Evaluation of Ecosystem Services Provided by 10 Typical Rice Paddies in China

XIAO Yu*, AN Kai, XIE Gaodi and LU Chunxia

Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China

Abstract: Based on reference review, this study investigated ecosystem services supported by 10 typical rice paddies in six rice planting regions of China. The services were primary production, gas regulation, nitrogen transformation, soil organic matter accumulation, and water regulation and flood control. The results indicated that grain production of the 10 rice paddies was between 4.71 and 12.18 t ha\(^{-1}\) y\(^{-1}\); straw production was 4.65 to 9.79 t ha\(^{-1}\) y\(^{-1}\); gas regulation was calculated to emit O\(_2\) ranging from 8.27 to 19.69 t ha\(^{-1}\) y\(^{-1}\) and to assimilate greenhouse gases ranging from -2.13 to 19.24 t ha\(^{-1}\) y\(^{-1}\) (in CO\(_2\) equivalent); nitrogen transformation was estimated as nitrogen input ranging from 209.70 to 513.93 kg N ha\(^{-1}\) y\(^{-1}\) and nitrogen output of 112.87 to 332.69 kg N ha\(^{-1}\) y\(^{-1}\); soil organic matter accumulation was calculated to be between 0.69 and 4.88 t C ha\(^{-1}\) y\(^{-1}\); water regulation was estimated to consume water resources of 19875 m\(^3\) ha\(^{-1}\) y\(^{-1}\) and to support water resources of 6430 m\(^3\) ha\(^{-1}\) y\(^{-1}\); and flood control of several of the rice paddies was calculated to be 1500 m\(^3\) ha\(^{-1}\) y\(^{-1}\). The integrated economic value of ecosystem services of these rice paddies was estimated at USD 8605–21 405 ha\(^{-1}\) y\(^{-1}\), of which 74%–89% of the value can be ascribed to ecosystem services outside primary production. The results also indicated that the integrated economic value of the ecosystem services of the 10 rice paddies was higher when nitrogen fertilizer was applied in the range of 275 to 297 kg N ha\(^{-1}\). Until now, the economic value of the rice paddy ecosystem has been underestimated as only the economic value of grain and straw production was previously calculated. As more and more forest land and grassland is lost to urban and industrial use, cropland and especially rice paddies, will become more ecologically important to society. The economic value of ecosystem services supplied by rice paddies, outside primary production, are worthy of increased research attention.

Key words: rice paddy; ecosystem services; gas regulation; soil organic matter accumulation; nitrogen transformation

1 Introduction

Rice paddies are the largest human controlled ecosystem. They provide a number of ecosystem services such as food production, nutrient cycling, soil protection, flood control, gas regulation, pollination, aesthetic scenery and provide habitat for birds, insects and soil organisms (Xiao et al. 2005b; Pan et al. 2009; Köel-Knabner et al. 2010; Verhoeven and Setter 2010; Yoshikawa et al. 2010; Zhang et al. 2010a). At the same time, rice paddy ecosystems can have adverse effects on the environment when there is an excessive addition of chemical fertilizers and pesticides and through greenhouse gases emissions (Knoblauch et al. 2010; Itoh et al. 2011).

According to FAOSTAT, 1.58×10\(^8\) ha of rice was planted globally in 2009, and the rice grain yield was 6.85×10\(^3\) t, accounting for 28% of the world grain production. In 2009, the rice grain yield in China was 1.95×10\(^3\) t, which amounted to 40% of the total grain yield in China (NBSC 2010). For most countries in Southeast Asia rice is the most important food source. Further, rice straw is the main fuel for many rural families and is an important material for several industries (Ferng 2005; de Fraiture et al. 2010; Godfray et al. 2010). During the rice growth period, the rice plant assimilates CO\(_2\) and emits O\(_2\) through photosynthesis, and emits CO\(_2\) and consumes

Received: 2011-06-27 Accepted: 2011-10-21

Foundation: Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05050203); National Natural Science Foundation of China (31140048, 30770410 and 31070384); Innovation Project of Institute of Geographic Sciences and Natural Resources Research, CAS (200905010).

* Corresponding author: XIAO Yu. Email: xiaoy@igsnrr.ac.cn.
O₂ through respiration. The rice paddy ecosystem has received considerable attention as the main source of CH₄ and N₂O (Lee et al. 2010; Itoh et al. 2011). Bouquet et al. (2006) indicated that CH₄ emission from natural wetlands and rice paddies accounted for 34% of the total CH₄ emissions globally. The IPCC (2007) estimated that N₂O emissions from agricultural sources amounted to 60% of the global N₂O emissions from anthropogenic sources, and that N₂O emissions from agricultural sources increased by 17% from 1990 to 2005. Rice paddy soil is one of the main sources of N₂O as paddy soil alternates between dry and wet conditions with intermittent irrigation.

