Postprint: Assessment of Carbon Sink Effects and Benefits in Double-Cropping Rice Paddies under Different Organic Fertilization Modes

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Abstract

This study was based on a long-term stationary experiment on organic fertilizer initiated in 1981, investigating the effects of different organic fertilizer types, application rates, and application methods on carbon emissions, system carbon sequestration, and net carbon sink in paddy field ecosystems, and comparing the economic benefits of each treatment to provide theoretical reference for achieving low-carbon, high-value, and high-efficiency agricultural production. The organic fertilizer treatments selected in this study included: no-fertilizer control (CK); early rice with milk vetch green manure at 15 $t \cdot hm^{-2}$, late rice without organic fertilizer (M1); early rice with double amount of milk vetch green manure at 30 $t \cdot hm^{-2}$, late rice without organic fertilizer (M2); early rice with milk vetch green manure at 15 $t \cdot hm^{-2}$ and pig manure at 15 $t \cdot hm^{-2}$, late rice without organic fertilizer (M3); early rice with milk vetch green manure at 15 $t \cdot hm^{-2}$ + late rice with pig manure at 15 $t \cdot hm^{-2}$ and winter straw mulching at 4,500 $kg \cdot hm^{-2}$ (M4); and long-term chemical fertilizer application (NPK), totaling 5 treatments. Soil samples were collected every 5 years after late rice harvest to determine soil organic carbon content, and annual early and late season rice yields and biomass were measured to estimate system benefits and carbon budget (5-year average). The results showed that: compared with the no-fertilizer control, all fertilization treatments significantly increased rice yield ($P<0.05$), with an increase range of 30.88%~96.52%, and the M4 treatment showed the greatest yield increase effect with increasing fertilization years. Long-term organic fertilizer application significantly improved the soil carbon sequestration capacity of red soil paddy fields, and increased application rates enhanced system soil carbon sequestration capacity, with soil carbon sequestration amounts in M2, M3, and M4 treatments being significantly higher than those in M1, NPK, and CK treatments; plant carbon sequestration in paddy fields also increased significantly ($P<0.05$), with M4 and M3 being the highest, and double-cropping rice plant carbon sequestration was 6.76~8.83 t(C) · hm^{-2} · a^{-1}. Long-term organic fertilizer application significantly increased the net carbon sink of paddy field systems, with fertilization treatments (M1, M2, M3, M4, NPK) increasing system net carbon sink by 1.43~3.93 t(C) · hm^{-2} · a^{-1} compared with the control, showing significant system carbon sink effects ($P<0.05$). For the same treatment, carbon emissions caused by production activities remained constant across different fertilization years, and differences in system net carbon sink were mainly manifested in system carbon sequestration, with trends consistent with rice yield changes. Long-term organic fertilizer application significantly reduced chemical fertilizer input, and economic benefits of paddy field ecosystems increased significantly ($P<0.05$), with the M4 treatment being the highest, reaching 25,683.7 ¥ · hm^{-2} · a^{-1}. In summary, the results showed that: long-term organic fertilizer application significantly improved the carbon sink effect and economic benefits of double-cropping rice paddies ($P<0.05$), and the combined application of milk vetch green manure with pig manure and straw in paddy field ecosystems showed obvious advantages in carbon sink benefits and economic benefits compared with single application of milk vetch green manure.

Full Text

Evaluation of Net Carbon Sink Effects and Costs/Benefits of Double-Cropped Rice Fields Under Different Organic Fertilizer Applications

