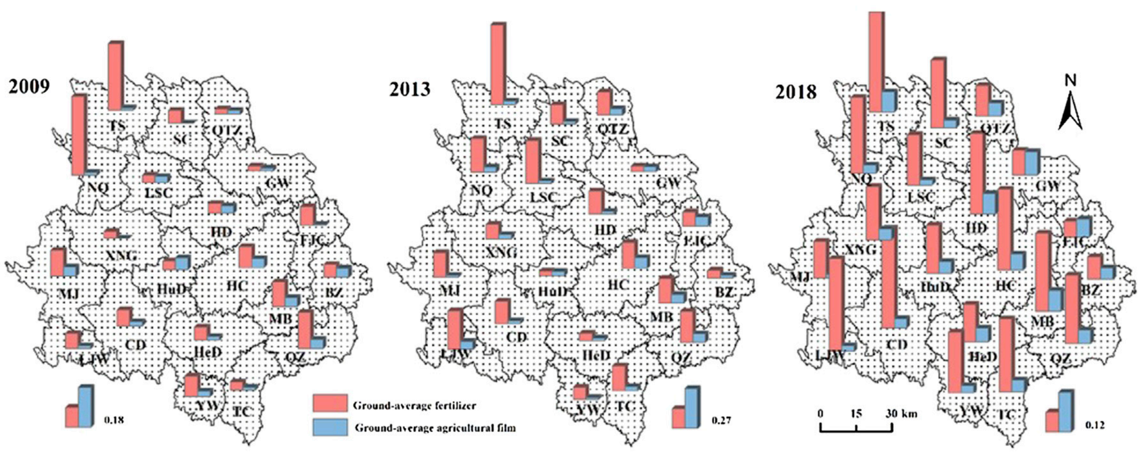

FIGURE 6 | Spatial changes in planting structure in Huan County from 2009 to 2018.

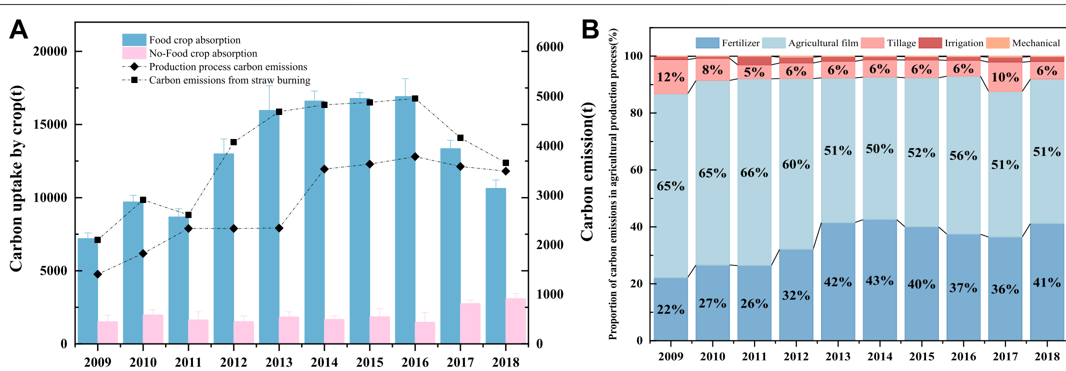

FIGURE 7 | Characteristics of carbon effect change in Huan County. **(A)** Changes in carbon absorption and carbon emission from 2009 to 2018, **(B)** Changes in the percentages of carbon emissions from the annual input structure.

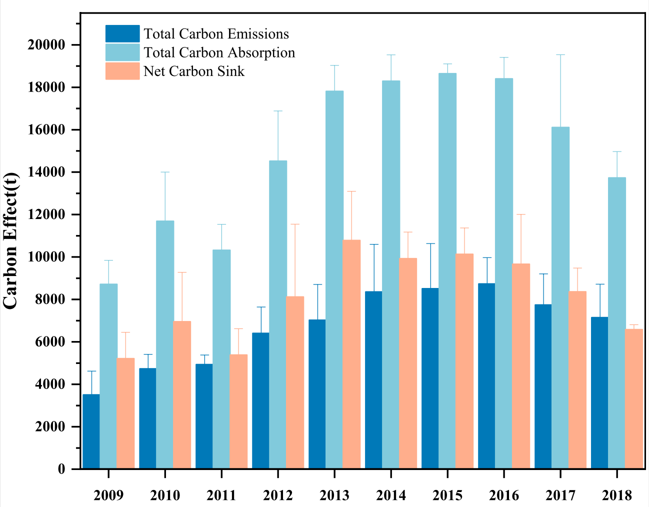

FIGURE 8 | Changes in agricultural production carbon sinks, carbon emissions and net carbon sinks in Huan County.

fixed effect, α_0 , β_0 , δ_0 , λ_0 is the fixed intercept, and ε_{it} is the random error term The empirical process is as follows:

The first step: (Total Effect) Regression Model 1. If the α_1 is significantly positive or negative, the rural population structure can affect the agricultural net carbon sink. Then, the next test is carried out. The second step (Configuration Effect): Regression Model 2 and Model 3 at the same time. If β_1 is significant, changes in population structure will affect the planting structure. If δ_1 is significant, changes in population structure will affect the input structure. This is consistent with the theoretical hypothesis and can be further tested. Step 3 (Direct Effect): Regression Model 4. If λ_1 is not significant, λ_2 and λ_3 are significant, planting structure and input structure play a fully mediating role in the impact on the net carbon sink of agricultural production. If λ_1, λ_2, λ_3 are all significant, the planting structure and the input structure only have partial mediating effects. The model construction of rural population quality structure and age structure is the same as above.

