

Original Research

The Economic Value of Gas Exchange in a Paddy Field Ecosystem Using Water-Saving Irrigation

Yang Shihong^{1,2*}, Xiao Yanan², Xu Junzeng^{1,2}

¹State Key Laboratory of Hydrology – Water Resources and Hydraulic Engineering, Hohai University, Nanjing, P.R. China

²College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, P.R. China

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Abstract

The ecosystem services value of paddy fields has received increasing attention in agricultural policy decisions. This paper presents the first study to investigate the effects of rice water-saving irrigation on the economic value of gas exchange in a paddy field ecosystem based on a field experiment. The results showed that, compared to traditional flooding irrigation (FI), controlled irrigation (CI) decreased irrigation water input while maintaining high rice yield. Irrigation methods showed no significant influence on O₂ production and its value in paddy fields. CI significantly reduced CH₄ emissions and its negative economic value by 81.80%, but increased N₂O by 136.86%. The economic value of CO₂ uptake far outweighed the absolute value of negative economic values caused by CH₄ and N₂O emissions. Therefore, the irrigation methods showed no significant difference in economic value caused by greenhouse gas emissions (GHGs) from rice paddies. CI management significantly decreased ammonia volatilization (AV) and its economic value by 19.56%. Overall, CI increased economic value of gas exchange (O₂ production, GHGs emission, and AV) by 8.96% compared to FI paddies. Our results suggest that CI significantly increased the economic value of gas exchange in a paddy field ecosystem while drastically reducing irrigation water input and ensuring rice yields.

Keywords: water-saving irrigation, rice paddy ecosystem service, O₂ emissions, GHG emissions, ammonia volatilization

Introduction

Although the main function of rice fields is to produce rice, they also provide a range of other ecosystem services [1], including O₂ production, CO₂ reduction, summer temperature cooling, flood mitigation, and so on [2]. Meanwhile, paddy fields have

a negative effect on the environment through greenhouse gas emissions and agricultural non-point pollution [3-4]. Much literature has evaluated these ecosystem services by rice paddies, and these results show that rice fields provide more positive values in maintaining the sustainability of a regional or even global ecosystem [5-7]. Ecosystem services have been recognized throughout the rice-growing world and been considered in agricultural policy-making [8-9].

*e-mail: ysh0873@163.com

Gas exchange is an important component of ecosystem services in rice fields [2]. In addition to carbon dioxide (CO_2) fixation and oxygen (O_2) release through rice leaf photosynthesis, a paddy field is one important source of atmospheric greenhouse gases (GHGs) [10]. The main proportion of GHGs are CO_2 , methane (CH_4), and nitrous oxide (N_2O). In 2010, the CH_4 emission of rice cultivation in China was 5.2 Tg, accounting for 22% of the total CH_4 emissions of rice production in the world [11]. In addition, a rice paddy with traditional flooding irrigation management is a small source of N_2O [12]. A small amount of research has analyzed the value of gas exchange in rice fields. The results conducted in Shanghai and Jiangsu Province of China showed that the total economic value of gas exchange from rice paddies was 12.99×10^3 and 26.15×10^3 RMB ha^{-1} [13-14]. Moreover, gas exchange values of paddy fields in 10 typical rice cultivation areas were 4.61×10^3 - 16.72×10^3 USD ha^{-1} [15]. Existing research about the economic value of gas exchange in paddy fields only considered O_2 , CO_2 , CH_4 , and N_2O . Ammonia volatilization (AV) is another important gas emission from paddy fields due to excessive nitrogen input. Sun's research showed that AV from urea fertilizer was a major pathway for nitrogen loss in tropical flooded rice fields, often causing losses of 50% or more of applied nitrogen fertilizer [16]. Therefore, AV should be taken into account when evaluating the value of gas exchange in paddy fields.

