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The value of gas exchange as a service by rice paddies in suburban Shanghai, PR China

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Abstract

Valuating ecosystem services is crucial for making the importance of ecosystem functioning explicit to the public and decision makers as well as scientists. Investigations of the value of agricultural ecosystems have focused mainly on value food and fibre production and been carried out at relatively coarse scales. However, such studies may have underestimated services provided by agricultural ecosystems because they did not consider additional services such as gas regulation, pollination control, nutrient transformation, and landscape aesthetics. We present the results of a field experimental study of gas regulation services and their economic values provided by rice paddy ecosystems in suburban Shanghai, China. Two major components of gas regulation by paddy fields are O_2 emissions and greenhouse gases (GHGs) regulation (including the uptake of CO_2 and emissions of CH_4 and N_2O). Seasonal emissions of O_2 from experimental plots with different urea application rates ranged from 25,365 to 32,612 kg ha^{-1} year^{-1}, with an economic value of 9549–12,277 RMB ha^{-1} year^{-1} (Chinese currency; 1 euro = 10.7967 RMB, Jan 18, 2005). The net GHGs regulation ranged from 705 to 2656 kg CO_2–C ha^{-1} year^{-1}, with an economic value ranging from 531 to 2000 RMB ha^{-1} year^{-1}. Thus, the overall economic value of gas regulation provided by the rice paddy ecosystems ranged from 10,080 to 14,277 RMB ha^{-1} year^{-1}. Our results refined, and in some cases, modified previous estimates of agricultural ecosystem services based mainly on coarse-scale studies. Our study also demonstrated a systematic method to valuate the gas regulation services provided by rice paddy ecosystems, which will be useful for understanding regulation of atmospheric chemistry and greenhouse effects by other agriculture ecosystems.

Keywords: Ecosystem services; Paddy rice ecosystem; Gas regulation; O_2 emission; GHGs emission

1. Introduction

Croplands are of great importance to human beings, as they provide most of our food and fibre. They also supply many other ecosystem services, such as modulating water quality and quantity, organic

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waste disposal, soil formation, biological nitrogen fixation, maintenance of biological diversity, biotic regulation, and contribution to global climatic regulation (Paoletti et al., 1992; Pimentel et al., 1997; Björklund et al., 1999). In fact, the contribution of these ecosystem services to human welfare may be comparable to that of food and fibre production (Pimentel et al., 1997). However, because most of these ecosystem services are indirect, they are seldom recognized by the general public (Lillemor and Söderqvist, 2002). Therefore, there is a need to develop an effective way of valuating the ecosystem services provided by croplands that is comprehensible to the public (Björklund et al., 1999).

In cropland ecosystems, plants transform solar energy into biotic energy through photosynthesis, fixing CO_2 and releasing O_2. Plants and soil organisms release CO_2 through respiration. In the rice paddy ecosystems, CH_4 and N_2O also are emitted throughout the growing season. CO_2, CH_4 and N_2O are all greenhouse gases (GHGs). Although they play a beneficial role in plant growth, all three gases contribute to greenhouse effect and adverse ecological consequences. Thus, GHGs sequestration by plants has positive economic values whereas GHGs emission has negative values. Studies have shown that a large amount of GHGs is released from the paddy fields and that a substantial quantity of CO_2 is sequestered by plants in paddy fields (Bruce et al., 1999; Liou et al., 2003; Zou et al., 2003; Yang and Chang, 1999). These two processes constitute the GHGs regulation by rice paddy ecosystems. China has the second largest amount of the rice paddy fields in the world in terms of the total area (Food and Agriculture Organization, 2003; http://apps.fao.org), and the gas exchange by these fields may be of global importance (Li et al., 2004). In particular, these rice ecosystem services may significantly affect GHGs regulation and thus have implications for understanding global climate change (Costanza et al., 1997).