5 RESULTS

5.1 Characteristics of Changes in Rural Population Structure

The overall rural population structure index in Huan County showed a downward trend, from 72.6% in 2009 to 49.4% in 2018, with an average annual decrease of 2.3% (**Figure 3A**). During the same period, all townships in Huan County experienced the loss of the agricultural labor force. Moreover, the labor force loss in the Loess Hilly Region in the northwest was more serious (**Figure 3B**). The population quality structure index showed an overall upward trend, from 9.7% in 2009 to 15.1% in 2018, with an average annual increase of 0.5%. The population quality structure of 19 townships has been continuously optimized, accounting for 95.0% of the total number of townships. The educational level of most of the township labor force has been improved. The labor force quality in the River Valley and Plain Area was better (**Figure 3C**). The population age structure index showed a fluctuating upward trend, rising from 5.2% in 2009 to 8.3% in 2018, with an average annual increase of 0.3%. All townships in Huan County are facing the problem of the aging of the rural labor force, especially in the Loess Hilly Region in the northwest (**Figure 3D**). With the continuous advancement of rural urbanization, backward rural infrastructure, and rising farming costs, under the dual effects of urban pull and rural push, rural young labor force is transferred to cities on a large scale, and rural labor force selectively flows out. The labor force broke the original rural population's quantity, quality and age structure (Long and Tu, 2017). Farmers are the main body of rural social development and land use decision-making. The interaction of man-land relationship is realized through farmers' agricultural production practice. The endowment of household labor resources, such as the quantity, quality and age structure of agricultural labor, has an important impact on the decision-making behavior of agricultural production. It is reflected in the decision-making changes of planting structure and input structure.

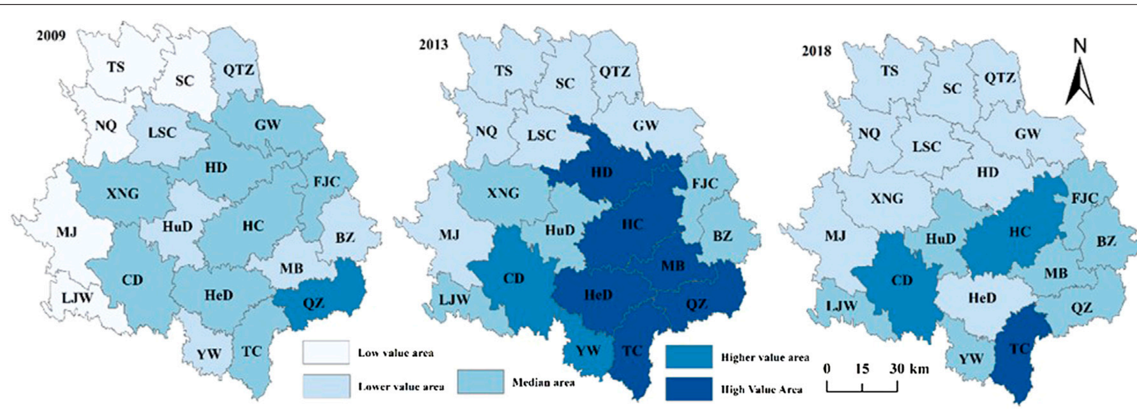

FIGURE 9 | Spatial changes in the net carbon sink of agricultural production in Huan County from 2009 to 2018.

5.2 Characteristics of Changes in Rural Agricultural Production

5.2.1 Analysis of Changes in Planting Structure

The proportion of food crops in the total area of crops in Huan County showed an inverted "U"-shaped trend (**Figure 4A**). It increased from 76.4% in 2009 to 86.2% in 2015, and then decreased to 73.10% in 2018. From 2009 to 2015, it showed a fluctuating upward trend, with an average value of 82.5% during this period. This is closely related to the policy of "stabilizing the sown area of grain and enhancing the food security capability" in China. From 2016 to 2018, it showed a downward trend, with an average value of 79.4%. This is because Gansu Province promoted the policy of "supply-side structural reform of planting industry" proposed by the government of China, and the area of grain production was reduced. The planting structure index of the Loess Hilly Region in the northwest showed an exponential upward trend, from 3.4 in 2009 to 5.9 in 2018, with an average annual increase of 0.07%. The planting structure in Pingchuan District of the southeastern valley increased first and then decreased exponentially (**Figure 4B**). It rose from 6.1 in 2009 to 6.9 in 2013, and then fell to 4.8 in 2018, with an average annual decrease of 0.02%. There are nine countries and towns with a decrease in the planting structure index, of which 8 are in the River Valley and Plain Area in the southeast. It indicates that there are differences in planting structure between regions because of differences in natural endowments and traffic conditions. That is, the soil is more fertile, more convenient for transportation, and more water resources, which makes the conditions in the southeast region for non -grain planting. Although the moderate non-grain conversion of arable land meets the needs of agricultural planting structure adjustment in some regions of China and helps the transformation and upgrading of local agricultural development, there are also some potential risks, such as the use of pesticides and fertilizers when planting commercial crops on arable land. Excessive application will aggravate the agricultural non-point source pollution of cultivated land and destroy the soil cultivated layer, which will lead to a series of ecological and environmental problems, and for areas with low forest coverage such as Huan County, it is more dependent on the carbon sink function of food crops (Song, 2017), and it will also directly affect the sustainability and stability of food security.

5.2.2 Analysis of Changes in Input Structure

From 2009 to 2018, the input structure index showed a trend of first increase and then decrease. The average amount of fertilizer applied and the amount of agricultural plastic film used increased from 0.82 and 0.22 t/hm^2 in 2009 to 1.62 and 0.73 t/hm^2 in 2016, and then decreased to 1.56 and 0.65 t/hm^2 in 2018, respectively. The production electricity consumption per land and total mechanical power per capita increased from 0.061×10^4 kwh/hm^2 and 1.94 kwh/person in 2009 to 0.089×10^4 kwh/hm^2 and 8.63 kwh/person in 2013, and then decreased to 0.086×10^4 kwh/hm^2 and 7.20 kwh/person in 2018, respectively (**Figure 5**). Each index has declined around 2016. The average fertilizer application per unit area was greater in the loess hilly and gully area in the northwest. The average film usage per unit area was greater in the southeastern River Valley and Plain Area was larger (**Figure 6**). One reason is that the Loess Hilly Region with poorer soils are more dependent on the input of chemical fertilizers. Second, to solve the aggravating problem of environmental pollution, the government put forward a "recycling sustainable agricultural development mode that advocates ecological and environmental protection" during the period of the "13th Five-Year Plan." This is the achievement of the concept of ecological civilization in the agricultural field. At present, Huan County agriculture relies on a high degree of agricultural inputs such as chemical fertilizers, which not only pollutes the environment, but also has side effects on the human body. It is not a sustainable business model. However, without agricultural inputs such as chemical fertilizers, the rural areas in the loess hilly and gully areas with poor soil will face the risk of failure and no harvest. Faced with this dilemma, agriculture in the Loess Hilly Region urgently needs to explore a low-carbon and high-quality development path.