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Abstract: Based on a long-term organic fertilizer experiment initiated in 1981, this study investigated the effects of different organic fertilizer types, application rates, and methods on carbon emissions, carbon sequestration, and net carbon sink effects in paddy field ecosystems, while comparing the economic benefits of each treatment to provide theoretical reference for low-carbon, high-value, and efficient agricultural production. The selected organic fertilizer treatments included: no fertilizer control (CK); early rice with green manure *Astragalus sinicus* at 15 t · hm^{-2}, no organic fertilizer for late rice (M1); double amount of green manure *A. sinicus* at 30 t · hm^{-2} for early rice, no organic fertilizer for late rice (M2); early rice with green manure *A. sinicus* at 15 t · hm^{-2} plus pig manure at 15 t · hm^{-2}, no organic fertilizer for late rice (M3); early rice with green manure *A. sinicus* at 15 t · hm^{-2} plus late rice with pig manure at 15 t · hm^{-2} and winter straw mulching at 4,500 kg · hm^{-2} (M4); and long-term chemical fertilizer application (NPK). Soil samples were collected every five years after late rice harvest to determine soil organic carbon content, and annual early and late rice yields and biomass were measured to estimate system benefits and carbon budget (five-year average). Results showed that compared with the control, all fertilization treatments significantly increased rice yield by 30.88%-96.52% ($P<0.05$), with M4 showing the greatest yield increase over time. Long-term organic fertilizer application significantly enhanced soil carbon sequestration capacity in red paddy soil, with higher application rates leading to stronger soil carbon sequestration. Soil carbon sequestration in M2, M3, and M4 treatments was significantly higher than in M1, NPK, and CK treatments. Plant carbon sequestration also increased significantly ($P<0.05$), with M4 and M3 achieving the highest values, reaching 6.76-8.83 $t(C) \cdot hm^{-2} \cdot a^{-1}$ for double-cropped rice. Long-term organic fertilizer application significantly increased the net carbon sink of paddy systems, with fertilization treatments (M1, M2, M3, M4, NPK) increasing the net carbon sink by 1.43-3.93 $t(C) \cdot hm^{-2} \cdot a^{-1}$ compared with the control, showing significant carbon sink effects ($P<0.05$). Carbon emissions from production activities remained constant across different fertilization years for the same treatment, with differences in net carbon sink mainly manifested in system carbon sequestration, showing a consistent trend with rice yield changes. Long-term organic fertilizer application significantly reduced chemical fertilizer input and markedly increased the economic benefits of paddy ecosystems ($P<0.05$), with M4 achieving the highest benefit at ¥25,683.7 $\cdot hm^{-2} \cdot a^{-1}$. In conclusion, long-term organic fertilizer application significantly enhanced both the carbon sink effect and economic benefits of double-cropped rice fields ($P<0.05$), with combined application of green manure *A. sinicus*, pig manure, and straw showing clear advantages over single green manure application in terms of carbon sink benefits and economic returns.

Keywords: Double-cropped rice field; Organic fertilizer application method; Yield; Carbon sequestration; Carbon sink effect; Economic benefit

Introduction

In recent years, climate issues such as global warming caused by the greenhouse effect have attracted widespread attention, making greenhouse gas emission reduction a focal point of current technological development. CH_4 and CO_2 are important greenhouse gases, with approximately 70% of atmospheric CH_4 and 20% of CO_2 originating from agricultural production activities [1]. Therefore, understanding carbon cycling in paddy ecosystems is crucial for reducing CH_4 and CO_2 emissions and mitigating the greenhouse effect. Farmland ecosystems are significantly influenced by both natural factors and human activities, such as tillage, fertilization, and irrigation, resulting in complex temporal and spatial variations in carbon emissions [2]. However, research on carbon budget balance in these systems remains limited [3-4].

China is one of the world' s most important rice (*Oryza sativa*) producing countries, ranking first in rice yield and second in planting area globally [5]. Consequently, investigating the carbon balance, variation patterns, and regulatory mechanisms of paddy ecosystems is essential for evaluating global atmospheric carbon budget balance, reducing farmland carbon emissions, and achieving low-carbon, sustainable agricultural production. Han et al. [6] demonstrated that improved tillage practices could significantly reduce CO_2 emissions from farmland ecosystems. Fertilization, as a critical agricultural practice, significantly affects carbon sinks in paddy fields. Li et al. [7-8] found that combined organic and inorganic fertilization significantly increased rice yield and carbon sequestration, with similar results reported by Peng et al. [9]. Furthermore, Yu et al. [10-11] studied the net carbon sink effects of double-cropped rice ecosystems under long-term fertilization in the Poyang Lake region, showing that appropriate organic fertilizer application significantly enhanced both carbon sink effects and economic benefits, representing an effective measure for increasing production, carbon sequestration, and emission reduction.