A number of studies have investigated the emission of GHGs from rice paddies (Yagi and Minami, 1990; Khalil et al., 1991; Wang and Shangguan, 1996). Singh et al. (1999) reported that application of urea increased the seasonal CH_4 emission from rice paddies in India from 14.84 to 18.78 g m^{-2} (unfertilized) to 20.93 to 26.12 g m^{-2} (fertilized). Liou et al. (2003) studied the effects of nitrogen fertilization on the emission of CH_4 from rice paddy fields in Taiwan, and found that the seasonal methane flux in the first crop season with $NH_4{}^+$–N and $NO_3{}^-$–N ranged from 2.48 to 2.78 and from 8.65 to 9.22 g m^{-2}, respectively. The corresponding values in the second crop season ranged from 24.6 to 34.2 and from 36.4 to 52.6 g m^{-2}, respectively. Shangguan et al. (1993) studied the CH_4 emission from rice paddies in Zhejiang Province, China and found that the CH_4 flux (47.02 mg m^{-2} h^{-1}) from rice paddies without chemical fertilizer is higher than that with fertilizer (26.19 mg m^{-2} h^{-1}), while Chen et al. (1995) reported that urea application increased CH_4 emission by paddy fields from 3.4 to 4.2 mg m^{-2} h^{-1}. Xu et al. (1999) found that the N_2O fluxes increased rice paddies in Jiangsu Province from 5.08 μg m^{-2} h^{-1} (without chemical fertilizer) to 23.03 μg m^{-2} h^{-1} (with 300 kg ha^{-1} urea) and 36.45 μg m^{-2} h^{-1} (with 300 kg ha^{-1} ammonium sulphate). Also, Zou et al. (2003) examined the emissions of CH_4, N_2O and CO_2 from rice paddies in Jiangsu Province, and indicated that the rice paddy ecosystems were a net carbon sink when the net primary production and respiration of rice plants, soil respiration, and methane emission were all considered.

Recently, there have been a number of studies on the valuation of ecosystem services, and different perspectives and methods have emerged (Costanza et al., 1997; Daly, 1998; Daily et al., 2000; Wilson and Howarth, 2002). In one of the most influential and controversial papers on ecosystem valuation, Costanza et al. (1997) estimated that the economic values of the gas regulation by open oceans, grasslands, wetlands, and forests were 38 US\$ ha^{-1} year^{-1} (315 RMB ha^{-1} year^{-1}), 7 US\$ ha^{-1} year^{-1} (58 RMB ha^{-1} year^{-1}), 133 US\$ ha^{-1} year^{-1} (1101 RMB ha^{-1} year^{-1}), and 141 US\$ ha^{-1} year^{-1} (1167 RMB ha^{-1} year^{-1}), respectively, but it did not explicitly consider the gas regulation by agricultural fields. Björklund et al. (1999) compared the contributions of the agricultural ecosystems of Sweden to global climatic regulation in 1950s versus 1990s. Their results revealed that about 22% of the total emission of GHGs (in CO_2 equivalents) was abated by the gas regulation by the agricultural ecosystems. Kundhlande et al. (2000) estimated the value of carbon sequestration services provided by a savanna ecosystem in Zimbabwe to be 3200 ZW\$ ha^{-1} (5 RMB ha^{-1}), by multiplying the amount of carbon sequestered with the cost of damages caused by an additional tonne of carbon dioxide released into the atmosphere.

Although there has been a great deal of information from field experiments on the gas emission of croplands and other ecosystems, only few studies have been conducted to estimate the economic values of these ecosystem services. These studies were mainly conducted at state or national levels with relatively coarse spatial resolutions. Thus, we have conducted one of the first detailed, field experiment-based efforts that systematically value the gas regulation services of the rice paddy fields in a suburban area of Shanghai. In addition, we investigate the effects of the application of fertilizers on the economic values of gas regulation by rice paddy field.

2. Materials and methods

2.1. Experimental field and rice cultivation

We established an experimental rice paddy field to measure plant biomass production and gas fluxes on the Wusi Farm (not only for experiment) in suburban Shanghai in China (30°52′N, 121°45′E). The region is characterized by a northern subtropical climate with typical monsoonal features. During the growing season (from June to October), the mean temperature is about 25 °C, the relative humidity is 84.2%, the total precipitation is 607.7 mm, and the total amount of sunshine is about 888 h. We measured the following soil properties of the rice paddy fields: pH 7.9–8.0, organic matter content 18.8 g kg^{-1}, total N 1.24 g kg^{-1}, available N 60.5 mg kg^{-1}, available P 23.1 mg kg^{-1}, available K 230 mg kg^{-1}, and salt content 0.08%.