5.3 Characteristics of Changes in Net Carbon Sink in Rural Agricultural Production

5.3.1 Changes in Carbon Absorption and Emission

From 2009 to 2018, the carbon absorption of food crops increased first and then decreased, and the carbon absorption of non-food crops showed a fluctuating upward trend. Food crops had the maximum carbon absorption in 2016, reaching 16,916t, and the minimum in 2009, only 7,199 t. Non-food crops had the maximum carbon absorption in 2018, reaching 3,098 t, and the minimum in 2016, only 1,489 t. This indicates that the agricultural carbon absorption in Huan County mainly depends on food crop. In addition, the changes of carbon emissions in the production process and from straw combustion both showed an inverted "U" shape. They fluctuated from 1,408 t and 2,648 t in 2009 to 3,654 t and 4,921 t in 2016, and then decreased to 3,436 t and 3,969 t in 2018, respectively (**Figure 7A**). The descending order of the annual average proportion of carbon emissions from agricultural production in Huan County is: agricultural film use (56.0%), fertilizer application (34.2%), tillage (7.0%), irrigation (1.5%) and machinery use (1.3%). The application of chemical fertilizers and the use of agricultural films are the main sources of carbon emissions from agricultural production in Huan County, accounting for 90% of the total carbon emissions from production. The proportion of carbon emissions from the use of agricultural films showed an overall trend of decline. The proportion of carbon emissions from fertilizer application shows a fluctuating upward trend. The proportion of carbon emissions from farming, irrigation, and mechanical use remained stable. It also indicates that the agricultural modernization process in Huan County was slow (**Figure 7B**).

5.3.2 Changes in Net Carbon Sinks

From 2009 to 2018, the agricultural carbon sinks, carbon emissions and net carbon sinks in Huan County all showed an inverted "U"-shaped change trend of increasing first and then decreasing (**Figure 8**). Agricultural carbon sinks and carbon emissions showed an increasing trend from 8,721 t and 3,507 t in 2009 to 18,645 t and 8,512 t in 2015, an

TABLE 5 | Empirical results on the impact of rural population size on net carbon sink in agriculture.

Var.	Total effect	Allocation effect of NS on mediating factors				The introduction of the mediating variable NS affects the direct effect of the net carbon sink					
	lnNCS	lnPS	lnINF	lnIPF	lnAML	lnPS	lnINF	lnIPF	lnAML	All	E
						lnNCS	lnNCS	lnNCS	lnNCS	lnNCS	
lnNS	0.340** (2.17)	0.032** (1.45)	−0.587*** (−3.27)	−1.059*** (−4.21)	−1.155*** (−26.45)	0.428** (2.38)	0.405** (2.16)	0.407** (2.22)	−1.003*** (−4.78)	0.214** (1.34)	—
lnPS	—	—	—	—	—	0.215*** (3.22)	—	—	—	0.112** (1.02)	1
lnINF	—	—	—	—	—	—	−0.197** (−2.42)	—	—	−0.112** (−3.13)	1
lnIPF	—	—	—	—	—	—	—	0.126** (2.45)	—	0.120*** (2.46)	1
lnAML	—	—	—	—	—	—	—		−0.884** (−9.66)	−0.802*** (−10.21)	1
Control	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	—
Cons	9.452*** (30.22)	−0.423** (−6.12)	−3.393*** (−12.60)	−4.447*** (−8.92)	−0.276*** (−4.19)	7.913*** (13.95)	7.712*** (20.69)	9.982*** (26.29)	8.589*** (31.50)	3.23*** (8.13)	—
Double effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—
R2	0.27	0.65	0.70	0.36	0.80	0.41	0.72	0.40	0.50	0.68	—
Obs	200	200	200	200	200	200	200	200	200	200	—

TABLE 6 | Empirical results of rural population quality affecting net carbon sink in agriculture.

Var.	Total effect	Allocation effect of QS on mediating factors				The introduction of the mediating variable QS affects the direct effect of the net carbon sink					
	lnNCS	lnPS	lnINF	lnIPF	lnAML	lnPS	lnINF	lnIPF	lnAML	All	E
						lnNCS	lnNCS	lnNCS	lnNCS	lnNCS	
lnQS	0.284*** (2.97)	−0.016* (−1.65)	−0.216*** (−3.15)	0.934** (1.98)	0.661*** (5.23)	0.253*** (2.67)	0.255*** (2.75)	0.268*** (2.80)	0.259*** (3.15)	0.107** (1.54)	—
lnPS	—	—	—	—	—	0.175* (1.23)	—	—	—	0.159* (1.91)	1
lnINF	—	—	—	—	—	—	−0.171*** (−2.68)	—	—	−0.209*** (−3.53)	1
lnIPF	—	—	—	—	—	—	—	0.091* (1.77)	—	0.118*** (2.63)	1
lnAML	—	—	—	—	—	—	—		−0.584** (−8.41)	−0.545** (−8.07)	1
Control	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	—
Cons	10.35*** (23.13)	−0.77*** (−16.62)	−2.76*** (−10.03)	−2.225** (−2.05)	1.834*** (6.42)	8.905*** (13.10)	8.49*** (12.40)	4.12*** (6.53)	9.86*** (25.40)	4.16*** (6.60)	—
Double effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—
R2	0.50	0.66	0.34	0.47	0.67	0.57	0.56	0.69	0.58	0.60	—
Obs	200	200	200	200	200	200	200	200	200	200	—

increase of 114 and 143%, with an average annual increase of 19 and 24%, respectively. There was a downward trend since 2015. The decline in carbon sinks was greater than that in carbon emissions, by 26 and 16%, respectively. The net carbon sink increased from 5,214 t in 2009 to 10,784 t in 2013. After 2014, the net carbon sink was fluctuant decreased, and decreased to 6,587 t in 2018. After 2015, the reduction rate of the agricultural carbon sink in Huan County was significantly faster than that of total carbon emissions. This indicating that Huan County agriculture did not have a significant effect in reducing carbon emissions and increasing carbon sinks.