Nutrient transformation in the rice paddy improves soil nutrient levels and enhances rice yield. Based on a long term field experiment from 1986 to 2003, Tong et al. (2009) found that the soil nitrogen content of rice paddy increased 5.2%–27.1% when NPK fertilizer was applied, compared to farming practices without the application of fertilizer. This occurred irrespective of the amount of manure applied. However, over-use of fertilizer usually increases nutrient loss through surface water and ground water from drainage, leaching and NH₃ volatilization, and this can result in eutrophication and ground water nitrite pollution (Köl-Knabner et al. 2010; Xiao et al. 2010). From field experiments, Liang et al. (2007) found that the proportion of nitrogen loss from rice paddy by NH₃ volatilization, drainage and leaching was 27.9%, 6.6% and 9.6% of total nitrogen added, respectively.

Paddy soil organic matter increases following rice cultivation. Based on a long term experiment Rui and Zhang (2010) estimated that paddy soil organic matter increased between 0.41 Mg ha⁻¹ y⁻¹ and 0.34 Mg ha⁻¹ y⁻¹ through straw abandonment and the application of manure. Rice paddy ecosystems consume water through irrigation, supplied surface water with drainage systems, and recharge ground water after irrigation and precipitation. The integration of rice paddies, ditches and ponds in rural areas serve as a reservoir to control flooding. In Niigata, Japan, Yoshikawa et al. (2010) simulated the flood mitigation performance of paddy fields where runoff control devices had been installed. The results showed that the main channel discharge would have decreased by 26% and the water level dropped by 0.17 m in the case of the largest observed rainfall event.

There has been controversy around the outcomes of intensive rice farming and rice paddy ecosystems. The passive effects of intensive rice farming are things such as environmental pollution and climate change. The traditional rice paddy ecosystem is now seen to support many fundamental and essential goods and services for people. Thus, it is crucial to investigate the integrated impacts of rice paddy ecosystems on human well-being. Here, ecosystem services such as primary production, gas regulation, nitrogen transformation, soil organic matter accumulation and water regulation and flood control by 10 typical rice paddies across six rice planting regions of China were examined. The impact of nitrogen fertilizer application is also investigated.
2 Material and methods

2.1 Focal rice paddies

According to biophysical characteristics (temperature, sunlight and location) and management practices (planting system, application of fertilizer and water management), rice planting in China is divided into six rice planting regions (CNRRRI 1988). They are the Double Harvest Rice Area in South China (DHRASC), the Double and Single Harvest Rice Area in Central China (DSHRACC), the Single and Double Harvest Rice Area on the Plateau of Southwest China (SDHRAPSC), the Single Harvest Rice Area in North China (SHRANC), the Single Early Harvest Rice Area in Northeast China (SEHRANC), and the Single Harvest Rice Area in the Arid Region of Northwest China (SHRAARNC) (Fig. 1). We selected 10 typical rice paddies from these rice planting regions to examine ecosystem services of rice paddies. They were located at Guangzhou in Guangdong Province, Changshu in Jiangsu Province, Chengdu in Sichuan Province, Taoyuan in Hunan Province, Yingtan in Jiangxi Province, Bijie in Guizhou Province, Fengqiu in Henan Province, Shenyang in Liaoning Province, Hailun in Heilongjiang Province, and Lingwu in Ningxia Hui Autonomous Region (Table 1).

2.2 Method to estimate ecosystem services by rice paddies and their economic values

2.2.1 Primary production

Primary product outputs from rice paddies include grain and straw. The economic value of primary production is estimated by the following equation:

\[ V_{pp} = q_s \times p_s + q_{st} \times p_{st} \]  

(1)

where \( V_{pp} \) is the economic value of primary production of the rice paddy (USD ha\(^{-1}\) y\(^{-1}\)); \( q_s \) is the quantity of rice grain (kg ha\(^{-1}\) y\(^{-1}\)); \( p_s \) is the price of rice grain (USD 0.28 kg\(^{-1}\); early rice, USD 0.29 kg\(^{-1}\); late rice, and USD 0.31 kg\(^{-1}\) for single rice) (DPNDRC 2010) (USD 1 = 6.831 CNY in 2009); \( q_{st} \) is the quantity of rice straw (kg ha\(^{-1}\)); and \( p_{st} \) is the price of rice straw (USD 0.01 kg\(^{-1}\)) (DPNDRC 2010).

