Research on Carbon Sources and Sinks of Agricultural Ecosystems Based on Carbon Footprint: Evidence from Shaanxi Province, China

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ABSTRACT

The carbon footprint size of agricultural ecosystems in Shaanxi Province was evaluated using the input-output approach and the statistical data of agricultural output as well as agricultural modernization in Shaanxi Province from 2000 to 2019, then the characteristics and reasons for variations in its time series were analyzed. The results reveal that (1) over a 20-year period, the carbon sequestration of farmland systems in Shaanxi Province increased by 1,199.63 million t, with vegetables, maize, and wheat accounting for the majority of the increase; and (2) the carbon emissions caused by agricultural inputs in Shaanxi Province increased from 78.91 million t in 2000 to 98.64 million t in 2019, with agricultural irrigation accounting for the majority of the total carbon emissions. (3) The carbon footprint of agricultural ecosystems in Shaanxi Province was 0.106 ($10^6 C \cdot hm^{-2} \cdot a^{-1}$) in 2019, indicating a downward trend, and the province has been in a carbon ecological reserve for 20 years. To diminish the carbon source, Shaanxi Province should improve the efficiency of fossil energy and agricultural chemicals; at the same time, measures such as straw return and crop management should be taken to improve the carbon sequestration efficiency of productive land and enhance the carbon sink, promoting the development of low-carbon agriculture in Shaanxi Province.

Keywords: *Agricultural Ecosystems, Carbon Footprint, Carbon Sinks, Carbon Sources, Shaanxi Province.*

1. INTRODUCTION

1.1. Research Background and Motivation

Since the 1990s, the trend of global warming caused by greenhouse gas emissions has become a hot issue of concern worldwide. As a measure of the influence and strain of human activities on the environment, the "Ecological Footprint" has become a hot topic of research in the field of ecology and environment both domestically and overseas in recent years. The concept of “Carbon Footprint” is derived from “Ecological footprint”, which is a measurement of greenhouse gas emissions emitted directly or indirectly by a product or activity over the course of its life cycle [1]. The input-output method, life-cycle method, and hybrid life-cycle method are all ways of accounting for carbon footprint, and this article uses the input-output approach to account for the size of the carbon footprint of agricultural producing activities in the life-cycle. Agricultural ecosystems are a vital component of terrestrial ecosystems and a significant source and sink of carbon in the atmosphere. Agricultural ecosystems release greenhouse gases into the atmosphere through crop respiration, input consumption, tillage, farming, and waste disposal, and they store carbon in the soil through the carbon sequestration effect of crops and organic matter. Not only should the carbon emissions and sequestration of farmland ecosystems be included in the research of carbon sources and sinks, but also the carbon footprint effect should be accounted for.

1.2. Literature Review

At present, Scholars have mostly investigated carbon emissions and carbon sequestration in farmland ecosystems, i.e., carbon sources and sinks, and have not delved further into farmland ecosystems' carbon footprint [2]. Existing carbon footprint research focuses primarily on industrial and residential carbon footprints, with little attention paid to the carbon footprint of farming ecosystems [3,4]. The current research on carbon sinks and sources in agriculture mainly focuses on soil carbon in agricultural fields, and fewer studies are conducted on

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carbon sources and sink in agricultural production processes [5-7]. This paper estimated the carbon footprint of agricultural ecosystems in Shaanxi Province by measuring their carbon sources and sinks in this article, which can help develop a carbon emission inventory of farmland, understand the position of farmland systems in the carbon cycle, and provide a scientific basis for developing low-carbon and ecological agriculture and formulating emission reduction plans in Shanxi Province.

1.3. Research Contents and Framework

In this paper, from the perspective of carbon ecological footprint, the carbon sequestration and carbon emission of farmland ecosystems in Shaanxi Province are estimated separately; secondly, the carbon footprint of agricultural ecosystems in Shaanxi Province is accounted for by using carbon sequestration, carbon emission, and cultivated area; finally, the environmental carrying capacity of agricultural ecosystems in Shaanxi Province is evaluated by the size of carbon footprint.

2. METHODOLOGY

2.1. Data Sources

The data in this research comes from the *Shaanxi Provincial Statistical Yearbook* on the part of agricultural modernization from 2000 to 2019. It primarily consists of carbon sinks such as crop unit area production and planting area, as well as carbon sources such as agricultural diesel fuel use, agricultural plastic film use, agricultural fertilizer application, pesticide application, crop sowing area, and total power of agricultural machinery.