In addition, with increasing water scarcity and rising grain demand, water-saving irrigation techniques are being widely implemented in paddy fields [17]. The wet-dry cycles of water-saving irrigation changes the agro-ecosystem environment, including soil properties, soil water cycle, and soil nitrogen transfer and transformation and gases exchange. It is well documented that water-saving irrigation techniques such as midseason drainage, intermittent irrigation, and controlled irrigation can significantly reduce CH_4 emissions but trigger substantial N_2O emissions from paddy fields [12]. Xu et al. found that controlled irrigation reduced AV from paddy fields by 14% compared to flooding irrigation [18]. But Cui et al. found that intermittent irrigation significantly increased AV from paddy fields by 22.9% compared to flooding irrigation [19]. The changes of gases exchange caused by water-saving irrigation will affect its economic value in

paddy fields. But relevant study is not available. Thus, we conducted one of the first detailed field experiments to systematically evaluate the gases exchange services of rice paddies under water-saving irrigation. The objectives of this study were to: 1) reveal the effect of water-saving irrigation on rice yield and irrigation water use efficiency; 2) investigate O_2 release, GHG emissions, and AV of paddy fields with different irrigation management, and quantify their economic values; and 3) comprehensively analyze the economic value of gases exchange of paddy fields under water-saving irrigation.

Materials and Methods

Experimental Field and Rice Cultivation

The measurements were conducted in 2009 and 2010 during the rice growth stage at the Kunshan Irrigation and Drainage Experiment Station ($31^\circ 15' 15''\text{N}$, $120^\circ 57' 43''\text{E}$) in the Taihu Lake region of China. The study area has a subtropical monsoon climate with an average annual air temperature of 15.5°C , mean annual precipitation of 1.10×10^3 mm, and annual evaporation of 1,365.9 mm. The soil on the top layer is hydric anthrosol soil, which is typical in this region. The properties of the 0-60 cm soil in the experimental station are described as follows: organic matter 21.9 g kg^{-1} , total nitrogen 1.03 g kg^{-1} , total phosphorus 1.35 g kg^{-1} , total potassium 20.9 g kg^{-1} , and pH 7.4.

Two irrigation treatments – namely flooding irrigation (FI) and controlled irrigation (CI) – were designed in this field experiment. Each irrigation treatment had three replicates. The replicates were established in six plots with an area of 35 m^2 ($5 \times 7 \text{ m}$) in a randomized block design. In the FI paddy fields there was a 3-5 cm shallow water layer after transplanting except during the midseason drainage period (inhibited ineffective tiller during the later tillering stage) and the yellow maturity stage of rice. For the CI treatment, the 5-25 mm shallow flooding water was maintained in the regreening stage. The irrigation was applied only to saturate the soil without flooding in other periods except during the application of fertilizers, herbicides, and pesticides with 3-5 days-worth of flooding water. The lower soil moisture thresholds for the controlled irrigation are shown in Table 1.

Table 1. Limits for controlled irrigation in different rice growth stages.

Limit	Regreening stage	Tillering stage			Jointing and booting stage	Heading and flowering stage	Milk stage	Ripening stage
		Initial	Middle	Late				
Upper limit	25 mm	$100\%\theta_{s1}^a$	$100\%\theta_{s1}$	$100\%\theta_{s1}$	$100\%\theta_{s2}$	$100\%\theta_{s3}$	$100\%\theta_{s3}$	Naturally drying
Lower limit	5 mm	$70\%\theta_{s1}$	$65\%\theta_{s1}$	$60\%\theta_{s1}$	$75\%\theta_{s2}$	$80\%\theta_{s3}$	$70\%\theta_{s3}$	
Monitored soil depth (cm)	–	0-20	0-20	0-20	0-30	0-40	0-40	

θ_{s1} , θ_{s2} , and θ_{s3} represent the saturated volumetric moisture content of the soil in different rice growth stages.

Table 2. Date and rate of nitrogen fertilization during the rice growth stage (kg N ha⁻¹).

N fertilizer application	2009	2010
Base fertilizer (22 June ^{a)})	56.25 (CF ^{b)} , 22 June)	48.00 (CF, 26 June)
Regreening fertilizer (28 June)	76.95 (AB, 28 June)	64.13 (AB, 1 July)
Tillering fertilizer (7 July)	121.80 (U, 7 July)	121.28 (U, 17 July)
Panicle fertilizer (12 August)	69.60 (U, 12 August)	69.30 (U, 13 August)
Total nitrogen	324.6	302.7

^{a)} Date in the bracket is the time for the fertilizer applied.