In order to more intuitively reflect the spatial distribution characteristics of agricultural net carbon sinks in Huan County, we divided the net carbon sinks of 20 townships in the county into 5 grades based on absolute quantitative differences and interval distribution (**Figure 9**). The number of high-value areas of net carbon sinks was 0 in 2009, increased to 6 in 2013 and then reduced to 1 in 2018. The number of higher-value areas was 1 in 2009, increased to 2 in 2013. In 2018, the number of higher-value areas did not change, but the specific areas did. The number of medium was 8 in 2009, decreased to 5 in 2013, and then increased to 7 in 2018. The number of low-value areas increased from 5 in 2009 to 7

TABLE 7 | Empirical results on the effect of age of rural population on net carbon sink in agriculture.

Var.	Total effect	Allocation effect of AS on mediating factors				The introduction of the mediating variable AS affects the direct effect of the net Carbon Sink					
	lnNCS	lnPS	lnINF	lnIPF	lnAML	lnPS	lnINF	lnIPF	lnAML	All	E
						lnNCS	lnNCS	lnNCS	lnNCS	lnNCS	
lnAS	−0.244*** (−3.21)	−0.012* (−1.46)	0.143* (1.94)	0.112 (1.50)	0.240*** (4.02)	−0.084 (−1.22)	−0.226* (−2.97)	−0.246*** (−3.30)	−0.057 (−0.91)	−0.126*** (−1.07)	—
lnPS	—	—	—	—	—	0.221*** (2.34)	—	—	—	0.123* (1.46)	2
lnINF	—	—	—	—	—	—	−0.202*** (−3.01)	—	—	−0.196** (−2.58)	1
lnIPF	—	—	—	—	—	—	—	0.157*** (2.72)	—	0.194*** (3.30)	0
lnAML	—	—	—	—	—	—	—	—	−0.599*** (−8.28)	−0.623*** (−11.34)	2
Control	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	—
Cons	7.30*** (24.40)	−0.45 (−5.64)	−1.503*** (−3.41)	−3.645*** (−6.37)	0.298 (0.83)	7.554*** (11.84)	7.75*** (14.00)	7.656*** (18.12)	9.19*** (25.05)	7.43*** (18.14)	—
Double effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—
R2	0.19	0.78	0.54	0.12	0.29	0.40	0.45	0.24	0.45	0.54	—
Obs	200	200	200	200	200	200	200	200	200	200	—

*Note: Column 2 verifies the total effect of rural population structure on agricultural net carbon sinks; Columns 3 to 6 verify the configuration effects of rural population structure on the four mediating factors of planting structure and input structure, respectively; Columns 7 to 10 verify the direct effect of rural population structure on agricultural net carbon sinks after introducing each mediating variable element in turn; Column 11 verifies the direct effect of rural population structure on agricultural net carbon sinks after introducing 4 mediating variables; Column 12 is the effect (E) judgment, "0" means no mediating effect; "1" means partial mediating effect; "2" means complete mediating effect. *, **, and *** represent the significance levels of 10, 5, and 1%, respectively. The arrays in parentheses are the robust standard errors of county-level clustering.*

in 2013, and further increased to 10 in 2018. It indicates that the gap in net carbon sinks among townships in Huan County is gradually narrowing, and the phenomenon of homogeneity is more significant and develops towards lower value areas.

5.4 The Impact of Rural Population Structure on the Net Carbon Sink of Agricultural Production

5.4.1 The Impact of Rural Population Structure on Agricultural Production

In **Tables 5–7**, the panel data analysis of changes in rural population structure and planting structure shows that the population quality structure and age structure have a significant negative effect on the planting structure index, and the regression coefficients are −0.016 and −0.012 respectively, while the population quantity structure has a significant positive effect on the planting structure index, and the regression coefficient is 0.032, which has passed the significance test. This indicates that with the continuous reduction of agricultural employees in Huan County, the aging of the labor force, the gradual optimization of labor quality, the planting area of food crops is decreasing day by day. Farmers are the main body of rural development and have the ability to make independent decisions. Under certain technical conditions, the change of rural population structure requires the matching of planting structure. Under labor constraints, in order to adapt to the fact that the number of family labor is insufficient, the age structure of laborers is aging, and labor capacity is weakened, farmers will choose to plant crops that are easy to cultivate and require less labor, or reduce the planting area of various crops, or Growing more labor-productive crops to maximize economic benefits (Tian et al., 2009).

In **Tables 5–7**, the panel data analysis of changes in rural population structure and input structure shows that the population quantity structure and quality structure have significant negative effects on the average nitrogen fertilizer use index per unit area, respectively. The regression coefficients are −0.587 and −0.216, respectively. The population age has a significant positive effect on the average nitrogen fertilizer usage per unit area index. The regression coefficient is 0.143, all of which pass the significance test. The population structure has a significant negative effect on the average film usage per unit area. The regression coefficient is −1.059. The population quality structure and age structure have positive effects on the average film usage per unit area. The regression coefficients are 0.934 and 0.112, respectively. However, the population age structure did not pass the significance test. The population quantity structure have significant negative effects on the total mechanical power per capita. The regression coefficients is −1.155, respectively. The population age structure and quality structure has a significant positive effect on the total mechanical power per capita. The regression coefficients are 0.661 and 0.240. And all passed the significance test. With the reduction of agricultural employees in Huan County, the input of agricultural resources such as chemical fertilizers, agricultural films, and machinery has gradually increased. Optimizing the quality of the rural labor force and increasing environmental awareness will help reduce the use of chemical fertilizers, etc. The aging of the rural labor force has increased the use of chemical fertilizers and machinery. The

TABLE 8 | Empirical results on the impact of rural population size on net carbon sink in agriculture (County level).

