Evaluation of ecosystem service of straw return to soil in a wheat field of China

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Abstract: Crop straw is an important natural resource in China because it is rich in nutrients. When returned to fields after harvests, the straw can improve soil quality and the next crop's yield. Evaluating the economic values of the main ecological services of a farmland ecosystem while implementing the straw return technique can be a more systematic and comprehensive approach to better understand the contribution of straw return to the development of ecological agriculture. Based on the data of a field experiment established in 2010 with varying numbers of years of straw return, four ecological services, i.e., agricultural product and industrial raw materials, atmospheric regulation and purification, soil nutrient accumulation, and water conservation, were selected to estimate a net ecosystem service value (ESV) of a wheat field's ecosystem services. Agro-ecosystem service appraisal theories were applied to estimate the economic value of each service. Results showed that straw returning improved the total ESV in the wheat system. Compared to the no straw return treatment, 1 year, 3 years, 5 years or 7 years of straw returning altered the economic value of the agricultural product and industrial raw materials (EVAIM) by –5.93% to 7.84% and improved atmospheric regulation (EVAR) by 13.66%-30.80%, soil nutrient accumulation (EVSNA) by 59.87%-233.31% and water conservation (EVWC) by 2.60%-13.26%. The total ESV of wheat plots with 1-7 years of straw returning was 3.67%-27.41% higher than that with no straw return, and the total ESV increased with the increase in years of straw return. The proportion of EVAIM out of the total ESV in this wheat field system was highest (accounted for 47.09%-55.64%), followed by EVAR and EVWC. The value of EVSNA was the lowest. However, the proportion of EVSNA was higher than that of water conservation after the fifth year of straw return. In general, the adoption of continuous straw returning in a wheat field ecosystem is ecologically valuable. The results can inform the development and implementation of ecological compensation policies involving straw return.

Keywords: ecosystem service value, rice-wheat rotation, straw returning, farmland ecosystem, economic value, ecological service function
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1 Introduction

Crop straw is an important natural resource in rural areas of many countries. In China, annual straw production is about 600-800 million t[1]. Crop straw contains many nutrients for plant growth, such as organic carbon, nitrogen (N), phosphorus (P), potassium (K) and calcium. In fields where the use of chemical fertilizer is undesired and organic fertilizer is too costly and difficult to apply, returning the straw back into these fields has become a more attractive option to improve soil quality and replenish soil nutrient content. Straw return directly affects soil organic carbon (SOC) and N sequestration[2,3], crop yield[4], and farmland greenhouse gas emissions[5]. It also can increase contents of soil nutrients, such as N, P, and K[3]; reduce soil bulk density and increase soil porosity[6]; improve soil structure[7] and moisture[4]; help avoid environmental pollution caused by straw burning[8]. Previous research of farmland ecosystems affected by straw return mainly focuses on crop yield, nutrient cycling, fertilizer substitution, carbon sequestration, etc[9-11]. However, these unilateral approaches are not comprehensive and a more complete understanding of the effect of straw returning on the farmland ecosystem is still lacking.

Ecosystem services refer to the natural environmental conditions and ecological processes of an ecosystem that provide some utility to human beings[12]. To date, there have been many studies on the evaluation of farmland ecosystem services[13,14]. Yu et al.[15] pointed out that the net value of ecosystem services can reveal the real benefits of an ecosystem, and assessments of the values among various ecosystem services under different land uses can help inform land-use policy. Cao et al.[16] evaluated six types of services in Jiangsu Province which were as follows: farmland ecosystem supply, regulation (including atmospheric, environmental quality and water resource regulations), cultural,

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supporting (including nutrient cycling, soil conservation and biodiversity maintenance), social guarantee (e.g. providing the unemployment insurance for the labors transferred from rural to urban) and reducing the environmental pollution. Xie et al.[17] assessed net ESV for services, agricultural product and industrial raw material, atmospheric regulation, soil nutrient accumulation, and water conservation, using the Ziyunying-early rice-late rice system in an eight-year field experiment. These studies also have provided a basis for assessing the effect of straw return on the value of the farmland ecosystem service.