2.2.2 Gas regulation

In the rice paddy ecosystem, plants transform solar energy into biotic energy through photosynthesis, fixing CO\(_2\) and releasing O\(_2\). At the same time, plants and organisms in the soil emit CO\(_2\) and consume atmospheric O\(_2\) through respiration. In this study, O\(_2\) emission and the economic value were estimated using the following equations (Xiao et al. 2011):

\[ Q_o = 1.19 \times m_{np} - q_{so} \]  

(2)

\[ V_o = Q_o \times p_o \]  

(3)

where \( Q_o \) is the quantity of O\(_2\) regulation of the rice paddy (t ha\(^{-1}\) y\(^{-1}\)); 1.19 is the coefficient of net primary production to O\(_2\) emission through photosynthesis; \( m_{np} \) is the net primary production (t ha\(^{-1}\) y\(^{-1}\)); \( q_{so} \) is the O\(_2\) consumption by organisms in the soil (t ha\(^{-1}\) y\(^{-1}\)); \( V_o \) is the economic value of O\(_2\) regulation of the rice paddy (USD ha\(^{-1}\) y\(^{-1}\)); \( p_o \) is the replacement price of O\(_2\) (USD 0.35 kg\(^{-1}\)) (Wang 2010).

In addition to CO\(_2\) regulation rice paddy ecosystems also emit or assimilate CH\(_4\) and N\(_2\)O throughout the growing season. Greenhouse gases regulation of the rice paddies and the economic value were calculated by the following equations:

\[ Q_g = (1.63 \times m_{np} - q_{so}) - (24.5 \times q_{so} + 320 \times q_{so})/1000 \]  

(4)

\[ V_g = Q_g \times p_g \]  

(5)

where \( Q_g \) is the quantity of greenhouse gases regulation of the rice paddy (t ha\(^{-1}\) y\(^{-1}\), in CO\(_2\) equivalent); 1.63 is the coefficient of net primary production to CO\(_2\) assimilation through photosynthesis; \( q_{so} \) is the CO\(_2\) emission by organisms in the soil (t ha\(^{-1}\) y\(^{-1}\)); 24.5 is the GWP coefficient of CH\(_4\) (Björklund et al. 1999); \( q_{so} \) is the CH\(_4\) emission of the rice paddy (kg ha\(^{-1}\) y\(^{-1}\)); and 320 is the GWP coefficient of N\(_2\)O (Björklund et al. 1999); \( q_{so} \) is the N\(_2\)O emission of the rice paddy (kg ha\(^{-1}\) y\(^{-1}\)).

Table 1 Characteristics of focal rice paddies.

<table>
<thead>
<tr>
<th>Rice planting areas</th>
<th>Study site</th>
<th>Temperature (°C)</th>
<th>Rainfall (mm)</th>
<th>Rice seasons</th>
<th>Growth stage</th>
<th>Fertilizer dose (kg N ha(^{-1}))</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHRASC</td>
<td>Guangzhou</td>
<td>20.2</td>
<td>1875</td>
<td>Early</td>
<td>March to July</td>
<td>220</td>
<td>Yang et al. (1996); Li et al. (1998)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Late</td>
<td>July to November</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>DSHRACC</td>
<td>Changshu</td>
<td>15.5</td>
<td>1038</td>
<td>Single</td>
<td>June to October</td>
<td>173</td>
<td>Xu et al. (1998); Wang et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Chengdu</td>
<td>17</td>
<td>1050</td>
<td>Single</td>
<td>April to September</td>
<td>218</td>
<td>Ren et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>Taoyuan</td>
<td>16.5</td>
<td>1448</td>
<td>Early</td>
<td>April to July</td>
<td>121</td>
<td>Li et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>Yingtan</td>
<td>17.5</td>
<td>1600</td>
<td>Early</td>
<td>April to July</td>
<td>120</td>
<td>Liu et al. (1995); Xiong et al. (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Late</td>
<td>July to October</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>SDHRAPSC</td>
<td>Bijie</td>
<td>13</td>
<td>1122</td>
<td>Single</td>
<td>April to September</td>
<td>135</td>
<td>Yu (2002); Ye and Zhang (2002)</td>
</tr>
<tr>
<td>SHRANC</td>
<td>Fengqiu</td>
<td>13.9</td>
<td>600</td>
<td>Single</td>
<td>June to October</td>
<td>428</td>
<td>Cai et al. (1998); Xu et al. (2000)</td>
</tr>
<tr>
<td>SEHRANC</td>
<td>Shenyang</td>
<td>7.5</td>
<td>675</td>
<td>Single</td>
<td>May to September</td>
<td>187</td>
<td>Luo et al. (1999); Shi et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Hailun</td>
<td>7.5</td>
<td>570</td>
<td>Single</td>
<td>May to September</td>
<td>150</td>
<td>Han et al. (2003); Yue et al. (2003)</td>
</tr>
<tr>
<td>SHRAARNC</td>
<td>Lingwu</td>
<td>8.6</td>
<td>202</td>
<td>Single</td>
<td>May to September</td>
<td>300</td>
<td>Zhang et al. (2010b); Yin et al. (2002)</td>
</tr>
</tbody>
</table>
emission of the rice paddy (kg ha⁻¹ y⁻¹); \( V_y \) is the economic value of greenhouse gases regulation of the rice paddy (USD ha⁻¹ y⁻¹); and \( p_y \) is the cost of Sweden carbon tax (USD 0.55 kg⁻¹ CO₂).