^{b)} CF is compound fertilizer (N, P₂O₅ and K₂O contents are 15%, 15% and 15% in 2009, and 16%, 12% and 17% in 2010). AB is ammonium bicarbonate (N content is 17.1%). U is urea (N content is 46.2%).

Rice variety was Japonica Rice Nanjing 46 in this experiment. Rice seedlings were transplanted with a 13.0 × 25.0 cm hill spacing on 23 June and harvested on 26 October in 2009. In the 2010 experiment, rice seedlings were transplanted with the same hill spacing on 26 June and harvested on 25 October. The local farmer fertilizer practice was adopted in this experiment (Table 2). Only the basal fertilizers were incorporated into the ploughed layer, while the other fertilizers were broadcast evenly onto the soil surface.

Gas Sampling

CH₄ and N₂O samples were collected by the static chamber technique [20]. The chamber, consisting of two separate layers with the same size (0.5 × 0.5 × 0.6 m), was made of polyvinyl chloride. The bases for the chambers were installed in all plots before rice transplantation, and remained there until rice harvesting. Samples were collected by 60 mL syringes, which were connected to chambers and sealed airbags through three stopcocks. Gas samples were collected at 10:00-11:00 at an interval of 2 days for 12 days after each fertilizer application, then at an interval of 3-4 days; and a 7-day sampling interval was used during the last 2 months of rice growth. Air temperatures in the chamber were recorded simultaneously. This sampling time was based on the diurnal variation patterns of gas emission, assuming this pattern remained the same the whole season [21]. From each chamber, 4 gas samples were collected (0, 10, 20, and 30 min). Gas samples were analyzed using a gas chromatograph (Agilent 7890A) with electron capture detectors for CH₄ and N₂O analyses. The CH₄ and N₂O fluxes were calculated according to the equation given by Zheng et al. [22],

$$F = \rho \times h \times \frac{273}{273 + T} \times \frac{dC}{dt} \quad (1)$$

...where F is the gas emission flux (mg m⁻² h⁻¹ for CH₄; μg m⁻² h⁻¹ for N₂O), ρ is the gas density at standard state, h is the height of chamber above the water surface (m), dC/dt is the gas mixing ratio concentration (mg m⁻³ h⁻¹ for CH₄; μg m⁻³ h⁻¹ for N₂O), and T is the mean air temperature inside the chamber during sampling (°C). The cumulative gas emissions during the study period were calculated by integrating cumulative gas emissions on the sampling days.

Paddy soil respiration was measured by transparent static chamber-WEST Systems portable soil flux meter (West Systems S.r.l., Italy). The sampling device consisted of three parts: a base, a transparent column, and a WEST Systems portable soil flux meter. The base and transparent column were made of polyvinyl chloride material (PVC) and transparent methyl methacrylate (organic glass), respectively. The PVC base, with diameter and height of 20 cm and 10 cm, was embedded 5 cm into the paddy soil (without rice) before rice transplantation, and remained there until rice harvesting. The transparent column was divided into two separate layers (with diameter of 20 cm and height of 20 cm or 40 cm) for different height of rice. The WEST Systems flux meter was a portable instrument for measuring soil gas flux based on the accumulation chamber method. It consisted of an air chamber (with diameter and height of 20 cm and 10 cm) and a host (an LI840 analyzer meter). A sealed water channel was used to join the base, transparent column and WEST Systems portable soil flux meter. Paddy soil respiration was measured at 10:00-11:00 at an interval of 7-10 days from transplanting to harvest. As CH₄ and N₂O, soil respiration rate at this sampling time were considered to be daily means. The output result from the system was the variation rate of the CO₂ concentration in the chamber. And the paddy soil respiration can be calculated as Equations (2) and (3):

$$F = K \times S \quad (2)$$

$$K = \frac{86400 \times P}{10^6 \times R \times T_k} \times \frac{V}{A} \quad (3)$$

...where K is the accumulation chamber factor in mol s ppm⁻¹ m⁻² d⁻¹, S is the variation rate of the CO₂ concentration in ppm s⁻¹, F is the flux of CO₂ in mol·m⁻²·d⁻¹, P represents the barometric pressure expressed in mBar, R is the gas constant (0.0831451 bar L K⁻¹ mol⁻¹), T_k represents the air temperature expressed in kelvin, V is the chamber net volume in cubic meters, and A represents the chamber inlet net area in square meters. Cumulative CO₂ emission through soil respiration for the rice growth stage was calculated by integrating cumulative soil respiration rates on the sampling days.