The experimental site included 15 plots of about 25 m^2 each, and the experiment followed a completely randomized block design. A 0.5-m wide buffering zone separated the experimental field from other rice fields, and all the plots were separated by artificially-built levees (Fig. 1). The rice variety 9734 was seeded directly in the fields. At the time of plowing, 375 kg ha^{-1} of calcium superphosphate was applied to each plot as a basal treatment. Urea fertilizer was added to the soil at five levels: 0 kg N ha^{-1} (treatment N0), 225 kg N ha^{-1} (treatment N1), 300 kg N ha^{-1} (treatment N2), 375 kg N ha^{-1} (treatment N3), and 525 kg N ha^{-1} (treatment N4), with each level applied to three replicate plots. The urea applications were spread over four plant growth stages: seedling (June 18), tillering (July 2), booting (August 9), and flowering (August 20). Except for the urea application, all other agricultural practices were the same for all the plots. The entire experimental duration was 130 days, and included the following field operations: plowing on May 27, flooding on June 4, seeding on June 7, continued flooding until October 2 (with intermittent irrigation from July 15 to August 2), and harvesting on October 15.

Fig. 1. The layout of the experimental plots in the Wusi Farm of suburban Shanghai.

2.2. Gas sampling

Fluxes of CH_4, N_2O and CO_2 were measured using the static chamber technique as described by Singh et al. (1999). Compared to continuous chamber techniques, static chamber techniques need more people to sample, are more subject to environment (such as raining and night) and get less samples, but these techniques are simpler, cheaper, and less destructive to the rice paddy fields. Based on the statistical analysis of about 30,000 gas flux measurements from rice paddy fields in China, Li et al. (1998a) demonstrated that samples taken with static chamber techniques could accurately estimate seasonal methane fluxes compared with continuous measurements. Thus, static chamber techniques have been used worldwide (e.g., Cicerone et al., 1983; Seiler et al., 1984; Sass et al., 1991).

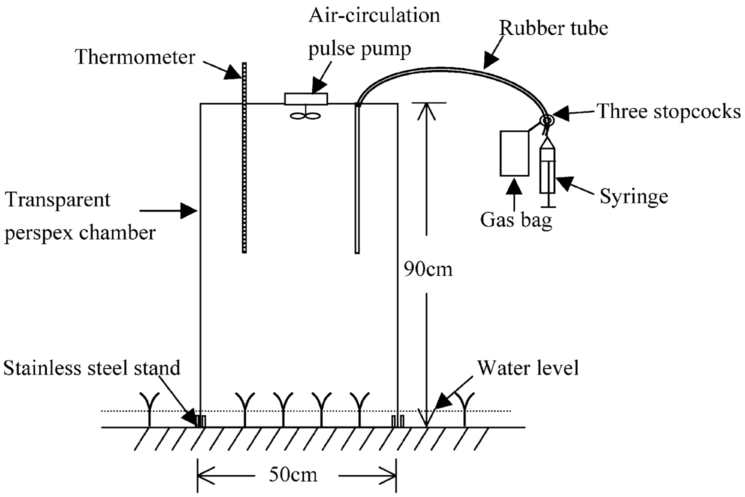

Fig. 2. Illustration of the static chamber used to measure gas fluxes in the rice paddy fields.

We used a transparent perspex chamber ($L \times W \times H = 50$ cm × 50 cm × 95 cm, covering an area of 0.25 m^2) with a stainless steel stand placed under water (Fig. 2). A battery-operated air-circulation pulse pump mounted on the top of the chamber mixed the air inside the chamber. A rubber tube was inserted into the chamber from the top, and was connected outside to three stopcocks used to draw air samples (0, 15 and 30 min) with the 100 ml syringe from the headspace into gas bags (Guangming Research & Design Institute of Chemical Industrial, Dalian, China). Gas samples were taken at different rice growth stages on the 15th, 18th, 21st and 25th of August, and the 2nd, 8th, 14th and 22nd of September. Samples were taken between 09:00 and 11:00 in the morning. The temperature inside the perspex chamber was recorded using a mercury thermometer inserted through a rubber septum installed at the top of the chamber. Our sampling procedures and time schedule were similar to those in other studies (e.g., Singh et al., 1998; Liou et al., 2003; Suratno et al., 1998).