2.2.3 Nitrogen transformation

In our study, nitrogen transformation in the rice paddy ecosystem refers to N transference between the rice paddy ecosystem, the atmosphere, surface water, ground water and human society (Xiao et al. 2005a). Nitrogen transformation between the rice paddy ecosystem and the atmosphere included biological N₂ fixation, nitrogen deposition, N₂O emission and NH₃ volatilization. Drainage and irrigation were the methods of nitrogen transformation between rice paddy ecosystem and surface water while leaching and irrigation were the main methods of nitrogen transformation between the rice paddy ecosystem and ground water. Nitrogen transformation between human society and the rice paddy ecosystem was through the application of fertilizer, seedlings and harvesting.

Nitrogen inputs to the rice paddy and the economic value were estimated by the following equations:

\[
Q_{ni} = q_{sh} + q_{sf} + q_r + q_i \quad (6)
\]

\[
V_{ni} = Q_{ni} \times p_n \quad (7)
\]

where \( Q_{ni} \) is the quantity of nitrogen input of the rice paddy (kg ha⁻¹ y⁻¹ in pure N); \( q_i \) is the nitrogen input by application of fertilizer (kg ha⁻¹ y⁻¹ in pure N); \( q_{sf} \) is the nitrogen input by biological nitrogen fixation (kg ha⁻¹ y⁻¹ in pure N); \( q_{sh} \) is the nitrogen input by seedlings (kg ha⁻¹ y⁻¹ in pure N); \( q_r \) is the nitrogen input by irrigation (kg ha⁻¹ y⁻¹ in pure N); \( V_{ni} \) is the economic value of nitrogen input by the rice paddy (USD ha⁻¹ y⁻¹); and \( p_n \) is the replacement price of nitrogen (USD 0.62 kg⁻¹ in pure N) (DPNDRC 2010).

Nitrogen output of the rice paddy and the economic value were calculated with the following equations:

\[
Q_{no} = q_{sh} + q_{sf} + q_{sr} + q_{sv} + q_{s} + q_i \quad (8)
\]

\[
V_{no} = Q_{no} \times p_n \quad (9)
\]

where \( Q_{no} \) is the quantity of nitrogen output of the rice paddy (kg ha⁻¹ y⁻¹ in pure N); \( q_{sh} \) is the harvest nitrogen in rice grain (kg ha⁻¹ y⁻¹ in pure N); \( q_{sr} \) is the harvested nitrogen in rice straw (kg ha⁻¹ y⁻¹ in pure N); \( q_{sv} \) is the nitrogen loss by \( NH_3 \) volatilization (kg ha⁻¹ y⁻¹ in pure N); \( q_s \) is the nitrogen loss by drainage (kg ha⁻¹ y⁻¹ in pure N); \( q_i \) is the nitrogen loss by leaching (kg ha⁻¹ y⁻¹ in pure N); \( V_{no} \) is the economic value of nitrogen output of the rice paddy (USD ha⁻¹ y⁻¹); \( p_n \) is the replacement marginal price of grain protein (USD 11.75 kg⁻¹ in pure N; USWA 2009); \( p_s \) is the replacement price of nitrogen fertilizer (USD 0.62 kg⁻¹ in pure N) (DPNDRC 2010); and \( p_r \) is the replacement cost of nitrogen loss in drainage and leaching water and \( NH_3 \) volatilization (USD 9.61 kg⁻¹ y⁻¹ in pure N in 2009 price) (Turner et al. 1999).