Currently, research on the effects of organic fertilizer application on carbon sink effects in paddy ecosystems has primarily focused on comparisons between organic and chemical fertilizers. However, double-cropped rice regions feature diverse organic fertilizer types (rice straw, winter green manure, livestock manure, etc.) with low utilization rates and varied application methods. Studies investigating the mechanisms through which different organic fertilization modes affect carbon sink effects in double-cropped paddy ecosystems remain scarce. Therefore, based on data accumulated from a long-term organic fertilizer experiment at the Jiangxi Institute of Red Soil in a red soil hilly region, this study uses different organic fertilization modes as the entry point to improve organic fertilizer resource utilization in double-cropped rice areas. By analyzing 30 years of experimental data from 1981-2010, we examined differences in carbon emissions, carbon sequestration, and net carbon sink effects under various organic fertilizer types, application rates, and methods, while comparing the economic benefits of each treatment to provide theoretical reference for low-carbon, high-value, and efficient agricultural production.

1.1 Site Description

The experiment was conducted at the Jiangxi Institute of Red Soil in Jinxian County, Nanchang City, Jiangxi Province (116°20 24 N, 28°15 30 E), located in a typical subtropical monsoon climate zone with average annual precipitation of 1,727 mm and annual evaporation of 1,100 mm. The average annual temperature ranges from 17.7-18.5°C, with mean temperatures of 4.6°C in the coldest month (January) and 28.0-29.8°C in the hottest month (July). The site has an elevation of 25-30 m, representing a typical low-hill red soil region with soil type classified as hydromorphic paddy soil developed from Quaternary red clay. The experiment began in spring 1981. Initial topsoil properties included: pH 6.9, organic carbon content 16.3 $g \cdot kg^{-1}$, total nitrogen 0.95 $g \cdot kg^{-1}$, total phosphorus 1.02 $g \cdot kg^{-1}$, total potassium 15.41 $g \cdot kg^{-1}$, available nitrogen 144 $mg \cdot kg^{-1}$, available phosphorus ($NaHCO_3$-P) 10.3 $mg \cdot kg^{-1}$, and available potassium

(NH_4OAc-K) 125.1 mg · kg^{-1}.

1.2 Experimental Design

The experiment was established in 1981 with nine treatments, from which six fertilization treatments were selected for this study (Table 1): (1) no fertilizer control (CK); (2) green manure application for early rice (M1); (3) double amount of green manure for early rice (M2); (4) green manure plus pig manure application for early rice (M3); (5) green manure for early rice plus pig manure for late rice with winter straw mulching (M4); and (6) long-term chemical fertilizer application (NPK). Each plot measured 60 m^2 with sequential arrangement and three replications. Fertilization details are shown in Table 1. Organic fertilizers, phosphorus, and potassium were applied as basal fertilizers, while nitrogen was split equally between basal and topdressing applications. Rice varieties commonly used in the region were planted every five years at a spacing of 20 cm × 20 cm. Other field management practices followed local high-yield cultivation standards. Organic fertilizers used included *Astragalus sinicus*, fresh pig manure, and straw, with nutrient contents shown in Table 2 .

To ensure normal rice growth, supplementary chemical fertilizers were applied from 1981-1988 (45 kg · hm^{-2} N and 30 kg · hm^{-2} P_2O_5 per season for all treatments except NPK, which received supplementation only in the late rice season). From 1989-1995, 37.5 kg · hm^{-2} K_2O was added to the above rates. Beginning with the early rice season in 1996, supplementary rates were increased to 69 kg · hm^{-2} N, 30 kg · hm^{-2} P_2O_5, and 67.5 kg · hm^{-2} K_2O per season for M1, M2, M3, M5, and NPK treatments.

1.3 Measurements

During the experimental period, rice yield, biomass, and actual yield from each plot were measured every five years as the sum of early and late rice seasons. Rice biomass was determined from plant samples collected at harvest. Soil carbon content was measured in topsoil samples (0-17 cm) collected after late rice harvest and analyzed using the method of Lu Rukun [12] to determine organic matter content, which was then converted to carbon content. Soil bulk density was measured using the core method [12]. Data on material and resource inputs and outputs from 1981-2011 were estimated using 2015 market prices (Table 3). The study focused on material cycling and economic value during the specific crop period from sowing to harvest, excluding product destination.