2.2. Empirical Analysis

A Carbon Sink is any process, activity, or mechanism that eliminates greenhouse gases, aerosols, or greenhouse gases from the atmosphere, according to the United Nations Framework Convention on Climate Change (UNFCCC). A Carbon Source is a process or activity that releases greenhouse gases into the atmosphere. Agricultural ecosystems are semi-natural ecosystems that rely on natural elements such as soil, water, and light anthropogenic inputs such as pesticides, fertilizers, machinery, and irrigation to produce agricultural products [8]. Therefore, the agricultural ecosystem is an input-output system that involves significant material and energy exchange [9]. The carbon sink effect of agricultural ecosystems is primarily due to the carbon sequestration effect of crops themselves, according to the whole crop reproductive period approach; sources of carbon emissions from farmland include energy use, carbon emissions generated in the production and transportation of fertilizers and pesticides, and carbon emissions from irrigation and agricultural machinery.

Table 1. Types of carbon sinks and sources in agricultural ecosystems

Type	Source
sink	The carbon sequestration effect of crops themselves
source	Carbon emissions from the transport and use of agricultural machinery
	Carbon emissions from the production and use of agricultural diesel fuel
	Carbon emissions from agricultural irrigation
	Carbon emissions from the production and application of pesticides
	Carbon emissions from the production and application of chemical fertilizers
	Carbon emissions from the production and application of agricultural films

2.2.1. Estimation of Carbon Sequestration

This article calculated the carbon sequestration of crops across the entire reproductive period as C_t. The carbon sequestration impact of crops is included in the estimation, as well as the carbon sequestration of crops during photosynthesis, allowing for a more comprehensive assessment of agricultural ecosystem carbon sink capacity. The following is the estimation equation.

$$C_t = \sum_{i}^{k} C_i = \sum_{i}^{k} ca_i \times \frac{Y_i}{HI_i} \tag{1}$$

Where: C_t is the total carbon sequestration of agricultural ecosystems in Shaanxi Province, unit tC/a; C_i is the carbon uptake of the *i*th crop, unit tC/a; k indicates the total number of crop species in Shaanxi Province; ca_i is the carbon sequestration rate of crops, i.e., the carbon required for the total crop to synthesize a unit of organic matter through photosynthesis; Y_i is the yield of the *i*th crop, unit t/a; HI_i is the economic coefficient of the *i*th crop, see Table 2.

Table 2. Economic coefficients and carbon sequestration rates of major crops

Crop	Economic coefficient	Carbon sequestration rate	Crop	Economic coefficient	Carbon sequestration rate
Wheat	0.40	0.485	Cotton	0.10	0.450
Rice	0.45	0.414	Potato	0.70	0.423
Corn	0.40	0.471	Sugarcane	0.50	0.450
Beans	0.34	0.450	Vegetables	0.60	0.450
Canola	0.25	0.450	Melon	0.70	0.450
Peanut	0.43	0.450	Other Crops	0.40	0.450

2.2.2. Estimation of Carbon Emissions

The following is the formula for calculating carbon emissions from agricultural ecosystems in Shaanxi Province.

$$T = \sum T_i \sum E_i \times \beta_i \quad (2)$$

Where T represents the total carbon emission of agricultural ecosystems in Shaanxi Province, E_i represents the carbon emission of the *i*th carbon source, and β_i represents the carbon emission coefficient of the *i*th carbon source. The carbon emission coefficients in this paper are mainly from the published data of IPCC and other organizations, which are shown in Table 3.

Table 3. Agricultural carbon emission source factors

Carbon Source	Indicators	Carbon emission factor	Source of coefficients
Fertilizer	Amount of chemical fertilizer used	$0.8956(\mathrm{kg \cdot kg^{-1}})$	ORNL
Pesticides	Amount of pesticides used	$4.9341(\mathrm{kg \cdot kg^{-1}})$	ORNL
Agricultural film	Amount of agricultural film used	$5.1800(\mathrm{kg \cdot kg^{-1}})$	IREEA
Agricultural Machinery	Total power of agricultural machinery	$0.1800(\mathrm{kg \cdot kw^{-1}})$	IPCC
Rice cultivation	Irrigated area	$266.48(\mathrm{kg \cdot hm^{-2}})$	IPCC