To measure CH_4, air samples were analyzed on a gas chromatograph equipped with a flame ionization detector (FID) and Porapak Q column. The temperatures of the detector and the column were maintained at 90 and 150 °C, respectively. Nitrogen, with a flow rate of 23 ml min^{-1}, served as carrier gas. To measure N_2O, we used a gas chromatograph equipped with an electron capture detector (ECD) and Porapak Q column with the temperatures of the detector and the column were the same as for CH_4. The carrier gas for N_2O was a mixture of argon and 5% CH_4 with a flow rate of 25 ml min^{-1}. The concentration of CO_2 was measured with LI-COR6252 carbon dioxide infrared analyzer. Fluxes were calculated from changes in CH_4, N_2O and CO_2 concentration in the headspace of the chamber using the following equation (Singh et al., 1998):

$$F = \frac{dm}{A dt} = \frac{\rho V dc}{A dt}. \tag{1}$$

For our study this equation was reduced to:

$$F = \frac{MPh}{RT}\frac{dc}{dt} \tag{2}$$

where F is the gas flux (mg m^{-2} h^{-1}); ρ the gas density; R the gas constant; dm and dc the rates of changes in the quality and concentration of gases in the chamber, respectively; h, A and V the height (m), bottom area (m^2) and volume (m^3) of the chambers; M the molecular weight of the gas; and T and P the temperature (K) and air pressure (Pa) inside the chamber. The seasonal CO_2 emission was computed as the product of the flux of CO_2 and the rice growth period.

2.3. Paddy biomass measurement

At the mature seed stage, rice hills similar to those within the area covered by the stainless steel stands were harvested with roots to estimate biomass. The roots were carefully washed with tap water to remove attached soil, and subsequently were separated from shoots. Roots, shoots and seeds were dried separately at 120 °C for 24 h to estimate paddy biomass production.

2.4. Estimating the economic value of gas regulation

Based on paddy biomass, O_2 emission was estimated used the formula of photosynthesis (Guo et al., 2001):

$$\underset{264}{6n\mathrm{CO_2}} + 6n\mathrm{H_2O} \rightarrow \underset{180}{n\mathrm{C_6H_{12}O_6}} + \underset{192}{6n\mathrm{O_2}} \rightarrow \underset{162}{n\mathrm{C_6H_{10}O_5}}. \quad (3)$$

That is, while producing 162 g of plant biomass (dry weight), paddy fields can supply 192 g of O_2. We calculated the economic value of O_2 emission from paddy fields using the average value of the price of industrial O_2 and the cost of afforestation in China (Ouyang et al., 1999):

$$V_{\mathrm{O_2}} = \frac{1}{2}\left(C_{\mathrm{p}} + C_{\mathrm{f\_O_2}}\right) \times M_{\mathrm{O}} \quad (4)$$

where $V_{\mathrm{O_2}}$ is the economic value of O_2 emission (RMB $\mathrm{ha^{-1}}$), C_{p} the price of industrial O_2 in China (0.4 RMB $\mathrm{kg^{-1}}$; NBSC, 1992), $C_{\mathrm{f\_O_2}}$ the cost of afforestation in China (0.3529 RMB $\mathrm{kg^{-1}}$; MFC, 1990), and M_{O} the O_2 emission from paddy fields (kg $\mathrm{ha^{-1}}$).

Global warming potential (GWP) can be used to compare the impacts of emissions and reductions of different gases (EPA, 2002). GWP is defined as the direct and indirect effects of cumulative radiative forcing integrated over a period of time from the emission of a unit mass of a gas relative to some reference gas (Houghton et al., 1996). We chose carbon dioxide (CO_2) as the reference gas. The GWP values of CH_4 and N_2O are 21 and 310, respectively (in a timeframe of 100 years; Houghton et al., 1996). Thus, the fluxes of CH_4 and N_2O from paddy fields can be converted to CO_2 equivalents (Ghosh et al., 2003), which can further be converted to the pure C flux using the following equation:

$$M_{\mathrm{C}} = 0.2729 \times \alpha \times M \quad (5)$$

where M_{C} is the emission of CO_2, CH_4 or N_2O in pure C (kg $\mathrm{ha^{-1}}$); α the GWP of CO_2, CH_4 and N_2O, which is 1, 21 and 310, respectively (Houghton et al., 1996); M the emission of CO_2, CH_4 or N_2O (kg $\mathrm{ha^{-1}}$). Note that the flux of CO_2 was the net flux of the rice paddy ecosystems that is the balance among the fluxes of CO_2 fixed by photosynthesis minus the CO_2 released by plant respiration and emitted by paddy soils.