The wheat field ecosystem is one of the most important farmland ecosystems in China. The application of straw return may affect this system's services, such as agricultural productivity, soil nutrient accumulation and water conservation[18]. However, a simple comparative analysis or study of a single variable cannot comprehensively and systematically evaluate the advantages and disadvantages of straw returning in a wheat field ecosystem. Thus, ecological economics-related methods were adopted to establish a valuation system to determine net ESV of a wheat field ecosystem. To obtain the ESV, rather than use a single factor, four types of services were appraised: agricultural product and industrial raw materials, atmospheric regulation, soil nutrient accumulation, and water conservation. Additionally, by testing different numbers of years of straw returning or no straw returning, the effects of short, moderate, and long-term straw return on the ecosystem service value (ESV) of the wheat ecosystem were more comprehensively and systematically assessed. These findings may better inform the development and implementation of ecological compensation policies involving straw return in farm fields.

2 Materials and methods

2.1 Experimental site

The experiment was conducted at Yangzhou University, Jiangsu Province (32°23′N, 119°25′E) from 2010 to 2018 using a rice-wheat rotation field where straw return had not been applied. This area has a subtropical monsoon climate with an annual average temperature of 13.2°C-16°C and annual precipitation of 800-1200 mm. During the periods of wheat growth, the total accumulated temperature was 2359°C, the total accumulated precipitation was 462 mm, and the total sunshine duration was 1139 h. The predominant soil was classified as a Stagnic Anthrosol[19]. Soil samples were taken from the 0-20 cm soil layer in 2010 providing estimates for basic soil properties: bulk density (1.45 g/cm^3); pH (7.21); and dry soil contents of SOC (15.73 g/kg), total N (TN, 1.24 g/kg), available potassium (16.32 mg/kg), and available phosphorus (146.12 mg/kg). Rice-wheat is the dominant cropping system in this area.

2.2 Experimental design

The experiment included five treatments: no straw returning (NR) and one (SR1), three (SR3), five (SR5), and seven (SR7) consecutive years of straw returning. Each treatment was established with a completely randomized block design with three repetitions. For each of the four straw return treatments, an annual amount of 9000 kg/hm^2 (fresh weight) rice residue was applied within a soil depth of 10 cm. Wheat straw was removed after harvest for paper making.

The wheat variety was Yangfumai 4, and its growing season was from mid-November to early May, while the growing season of rice was from late May to late October. The total amount of nitrogen applied during wheat growth was 240 kg/hm^2, of which 50% was applied as basal fertilizer, 10% was applied during the tillering stage, 20% was applied during the jointing stage, and 20% was applied during the booting stage. Phosphate fertilizer (P_2O_5) and potassium fertilizer (K_2O) were applied in amounts of 90 kg/hm^2 and 150 kg/hm^2, respectively, where 50% of each fertilizer was applied as base fertilizer and the other 50% was applied during the jointing stage. The fertilization regime for the rice crop was the same as that of wheat, except that 150 kg/hm^2 of urea was applied at the tiller stage and booting stages.

2.3 Data sampling

Data collected from the wheat field ecosystem included wheat grain and straw yield; physical and chemical properties of the plow layer (bulk density, saturated water content, organic matter, TN, available phosphorus and available potassium, etc.); and CO_2, CH_4 and N_2O emissions.

From each plot, three 1 m^2 sections of plants were harvested to measure wheat grain, straw yields and biomass yields.

Soil samples from the plow layer (0-20 cm) were collected after wheat plants reached maturity. Analyses of soil physical and chemical properties were performed as published in Soil Agro-chemistries Analysis[20]: SOC content was measured by the potassium dichromate oxidation method, TN content was measured by the semi-micro Kjeldahl method, available phosphorus content was determined by the sodium bicarbonate extraction-molybdenum antimony colorimetric method, available potassium content was determined by acetamide extraction-flame spectrophotometry, and soil bulk density and saturated water content were determined by the ring knife method. Yield, soil nutrient contents, and soil physical property data from 2011 to 2018 were averaged annually from all years for each treatment. Greenhouse gas emissions data were obtained from the study conducted at the same site by Niu[21].