Var.	Total effect	Allocation effect of NS on mediating factors				The introduction of the mediating variable NS affects the direct effect of the net carbon sink					
	lnNCS	lnPS	lnINF	lnIPF	lnAML	lnPS	lnINF	lnIPF	lnAML	All	E
						lnNCS	lnNCS	lnNCS	lnNCS	lnNCS	
lnNS	0.328***	0.075*	−1.054***	−1.126***	0.945***	0.266***	0.517*	0.356**	0.983***	0.121**	—
	(1.21)	(0.35)	(−7.43)	(−9.21)	(7.02)	(1.29)	(1.83)	(4.23)	(3.72)	(1.96)	
lnPS	—	—	—	—	—	0.813***	—	—	—	0.767***	1
						(20.61)				(20.71)	
lnINF	—	—	—	—	—	—	−0.180*	—	—	−0.178***	1
							(−2.29)			(−3.17)	
lnIPF	—	—	—	—	—	—	—	0.132**	—	0.126***	1
								(3.45)		(3.01)	
lnAML	—	—	—	—	—	—	—		−0.694***	−0.550***	1
									(−8.91)	(−9.27)	
Control	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	—
Cons	−0.134***	4.668***	−3.122	−6.112***	−5.438***	−3.928***	1.580	3.782***	−4.504***	−5.48***	—
	(−0.22)	(9.39)	(−5.12)	(−10.67)	(−16.84)	(−7.71)	(1.62)	(5.34)	(−5.90)	(−6.98)	
Double effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—
R2	0.30	0.23	0.67	0.37	0.28	0.60	0.30	0.61	0.39	0.65	—
Obs	860	860	860	860	860	860	860	860	860	860	—

TABLE 9 | Empirical results of rural population quality affecting net carbon sink in agriculture (County level).

Var.	Total effect	Allocation effect of QS on mediating factors				The introduction of the mediating variable QS affects the direct effect of the net carbon sink					
	lnNCS	lnPS	lnINF	lnIPF	lnAML	lnPS	lnINF	lnIPF	lnAML	All	E
						lnNCS	lnNCS	lnNCS	lnNCS	lnNCS	
lnQS	0.314***	−0.138***	−0.316***	1.067*	0.823***	0.291*	0.211***	0.236***	0.259***	0.197***	—
	(2.22)	(−2.97)	(−2.10)	(5.38)	(4.14)	(2.99)	(2.12)	(2.15)	(3.15)	(3.17)	
lnPS	—	—	—	—	—	0.708***	—	—	—	0.638***	1
						(17.77)				(17.24)	
lnINF	—	—	—	—	—	—	−0.747***	—	—	−0.371***	1
							(−15.54)			(−6.36)	
lnIPF	—	—	—	—	—	—	—	0.178*	—	0.120***	1
								(4.89)		(3.01)	
lnAML	—	—	—	—	—	—	—		−0.413***	−0.381***	1
									(−5.19)	(−7.12)	
Control	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	—
Cons	9.123***	−0.864***	−2.156***	−2.178***	1.584***	−4.94***	2.64***	4.675***	−5.48***	−1.97***	—
	(10.25)	(−3.27)	(−9.87)	(−8.36)	(3.16)	(−9.87)	(3.24)	(6.37)	(−7.89)	(−4.56)	
Double effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	—
R2	0.45	0.66	0.20	0.39	0.60	0.63	0.51	0.66	0.48	0.70	—
Obs	860	860	860	860	860	860	860	860	860	860	—

allocation decision of farmers' production factors is a dynamic process. In the process of agricultural production, the changes of farmers' family labor factors and land factors promote the adjustment of farmers' production decision-making. The changes in the quantity, quality and age structure of rural agricultural labor force will gradually replace traditional production factors such as labor force by modern agricultural production technology and factors, and this substitution relationship will gradually strengthen with the passage of time (Liao et al., 2021).

5.4.2 The Impact of Rural Population Structure on Agricultural Net Carbon Sinks

A multiple mediating effect model was used to test the impact of rural population structure on agricultural net carbon sinks. From the perspective of the total effect, population quantity, and quality structure have significant positive effects on the agricultural net carbon sink index. The regression coefficients are 0.340 and 0.284, respectively. The population age structure has a significant negative effect on the agricultural net carbon sink index. The regression coefficient is -0.244, which have passed the significance test. From

TABLE 10 | Empirical results on the effect of age of rural population on net carbon sink in agriculture (County level).

Var.	Total effect	Allocation effect of AS on mediating factors				The introduction of the mediating variable AS affects the direct effect of the net carbon sink					
	lnNCS	lnPS	lnINF	lnIPF	lnAML	lnPS	lnINF	lnIPF	lnAML	All	E
						lnNCS	lnNCS	lnNCS	lnNCS	lnNCS	
lnAS	−0.134*** (−2.19)	−0.098** (−1.08)	0.213*** (1.90)	0.187 (1.52)	0.310 (5.08)	−0.090*** (−1.15)	−0.087*** (−1.35)	−0.021 (−1.03)	−0.051 (−0.97)	−0.076*** (−2.09)	—
lnPS	—	—	—	—	—	0.708*** (17.77)	—	—	—	0.633*** (17.29)	1
lnINF	—	—	—	—	—	—	−0.663*** (−9.24)	—	—	−0.444*** (−7.21)	1
lnIPF	—	—	—	—	—	—	—	0.217*** (2.02)	—	0.187*** (2.98)	2
lnAML	—	—	—	—	—	—	—		−0.486*** (−6.96)	−0.377*** (−6.94)	0
Control	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled	—
Cons	4.254*** (10.09)	−0.74** (−9.69)	−1.087 (−2.90)	−3.213*** (−6.59)	0.134*** (0.98)	−4.940*** (−9.87)	2.640*** (3.24)	8.023** (16.10)	−5.48*** (−7.89)	−3.49*** (−4.55)	—
Double effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
R2	0.24	0.74	0.17	0.21	0.46	0.63	0.51	0.37	0.48	0.69	—
Obs	860	860	860	860	860	860	860	860	860	860	

*Note: Column 2 verifies the total effect of rural population structure on agricultural net carbon sinks; Columns 3 to 6 verify the configuration effects of rural population structure on the four mediating factors of planting structure and input structure, respectively; Columns 7 to 10 verify the direct effect of rural population structure on agricultural net carbon sinks after introducing each mediating variable element in turn; Column 11 verifies the direct effect of rural population structure on agricultural net carbon sinks after introducing 4 mediating variables; Column 12 is the effect (E) judgment, "0" means no mediating effect; "1" means partial mediating effect; "2" means complete mediating effect. *, **, and *** represent the significance levels of 10, 5, and 1%, respectively. The arrays in parentheses are the robust standard errors of county-level clustering.*

the perspective of the direct effect, the population quantity structure and quality structure have significant positive effects on the agricultural net carbon sink index, but the regression coefficient decreases to 0.214 and 0.107, respectively. The population age structure has a significant negative effect on the agricultural net carbon sink index. The regression coefficient increases to −0.126. All of them pass the significance test. In the influence mechanism of rural population structure on the agricultural net carbon sink, the mediating factor played a strong mediating effect.