2.2.3. Accounting for the Carbon Footprint

The carbon footprint is considered as part of the ecological footprint in this study, using the definition of the productive land area occupied by carbon emissions consumption, computed using the formula:

$$EF = \frac{T}{NEP}, NEP = \frac{C_t}{S} \quad (3)$$

Where: T is the total carbon emission of agricultural ecosystem in Shaanxi Province; NEP is the amount of carbon that can be absorbed by $1\mathrm{hm^2}$ crops in 1 year ($\mathrm{C \cdot hm^{-2} \cdot a^{-1}}$) , i.e., the carbon sequestration intensity of farmland ecosystem; C_t is the total carbon sequestration of the agricultural ecosystem; S is the commonly used productive cropland area in Shaanxi Province.

In this paper, the Cultivated Area is used to estimate the ecological carrying capacity of an agricultural ecosystem; if the regional ecological carrying capacity (cultivated area) is greater than the carbon footprint of the agricultural system, it indicates a carbon ecological reserve; if the ecological carrying capacity is less than the ecological carbon footprint of regional farmland, it indicates a carbon ecological deficit.

$$(CEF < CEC)\ CER = CEC - CEF \quad (4)$$

$$(CEF > CEC)\ CED = CEF - CEC \quad (5)$$

Where CER is the carbon ecological reserve, CED is the carbon ecological deficit, and CEC is the ecological carrying capacity, i.e., the cultivated area.

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Analysis of Carbon Sequestration Changes in Agricultural Ecosystems

The carbon sequestration of agricultural ecosystems in Shaanxi Province from 2000 to 2019 is shown in Table 4. The total carbon sequestration of agricultural crops in Shaanxi Province exhibited a clear upward trend, going from 1,598.90 million t in 2000 to 2,639.63 million t in 2019, an increase of 75.03 %, with an average yearly growth of 63.14 million t. Accordingly, the carbon sequestration intensity increased from 5.13 t/hm^2 in 2000 to 9.30 t/hm^2 in 2019, with an increase of 81.29%.

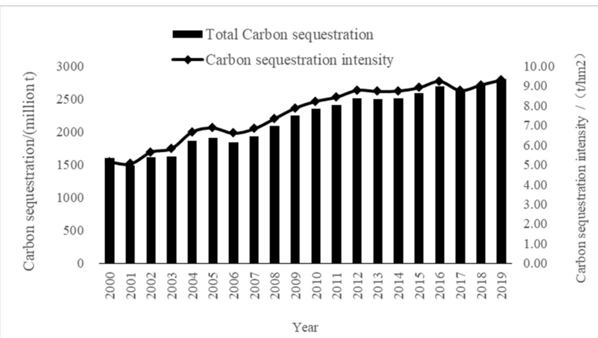

Figure 1 Carbon sequestration and carbon sequestration intensity of agricultural ecosystems in Shaanxi Province, 2000-2019

In terms of crop cultivation structure, wheat, corn, and vegetables have the strongest carbon sink function, accounting for 22.76%, 27.91% and 39.47% of the total carbon sequestration on average, respectively. Among these, increased vegetable output leads to a strongly growing trend in carbon sequestration, with vegetable carbon sequestration at 1,423.04 million t in 2019, up from 417.40 million t in 2000, a surge of 1,005.64 million t and a 240.92 % rise. Wheat and corn are the primary crops in Shaanxi Province, with good yields due to their adaptability to the monsoon climate's limited precipitation and considerable temperature differences. Because maize output fluctuates and increases, maize carbon sequestration fluctuates and increases as well, gradually increasing to 726.27 million t from 2000 to 2013, declining slightly in 2014 and 2017, and then remaining steady at 717.78 million t. Wheat, another vital food crop in Shaanxi Province, has a constant yield and no apparent trend in the carbon sinks, with an average carbon sink of 497.58 million t over the last 20 years.