The cost, price and price index (PI) data required for the evaluation of the ESV were derived from the "Specifications for the Evaluation of Forest Ecosystem Services"[22] and China Statistical Yearbook[23].

2.4 Valuation of four services and total ESV

The economic values of agricultural products and industrial raw materials (EVAIM), atmospheric regulation (EVAR), soil nutrient accumulation (EVSNA), and water conservation (EVWC) were estimated to determine the net ESV of a wheat field system. As various price parameters change from year to year, this study set the last experimental year, 2018, as the base year to convert prices of the other years with the price index (PI) of 2018 to obtain the economic values of each service[17].

2.4.1 Agricultural product and industrial raw materials

The main products of wheat ecosystems are wheat grain and wheat straw. The minimum purchase price of wheat grain in China in 2018 was 2.30 RMB/kg. Wheat straw can be used as industrial raw materials, such as for papermaking. According to the market price of such raw materials and its PI, 1.067, the estimated price of wheat straw was 81.95 RMB/t. The EVAIM was computed as:

$$V_g = \sum (M_y \times E_y) \tag{1}$$

where, V_g is EVAIM, RMB/hm^2; M_y is the yield of wheat grain or straw, kg/hm^2; and E_y is the price of wheat grain or straw, RMB/kg.

2.4.2 Atmospheric regulation

Farmland ecosystems perform atmospheric regulating functions by releasing oxygen, fixing CO_2 and emitting greenhouse gases (e.g., CO_2, CH_4, and N_2O) and pollutants (e.g., SO_2, NO_X, and dust). According to the equation of photosynthesis ($6nCO_2+6nH_2O \rightarrow nC_6H_{12}O_6+6nO_2 \rightarrow nC_6H_{10}O_5$), every 1.00 g of dry matter accumulated during plant growth can fix 1.63 g of CO_2 and release 1.19 g of O_2. The amount and economic value of fixed CO_2 and released O_2 can be calculated based on the dry matter mass of wheat at maturity. The economic values of releasing oxygen and fixing CO_2 from crops were computed using Equations (2) and (3), respectively.

$$V_{CO_2} = E_{CO_2} \times Q \times 1.63 \times N_c \tag{2}$$

$$V_{O_2} = E_{O_2} \times Q \times 1.19 \tag{3}$$

where, V_{CO_2} and V_{O_2} are respective values of carbon sequestration and oxygen release, RMB/hm^2; E_{CO_2} and E_{O_2} are respective costs of carbon sequestration and oxygen release, RMB/t; Q is crop biomass, kg/hm^2; N_c is the carbon content of CO_2 (27.3%). The cost of carbon sequestration (625.32 RMB/t) was averaged from the 2018 Swedish carbon tax rate (US$ 150/t or 992.61 RMB/t, based on the daily average exchange rate of 6.6174 RMB to USD in 2018) and the afforestation cost (258.03 RMB/t, estimated from a PI of 0.989). The cost of oxygen release, 383.725 RMB/t, was averaged from the afforestation cost (349.05 RMB/t, estimated from a PI of 0.989) and cost of industrial oxygen production (418.40 RMB/t, estimated from a PI of 1.046).

While farmland ecosystems fix CO_2 during crop growth, CO_2, CH_4, and N_2O emitted by crop and soil respiration are important components of greenhouse gases. Emissions of CH_4 and N_2O are presented as CO_2 equivalents and calculated based on their global warming potential on the 100a scale determined to be 25 times and 298 times greater than that of CO_2, respectively[24]. Because greenhouse gas emissions have a negative effect on the environment, their economic value was expressed as a negative value. The economic value of greenhouse gas emission was calculated from Equation (4).

$$V_{a1} = (F_{CH_4} \times 25 + F_{N_2O} \times 298 + F_{CO_2}) \times E_{CO_2} \times N_c \tag{4}$$

where, V_{a1} is the negative value of greenhouse gas emissions, RMB/hm^2; F_{CH_4}, F_{N_2O}, and F_{CO_2} are accumulative seasonal emissions of CH_4, N_2O and CO_2 (kg/hm^2), respectively.