2.2.4 Soil organic matter accumulation

In rice paddies organic matter input and output changes soil organic matter (SOM) content. The methods of SOM input included manure application, withered leaves, ineffective tillers, roots, root exudation and abandoned straw. In our study, only the roots, root exudation and abandoned straw were calculated as the sources of SOM increase. The methods of SOM output were \( CO_2 \) and \( CH_4 \) emissions. SOM accumulation and economic value were estimated with the following equations:

\[
Q_{sa} = q_{f} + q_{sw} + q_{r} + q_{re} - q_{sc} - q_{m} \quad (10)
\]

\[
V_{sa} = Q_{sa} \times p_{om} \quad (11)
\]

where \( Q_{sa} \) is the quantity of SOM accumulation of the rice paddy soil (kg ha⁻¹ y⁻¹ in pure C); \( q_{f} \) is the organic matter by manure application (kg ha⁻¹ y⁻¹ in pure C); \( q_{sw} \) is the abandoned straw in the rice paddy (calculated as 11% of the total straw biomass) (kg ha⁻¹ y⁻¹ in pure C); \( q_{r} \) is the biomass of rice root (kg ha⁻¹ y⁻¹ in pure C); \( q_{re} \) is the biomass of rice root exudation (estimated as the four times of the root biomass) (Watanabe and Roger 1985) (kg ha⁻¹ y⁻¹ in pure C); \( V_{sa} \) is the economic value of SOM accumulation of the rice paddy (USD ha⁻¹ y⁻¹); and \( p_{om} \) is the replacement price of SOM (USD 0.71 kg⁻¹ in pure C).

2.2.5 Water regulation and flood control

Rice paddy irrigation consumes surface water and/or ground water. Draining the rice paddy supplies surface water and leaching recharges the ground water. Water regulation of the rice paddy and the economic value were calculated with the following equations:

\[
Q_{wr} = (v_g + v_l - v_i) \times 10 \quad (12)
\]

\[
V_{wr} = Q_{wr} \times p_w \quad (13)
\]

where \( Q_{wr} \) is the quantity of water regulated of the rice paddy (m³ ha⁻¹ y⁻¹); \( v_g \) is the quantity of drainage water (mm); \( v_l \) is the quantity of leaching water (mm); \( v_i \) is the quantity of irrigation water (mm); \( V_{wr} \) is the economic value of water regulation (USD ha⁻¹ y⁻¹); and \( p_w \) is the price of irrigation water (USD 0.01 m⁻³) (MWR 2010).

As one of the important types of wetlands in China, rice paddies, with their ridges and rice plants, serve as reservoirs that reduce flooding. The economic value of flood control of the rice paddy was calculated with the following equation:

\[
V_{wc} = q_{wc} \times p_{wc} \times 10 \quad (14)
\]

where \( V_{wc} \) is the economic value of flood control of the rice paddy (USD ha⁻¹ y⁻¹); \( q_{wc} \) is the quantity of flood control by ridge of rice paddy (mm, calculated as 150 mm y⁻¹); and \( p_{wc} \) is the replacement price of flood control (USD 0.25 m⁻³ in 2009 price) (Zhang and Gu 2004).
2.3 Data compilation
From scientific literature published up until 2010, we compiled data on grain yield, greenhouse gases emissions, nitrogen transformation, soil organic matter and water management of rice paddies in China. Data from the CERN (Chinese Ecosystem Research Net) data center was also collected. All data from the literature and CERN were classified according to the six rice planting areas of China. Based on data compilation, we estimated the economic values of ecosystem services of 10 focal representative rice paddies.

3 Results
3.1 Primary production
The grain yield per unit area of the 10 typical rice paddies in China ranged from 4.71 to 12.18 t ha\(^{-1}\) y\(^{-1}\), and the straw yield per unit area from 4.65 to 9.79 t ha\(^{-1}\) y\(^{-1}\). The grain and straw yields per unit area of Taoyuan, Guangzhou and Yingtan were relatively higher than others because of their double rice planting systems, and those of Fengqiu, Hailun and Bijie were much lower. Of the sites in the single rice planting system, the grain yields in Changshu, Shenyang and Lingwu were a little higher than others (Fig. 2a).

Fig. 2 Ecosystem services supported by 10 rice paddies.
3.2 Gas regulation

O\textsubscript{2} regulation was between 8.27 and 19.69 t ha\textsuperscript{-1} y\textsuperscript{-1}, and greenhouse gases (GHGs) regulation ranged from –2.13 to 19.24 t ha\textsuperscript{-1} y\textsuperscript{-1} (in CO\textsubscript{2} equivalent) (Fig. 2b). The O\textsubscript{2} regulation of the rice paddy ecosystems in Taoyuan, Changshu and Guangzhou was a little higher than the others, while that in Fengqiu, Hailun and Chengdu was relatively lower. The integrated regulation of GHGs by the rice paddy in Yingtang was estimated to emit 2.13 t ha\textsuperscript{-1} y\textsuperscript{-1} (in CO\textsubscript{2} equivalent) of GHGs (including CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O) into the atmosphere (Fig. 2b). Quantities of CO\textsubscript{2} assimilation through photosynthesis and respiration were similar in the double rice planting system in Guangzhou, Taoyuan and Yingtang, but CH\textsubscript{4} and N\textsubscript{2}O emissions from the rice paddy in Yingtang were significantly higher because of the application of fertilizer before seedling transplantation. With enough soil organic matter input, CH\textsubscript{4} emission from paddy soil was accelerated, and the legume supported reaction substrate and energy to soil denitrification which improved N\textsubscript{2}O emission (Xiong et al. 2003).