The economic value associated with GHGs emission can be estimated using the average value of the Sweden carbon tax (SEPAC, 1997) and the cost of afforestation in China (Ouyang et al., 1999; Dixon et al., 1993; Hall and House, 1994), using the following equation:

$$V_{\mathrm{C}} = \frac{1}{2}\left(C_{\mathrm{t}} + C_{\mathrm{f\_CO_2}}\right) \times M_{\mathrm{C}} \quad (6)$$

where V_{C} is the economic value associated with GHGs emission, C_{t} the Sweden carbon tax (1.245 RMB $\mathrm{kg^{-1}}$; SEPAC, 1997), $C_{\mathrm{f\_CO_2}}$ the average cost of afforestation in China (0.2609 RMB $\mathrm{kg^{-1}}$; MFC, 1990), and M_{C} the same as in Eq. (5).

2.5. Statistical analysis

The one-way analysis of variance (ANOVA) and Duncan's multiple range test ($p = 0.05$) were used to determine the temporal variations of gas fluxes, and examine the effects of fertilizer application on the flux density, seasonal emission and economic values. Statistical analyses were performed using the statistical software package SPSS (Windows version 11.5; Statistical Product and Service Solutions Inc.).

3. Results and discussion

3.1. Biomass production, O_2 emissions, and their economic values

Biomass production and calculated O_2 emission and their economic values with different dose of nitrogen fertilizers are shown in Table 1. In general, urea application increased rice biomass production, which was consistent with other similar studies of different rice varieties (e.g., Singh et al., 1999; Shen et al., 2003). The plots with treatment N3 (addition of 375 kg N $\mathrm{ha^{-1}}$of urea) produced the highest biomass among the four treatments. Seasonal O_2 emission, calculated using the biomass data, also increased with

Table 1
Seasonal biomass and O_2 emissions and their economic values from paddy fields with different urea application treatments

Treatment	Biomass (10^3 kg ha^{-1} $year^{-1}$)	O_2 emission (10^3 kg ha^{-1} $year^{-1}$)	Value of O_2 emission (10^3 RMB[a] ha^{-1} $year^{-1}$)
N0	21.32 ± 2.23 a	25.36 ± 2.65 a	9.55 ± 1.00 a
N1	23.10 ± 2.38 ab	27.49 ± 2.83 ab	10.35 ± 1.06 ab
N3	27.41 ± 1.93 b	32.61 ± 2.30 b	12.28 ± 0.86 b
N4	26.88 ± 0.15 b	31.99 ± 0.18 b	12.04 ± 0.07 b

All values are represented as mean ± S.D., and the numbers in the same column that do not share the same alphabets are significantly different at the 5% significance level according to the Duncan's multiple range test.

[a] 1 euro = 10.7967 RMB, Jan 18, 2005.

urea application. The results of ANOVA showed that the average seasonal O_2 emission with treatment N1 was significantly different from that with treatment of N3 and N4 because of the enhancement of urea application on the productivity of paddy fields as reported in Singh et al. (1999) and Shen et al. (2003). We estimated the economic value of O_2 emission of the paddy ecosystems with different urea application treatments to range from 9549 to 12,277 RMB ha^{-1} $year^{-1}$ (Table 1). These values were higher than those for the rice paddy ecosystems in Guangzhou of Southeast China (3955 RMB ha^{-1} $year^{-1}$) as reported in Xu et al. (2003).

3.2. GHGs regulation and its economic values

3.2.1. CO_2 fluxes

Rice paddy fields were net sinks for CO_2 both on a measured flux (Table 2) and calculated seasonal uptake (Table 3) basis. While our values are for the season during which rice is produced in these fields, annual gas exchange values would have to consider other crops grown in these fields during other seasons and fallow periods. Although our ANOVA analysis indicated that the different urea treatments produced no significant differences in CO_2 flux, the plots receiving 300 kg N ha^{-1} urea (treatment N3) took up the most CO_2 (Tables 2 and 3). However, the plots with 525 kg N ha^{-1} of urea (treatment N4) assimilated less CO_2 than treatment N3 (Tables 2 and 3). This might have been caused by the acceleration of soil microbial activities by the excessive available N that produced more CO_2 through respiration. This needs to be further confirmed by mechanistic studies. Meanwhile, it has been reported that extremely high dosage of urea can inhibit the growth of crops (Bloom et al., 1993).