Pollutant emissions from straw return treatments were considered to be zero because the CO_2 emissions from these treatments have been included in the calculations of greenhouse gas emissions, and the straw was mixed with the soil. Thus N, S and other substances released from the straw directly entered the soil and was used in soil-related reactions instead of being emitted.

For the NR treatment, the straw was incinerated. Straw incineration releases CO_2, SO_2, NO_X, dust and other pollutants. According to Li et al.[25], the amounts of various pollutant gases, SO_2, NO_X, dust (calculated from the sum of PM2.5 and PM10), and CO_2 released from the burning of rice straw were 0.9 g/kg, 3.1 g/kg, 18.78 g/kg, and 1460 g/kg, respectively. According to the atmospheric regulation costs in the "specifications for the Evaluation of Forest Ecosystem Services", estimated from a PI of 1.046, the regulation costs of SO_2, NO_X and dust were 1255.20 RMB/t, 658.98 RMB/t, and 156.90 RMB/t, respectively. Because pollutants and CO_2 emissions have a negative effect on the environment, the economic value of pollutant emissions from straw incineration was also expressed as a negative value and was calculated as:

$$V_{a2} = D \times M \times E_d + V_{a3} \tag{5}$$

where, V_{a2} is the negative value of pollutant emissions from straw incineration, RMB/hm^2; D is pollutant emissions, g/kg; M is the amount of straw returned to a field, t/hm^2; E_d represents regulation costs of SO_2, NO_X and dust, RMB/kg; and V_{a3} is the value of CO_2 emissions from straw incineration, RMB/hm^2, refer to Equation (4) for its calculation.

The sum of resulting values from Equations (2) to (5) determines EVAR (V_a):

$$V_a = V_{CO_2} + V_{O_2} + V_{a1} + V_{a2} \tag{6}$$

2.4.3 Soil nutrient accumulation

According to the organic matter and fertilizer prices in the "Specifications for the Evaluation of Forest Ecosystem Services", estimated from a PI of 1.074, the unit price of each nutrient was: organic matter, 343.68 RMB/t; N, 1132.74 RMB/t; P_2O_5, 2894.75 RMB/t; and K_2O, 3937.93 RMB/t. Since soil nutrients cannot be directly traded in the market, the values of soil organic matter, TN, available phosphorus, and available potassium were replaced by the market values of their corresponding fertilizers containing equivalent substances and were calculated as:

$$V_N = \rho \times B \times \sum (N_1 \times E_n) \tag{7}$$

where, V_N is the EVSNA, RMB/hm^2; ρ is the soil bulk density of the 0-0.20 m soil layer, g/cm^3; B is the soil volume, m^3/hm^2; N_1 is the nutrient content changes, g/g; and E_n is the nutrient price, RMB/t. The changes in nutrient contents were calculated as the differences in the measured values for each treatment from the initial values obtained prior to the start of the experiment.

2.4.4 Water conservation

The water conservation function of farmland ecosystems is mainly realized through soil. According to the price of construction per unit of reservoir storage capacity in the "Specifications for the Evaluation of Forest Ecosystem Service Functions", combined with a PI of 1.072, reservoir construction cost was 6.55 RMB/t. Similar to soil nutrients, soil water cannot be directly traded in the market, thus the EVWC was calculated based on the construction cost of a reservoir.

$$V_w = \theta_f \times h \times \rho_w \times E_w \times 10 \tag{8}$$

where, V_w is the EVWC, RMB/hm^2; θ_f is saturated soil water content; H is the depth of tilled soil (0.2 m); ρ_w is water density (1000 kg/m^3); E_w is the price of construction per unit of reservoir storage capacity, RMB/t.

2.5 Statistical analyses

Statistical calculations and analyses were performed using Excel 2010 and SPSS 17.0. Least-significant difference (LSD) test was applied for multiple comparisons. Pearson coefficient was used for correlation analysis.