To study the impact of rural population structure on agricultural net carbon sinks, this paper considered four mediating variables: planting structure, average fertilizer application per unit area, agricultural film usage per unit area and total mechanical power per capita index in the regression model. The results showed that they all played a certain mediating effect (**Table 5**). In the impact of population quality structure on agricultural net carbon sinks, planting structure, average fertilizer application per unit area, agricultural film usage per unit area and total mechanical power index per capita, all have mediating effect (**Table 6**). In the influence of population age structure on agricultural net carbon sinks, the average fertilizer application per unit area played a partial mediating role. The planting structure and total mechanical power per capita played complete mediating roles. The average agricultural film usage per unit area did not have a mediating effect (**Table 7**).

5.4.3 Robustness Check

In this paper, we learn from Yi et al. (2019) to test the robustness by expanding the sample size and improving the data dimension. In order to investigate the reliability of township level indicators, we also obtained relevant indicators at the county level based on Gansu statistical yearbook and regressed them accordingly. The specific estimation results are shown in attached **Tables 8–10**. We find that the impact of rural population structure on agricultural net carbon sink is basically the same under the two scales, and the previous conclusions remain robust. The selection of the panel model is the same as the above steps. From **Tables 11**, **12**, we can see that the two-way fixed model is still selected at the county level.

TABLE 11 | Panel model selection results (county level).

		Test value (*p*)	Result
Hausman test	NS	13.305 (0.000)	FE model
	QS	10.908 (0.000)	FE model
	AS	14.529 (0.000)	FE model

TABLE 12 | Panel model selection results (county level).

		Test Value (*p*)	Result
Time effect test	NS	29.245 (0.000)	Two-way fixed-effects model
	QS	23.612 (0.000)	Two-way fixed-effects model
	AS	19.120 (0.000)	Two-way fixed-effects model

6 CONCLUSION

(1) The rural labor force in Huan County has suffered a serious loss in quantity, a steady improvement in

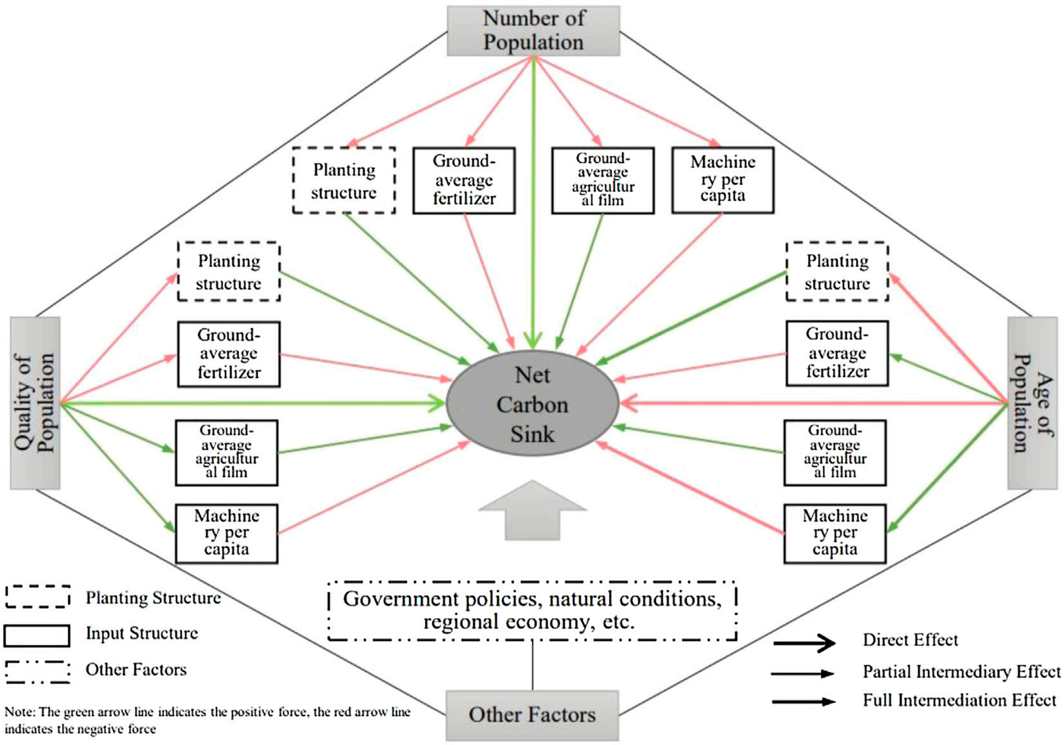

FIGURE 10 | The transmission mechanism of rural population structure affecting agricultural net carbon sinks.

quality, and the aging problem. The proportion of agricultural employees in Huan County decreased from 72.6 to 49.4%, with an average annual decrease of 2.3%. The proportion of people with high school education and above increased from 9.7 to 15.1%, with an average annual increase of 0.5%. The proportion of people over working age who participated in labor increased from 5.2% rose to 8.3%, with an average annual increase of 0.3%.

(2) The Loess Hilly Region in the northwest of Huan County is "grain-trending," and the River Valley and Plain Area in the southeast is "grain-removing." The input structure index increased first and then decreased, and the loess hilly and gully area was more dependent on the input of chemical fertilizers.

(3) The rural population structure of Huan County affects the agricultural net carbon sink by affecting the planting structure and input structure index. From the perspective direct effect, the rural population quantity and quality structure have significant positive effects on the agricultural net carbon sink, while the population age structure has a significant negative effect on the agricultural net carbon sink. From the perspective mediating effect, the loss of population will cause the change of agricultural net carbon, thereby increasing the average fertilizer application per unit area and the total mechanical power per capita index. In addition, the proportion of the sown area of food crops and of the average agricultural film usage per unit area index will decrease. The improvement of population quality will promote the growth of agricultural net carbon sinks by affecting the proportion of the sown area of food crops and the increase in the average film usage per unit area, the average fertilizer application amount per unit area, and the decline in the average mechanical power per capita. The aging of the population leads to a decrease in the index of the sown area of food crops, an increase in the average fertilizer application per unit area, and an increase in the total mechanical power index per capita. This will result in a decline in the net agricultural carbon sink.