3.2.2. CH_4 flux

The average flux and seasonal emission of CH_4 from paddy fields decreased significantly with increasing urea application rates (Tables 2 and 3). Methane production decreases when soil pH is too low or too high because most methanogenic bacteria grow in soils with a pH value of 6.5–7.5 (Mah and Smith, 1981; Wang et al., 1993). The soil pH of our experiment field was about 8.0, which was unfavorable for methane production. Urea application can increase soil pH, and may have further inhibited methane emission in the paddy fields. Our results supported the finding that urea application reduces CH_4 emission (Schütz et al., 1989; Wassmann et al., 1994; Yang and Chang, 1998).

Table 2
Fluxes of CH_4, CO_2 and N_2O from paddy fields with different urea application treatments, given in mg m^{-2} h^{-1}

Treatment	CO_2 uptake[a]	CH_4 emission	N_2O emission
N0	411.89 ± 170.42 a	15.45 ± 4.52 c	0.0149 ± 0.0078 a
N1	469.60 ± 170.03 a	12.54 ± 3.96 bc	0.0211 ± 0.0139 a
N3	500.11 ± 233.54 a	8.51 ± 3.92 ab	0.0304 ± 0.0231 ab
N4	364.09 ± 81.42 a	8.07 ± 3.82 a	0.0440 ± 0.0259 b

All values are represented as mean ± S.D., and Duncan's multiple range test was used to detect differences between treatments at the 5% significance level.

[a] CO_2 uptake rates are net exchange values considering CO_2 loss from respiration.

Table 3
Seasonal emission of CH_4 and N_2O and seasonal uptake of CO_2 from paddy fields with different urea application treatments

Treatment	CO_2 uptake[a] (10^3 kg CO_2 ha^{-1} year^{-1})	CH_4 emission (kg CH_4 ha^{-1} year^{-1})	N_2O emission (kg N_2O ha^{-1} year^{-1})	GHGs regulation (10^3 kg C ha^{-1} year^{-1})
N0	12.85 ± 5.32 a	482.06 ± 141.11 c	0.47 ± 0.24 a	0.70 ± 1.28 a
N1	14.65 ± 5.31 a	391.16 ± 123.40 bc	0.66 ± 0.43 ab	1.70 ± 1.48 ab
N3	15.60 ± 7.29 a	265.50 ± 122.24 ab	0.95 ± 0.72 ab	2.66 ± 2.26 b
N4	11.36 ± 2.54 a	251.68 ± 119.06 a	2.12 ± 2.71 b	1.49 ± 1.08 ab

Values are represented as mean ± S.D., and Duncan's multiple range test was used at the 5% significance level.

[a] CO_2 uptake rates are net exchange values considering CO_2 loss from respiration.

3.2.3. N_2O flux

The flux of N_2O (Table 2) and seasonal emission rate (Table 3) increased with urea application rates. The results of ANOVA analysis indicated that significant differences existed among urea application treatments. The concentration of soil NH_4^+ likely increased with urea application, which enhanced nitrification and denitrification processes to produce more NO_2^- (e.g., Xu et al., 1998; Suratno et al., 1998).

3.2.4. GHGs regulation and its economic values

During the rice cultivation period, all plots were sinks for GHGs (i.e., uptake rates > emission rates) although the strength of the sinks varied with different urea application treatments. Our ANOVA analysis showed that the differences among urea treatments were statistically significant. The plots of treatment N3 receiving 375 kg N ha^{-1} of urea, which was comparable to the actual urea application rate by the farmers in the area (330 kg N ha^{-1}), had the largest average GHGs uptake rate (2656 kg CO_2–C ha^{-1} year^{-1}).

Correspondingly, the economic value of GHGs regulation by rice paddies was positive for all the plots although the exact value varied with different urea application treatments. The economic value increased with increasing urea addition, peaking at treatment N3 (375 kg N ha^{-1}), and then declining at treatment N4 (Fig. 3). The economic values for CO_2 fixation by the paddy fields ranged from 2334 to 3206 RMB ha^{-1} year^{-1} (Fig. 3). The economic values of the emissions of methane and N_2O were negative because of these adverse impacts on the environment. Urea application increased the economic value of CH_4 release (i.e., becoming less negative), whereas the plots with the most urea application (N4 treatment) had the most negative values for N_2O emission. Thus, the maximum value of GHGs regulation was obtained at a medium level of urea application. In our experiment, this level was 375 kg N ha^{-1}, which was close to the field application rate of 330 kg N ha^{-1} in this area.