3 Results

3.1 Economic value of agricultural product and industrial raw materials

In this study, yields of wheat grain and wheat straw were used to calculate EVAIM. Compared with the respective yields of NR, wheat grain and straw yields of SR1 and SR3 were lower, while that of SR5 and SR7 were higher (Table 1). The EVAIMs of SR1 and SR3 were respectively 5.93% and 2.22% lower than that of NR, while the EVAIMs of SR5 and SR7 were respectively 3.35%, and 7.84% greater than that of NR.

3.2 Economic value of atmospheric regulation

Compared with straw incineration, straw returning mainly reduced the amounts of air pollutants and CO_2 emissions, and ultimately, straw returning significantly increased the EVAR (Table 3). Compared with NR, SR1 and SR3 reduced the biological yield of wheat (Table 1), and their economic values of carbon fixation and oxygen release decreased by 6.02% and 2.26%, respectively. In contrast, that of SR5 and SR7 increased by 3.35% and 7.94%, respectively. The cumulative greenhouse gas emissions during the wheat growth period increased with increasing years of straw returning (Table 1), and the negative economic value of greenhouse gas emissions also increased. The negative economic values of greenhouse gas emissions of SR1, SR3, SR5 and SR7 were 22.67%, 28.71%, 37.12% and 40.30% higher than that of NR, respectively. Only in the NR treatment were pollutants produced due to straw incineration. The annual amount of straw returned to plots was 9000 kg/hm^2, and the economic value of the pollutants and CO_2 emission of this amount of incinerated straw was –55.07 RMB/hm^2 and –2243.16 RMB/hm^2, respectively, in a total of –2298.23 RMB/hm^2. Compared with the EVAR of NR, the EVAR of SR1, SR3, SR5 and SR7 were greater by 13.66%, 17.72%, 24.01% and 30.80%, respectively.

Table 1 Ecosystem service measures from different treatments of a wheat system

Ecological service function		NR	SR1	SR3	SR5	SR7
Wheat yield /kg·hm^{-2}	Grain yield	7458.76^{bc}	7009.73^{d}	7290.51^{cd}	7708.67^{ab}	8050.72^{a}
	Straw yield	8304.64^{bc}	8010.71^{c}	8189.56^{c}	8579.54^{ab}	8755.80^{a}
	Biological yield	16214.70^{bc}	15238.55^{d}	15848.93^{cd}	16757.99^{ab}	17501.57^{a}
Greenhouse gas emission/kg·hm^{-2}	CO_2	16210.97^{c}	20401.69^{b}	21307.62^{b}	22710.96^{a}	23232.57^{a}
	CH_4	-1.41^{d}	-0.24^{c}	0.31^{b}	0.19^{c}	0.47^{a}
	N_2O	4.25^{a}	3.36^{c}	3.81^{b}	4.03^{ab}	4.12^{ab}
Soil nutrient accumulation/g·kg^{-1}	Organic mater	2.39^{d}	3.32^{c}	4.90^{b}	6.16^{a}	6.68^{a}
	Total nitrogen	-0.03^{c}	0.04^{c}	0.16^{b}	0.18^{b}	0.27^{a}
	Available phosphorus	-1.46^{e}	0.23^{d}	1.58^{c}	2.00^{b}	3.07^{a}
	Available potassium	-21.76^{e}	-14.01^{d}	-3.72^{c}	4.19^{b}	10.43^{a}
Soil physical property	Bulk density/g·cm^{-3}	1.42^{a}	1.39^{ab}	1.36^{ab}	1.31^{bc}	1.24^{c}
	Saturation water content/g·cm^{-3}	0.43^{c}	0.44^{bc}	0.45^{abc}	0.46^{ab}	0.48^{a}

Note: 1. Soil nutrient accumulation were the differences of each nutrient from the corresponding nutrient contents measured before application of treatments; 2. Different letters in the same row indicate significant differences at the 0.05 level (LSD test) among treatments at the same soil depth.

Table 2 Economic value of agricultural products and industrial raw materials for different treatments of a wheat system (RMB/hm^2)

Product	NR	SR1	SR3	SR5	SR7
Wheat grain	17155.15^{bc}	16122.39^{d}	16768.17^{cd}	17729.95^{ab}	18516.66^{a}
Straw	680.53^{bc}	656.44^{c}	671.10^{c}	703.06^{ab}	717.50^{a}
Economic value	17835.68^{bc}	16778.83^{d}	17439.26^{cd}	18433.01^{ab}	19234.15^{a}

Note: Different letters in the same row indicate significant differences at the 0.05 level (LSD test) among treatments at the same soil depth.