(4) To increase agricultural net carbon sinks and reduce the carbon emissions, it is necessary to carry out work from three aspects: encouraging rural labor to return home, improving production methods; strengthening skills training, improving the quality of rural labor; promoting technological innovation, and releasing the value of rural aging labor. This lay a solid foundation for achieving the overall reduction of carbon emission from agricultural production in the Loess Hilly Region.

7 DISCUSSION

7.1 The Change Mechanism of the Net Carbon Sink in Rural Agricultural Production

7.1.1 The Transmission Mechanism of the Rural Population Number Affecting Agricultural Net Carbon Sink

With the reduction of the rural labor force, the adjustment of the division of labor within the family will tend to plant food crops with low market risk and high degree of division of social services. This will promote the growth of the agricultural net carbon sink, that is, the decrease of labor force—the increase of the proportion of food crops—the increase of the agricultural net carbon sink. With the continuous loss of the rural labor force, increasing the chemical fertilizer application per unit area has become an effective means to make up for the shortage of labor force and increase production and income. The excessive use of fertilizers leads to the decline of the agricultural net carbon sink, that is, the decrease of the labor force—the increase of chemical fertilizer application—the decrease of the agricultural net carbon sink. The shortage of agricultural water and heat conditions in Huan County has increased the average agricultural film usage per unit area. This has played a significant role in regulating ground temperature, retaining water and fertilizer, inhibiting the growth of weeds, alleviating diseases, etc., thereby promoting the growth of agricultural net carbon sinks, that is, the reduction of the labor force—the increase of agricultural film use—the increase of net carbon sink. Since the "12th Five-Year Plan," the Chinese government has paid attention to agricultural modernization, accelerated the innovation of agricultural science and technology, and enhanced the support capacity of agricultural science and technology. During this period, the total mechanical power per capita in Huan County has increased to a certain extent, but the use efficiency was low. This led to the reduction of agricultural net carbon sinks, that is, the reduction of labor force—the increase of total mechanical power per capita - the decrease of net carbon sink (**Figure 10**).

7.1.2 Transmission Mechanism of Rural Population Quality Affecting Agricultural Net Carbon Sinks

With the progress of economic reform, the Chinese government has attached great importance to the development of rural education, actively changed the backward situation of rural education and made great progress. The pursuit of profit is the original intention of farmers to adjust the planting structure, that is, the quality of labor is optimized—decrease in proportion of food crops—decrease in net carbon sink. With the improvement of labor quality, environmental protection awareness and government control, the control of chemical fertilizer application has promoted the growth of agricultural net carbon sinks, that is, the improvement of labor quality—reduction of chemical fertilizer application—increase of net carbon sinks. The improvement of labor quality, the enhancement of learning ability, and the promotion and use of full-film double-furrow sowing technology have promoted the growth of agricultural net carbon sinks, that is, the improvement of labor quality—the increase of agricultural film use—the increase of net carbon sinks. The urban-rural development gap has led to a serious loss of high-quality rural population. The improvement of labor quality makes mechanized production possible, that is, the improvement of labor quality—increase in total mechanical power - decrease in net carbon sink.

7.1.3 The Transmission Mechanism of Rural Population Age Affecting the Agricultural Net Carbon Sink

With the aging of the rural labor force, farmers tend to choose non-food crops that are easy to cultivate and have higher economic value in planting structure. This will inhibit the growth of agricultural net carbon sink, that is, the aging of the labor force—the decline in the proportion of food crops—the reduction of net carbon sinks. With the aging of the rural labor force, the weak labor ability of the elderly farmers makes them increase the amount of fertilizer application per unit area. Unscientific fertilization has inhibited the growth of agricultural net carbon sinks, that is, the aging of the labor force—the increase of fertilizer application - the decrease of net carbon sink (**Figure 10**). Due to the aging of the rural population, farmers purchase agricultural machinery to reduce the pressure on labor supply. Blind purchase makes the use of machinery inefficient, thereby reducing agricultural net carbon sinks, that is, the aging of the labor force—the increase of total power of machinery—the decrease of net carbon sinks.

7.2 The Ways of Increasing Agricultural Sinks and Reducing Emissions Under the Changing Rural Population Structure

7.2.1 Encourage Rural Laborers to Return Home and Improve Production Methods

Low income, slow cost recovery, and difficulty in living security are the main reasons for the transfer of rural labor in the Loess Hilly Region or ecologically sensitive areas. In order to attract the return of labor, governments in areas with more labor loss should adopt diversified policies to attract migrant workers to return to their hometowns to start businesses. The first is to build a mechanism that can attract talents back, and create an agricultural talent pool. Increase the publicity of the return mechanism, and provide reliable guarantee for the implementation of the mechanism, so as to eliminate the psychological scruples of returnees. Public rewards will be given to those returning home to set an example, so as to drive more outstanding people to return to their hometowns to start their own businesses. Providing a good rural environment that is both productive and livable for returning labor is an effective means to weaken the resistance to return. Formulate and implement a series of effective security measures to make returning laborers willing to stay in the countryside. For example, when dealing with basic livelihood issues such as children's schooling, pension, and employment, formulate corresponding security policies with local solutions as the core concept; Second, the low income from growing grains is an important reason for the phenomenon of "de-graining" in the southeast of Huan County. The subsidy mechanism for the income from grain planting is a great support for the business entities who are willing to plant grain. The expansion of the acreage of food crops can prevent "de-graining" and ensure food security. Increasing the proportion of food crops is an important way to promote carbon absorption in the northwest China with little forest; Third, in the Huan County where the level of modern agriculture is not high, government subsidies are not only limited to financial subsidies, but can also enhance subsidies in the form of planting technologies. For example, the government regularly conducts technical training for large-scale farmland operators, promotes advanced seeding technology to farmland operators, and helps the loess hilly and gully areas in the northwest to introduce machines and tools suitable for hilly and mountainous areas. Farmers in Huan County have a low level of planting technology, pay attention to yield, ignore quality, and rely too much on chemical fertilizers. A large number of organic fertilizers are discarded, and most of the straw and agricultural film are incinerated. Therefore, the government of the Huan County should improve and optimize the farming measures, increase the amount of straw and organic matter returned to the field. The government should promote the less and no-tillage technology, and adopt a series of measures such as returning the straw to the field, increasing the application of organic fertilizers, rotary tillage, and deep loosening the soil, to improve the physicochemical properties of soil, regulating soil fertility; In addition, for the northwestern regions where are more dependent on chemical fertilizers, the government should also advocate precise fertilization and reduction, free soil sampling, soil testing and prescribing for farmers, optimize the fertilization structure, and improve the utilization rate of fertilizers. For the southeastern region where the amount of agricultural film usage is greater, a waste plastic film recycling account should be established, and the recycling point delivery account should be funded and guaranteed by the district finance bureau, and gradually form a cycle mechanism "use-recycling-processing-reuse" of agricultural film.