1.4 Research Methods

This study focused on the double-cropped rice ecosystem in red soil regions, with experimental plots as boundaries. Carbon fixation-emission and economic input-output analyses targeted the soil-crop system and associated agricultural activities such as tillage, irrigation, pesticide application, and harvesting. The study referenced methods from Li et al. [7-8] to calculate carbon balance, carbon absorption, carbon emissions, and economic flows in the double-cropped rice ecosystem. Specific methods are as follows:

System carbon absorption (Ca) calculation:

$$Ca = C_{crop} + C_{SOC} \quad (1)$$

where C_{crop} represents carbon fixed in aboveground crop biomass and C_{SOC} is soil organic carbon.

System carbon emissions (Ce) include carbon emissions from production activities (E_h), comprising energy-related emissions from agricultural chemical inputs (C_{ac}), emissions from farm management (C_m), and emissions from labor inputs (C_l):

$$Ce = E_h = C_{ac} + C_m + C_l \quad (2)$$

Net carbon sink (Cs) is calculated through carbon balance between absorption and emissions:

$$Cs = Ca - Ce \quad (3)$$

Carbon component parameter estimation:

Crop aboveground carbon sequestration (C_{crop}) estimation:

$$C_{crop} = (Y_{er} + Y_{lr}) \times Cf \quad (4)$$

where Y_{er} is early rice biomass yield, Y_{lr} is late rice biomass yield, and Cf is atmospheric carbon absorbed per unit of dry biomass, with a value of 0.41 for rice.

Soil organic carbon (C_{SOC}) calculation:

$$C_{SOC} = W_s \times (X_y - X_o) \times \frac{1}{1.724} \quad (5)$$

where W_s is the weight of cultivated soil per hectare, converted from soil bulk density; X_y is soil organic matter content in the sampling year; X_o is initial soil organic matter content at the experiment start; and 1.724 is the conversion coefficient between organic matter and carbon.

Energy-related carbon emissions from agricultural chemical inputs (C_{ac}) include emissions from pesticide production ($C_{pesticides}$) and fertilizer production ($C_{fertilizers}$):

$$C_{pesticides} = V_{in-CO_2} \times W_p \quad (6)$$

where V_{in-CO_2} is CO_2 emissions from pesticide production, valued at 4,931.93 kg(C) • Mg^{-1}, and W_p is pesticide application rate (kg • hm^{-2}).

$$C_{fertilizers} = \sum_i U_{fi-CO_2} \times W_{fi} \quad (7)$$

where U_{fi-CO_2} is carbon emissions per ton of fertilizer production: 1.74 t(C) • t^{-1} for nitrogen fertilizer, 165.09 kg(C) • t^{-1} for phosphorus fertilizer, and 120.28 kg(C) • t^{-1} for potassium fertilizer; i represents different fertilizer types; and W_{fi} is chemical fertilizer application rate per unit area (kg • hm^{-2}).

Farm management carbon emissions (C_m) include irrigation ($C_{irrigation}$) and machinery operations ($C_{machine}$):

Irrigation carbon emissions ($C_{irrigation}$) estimation:

$$C_{irrigation} = V_{irrigation-CO_2} \times W \quad (8)$$

where $V_{irrigation-CO_2}$ is the carbon intensity coefficient of coal-powered electricity, 0.92 kg(CO_2) • $(kW \cdot h)^{-1}$, and W is electricity consumption for irrigation (kW • h).

Machinery carbon emissions ($C_{machine}$):

$$C_{machine} = V_{m-CO_2} \times L \quad (9)$$

where V_{m-CO_2} is the carbon intensity coefficient of diesel, 2.63 kg(CO_2) • L^{-1}, and L is total annual diesel consumption per unit area for tillage and harvesting (L).

Labor carbon emissions during field operations (C_l) calculation:

$$C_l = V_{CO_2} \times N_l \quad (10)$$

where V_{CO_2} is daily CO_2 exhalation volume for an adult (60 kg body weight) and N_l is total labor input per crop season (person • d^{-1}).

1.5 Data Processing

This study utilized 30 years of experimental data from 1981–2010. Statistical analysis was performed using SAS 9.2 software, with significant differences compared using Duncan’ s method. Microsoft Excel was used for graphing.