The vented method, which is simpler in structure, easier to operate, and higher in precision and accuracy [23], was used to monitor ammonia (NH₃) volatilization from the paddy fields in this study. The vented

chamber consisted of a PVC collector (20 cm high) and a phosphoglycerol-soaked sponge to absorb ammonia. The sponges were collected and replaced daily after N fertilizer application for one week, collected at 2-3 days of interval for another week, and then at one-week intervals. Then sponges were immersed in 300 ml of 1.0 M KCL solution in 500 ml containers and shaken on a reciprocating shaker before the extract solutions were analyzed by an ultraviolet-visible spectrophotometer (UNICO 2800) followed by Nessler's reagent colorimetric method [24]. And NH_3 volatilization rate was calculated according to Eq. (4):

$$R_{AV} = \frac{M}{A \times D} \times 10^{-2} \quad (4)$$

...where R_{AV} is the NH_3 volatilization rate in $\text{kg N hm}^{-2} \text{ d}^{-1}$, M is the NH_3 -N collected by the PVC collector in mg, A is the cross sectional area of the PVC collector in m^2 , and D is the interval for NH_3 volatilization samples collection in d. Cumulative NH_3 volatilization was calculated as the sum of daily volatilization over the given period.

Irrigation was conducted according to soil moisture and water layer of paddy fields. Soil moisture or pond water depths were measured every day by a time domain reflectometer (TDR, Soil Moisture Equipment Limited Corporation of America) and vertical rulers, respectively. Irrigation water volumes were measured by a water meter installed on the pipes of every plot. Yield was determined for each plot after rice was harvested. Rice dry matter amount (included root) of every plot was measured at the ripening stage. The rice plants were dried at 105°C for 30 min for deactivation of enzymes, and then dried at 80°C to constant weight. The constant weight was the rice dry matter amount.

Estimating the Economic Value of Gases Exchange

According to the formula of photosynthesis, O_2 emission can be estimated by the rice dry matter amount. While producing 162 g dry matter, a paddy field can supply 193 g oxygen. Then the economic value of O_2 emissions from paddy fields was calculated using the rice dry matter amount and the price of medical O_2 in China:

$$V_{O_2} = C_a \times \alpha \times M_d \quad (5)$$

...where V_{O_2} is the economic value of O_2 emissions (RMB ha^{-1}), C_a is the price of medical O_2 in China (0.4 RMB kg^{-1} , [25]), α is the coefficient of conversion from rice dry matter amount to O_2 emission (1.19), and is the rice dry matter amount (kg ha^{-1}).

The CH_4 and N_2O emissions from paddy fields can be converted to CO_2 equivalents through global warming potential (GWP). GWP is an index defined as the cumulative radiative forcing between the present

and some chosen later time "horizon" caused by a unit mass of gas emitted now (CO_2 is the reference gas). On a 100-year time horizon, the GWP for CH_4 is 34, whereas that for N_2O is 298, when GWP value for CO_2 is taken as 1 [26]. Thus, the emissions of CH_4 and N_2O from paddy fields can be converted to CO_2 equivalents, which can further be converted to pure C emissions using the following equation:

$$M_C = 0.2729(M_{CO_2} + 34M_{CH_4} + 298M_{N_2O}) \quad (6)$$

...where M_C is the emission of CO_2 , CH_4 , and N_2O in pure C from paddy field (kg ha^{-1}), M_{CO_2} , M_{CH_4} , and M_{N_2O} are the emissions of CO_2 , CH_4 , and N_2O from paddy field, respectively (kg ha^{-1}). CO_2 emissions of paddy field ecosystem is the difference between CO_2 fixed by rice photosynthesis and the CO_2 released by paddy soil respiration.

$$M_{CO_2} = \beta \times M_d \quad (7)$$

...where β is the coefficient of conversion from rice dry matter amount to CO_2 emission (1.63).