Table 4 Carbon sequestration and carbon sequestration intensity of agricultural ecosystems in Shaanxi Province, 2000-2019

Year	Carbon sequestration/(million t)										Total	Carbon sequestration intensity / (t/hm^2)
	Wheat	Rice	Corn	Beans	Cotton	Canola	Peanut	Vegetables	Sugarcane	Other Crops		
2000	507.55	87.12	487.13	29.38	12.33	40.32	7.67	417.40	1.61	8.38	1598.90	5.13
2001	493.04	84.69	415.43	25.94	22.41	41.63	7.42	394.10	1.75	7.16	1493.56	5.04
2002	491.43	73.88	440.97	28.06	19.35	44.24	7.34	495.36	2.79	5.86	1609.28	5.64
2003	479.54	69.46	439.44	21.04	23.72	48.69	7.22	531.71	0.72	5.57	1627.11	5.82
2004	494.58	74.36	559.74	39.94	37.04	53.01	7.51	589.01	0.60	6.11	1861.90	6.66
2005	486.46	72.96	553.54	42.08	35.01	54.59	7.93	652.45	0.27	6.72	1912.00	6.86
2006	476.06	61.05	528.19	29.28	39.74	49.12	7.90	636.36	0.22	6.90	1834.81	6.59
2007	431.13	66.27	590.60	53.06	37.62	47.92	7.40	695.18	0.28	6.11	1935.56	6.81
2008	465.41	74.45	587.25	66.43	39.51	58.70	8.88	780.41	0.27	7.46	2088.77	7.33
2009	453.64	73.74	648.78	61.43	31.50	61.74	10.70	901.35	0.15	7.32	2250.35	7.87
2010	477.18	70.67	666.49	59.36	23.67	63.74	9.95	970.87	0.18	6.55	2348.65	8.21
2011	477.42	72.74	689.66	57.56	21.33	65.41	10.57	1007.03	0.14	7.13	2409.00	8.42

2012	505.15	74.19	709.95	56.65	19.98	66.80	11.32	1059.34	0.15	8.15	2511.67	8.77
2013	441.06	77.30	726.27	40.87	15.98	65.75	11.12	1114.20	0.14	7.31	2500.01	8.71
2014	467.47	73.62	667.89	30.59	10.94	67.63	12.14	1167.12	0.14	5.96	2503.48	8.74
2015	512.97	73.94	668.47	20.90	9.32	70.24	11.86	1210.09	0.14	5.74	2583.65	8.90
2016	488.86	74.03	749.14	32.18	7.61	67.48	12.86	1250.20	0.14	5.14	2687.63	9.22
2017	492.77	74.12	648.98	31.65	5.40	68.99	13.04	1300.49	0.15	4.35	2639.95	8.76
2018	486.62	74.23	688.20	31.67	4.46	66.62	13.19	1356.33	0.12	3.86	2725.30	9.04
2019	463.22	73.94	717.78	30.96	3.42	67.07	12.87	1423.04	0.12	6.12	2798.53	9.30

3.1.2. Analysis of Carbon Emission Changes in Agricultural Ecosystem

Table 5 shows that carbon emissions from agriculture use in Shaanxi Province increased slightly from 2000 to 2019. In 2019, carbon emissions total 98.64 million t, up 19.73 million t from 2000, with an average annual growth of 1.04 million t. In 2019, the carbon emission intensity grew from 0.25 t/hm^2 to 0.32 t/hm^2, indicating a steady rise in the trend. Carbon emission intensity increased significantly from 2009 to 2010.

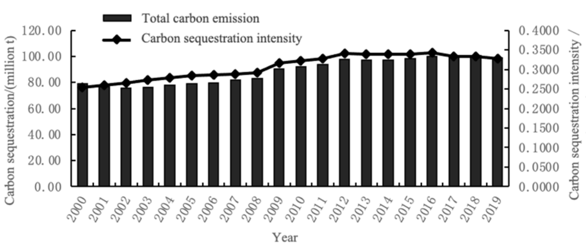

Figure 2 Carbon emissions and carbon emission intensity of agricultural ecosystems in Shaanxi Province, 2000-2019

Carbon emissions from six different sources, including fertilizer, pesticides, agricultural film, agricultural fuel, irrigation, and agricultural machinery, show varying growth paths. Agricultural irrigation provides the most carbon emissions, but its share of overall emissions declines year after year, from 48.04 % to 39.01 % in 2019. However, with an annual average of 37.56 million t, there is no notable growth in the absolute scale of its carbon emissions from 2000 to 2019. As a result, it is evident that agricultural irrigation remains the primary producer of carbon. The use or manufacturing of agricultural films and fertilizers resulted in the greatest increase in carbon emissions. Agricultural film emissions climbed by 10.07 million t over 20 years, reaching 23.20 million t in 2019, roughly 1.77 times what they were in 2000. The amount of agricultural film used per hectare in Shaanxi Province increased from 8.14 kg in 2000 to 14.87 kg in 2019, demonstrating an upward trend in the time series. This is because agricultural films are frequently employed in agricultural production because of their moisture retention and temperature increase properties. Carbon emissions from the other carbon sources amounted to 37.95% of total emissions, while agricultural machinery, fuel, and pesticide emissions were steady.