Results

2.1 Effects of Long-Term Organic Fertilizer Application on Rice Yield

Long-term organic fertilizer application significantly affected rice yield (Figure 1 [Figure 1: see original paper]). Compared with the no-fertilizer control, fertilization treatments (M1, M2, M3, M4, NPK) significantly increased yield by 1.95–4.87 $t \cdot hm^{-2}$, representing a 30.88%–96.52% increase ($P<0.05$). Organic fertilizer rate, type, and application method significantly influenced rice yield. With increasing fertilization years, the treatment with green manure for early rice plus pig manure for late rice and winter straw mulching (M4) showed the greatest yield-promoting effect, followed by the treatment with green manure and pig manure for early rice (M3), both significantly higher than M2 and NPK treatments. M1 showed the smallest yield increase. Increased organic fertilizer rates improved rice yield, and combined application of pig manure, straw, and *A. sinicus* demonstrated clear advantages over single *A. sinicus* application for double-cropped rice yield enhancement.

2.2 Carbon Emission Status Under Different Organic Fertilizer Management

Since fertilization, pesticide application, and irrigation management remained consistent annually throughout the experiment, carbon emissions from production activities showed no significant differences across fertilization years for the same treatment (Table 4). Differences in system carbon emissions among treatments mainly reflected variations in chemical fertilizer application rates and labor inputs. The no-fertilizer control (CK) had the lowest emissions at 1.06 $t(C) \cdot hm^{-2} \cdot a^{-1}$, significantly lower than other treatments ($P<0.05$). The highest emissions occurred in the chemical fertilizer treatment (NPK) at 1.34 $t(C) \cdot hm^{-2} \cdot a^{-1}$, followed by the M4 treatment at 1.32 $t(C) \cdot hm^{-2} \cdot a^{-1}$.

2.3.1 Effects of Organic Fertilizer Management on Soil Carbon Sequestration

Different organic fertilizer application rates, types, and modes significantly affected soil carbon sequestration in double-cropped paddy ecosystems (Figure 2 [Figure 2: see original paper]). During the initial 0–5 years, soil carbon content decreased in both the no-fertilizer control (CK) and chemical fertilizer (NPK) treatments. Organic fertilizer application significantly increased soil carbon sequestration, with the M4 treatment achieving the highest sequestration rate of 0.263 $t(C) \cdot hm^{-2} \cdot a^{-1}$, followed by M3, while M2 and M1 treatments maintained soil carbon content near original levels. With increasing fertilization years, soil carbon content in all treatments began to increase after 10 years, with M2, M3, and M4 treatments gradually converging and significantly exceeding other treatments, followed by M1 and NPK treatments, while CK showed the lowest sequestration. These results demonstrate that long-term organic fertilizer application significantly enhances soil carbon sequestration in paddy ecosystems, with higher application rates increasing system soil carbon sequestration capacity.

2.3.2 Plant Carbon Sequestration Under Different Fertilization Modes

Long-term organic fertilizer application significantly increased rice yield and dry matter accumulation in red paddy soil, with significant differences in plant carbon sequestration among treatments (Table 5). During the experimental period, the no-fertilizer control (CK) consistently showed the lowest double-season plant carbon sequestration at 4.03-5.28 $t(C) \cdot hm^{-2} \cdot a^{-1}$, significantly lower than other fertilization treatments ($P<0.05$). The M4 treatment achieved the highest plant carbon sequestration at 6.76-8.83 $t(C) \cdot hm^{-2} \cdot a^{-1}$. M3 and M4 treatments showed significant differences only at 20 years of fertilization, with both significantly exceeding other treatments throughout the experiment ($P<0.05$). Initially, NPK treatment plant carbon sequestration was similar to M3 and M4, but became significantly lower after 15 years of fertilization ($P<0.05$). M1 treatment was consistently higher than CK but lower than other fertilization treatments ($P<0.05$). At the experiment' s start, M2 treatment was significantly lower than NPK ($P<0.05$), but showed no significant difference after 10 years of fertilization. These results indicate that organic fertilizer application is more effective than long-term chemical fertilization for increasing rice plant carbon sequestration, with higher organic fertilizer rates showing significant effects. Moreover, combined application of *A. sinicus*, pig manure, and straw was significantly superior to single *A. sinicus* application.