The economic value of greenhouse gases (GHGs) emission can be estimated by the Swedish carbon tax [27]:

$$V_C = C_b \times M_C \quad (8)$$

...where V_C is the economic value associated with GHGs emission (RMB ha^{-1}), C_b is the Swedish carbon tax ($0.15 \text{ USD kg}^{-1} \text{ C}$, 1.02 and $1.01 \text{ RMB kg}^{-1} \text{ C}$ according to the exchange rate between RMB and USD in 2009 and 2010).

The economic value of ammonia volatilization (AV) from a paddy field can be estimated according to following equation:

$$V_{NH_3} = C_C \times M_{NH_3} \quad (9)$$

...where V_{NH_3} is the economic value of AV (RMB ha^{-1}), C_C is the marginal reduction cost of AV ($79.15 \text{ RMB kg}^{-1} \text{ N}$ according to the marginal reduction cost method, [28]), and M_{NH_3} is the volatilization of NH_3 from a paddy field, respectively (kg N ha^{-1}).

Then the economic value of gases exchange of paddy fields (V_G) is the sum of V_{O_2} , V_C , and V_{NH_3} :

$$V_G = V_{O_2} + V_C + V_{NH_3} \quad (10)$$

Statistical Analysis

Statistical analysis was carried out following standard procedures on a randomized plot design (SPSS 17.0). Significant comparisons were calculated based on F-tests and least significant difference (LSD) tests.

Table 3. Rice yield and irrigation water use efficiency.

Treatment		Yield (10 ³ kg ha ⁻¹)	Irrigation water volume (mm)	IWUE (kg m ⁻³)
2009	FI	10.3 a	635.95 b	1.63 b
	CI	9.89 a	233.30 a	4.24 a
2010	FI	9.26 a	645.00 b	1.44 b
	CI	9.36 a	263.00 a	3.56 a

Means in the same column in 2009 or 2010 followed by the same letter are not significantly different ($p < 0.05$).

Results and Discussion

Rice Yield and Irrigation Water Use Efficiency

Compared to FI, rice yields in CI treatment were reduced by 4.32% in 2009 and increased by 1.04% in 2010 (Table 3). But irrigation methods showed no significant difference on rice yield. However, irrigation water volume was dramatically reduced by 63.31% and 59.22% in 2009 and 2010 owing to the application of water-saving irrigation techniques. The maintenance of high rice yields and the significant reduction of irrigation water volume obviously improved the irrigation water use efficiency in the CI treatment. Irrigation water use efficiency of the CI treatment in 2009 and 2010 were 2.60 and 2.47 times higher than those of FI.

O₂ Emission and its Economic Value

Rice dry matter, calculated O₂ emissions, and their economic values with different irrigation methods are shown in Table 4. Water-saving irrigation increased rice dry matter compared to flooding irrigation, which was consistent with similar studies of different rice water-saving irrigation [29-30]. Seasonal O₂ emissions and their economic values calculated through dry matter amount also showed the same results as dry matter amount between different irrigation methods. The average O₂ emission and its value of CI paddy fields was 26.92×10³ kg ha⁻¹ and 10.77×10³ RMB ha⁻¹, both increased by 2.08% compared to FI paddy field. But the results of ANOVA showed that rice dry matter amounts,

O₂ emissions, and their economic values under different irrigation management had no significant difference. These values of O₂ emissions were similar to those for the paddy field ecosystems in suburban Shanghai, also located in the Taihu Lake region of China (9549 to 12277 RMB ha⁻¹, [13]).