3.3. Overall economic value of rice paddy ecosystems

The economic values of specific gas regulation services (including O_2 emission and GHGs regulation) supported by paddy fields were summed up to obtain the overall economic values for different treatments. Our results showed that the overall values were all positive, implying that these ecosystems actually contribute to environmental sustainability in terms of the production of O_2 and reduction of GHGs. The maximum overall economic value of gas regulation was provided by the paddy fields with treatment N3.

3.4. Necessity to protect the rice paddies in China

In the past 20 years, rice paddy ecosystems have been regarded as a source of GHGs (Yagi and Minami, 1990; Khalil et al., 1991; Ghosh et al., 2003), contributing to the changes in atmospheric chemistry and global warming (Bouwman, 1991). However, the gas regulation services provided by rice paddy ecosystems have not been well studied at fine scales, and usually neglected or underestimated in the process of agricultural policy-making.

The role of croplands is usually perceived only to produce food and biomass, and thus the cost-benefit of crop fields is also considered to be lower than that of other land-use types. However, the economic values of rice paddy fields in terms of gas regulation are higher than urban areas and natural grasslands (Table 4). While the paddy fields have caused a great deal of concern for the emissions of GHGs (Yagi and Minami,

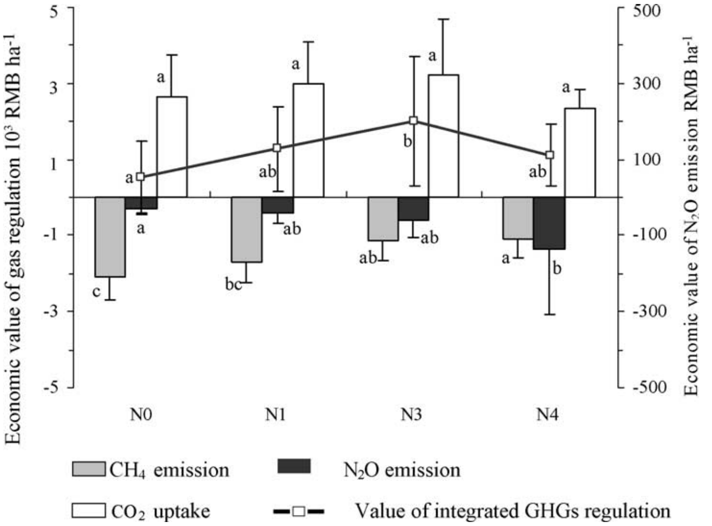

Fig. 3. The estimated economic values of CO_2 uptake, CH_4 emission, N_2O emission, and overall GHGs regulation from the rice paddy ecosystems during the growing season with different urea application rates in suburban Shanghai, China. The bars are the means of eight measurements ± S.D., each of which is the average of three reduplicate plots. Letters a, b, and c beside the same legend denote the significant difference in Duncan's multiple range test (at the 5% significant level) across four N treatments for CH_4 emissions, or N_2O emissions, or CO_2 uptake or integrated CHGs regulation.

Table 4
Comparison of gas exchanges among agricultural, urban, and natural ecosystems

Ecosystem types	Paddy fields in our study	Other paddy fields	Wheat fields	*Leymus chinensis* steppe	Urban area
O_2 emission (kg ha^{-1} $year^{-1}$)	24128	25686[f]	13384[f]	6160[h]	3843[j]
Economic value of O_2 emission (RMB[a] ha^{-1} $year^{-1}$[b])	9083	9669	5038	2319	1447
GHGs exchange in CO_2 equivalents[c] (kg ha^{-1} $year^{-1}$)	5185	21884	6925	1586	2793
Net CO_2 fixation	13615	35184[f]	18333[f]	8470[h]	2793[j]
CO_2 emission by soil		−7993[f]	−9706[f]	−6637[h]	
CH_4 emission	−8126	−4591[g]	–	79[i]	–
N_2O emission	−304	−716[g]	−1702[f]	−326[i]	–
Economic value of GHGs exchange (RMB[a] ha^{-1} $year^{-1}$)[d]	3904	16478	5214	1194	2103
Total economic value (RMB[a] ha^{-1} $year^{-1}$)[e]	12987	26147	10253	3513	3549

[a] 1 euro = 10.7967 RMB, Jan 18, 2005.