Table 3 Economic value of atmospheric regulation for different treatments of a wheat system (RMB/hm^2)

Classification	NR	SR1	SR3	SR5	SR7
Economic value of carbon fixation	4511.92^{bc}	4240.30^{d}	4410.14^{cd}	4663.10^{ab}	4870.01^{a}
Economic value of oxygen release	7404.16^{bc}	6958.42^{d}	7237.14^{cd}	7652.25^{ab}	7991.79^{a}
Economic value of greenhouse gas emissions	-2960.20^{d}	-3631.38^{c}	-3810.22^{b}	-4059.01^{ab}	-4153.27^{a}
Economic value of straw incineration pollutants and CO_2 emissions	–2298.23	0	0	0	0
Sum	6657.66^{d}	7567.34^{c}	7837.06^{bc}	8256.34^{ab}	8708.53^{a}

Note: Different letters in the same row indicate significant differences at the 0.05 level (LSD test) among treatments at the same soil depth.

3.3 Economic value of soil nutrient accumulation

Straw returning increased soil nutrient contents in the plow layer (Table 1). Table 4 shows that with the increasing number of years of straw return (1-7 years), the economic values of organic matter, TN, available phosphorus and available phosphorus accumulation increased from the corresponding values of NR by 36.11%-143.49%, 209.38%-780.37%, 115.29%-283.15%, and 37.01%-141.78%, respectively. The EVSNA of each straw return treatment also increased from that of NR by 59.87% (SR1), 154.999% (SR3), 210.86% (SR5) and 233.31% (SR7).

Table 4 Economic value of soil nutrient accumulation in different treatments of a wheat system (RMB/hm^2)

Soil nutrient	NR	SR1	SR3	SR5	SR7
Organic matter	2336.48^{d}	3180.10^{c}	4569.13^{b}	5535.32^{a}	5688.98^{a}
Total nitrogen	-110.71^{e}	121.09^{d}	481.57^{c}	530.35^{b}	753.19^{a}
Available phosphorus	-12.04^{e}	1.83^{d}	12.37^{c}	15.16^{b}	22.05^{a}
Available potassium	-243.77^{e}	-153.55^{d}	-39.77^{c}	43.07^{b}	101.85^{a}
Sum	1969.96^{d}	3149.48^{c}	5023.29^{b}	6123.89^{ab}	6566.07^{a}

Note: Different letters in the same row indicate significant differences at the 0.05 level (LSD test) among treatments at the same soil depth.

3.4 Economic value of water conservation

Straw returning increased the saturated water content in the plow layer (Table 1). As shown in Table 5, compared with NR's EVWC, the EVWC of SR1, SR3, SR5, and SR7 increased by 2.60%, 4.47%, 8.17%, and 13.26%, respectively.

Table 5 Economic value of water conservation from different treatments of a wheat system (RMB/hm^2)

	NR	SR1	SR3	SR5	SR7
Economic value	5594.93^{d}	5740.35^{cd}	5845.29^{bc}	6051.90^{b}	6336.73^{a}

Note: Different letters in the same row indicate significant differences at the 0.05 level (LSD test) among treatments at the same soil depth.

3.5 ESV of straw returning in wheat field

Straw returning was conducive to improving the economic values of ecosystem services from wheat fields (Table 6). The ESV for SR1, SR3, SR5, and SR7 increased by 3.67%, 12.75%, 21.23% and 27.41%, respectively, from that of NR. For all treatments, the EVAIM accounts for the highest proportion of the ESV (47.09% to 55.64% across treatments), followed by EVAR, then EVWC, and finally EVSNA. Values of EVSNA were the lowest with exceptions for SR5 and SR7 whose values were slightly higher than that of water conservation.