3.3 Nitrogen transformation

Nitrogen input ranged from 209.70 to 513.93 kg N ha\textsuperscript{-1} y\textsuperscript{-1}, and nitrogen output from 112.87 to 332.69 kg N ha\textsuperscript{-1} y\textsuperscript{-1} (Fig. 2c). Nitrogen input was mainly through the use of fertilizer, which accounted for more than 60% of the total nitrogen input. For the majority of rice paddies in this study, the most important methods of nitrogen output were grain and straw harvest, which amounted to 50%–77% of the total nitrogen output. The proportion of nitrogen output through NH\textsubscript{3} volatilization was also high, amounting to 10%–34% of total output. The proportions of nitrogen output through drainage and leaching were less than 10% of the total output (Fig. 2d). However, there were several exceptions. The proportion of nitrogen output through NH\textsubscript{3} volatilization of total nitrogen output of the rice paddy in Fengqiu was 54% because of a high soil pH of 8.6. Nitrogen output through leaching of the rice paddies in Lingwu and Shenyang amounted to more than 20% of total output. This was because there was no drainage during the rice growth period, resulting in higher nitrogen loss through leaching. The proportion of nitrogen output through drainage to the total output in the rice paddies in Bijie and Chengdu was more than 15% because of higher volumes of drainage water.

In total, soil nitrogen was in surplus after one rice growth season for most paddies, ranging from 1.90–253.15 kg N ha\textsuperscript{-1} y\textsuperscript{-1}. It can be concluded that, even though we did not consider nitrogen loss from NH\textsubscript{3} volatilization, drainage, leaching and N\textsubscript{2}O, the application of nitrogen fertilizer provided more nitrogen than was needed for rice growth. The surplus nitrogen that accumulated in the paddy soil may provide nutrients for the next growth season. However, it could also be argued that surplus nitrogen in the soil increased the risk of atmospheric pollution and eutrophication because of higher nitrogen loss from NH\textsubscript{3} volatilization, drainage and leaching.

3.4 Soil organic matter accumulation

Soil organic matter (SOM) input was 1.83–7.70 t C ha\textsuperscript{-1} y\textsuperscript{-1}, and SOM output 1.11–3.17 t C ha\textsuperscript{-1} y\textsuperscript{-1} (Fig. 2e). Most of SOM input was from root and root exudation, accounting for 37%–91% of the total. The main mode of SOM output was soil CO\textsubscript{2} emission (not including CO\textsubscript{2} emission from root respiration), which amounted to more than 85% of the total. The SOM surplus ranged from 0.69–4.88 t C ha\textsuperscript{-1} y\textsuperscript{-1}. The SOM surplus of the rice paddies in Taoyuan, Yingtang and Guangzhou was much higher than others as they had SOM input from rice root and root exudation from a double rice planting system.

3.5 Water regulation and flood control

Water regulation ranged from -19 875–6430 m\textsuperscript{3} ha\textsuperscript{-1} y\textsuperscript{-1} (Fig. 2f). The rice paddies in Lingwu, Hailun, Yingtang and Taoyuan were net consumers of water resources as irrigation water use for these rice paddies was much higher than water output by drainage and leaching. The rice paddies in Guangzhou, Bijie and Shenyang supplied surface water and recharged ground water as water output by drainage and leaching was more than the water consumed by irrigation. As there was no drainage water in the rice paddies in Shenyang, Hailun and Lingwu, their flood control function was not assessed. The ridges of the other seven rice paddies served as the reservoir walls that could contain flooding up to 15 cm, or 1500 m\textsuperscript{3} ha\textsuperscript{-1} y\textsuperscript{-1}.

3.6 Economic values of ecosystem services by rice paddies

The integrated economic value per unit area of ecosystem services for the 10 rice paddies was estimated at USD 8605–21 405 ha\textsuperscript{-1} y\textsuperscript{-1}. The proportion of economic value per unit area of gas regulation by the rice paddies to the total ranged from 48% to 88%, and primary production from 11% to 26% (Table 2). The nitrogen transformation of rice paddies in Fengqiu, Lingwu and Chengdu and water regulation of rice paddies in Lingwu and Hailun caused economic losses. The integrated economic values per unit area of ecosystem services of the rice paddies in Guangzhou (DHRASC), Taoyun, Changshu and Chengdu (DSHRACC), Shenyang and Hailun (SEHRANC), and Lingwu (SHRAARNC) were higher than others. The integrated economic values per unit area of ecosystem services by rice paddies in Bijie (SDHRAPSC) and Fengqiu (SHRANC) were a little lower. The rice biomass and yield in Bijie and Fengqiu were less than other sites. This was because paddy soil in Bijie and Fengqiu was not suitable for rice planting, having lower nutrient and organic matter content. To compensate for this more chemical fertilizer was used to improve rice yield. This resulted in higher N\textsubscript{2}O emissions and NH\textsubscript{3} volatilization.
and led to lower integrated values per unit area of ecosystem services.