GHG Regulation and its Economic Values

During the rice growth stage, a paddy field is as sink for CO₂, although the strength of the sink varies according to different irrigation modes (Table 5). The ANOVA results showed the CO₂ uptake in two irrigation managements showed no significant difference. CH₄ and N₂O emissions from paddy fields had an obvious trade-off relationship. The CH₄ emissions from the CI paddy field were significantly less than those from the FI paddy field ($p < 0.05$), on average by 81.80%. However, the N₂O emissions from the CI paddy field were significantly greater than those from the FI treatment ($p < 0.05$), on average by 136.86%. These results were due to CH₄ and N₂O formation in soils requiring contrasting soil redox potential (Eh) conditions. As a result, Yu and Patrick showed that ideal Eh values favoring N₂O formation (Eh > 180 mV) restricted CH₄ formation (which peaks at Eh = -150 mV) [31]. The non-ponding water management of a CI paddy field was the reason for mitigating CH₄ emissions and triggering substantial N₂O emissions in this study. Literature about the effect of other rice water-saving irrigation modes as intermittent irrigation, flooding-midseason drainage-frequent water logging with intermittent irrigation (FDF), and flooding-midseason drainage-reflooding-moist intermittent irrigation without water logging (FDFM) on CH₄ and N₂O emissions had been well documented [32-34]. In relation to continuous flooding irrigation, the intermittent irrigation reduced seasonal CH₄ emissions by 47%, and increased N₂O emissions by 876% in the Brazil paddy fields [35]. Midseason drainage significantly reduced seasonal CH₄ fluxes of paddy fields in South Korea by 50-53%, but significantly increased N₂O flux by 20-37% over conventional flooding [36]. Irrigation techniques had no significant effect on GHG regulation due to the main part of GHGs in this study being to uptake CO₂.

Table 4. Rice dry matter, O₂ emissions, and economic value.

Treatment		Dry matter (10 ³ kg ha ⁻¹)	O ₂ emission (10 ³ kg ha ⁻¹)	Value of O ₂ emission (10 ³ RMB ha ⁻¹)
2009	FI	22.64 a	26.94 a	10.78 a
	CI	23.12 a	27.52 a	11.01 a
2010	FI	21.68 a	25.80 a	10.32 a
	CI	22.12 a	26.32 a	10.53 a

Means in the same column in 2009 or 2010 followed by the same letter are not significantly different ($p < 0.05$).

Table 5. Seasonal CH₄, N₂O emissions, and uptake of CO₂.

Treatment		CO ₂ uptake (10 ³ kg CO ₂ ha ⁻¹)	CH ₄ emission (kg CH ₄ ha ⁻¹)	N ₂ O emission (kg N ₂ O ha ⁻¹)	GHGs regulation (10 ³ kg CO ₂ ha ⁻¹)
2009	FI	31.68 a	72.06 a	1.57 b	28.76 a
	CI	29.99 a	13.52 b	3.83 a	28.39 a
2010	FI	30.28 a	66.23 a	2.32 b	27.34 a
	CI	28.60 a	11.68 b	5.32 a	26.62 a

Means in the same column in 2009 or 2010 followed by the same letter are not significantly different ($p < 0.05$).

Table 6. Economical values of GHGs regulation (RMB ha⁻¹).

Treatment		CO ₂ up-take	CH ₄ emission	N ₂ O emission	GHGs regulation
2009	FI	8,852.31 a	-684.59 a	-130.41 b	8,037.31 a
	CI	8,380.90 a	-128.44 b	-318.62 a	7,933.85 a
2010	FI	8,384.49 a	-623.58 a	-191.53 b	7,569.38 a
	CI	7,919.55 a	-109.96 b	-439.36 a	7,370.23 a

Means in the same column in 2009 or 2010 followed by the same letter are not significantly different ($p < 0.05$).

Compared to FI treatment, CI management significantly reduced the negative economic value of CH₄ emissions on average by 81.80% from paddy fields, but significantly increased the negative economic value of N₂O emission on average by 136.86% (Table 6). The economic value of CO₂ uptake far outweighed the absolute value of negative economic values caused by CH₄ and N₂O emissions. Therefore, the economic values of GHGs regulation by rice paddies were all positive for both irrigation treatments. Moreover, ANOVA analysis showed that the differences among economic values of CO₂ uptake and GHGs regulation were not statistically significant. Average economic values of GHG regulations for FI and CI paddy fields were 7,803.35 and 7,652.04 RMB ha⁻¹.