With the increasing number of years of straw returning, the EVAIM initially decreased and then increased, while the EVAR, EVWC, and EVSNA gradually increased. Additionally, with the increasing number of years of straw return, the proportions of EVAIM and EVWC gradually decreased, while the proportion of EVSNA gradually increased, and the proportion of EVAR reached its peak at SR1, then dropped rapidly and then rose slowly.

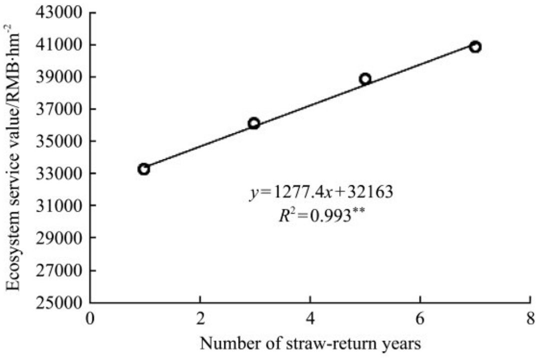
Table 6 Economic values and proportions of those values of the four services that account for net ESV (Sum) for the different treatments of a wheat system

Economic function	NR		SR1		SR3		SR5		SR7	
	Value /RMB·hm^{-2}	Proportion /%	Value /RMB·hm^{-2}	Proportion /%	Value /RMB·hm^{-2}	Proportion /%	Value /RMB·hm^{-2}	Proportion /%	Value /RMB·hm^{-2}	Proportion /%
Agricultural products and industrial raw materials	17835.68	55.64	16778.83	50.48	17439.26	48.25	18433.01	47.43	19234.15	47.09
Atmospheric regulation	6657.66	20.77	7567.34	22.77	7837.06	21.68	8256.34	21.24	8708.53	21.32
Soil nutrient accumulation	1969.96	6.14	3149.48	9.48	5023.29	13.90	6123.89	15.76	6566.07	16.08
Water conservation	5594.93	17.45	5740.35	17.27	5845.29	16.17	6051.90	15.57	6336.73	15.51
Sum	32058.23		33236.01		36144.91		38865.13		40845.47	

Note: Different letters in the same row indicate significant differences at the 0.05 level (LSD test) among treatments at the same soil depth.

3.6 Cumulative increase of ESV of SR7

The ESV of wheat fields continuously rose as the number of straw-return years increased and the linear relationship was significant (R^2=0.993, p<0.01, Figure 1). Using the linear model, the ESVs at 2 years, 4 years, and 6 years of straw return were estimated, which were 34 717.8 RMB/hm^2, 37 272.6 RMB/hm^2, and 39 827.4 RMB/hm^2, respectively. Notably, the cumulative increase of ESV in SR7 was the sum of the successive increases of ESV from NR through each successive treatment of straw return years, which was 36 501.71 RMB/hm^2.



Note: ** indicates significant difference at p<0.01.

Figure 1 Relationship between ESV and the number of straw-return years

4 Discussion

The number of years of straw return affected wheat straw yields, as well as wheat grain yields, both of which determined the EVAIM. Results in Table 2 show that compared with NR's EVAIM, short-term straw returning (≤3 years) reduced the EVAIM, while long term (≥5 years) increased it. Within the timeframe of short-term straw returning, straw likely did not decompose and convert into organic matter in time to provide nutrients to the subsequent wheat crop. Crude fiber from straw residues in the soil affects the growth of seedlings and the number of effective spikes and grain number per spike, which reduces yield[26]. As the years of straw returning increased, this allowed the time for straws to gradually decompose and accumulate in the soil and improve soil fertility; resulting in the gradual increase of 1000-grain weight and grain number per spike and ultimately, greater wheat yield[23,27]. Studies also showed that the effect of straw returning on crop yield was closely related to regional climate, soil conditions, tillage method, water and fertilizer management[27,28].

The economic value of carbon fixation and oxygen release by crops depends on the biological yield of the crops. Short-term straw returning (≤3 years) decreased the biological yield of wheat, which also decreased its economic values of carbon fixation and oxygen release. When the number of years of straw return was more than five, the biological yield of wheat exceeded that of NR, with a similar pattern for the EVAIM.