4 Discussion

Until now only the economic value of primary production (grain and straw) was calculated in the economic value of rice paddies in the social-economic statistical system. According to our study, the economic value per unit area of primary production amounted to only 11% to 26% of the integrated economic value per unit area of ecosystem services. The economic value per unit area of gas regulation, nitrogen transformation, soil organic matter accumulation and water regulation and flood control accounted for 74% to 89% of the integrated value per unit area. Based on field experiments and investigation, Wang et al. (2010) estimated the economic value per unit area of ecosystem services to be USD 10 807 ha⁻¹ y⁻¹ (USD 1 = 6.831 CNY in 2009). This included primary production, social security, gas regulation, soil organic matter accumulation and water conservation. According to Wang et al. (2010) the economic value of ecosystem services per unit area, not including the value of primary production, accounted for 74% of the total value per unit area. Qin et al. (2010) calculated economic value per unit area of primary production, gas regulation, water conservation, soil organic matter accumulation and nutrient retention by the conventional rice paddy and rice-duck paddy to be between USD 2236 and USD 2650 ha⁻¹ y⁻¹, in which economic value per unit area of ecosystem services, not including the value of primary production, amounted to 63% of the total economic value per unit area. Lv et al. (2010) evaluated the environmental externalities of the rice-wheat farming in Zhejiang Province, which included GHGs regulation, non-point pollution, carbon sequestration by crops, and soil and flood control. The environmental externalities were estimated to be USD 2.28×10⁶ y⁻¹ in total and averaged USD 13 202 ha⁻¹ y⁻¹. Even though the economic loss through GHGs emission and non-point pollution was counted, the economic value of environmental externalities of the rice-wheat system in Zhengjiang was large. From this research it is apparent that the economic value of rice paddies has been underestimated and their importance to society not taken into account. Furthermore, the economic values of aesthetic scenery and the maintenance of biodiversity were not calculated in the above studies because data was unavailable. Therefore, the estimates of the economic value of ecosystem services provided by rice paddies in these studies were conservative. The economic value of the ecosystem services of rice paddies was much higher than we estimated.

Since the 1960's increasing amounts of chemical fertilizer have been used in agriculture in China. Chemical fertilizer has been the most important way to enhance soil fertility and grain yield. However, while increasing grain yields, chemical fertilization has also resulted in severe environmental problems, such as eutrophication and nitrite pollution of ground water (Huang 2011). According to our study, the integrated value per unit area of ecosystem services increased with nitrogen fertilizer dose, peaked at the fertilizer dose of 278 kg N ha⁻¹, and then decreased with higher fertilizer doses. For different kinds of ecosystem services, the economic value of primary production peaked at the nitrogen fertilizer dose of 285 kg N ha⁻¹, gas regulation at 275 kg N ha⁻¹, soil organic matter accumulation at 297 kg N ha⁻¹, and nitrogen transformation obviously decreased with fertilizer dose (Fig. 3). The economic value per unit area of ecosystem services was relatively higher at a nitrogen fertilizer dose ranging from 275 to 297 kg N ha⁻¹.

Table 2 Integrated economic values per unit area of ecosystem services of 10 rice paddies in China (USD ha⁻¹ y⁻¹).

<table>
<thead>
<tr>
<th>Sites</th>
<th>Primary production</th>
<th>Gas regulation</th>
<th>Nitrogen transformation</th>
<th>SOM accumulation</th>
<th>Water regulation</th>
<th>Integrated economic values</th>
</tr>
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<tr>
<td>Guangzhou</td>
<td>3013</td>
<td>11 557</td>
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<td>2538</td>
<td>444</td>
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<td>317</td>
<td>852</td>
<td>387</td>
<td>18 351</td>
</tr>
<tr>
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<td>–71</td>
<td>2063</td>
<td>385</td>
<td>15 407</td>
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<td>367</td>
<td>21 405</td>
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<tr>
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<td>58</td>
<td>2509</td>
<td>359</td>
<td>9677</td>
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<tr>
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<td>497</td>
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<td>414</td>
<td>8605</td>
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<tr>
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<td>–1498</td>
<td>494</td>
<td>387</td>
<td>8657</td>
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<tr>
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<td>14 353</td>
<td>381</td>
<td>739</td>
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<td>17 002</td>
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<tr>
<td>Hailun</td>
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<td>13 687</td>
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<td>979</td>
<td>–22</td>
<td>16 338</td>
</tr>
<tr>
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<td>16 719</td>
<td>–906</td>
<td>1213</td>
<td>–204</td>
<td>18 878</td>
</tr>
</tbody>
</table>