Jiangxi is an important double-cropped rice region in China, where early and late rice growth and carbon fixation represent two relatively independent processes. Our results show that different fertilization treatments significantly affected plant carbon sequestration in both seasons (Table 5). In the early experiment stage, M3 and NPK treatments showed significantly higher early rice plant carbon sequestration than other treatments. With extended fertilization, M4 early rice plant carbon sequestration showed no significant difference from M3 after 15 years and significantly exceeded NPK after 20 years ($P<0.05$). Late rice plant carbon sequestration showed similar trends, with M4 initially highest and significantly exceeding other treatments, then becoming similar to M3 and significantly higher than other treatments as the experiment progressed.

2.4 Characteristics of Net Carbon Sink Changes

Different organic fertilizer management modes significantly affected the net carbon sink of double-cropped paddy ecosystems (Figure 3 [Figure 3: see original paper]), with patterns consistent with rice yield changes. The M4 treatment showed the greatest net carbon sink effect, followed by M3. Both M3 and M4 treatments exhibited significantly higher net carbon sinks than NPK after 15 years of fertilization ($P<0.05$), with increases of 0.61-1.07 $t(C) \cdot hm^{-2} \cdot a^{-1}$ and 0.66-1.41 $t(C) \cdot hm^{-2} \cdot a^{-1}$, respectively. No significant difference existed between M2 and NPK treatments, though both significantly exceeded M1 except at 20 years of fertilization. All fertilization treatments showed significantly higher net carbon sinks than the no-fertilizer control ($P<0.05$), with increases of 1.43-3.93 $t(C)\cdot hm^{-2}\cdot a^{-1}$. While some fluctuations occurred across fertilization years for the same treatment, all treatments showed trends consistent with rice yield changes, likely influenced by variety differences and inter-annual climate variations.

2.5 Effects of Different Organic Fertilizer Management on Economic Benefits of Paddy Ecosystem

The economic benefits of this system were primarily affected by rice yield and production input costs (Figure 4 [Figure 4: see original paper]). Significant differences in production inputs existed among treatments, with the chemical fertilizer treatment (NPK) showing the highest input at ¥5,256 $\cdot hm^{-2}\cdot a^{-1}$, significantly exceeding other treatments ($P<0.05$), while the no-fertilizer control (CK) showed the lowest at ¥3,206 $\cdot hm^{-2}\cdot a^{-1}$. Differences in production inputs among organic fertilizer treatments mainly resulted from labor input variations. Different fertilization treatments significantly affected rice yield, consequently influencing ecosystem economic benefits. Compared with the control, all fertilization treatments (M1, M2, M3, M4, NPK) significantly increased paddy ecosystem economic benefits ($P<0.05$), with differences among treatments generally consistent with yield differences. The M4 treatment achieved the highest benefit at ¥25,683.7 $\cdot hm^{-2}\cdot a^{-1}$, followed by M3, both significantly exceeding the long-term chemical fertilizer treatment (NPK). The M1 treatment showed the smallest benefit increase, with no significant difference from NPK.

Discussion

3.1 Effects of Different Fertilization Modes on Carbon Sink Effects in Double-Cropped Paddy

Research indicates that global surface temperature has risen by nearly 1°C over the past century [13]. Increasing global temperatures and frequent extreme weather events have become important factors limiting rice yield in China, as high temperature stress can cause reduced tillering, pollen sterility, lower seed setting rates, and consequently significant yield and quality reductions [14-17]. Emissions of greenhouse gases such as CO_2 and CH_4 are major contributors to global warming, with farmland ecosystems accounting for a large proportion of these emissions. Previous studies have extensively investigated methods to reduce farmland carbon emissions, mitigate greenhouse effects, and enhance carbon sequestration for sustainable agricultural development. Liang et al. [18] analyzed trends in farmland soil carbon across China using data from the first and second national soil surveys, providing methods and basis for research on farmland soil carbon sequestration capacity and potential. Zhang et al. [19] found that conservation tillage reduced soil erosion and damage, decreased surface organic carbon loss, and significantly increased surface soil organic matter content. Wu et al. [20] demonstrated that straw return showed significant carbon sink effects, with straw mulching and no-tillage significantly reducing CH_4 emissions from paddy fields.