Table 5 Carbon emissions and carbon emissions intensity of agricultural ecosystems in Shaanxi Province, 2000-2019

Year	Carbon emissions /(million t)							Carbon emissions intensity / (t/hm^2)
	Fertilizer	Pesticide	Film	Diesel	Irrigation	Machinery	Total	
2000	11.75	5.09	13.13	3.31	37.94	7.69	78.91	0.2534
2001	11.74	5.16	11.95	2.59	38.14	7.22	76.80	0.2589
2002	11.81	5.03	10.68	2.47	38.33	7.12	75.44	0.2643
2003	12.78	4.82	11.28	2.52	38.03	6.96	76.39	0.2732
2004	12.82	4.80	11.87	2.85	38.19	7.32	77.85	0.2785
2005	13.19	4.88	12.25	2.89	38.47	7.49	79.16	0.2839
2006	13.41	4.96	12.95	2.89	38.32	6.82	79.35	0.2851
2007	14.22	5.28	13.83	3.13	38.24	7.14	81.85	0.2881

2008	14.86	5.40	14.30	2.83	38.29	7.25	82.93	0.2912
2009	16.24	6.49	18.11	4.60	37.91	7.24	90.59	0.3167
2010	17.62	6.12	19.07	4.17	37.94	7.28	92.21	0.3223
2011	18.56	6.12	19.64	4.74	37.61	7.24	93.91	0.3282
2012	21.48	8.66	20.56	4.87	34.75	7.28	97.60	0.3407
2013	21.65	6.41	21.15	5.40	35.46	7.18	97.26	0.3388
2014	20.62	6.31	21.49	5.41	35.92	7.14	96.88	0.3380
2015	20.77	6.46	22.31	5.47	36.21	7.15	98.38	0.3388
2016	20.87	6.51	22.65	5.50	36.97	7.24	99.74	0.3421
2017	20.79	6.58	22.77	5.54	37.80	7.10	100.57	0.3337
2018	20.57	6.19	22.87	5.49	38.15	7.16	100.42	0.3331
2019	18.14	6.04	23.20	5.56	38.48	7.23	98.64	0.3277

3.1.3. Carbon Footprint Analysis of Agricultural Ecosystems

From 2000 to 2019, Table 6 depicts the carbon footprint, carbon ecological reserves, and carbon footprint intensity of agricultural ecosystems in Shaanxi Province. The carbon footprint intensity of agricultural land in Shaanxi Province has been dropping year by year, with a peak of 0.154 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$ in 2000 and a low of 0.106 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$ in 2019, and a decline of 0.048 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$ in the last ten years with one-ups and downs in 2017. Carbon emissions from agricultural ecosystems in Shaanxi Province have continued to rise as a result of increased fossil energy inputs such as agricultural films and diesel, but crop yields have been going up as well, especially vegetable yields, resulting in a continuous increase in carbon sequestration throughout the reproductive period of crops, and the growth rate of carbon emissions is greater than the growth rate of carbon sequestration, so the carbon lags. The carbon footprint intensity is decreasing, down from 0.049 $(C \cdot hm^{-2} \cdot a^{-1} \cdot hm^{-2})$ in 2000 to 0.014 $(C \cdot hm^{-2} \cdot a^{-1} \cdot hm^{-2})$ in 2010, demonstrating that the agricultural ecosystem in Shaanxi Province is showing a sustainable growth from the carbon source side.

Agriculture ecosystems in Shaanxi Province have been in an carbon ecological reserve for the past 20 years, maintaining a level of no less than 2.663 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$, and the cultivated area is much larger than the carbon footprint, indicating that agriculture ecosystems in Shaanxi Province can supplement the carbon ecological deficit generated by other sectors by carrying their carbon emissions and play an economic, social, and ecological role on sustainable development in Shaanxi Province. The carbon ecological reserve reached a minimum value of 2.663 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$ in 2007, then increased steadily and slowly to 2.755 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$ in 2014, and increased rapidly to a maximum value of 2.904 $(10^6 C \cdot hm^{-2} \cdot a^{-1})$ from 2015 to 2018, which is attributed to the fact that the cultivated land area remained stable during this period, but carbon emissions decreased, causing a subsequent decrease in carbon footprint.