The major greenhouse gas emissions from farmland are N_2O, CH_4 and CO_2. Crops can fix CO_2 through photosynthesis, while crops and soil respiration will emit CO_2. Unfortunately, some studies have ignored the role of CO_2 in the service of atmospheric regulation from farmland ecosystems[17] when its inclusion can provide a more comprehensive assessment of this service[18]. The results showed that straw returning reduced N_2O emissions from the soil and increased CH_4 and CO_2 emissions to greater than that of NR (Table 1). The decline in emissions of N_2O from soil may be due to the effect of straw return reducing the redox potential of soil[29]. Moreover, straw has a high C:N ratio, which can promote biological nitrogen fixation after straw is returned to fields. As the returned straw decompose, they may generate allelochemicals that inhibit denitrification[30]. In contrast, straw returning increased soil water and organic carbon content, which is not conducive to the activity of soil CH_4-oxidizing bacteria, leading to an increase in CH_4 emissions[31]. Because straw returning increases soil respiration, temperature[32], and organic carbon content[33], CO_2 emissions increase as well[34]. With the increasing number of years of straw return, cumulative emissions of N_2O, CH_4, and CO_2 gradually increased, likely caused by the continuous increase of soil C and N contents.

The straw return method deposits nutrients, such as organic matter, N, P, and K into the soil, which affects the accumulation of nutrients in the soil. This study showed that compared with the initially recorded measures of soil nutrient contents, N, P, and K contents in NR decreased, while the accumulation of those nutrients significantly increased in the two long-term straw return treatments (Table 1), as well as their economic values (Table 4). Congruent with these results, many other studies have shown that straw returning effectively increases the contents and stocks of soil organic carbon and nitrogen[35-37] and soil N, P, and K contents[3,38]. However, though soil C and N contents gradually increased with the increasing number of years of straw return, plant growth rates may decelerate[39].

Straw returning reduced soil bulk density (Table 1). It can also promote soil particle aggregation and aggregate stability[40] and increase soil porosity and soil moisture[4]. All these improvements ultimately benefitted the EVWC (Table 5).

Consistent with the results of Cao et al.[16], the valuation results showed that in the wheat field of this rice-wheat rotation system, the EVAIM accounted for the highest proportion of the net ESV, ranging from 47.09% to 55.64% among all treatments, followed by the value for atmospheric regulation.

Although the economic values of multiple services of a farmland ecosystem were determined in this study, additional services have not been examined. For example, biodiversity and soil conservation were not investigated because modern farm fields are inherently monocultures and we were unable to measure the amount of soil erosion. Therefore, the actual ESV of wheat field ecosystems is likely higher than the estimated value in this study. In addition, the longest number of straw return years applied in this study was seven; crops have been grown in the same fields for much longer lengths of time. Moreover, this valuation tested only one level of amount of returned straw, 9000 $kg/hm^2 \cdot a$. Despite the exclusion of many possible ecosystem services from this study, this investigation was broader in scope than previous studies by the examination of multiple services. In the future, establishing longer-term experiments in different types of farmland ecosystems and appraising more ecosystem services are needed to better evaluate the effect of straw return on the ESV of farmland ecosystems.

5 Conclusions

The effect of straw return on ESV, including EVAIM, EVAR, EVSNA and EVWC were studied in a wheat field ecosystem by establishing a valuation system. By comparing the ESV of different treatments of the number of straw-return years with that of a no straw return treatment, this study offers insight into the benefits of straw return where other fertilizer options are unavailable. The main conclusions of this study are as follows:

(1) Short-term straw return reduced EVAIM, but increased EVAR, EVSNA and EVWC and thus the net ESV in comparison to those of no straw return.

(2) The ESV showed a positive linear correlation with the number of straw-return years (R^2=0.993**, p<0.01), indicating that ESV increased with the increase in the number of years of straw return in a wheat field ecosystem.

(3) The cumulative increase of ESV of SR7 was 36 501.71 RMB/hm^2. Continuous years of straw returning are significant positive effects on farmland resource utilization and are important tools for the development and sustainability of agriculture.

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