7.2.2 Strengthen Skills Training and Improve the Quality of the Rural Labor Force

Accelerate the start of the farmer professionalization project, cultivate new-type farmers who meet the requirements of modern agricultural production through multiple channels, and ensure the stability of grain-growing groups through professional and specialized means. The first is to popularize rural vocational education that conforms to farmers' knowledge level and cognitive habits. The cultivation and training of new farmers shall be rooted in the local area, respect farmers' learning laws and learning ability, and combine farmers' daily discourse system and language habits to carry out training in simple language, targeted and batches. The second is the transfer of labor from the agricultural sector to the non-agricultural sector. The root cause is that the income of agricultural labor is lower than that of non-agricultural labor, and the labor intensity is much higher. Therefore, it is necessary to focus on improving agricultural technology, improving the technical level of the labor force, promoting the implementation of modern agriculture, balancing the agricultural input-output ratio, improving the income of agricultural labor, and stabilizing the population engaged in agricultural activities. The government should also promote scientific and reasonable technologies such as fertilization and film laying, so that farmers will not be blind when purchasing chemical fertilizers, so as to reduce the carbon emissions from agriculture in Huan County, and thus ensure green agricultural production. The third is to establish the concept of "saving energy and reducing emissions; waste of energy and ashamed of arbitrary emissions." In addition, the existing rural living conditions in Huan County are poor, the level of basic public services is low, and the problems of rural school-age children and adolescents with backward learning conditions are the current practical problems. Due to the long-term existence of these problems, the rural labor force is forced to move to seek more perfect living conditions. Therefore, in order to strengthen the basic public service system in rural areas, the government should increase investment in this area, improve the level of rural medical care and education, and provide a more comprehensive security system, so as to stabilize the labor force and prevent the large loss of labor force of the right age.

7.2.3 Promote Technological Innovation and Release the Value of the Rural Aging Labor Force

The problem of the aging of the rural labor force is becoming more and more serious in Huan County. It is necessary to optimize the social security of the rural elderly population, improve the agricultural production level of the elderly population who still have the ability to work, and promote the development of rural agriculture production and agricultural net carbon sinks from various aspects. It is necessary to take into account the various problems caused by the aging of the countryside, prevent the decline of agriculture, maintain the healthy development of agriculture, ensure the number of working-age laborers, and prevent the collapse of the countryside. Due to the outflow of young and middle-aged agricultural labor in Huan County, the problem of aging agricultural labor force is common at present. It is difficult to bring back young and middle-aged people in a short period of time. This situation is more common among the younger elderly groups, and even the elderly in some areas have become the backbone of agricultural producers. Therefore, the government should maximize the development of the value of the local rural elderly labor force while encouraging and absorbing the young labor force.

Modern agricultural technology can relieve the pressure of rural labor force and improve production efficiency. With the aging of the agricultural population in China, coupled with the barren land in Northwest China, farmers will increase the use of fertilizers and film per unit of area. As a result, these two agricultural resources are the main sources of carbon emissions in the agricultural production in Huan County, accounting for 90% of the total carbon emissions. The level of mechanization in Huan County is low. Therefore, modern agriculture should be introduced as soon as possible to alleviate this situation, and in order to implement modern agriculture, the government should play a leading role. First, the government should increase the preferential and subsidies for the purchase of agricultural machinery and equipment, and actively invest in agricultural productive capital equipment; second, the development and promotion of agricultural machinery should also adapt to the current trend of the aging rural labor force. Although the main agricultural machinery operations in field production will be increasingly provided by "outsourced" service agencies, some production links in small-scale agricultural production still need to be completed manually. Low-carbon and energy-saving household agricultural machinery; Third, the aging population is slow to accept new things, and it is difficult to master new technologies. In order to make this part of the agricultural population more proficient in mastering new agricultural technologies, the government should hire professionals to conduct technical docking during the early stage of technology expansion. Provide comprehensive and detailed technical training for the aging population; In addition, the construction and maintenance of rural mechanized roads and other infrastructure should also be strengthened. The areas with a serious aging workforce are mostly poor mountainous areas, with narrow roads and uneven land, making it difficult to realize agricultural mechanization. Promoting the scale of land management and enabling families with the ability to operate will expand the scale of production. This will not only increase agricultural output and increase agricultural income, but also attract young people who work abroad and alleviate the aging of the agricultural labor force to a certain extent.

7.3 Strength and Weakness of This Study

The analysis of the evolution of rural population structure is an effective perspective for the study of changes in net carbon sinks in rural agricultural production in Northwest China or ecologically sensitive areas. With the development of social urbanization, the quantity, quality and age of the rural labor force have changed. To maintain a certain level of agricultural income, the adaptive adjustment of cultivated land input structure and planting structure will affect agricultural carbon emissions and carbon absorption. This can affect the agricultural net carbon sink. net carbon sink. There are still some weaknesses in this paper: First, although this paper builds a theoretical framework for the relationship between population structure and agricultural production net carbon sinks, limited to the availability of township-level data, only the impact of the quantity, quality, and age structure of rural population on the agricultural production net carbon sinks is investigated. The impact of population mobility, gender structure, etc. has not been discussed. The interaction between population structure and net carbon sinks in agricultural production requires further analysis. Second, due to the lack of long-term survey data of 20 townships in Huan County, this paper only analyzed the 10-years data with the most drastic changes in the rural population structure. Therefore, there are limitations in conclusions. The generality of the conclusions remains to be verified by empirical studies in other similar regions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

LM: conceptualization, methodology, supervision, formal analysis, and editing. WZ: methodology, data analysis, and writing—review and editing. SW: methodology and writing—review and editing. ZS: methodology and writing—review and editing.

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