Ammonia Volatilization and its Economic Value

Seasonal AV of CI treatment was 58.35 and 54.16 kg N ha⁻¹, reduced by 18.57% and 20.55% compared to FI in 2009 and 2010 (Fig. 1). Due to the reduction of seasonal AV, CI management significantly decreased economic value of AV ($p < 0.05$). The economic value of AV from CI treatment was 4,618.20 and 4,286.65 RMB ha⁻¹ in 2009 and 2010, with an average reduction of 19.56% compared to FI. AV

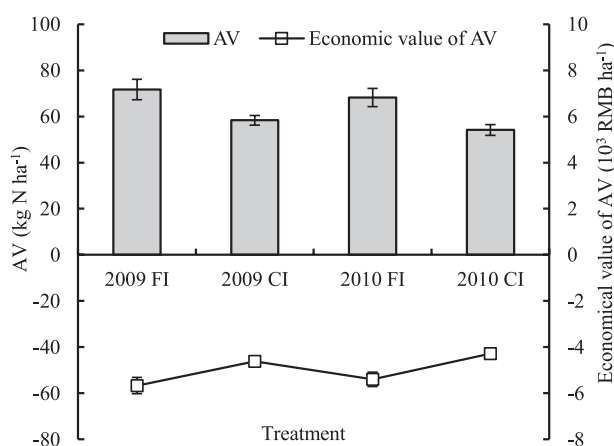


Fig. 1. AV from paddy fields and its economic values.

dominated the main part of nitrogen loss from paddy fields. Existing research shows that nitrogen loss through AV was about 10-60% of N application in a paddy field [37]. A large amount of AV would cause serious environmental problems as acidification, eutrophication of surface water [38], and changes in biodiversity. In this study, nitrogen loss caused by AV accounted for 17.89-22.52% of nitrogen fertilizer input. Much literature has addressed the variation, influencing factors, regulation measures, and so on of AV from paddy fields. But there has been no relevant research about the negative economic value of AV from paddy fields. The negative of economic value of AV from paddy fields under traditional flooding irrigation and water-saving irrigation were studied in this research.

Total Economic Values of Gas Exchange

Fig. 2 shows the economic values of gas exchange from paddy fields under different irrigation management. The economic values of gas exchange for CI paddy fields were 14.32×10^3 and 13.61×10^3 RMB ha⁻¹ in 2009 and 2010. For FI treatment, these values were 13.14×10^3 and 12.49×10^3 RMB ha⁻¹ in 2009 and 2010. Water-saving irrigation management had greater economic value of gas exchange of paddy fields, with an increase on average by 8.96% compared to traditional flooding irrigation while maintaining high rice yield and significantly decreasing irrigation water input.

There is a growing recognition through the rice-growing world that a better understanding of the ecosystem services of the rice environment is needed [9]. But relevant data are not available in many countries due to the challenge of some methodologies to measure and estimate the ecosystem service of paddy fields. This has led to the neglect and underestimation of rice paddies' ecosystem service in the process of agricultural policy-making. In China, large areas of paddy fields have been converted into urban and industrial lands with the acceleration of the urbanization process.

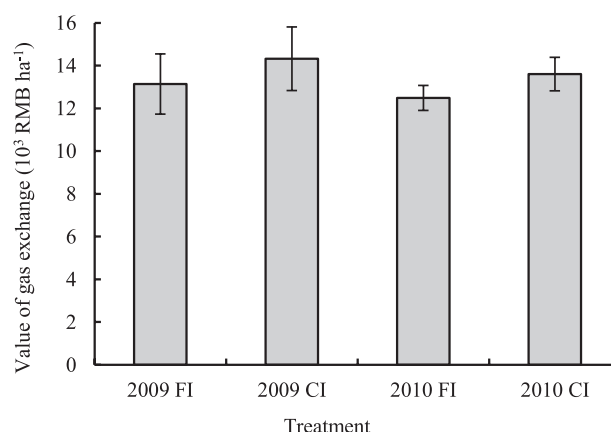


Fig. 2. Economic values of gas exchange of paddy fields.