Our results show that long-term organic fertilizer application significantly increased soil organic matter content and soil carbon sequestration capacity, consistent with findings by Yu et al. [10-11] and similar to results from Li et al. [8] in the Tai Lake region. Moreover, our analysis of carbon sink effects under different organic fertilizer application modes in double-cropped paddy revealed that both M4 and M3 treatments showed significantly higher system carbon sinks than M2 treatment, which in turn significantly exceeded M1 treatment. This indicates that increased organic fertilizer application rates significantly enhanced the carbon sequestration capacity of paddy ecosystems, and that combined application of *A. sinicus*, pig manure, and straw was significantly superior to single *A. sinicus* application. This advantage may relate to the nutrient composition of different organic fertilizers and their decomposition and release characteristics in soil. Table 2 shows that pig manure has relatively balanced NPK nutrients, while green manure season straw has notably low phosphorus content, providing important theoretical support for rational organic fertilizer use in paddy systems. However, the mechanisms by which degradation of different organic fertilizer types affects carbon sink effects in double-cropped paddy ecosystems remain unclear and require further investigation.

3.2 Effects of Long-Term Organic Fertilizer Application on Economic Benefits of Double-Cropped Paddy

Rice production represents an important income source for Chinese farmers, making high economic returns their primary production objective. Paddy ecosystem economic benefits consist of production input costs and grain output value. This study found that organic fertilizer treatments significantly reduced chemical fertilizer input costs compared with chemical fertilizer treatment, with both M3 and M4 treatments showing significantly higher annual benefits than NPK treatment ($P<0.05$). Yu et al. [8,10-11] also found that combined organic and inorganic fertilization significantly improved economic benefits of paddy ecosystems. Additionally, our study revealed that combined application of *A. sinicus* with other organic fertilizers (straw, pig manure) (M3, M4) produced significantly higher system economic benefits than single *A. sinicus* application (M1, M2) ($P<0.05$), with M4 achieving the highest benefit at ¥25,683.7 $\cdot$ $hm^{-2} \cdot a^{-1}$. Therefore, rational organic and chemical fertilizer application represents an important approach for improving paddy system economic benefits.

3.3 Ecological Benefits of Organic Fertilization

As the world’ s largest developing country with a huge population, limited arable land resources, and severe environmental challenges, China requires development of ecological high-value agriculture to overcome these constraints and achieve sustainable agricultural development [21]. Fertilization is an indispensable agricultural practice. This study found that long-term organic fertilizer application significantly increased soil organic matter content and rice yield, with the M4 treatment showing optimal paddy ecosystem carbon sink effects and economic benefits, significantly exceeding the control and other fertilization treatments. Thus, rational organic fertilizer application can significantly reduce chemical fertilizer use and carbon emissions in rice production, representing an important strategy for cost reduction, efficiency improvement, and ecological sustainability that aligns with China' s ecological high-value agriculture requirements.

Long-term organic fertilizer application significantly enhanced both carbon sink effects and economic benefits of red paddy soil systems. Compared with no organic fertilizer application, all organic fertilizer treatments significantly increased soil organic carbon, carbon sequestration capacity, and production capacity, with significant increases in net carbon sink. Compared with the no-fertilizer control, fertilization treatments (M1, M2, M3, M4, NPK) increased net carbon sink by 1.43-3.93 $t(C) \cdot hm^{-2} \cdot a^{-1}$. Compared with chemical fertilizer alone, M4 and M3 treatments significantly increased net carbon sink by 0.61-1.41 $t(C) \cdot hm^{-2} \cdot a^{-1}$ after 15 years of fertilization ($P<0.05$). Simultaneously, long-term organic fertilizer application reduced chemical fertilizer input, lowering production costs by ¥362-722 $\cdot hm^{-2} \cdot a^{-1}$ and markedly increasing economic benefits, with M4 achieving the highest benefit of ¥25,683.7 $\cdot hm^{-2} \cdot a^{-1}$, significantly exceeding other treatments ($P<0.05$). Furthermore, significant differences existed among different organic fertilization modes in both carbon sink effects and economic benefits, with increased organic fertilizer input improving both parameters. Compared with single green manure treatments, combined green manure, pig manure, and straw treatments increased both carbon sink effects and economic benefits. Therefore, rational regulation of organic fertilizer types is crucial for enhancing paddy ecosystem carbon sink effects and economic benefits, highly consistent with ecological high-value agriculture development requirements and conducive to achieving cost-effective production and ecological sustainability in red paddy soil agriculture.

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