[b] The economic values were calculated with Eq. (3) in the text.

[c] GHGs exchanges were the sums of the net CO_2 fixation by plants, CO_2 emission by soil, CH_4 emission and N_2O emission from the paddy fields in CO_2 equivalents. The negative numbers denote GHGs emission whereas the positive ones represent GHGs absorption.

[d] The economic values were calculated with Eq. (5) in the text.

[e] Total economic values were based on the sums of O_2 emission and GHGs exchange.

[f] Xu et al., 1998 (rice paddy fields in Jiangsu Province, China).

[g] Zheng et al. (1997)(rice paddy fields and wheat fields in Jiangsu Province, China).

[h] Li et al. (1998b). O_2 emission and CO_2 exchange (mean flux × 130 days) were for the natural grassland, *Leymus chinensis* steppe, in Inner Mongolia, China.

[i] Dong et al. (2000). The CH_4 absorption and N_2O emission (mean flux × 130 days) were for the natural grassland, *Leymus chinensis* steppe, in Inner Mongolia, China.

[j] The O_2 emission and net CO_2 absorption (mean flux × 130 days) were the means of three types of greenspace in urban areas (Li et al., 1999) with a coverage of 17.8% in Shanghai, China (Zhang et al., 2000).

1990; Khalil et al., 1991; Wang and Shangguan, 1996), rice paddy fields, being highly productive, actually could be a more significant sink of GHGs than other crops and natural ecosystems, despite the emission of CH_4 and N_2O (Table 4).

Large areas of farmland have been converted into urban and industrial lands in China with its rapid economic developments. Liu et al. (2003) estimated that 81% of newly converted lands in the 1990s were previous croplands, most of which croplands were paddy fields. China has the worlds largest human population of over 1.3 billions (National Bureau of Statistics of China, 2003), and the security of food supply is critical to the economic development and social stability of the country while maintaining environmental sustainability (Wu and Overton, 2002; Wu et al., 2002). Conservation of the existing croplands is one of the most important issues faced by the Chinese government to assure the food security of the country. To help address this issue, it is necessary for scientists to provide comprehensive valuations of crop fields. Our study was a step towards this direction, and more studies for different kinds of croplands and at different spatial scales are needed.

4. Conclusions

Two kinds of gas regulation services are provided by paddy fields: the production of O_2 and the regulation of GHGs (balance among the uptake of CO_2 and the emissions of CH_4 and N_2O). Our study showed that, during a single cultivation period, the rice paddy fields in the suburban Shanghai produced about 25,365–32,612 kg ha^{-1} $year^{-1}$ of O_2 with urea application. The economic value of the O_2 production was assessed to be about 9549–12,277 RMB ha^{-1} $year^{-1}$. Consumption of O_2 by soil respiration was not taken into account, but this may have resulted in only a slight overestimation of the economic value of O_2 production by rice paddies.

Until now, paddy fields have been regarded as the second largest source of atmospheric CH_4 next to cattle (Wang and Shangguan, 1996). They also have been considered to be a source of other GHGs such as N_2O and CO_2. However, our results have showed that rice paddy ecosystems may function as a significant CO_2 sink during the growing season. In CO_2 equivalents, the GHGs regulation by rice paddies was estimated to be 705–2656 kg CO_2–C ha^{-1} $year^{-1}$ based on the global warming potential (GWP). Its economic value was estimated to be 531–2000 RMB ha^{-1} $year^{-1}$. Our study showed that the plots of treatment N3 (addition of 375 kg N ha^{-1} of urea) provided the highest economic value of GHGs regulation, indicating a threshold effect of urea application on GHGs regulation.

Because the overall economic values of the gas regulation of and by rice paddy ecosystems were positive, we conclude that these ecosystems actually contribute to environmental sustainability in terms of the production of O_2 and reduction of GHGs in our study area. However, we caution that paddy fields in other areas with different agricultural practices (including fertilizer applications) may prove otherwise. Also, it must be noted that our study was conducted at a local scale, focusing on an individual paddy field. Whether landscape heterogeneity and different agricultural practices at large spatial scales may alter our results is yet to be tested, and is necessary for scaling up of our findings to the regional or national level.

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