Liu et al. found that the rice cultivation area of China showed a decreasing trend during 1980-2010, reduced from 33.87 million ha in 1980 to 29.87 million ha in 2010, and the lowest point appeared in 2003 (26.53 million ha) [39]. For China, which has a population of 1.38 billion [40], food security is an important basis for economic development, social stability, and national security [41]. In order to achieve sustainable development, conservation of existing rice paddies is one of the most important issues faced by the Chinese government for assuring food security [13]. Therefore, a comprehensive evaluation of rice field ecosystem is urgent. It enables people to realize the importance of rice fields, and also provides a scientific basis for setting agricultural policies.

Water scarcity is one reason for the decrease of rice planting area in China. With increasing water scarcity and rising grain demand, water-saving irrigation techniques are being widely implemented in paddy fields [17]. Rice water-saving irrigation can significantly reduce irrigation water input and maintain high rice yield. But its environmental effect has also aroused wide concern. As it can mitigate the greenhouse effect of methane and nitrous oxide emissions [33-34] and reduce nitrogen and phosphorus losses through runoff and leaching [3]. Water-saving irrigation affects not only the ability of rice fields to produce food but also the environment and the ecosystem service of rice fields. But relevant research about the effect of irrigation techniques on ecosystem service of paddy fields is not available. In this study, the value of gas exchange as a service in rice paddies under different irrigation modes was estimated. The results showed that water-saving irrigation management increased the economic value of gas exchange of paddy fields on average by 8.96% (1.15×10^3 RMB ha⁻¹) compared to traditional flooding irrigation while maintaining high rice yield and significantly decreasing irrigation water input. The study area located in Taihu Lake region, in which approximately 75% (1.24 million ha) of arable land is used for rice growth. In the event of a comprehensive promotion of rice water-saving irrigation in the Taihu Lake region, the irrigation input of rice cultivation will be decreased by 4.85 billion m³, and economic value of gas exchange of paddy fields will be increased by 1.42 billion RMB compared to traditional flooding irrigation according to the results of this study. The estimation showed that rice water-saving irrigation technique plays an important role in conserving and enhancing the economic value of gas exchange for rice paddies. In addition to gas exchange, rice paddies have some other ecosystem services, as primary production, soil organic matter accumulation, water regulation, and flood control and so on. Hence, further research about comprehensive evaluation of economic values of rice paddies under different irrigation modes is needed. This will contribute to widespread use of rice water-saving irrigation technologies and sustainable utilization of water and soil resources in paddy fields.

Conclusions

This is the first study to investigate the effects of rice water-saving irrigation on the economic value of gas exchange in a paddy field ecosystem. Three kinds of gas regulation services, the production of O₂, the regulation of GHGs, and the AV in rice paddy ecosystem were clearly affected by the irrigation method of rice. Compared to FI, CI led to a reduction by more than half of irrigation water input while maintaining high rice yield. The average O₂ emissions and its value of CI treatment were increased compared to FI, but the differences were not significant. A notable trade-off relationship between CH₄ and N₂O emissions was observed in the rice paddy ecosystem under both CI and FI. Compared to FI treatment, CI significantly reduced CH₄ emissions and its negative economic value on average, but significantly increased N₂O emissions and its negative economic value. CO₂ uptake of two irrigation management systems shows no significant difference. And the economic value of CO₂ uptake far outweighed the absolute value of negative economic values caused by CH₄ and N₂O emissions. Therefore, the economic values of GHG regulation by rice paddies were all positive for both irrigation treatments, and there was no significant difference. CI management triggered a significant decrease of AV and its economic value. Overall, water-saving irrigation management had greater economic value of gas exchange of paddy fields, increased on average by 8.96% compared to traditional flooding irrigation. According to the results of this study, 4.85 billion m³ of irrigation water will be saved and 1.42 billion RMB of ecosystem service value provided by gas exchange in paddy field will be increased in the event of a comprehensive promotion of rice water-saving irrigation in the Taihu Lake region. Our results suggest that CI significantly increased the economic value of gas exchange in the paddy field ecosystem while drastically reducing irrigation water input and ensuring crop yields.

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