Table 6 Carbon emissions and carbon intensity of agricultural ecosystems in Shaanxi Province, 2000-2019

Year	Cultivated area $(10^6 hm^2)$	Carbon footprint $(10^6 C \cdot hm^{-2} \cdot a^{-1})$	Carbon ecological reserve $(10^6 C \cdot hm^{-2} \cdot a^{-1})$	Intensity of Carbon footprint $(C \cdot hm^{-2} \cdot a^{-1} \cdot hm^{-2})$	Year	Cultivated area $(10^6 hm^2)$	Carbon footprint $(10^6 C \cdot hm^{-2} \cdot a^{-1})$	Carbon ecological reserve $(10^6 C \cdot hm^{-2} \cdot a^{-1})$	Intensity of Carbon footprint $(C \cdot hm^{-2} \cdot a^{-1} \cdot hm^{-2})$
2000	3.114	0.154	2.960	0.049	2010	2.861	0.112	2.748	0.039
2001	2.966	0.152	2.813	0.051	2011	2.861	0.112	2.749	0.039

2002	2.855	0.134	2.721	0.047	2012	2.864	0.111	2.753	0.039
2003	2.796	0.131	2.665	0.047	2013	2.871	0.112	2.759	0.039
2004	2.796	0.117	2.679	0.042	2014	2.866	0.111	2.755	0.039
2005	2.788	0.115	2.673	0.041	2015	2.904	0.111	2.794	0.038
2006	2.783	0.120	2.663	0.043	2016	2.915	0.108	2.807	0.037
2007	2.841	0.120	2.721	0.042	2017	3.014	0.115	2.900	0.038
2008	2.848	0.113	2.735	0.040	2018	3.015	0.111	2.904	0.037
2009	2.860	0.115	2.745	0.040	2019	3.011	0.106	2.904	0.035

3.2. Discussion

Carbon sequestration is much greater than carbon emissions in farmland systems in Shaanxi Province, indicating that Shaanxi farming systems have a strong carbon sink potential, similar to the findings of Rongqin Zhao and Tao Zhou et al[2,10]. This article only measured the total carbon source, carbon sink, and carbon footprint of the agricultural ecosystem in Shaanxi Province, but the spatial variation characteristics of the carbon footprint must be further decomposed to provide a more accurate list of agricultural sources and a scientific reference for agricultural restructuring, carbon sequestration, and emission reduction in Shaanxi Province.

4. CONCLUSION

Carbon sinks, carbon emissions, carbon footprints, and carbon ecological reserves of agricultural ecosystems in Shaanxi Province were calculated between 2000 and 2019, then a model for estimating carbon sources and sinks of farmland ecosystems in Shaanxi Province was constructed in this study. The findings reveal that carbon emissions and sinks are steady and increasing, whereas the carbon footprint reduces every year. However, because carbon sequestration growth outpaces carbon emission growth, the agricultural environment in Shaanxi Province has substantial carbon ecological reserves. The carbon sequestration ability of vegetables, maize, and wheat increased progressively and accounted for a bigger proportion of the various carbon pools. The most main carbon sources for agricultural ecosystems in Shaanxi Province are agricultural irrigation and agricultural films. The carbon ecological reserve of agricultural ecosystems is also steadily increasing, providing a green ecological guarantee to make up for the carbon deficit of residential and industry based on meeting agricultural carbon emissions.

Based on the results, the following recommendations are given to help Shaanxi Province achieve low-carbon agriculture in terms of both carbon emission and carbon sinks. To weaken carbon sources, firstly enhance the efficiency of fossil energy and agricultural chemicals. Promote the "recycling and reuse" of agricultural waste resources, the development of agricultural technology, and the reduction of agricultural input components. Reducing the high reliance on mechanization and fossil energy technology and improving farming techniques to achieve optimal resource usage with minimal production input variables while ensuring high agricultural yields. Secondly, in order to improve carbon sinks, the efficiency of carbon sequestration on productive land should be boosted. To begin, it should adopt organic fertilizer technology, promote straw return, and implement conservation tillage to enhance the yield and quality of agricultural products per unit area, increase the organic matter content of farmland soil carbon pools, and enhance the carbon sequestration capacity of cultivated area. Besides, to maximize the benefits of agricultural carbon ecological reserves, the management of carbon ecological reserves should be reinforced to safeguard the ecological environment and establish a good farmland ecosystem.

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