Note: As values of grain and straw harvest in nitrogen transformation and primary production were recalculated, only the economic value of primary production was calculated in the integrated value. As the economic value of N₂O emission was also recalculated in gas regulation and nitrogen transformation, only the economic value of N₂O emission in gas regulation was calculated in the integrated value.
applying nitrogen fertilizer at 300 kg N ha\(^{-1}\). The nitrogen loss from rice paddies at this level of fertilizer application was 45 kg N ha\(^{-1}\) more than the loss that would occur with the suggested optimal fertilizer application rate of Zhu. With field experiments and Coase principle in environmental economics, Huang et al. (2007) found that ecological and economic benefits of rice paddies in Taihu Lake area would be optimal with nitrogen fertilization ranging from 219 to 255 kg N ha\(^{-1}\); higher rates of nitrogen fertilizer application would result in serious environmental problems.

Therefore, nitrogen application has important impacts on ecosystem services provided by rice paddies. The economic value per unit area of ecosystem services by rice paddies would peak at a specific nitrogen fertilizer dose. For this study, the appropriate nitrogen fertilizer application range was based on an ecosystem services valuation of rice paddies with conventional nitrogen application in different rice planting areas. The results indicate that nitrogen fertilizer was over-used in most of the rice paddies in China, and the efficient use of nitrogen fertilizer was very low (Li 2009; Huang 2011). If the efficiency of nitrogen use of rice paddies increased, the appropriate range for nitrogen fertilizer application would change.
5 Conclusions

We estimated the economic value of ecosystem services of 10 typical rice paddies across six rice planting regions in China. These services comprised primary production, gas regulation, nitrogen transformation, soil organic matter accumulation, and water regulation and flood control. Our results indicated that the integrated economic value per unit area of ecosystem services of the 10 rice paddies ranged from USD 8605–21 405 ha⁻¹ yr⁻¹. The economic value per unit area of ecosystem services, not including the value of primary production, accounted for 74%–89% of the integrated value per unit area. The integrated value per unit area of ecosystem services increased with nitrogen fertilizer dose, peaked at fertilizer use of 275–297 kg N ha⁻¹, and decreased at higher application rates.

It appears that the economic value of rice paddies has been underestimated as the economic value of primary production was the only input used when calculating the economic value of the rice paddy. This neglected the economic value of gas regulation, nitrogen transformation, soil organic matter accumulation and flood control. As more and more forest land and grassland has been converted into urban and industrial use, cropland, especially rice paddies, will become more ecologically important to society. Apart from primary production, the economic value of ecosystem services such as gas regulation, soil organic matter accumulation, water regulation, and biodiversity maintenance is worthy of considerably more research attention.

References


态系统服务将受到越来越多的关注。森林、草地等转为城市和工业用途，农田特别是稻田生态系统将具有越来越高的生态重要性。稻田生态系统农产品生产以外的价值相对较高。目前仅以农产品生产来计算稻田生态系统的价值显著低估了稻田生态系统对人类社会的重要性。随着越来越多的生产、气体调节、氮素转化、土壤有机质累积以及水调节和洪水控制等5项生态系统服务。研究结果显示，稻田谷物产量为4.71 t ha\(^{-1}\)，氮素输入量为209.70 kg N ha\(^{-1}\)，温室气体调节量为-19 875 t CO\(_2\) eq ha\(^{-1}\)，节量为-19 875元 ha\(^{-1}\)，稻草为4.65 t C ha\(^{-1}\)，洪水控制量为1500 m\(^3\) ha\(^{-1}\)，输出量为112.87 kg CO\(_2\) eq ha\(^{-1}\) y\(^{-1}\)；土壤有机质库变化为0.69 t C ha\(^{-1}\) y\(^{-1}\)。研究结果还显示，10类稻田的生态系统服务价值为8605元 ha\(^{-1}\) y\(^{-1}\)；土壤有机质累积；氮素转化

关键词：稻田；生态系统服务；气体调节；土壤有机质累积；氮素转化

中国科学院地理科学与资源研究所，北京 100101

中国10类典型稻田生态系统服务评价

肖玉，安凯，谢高地，鲁春霞

摘要：在公开发表数据基础上，本研究评价了全国6大稻作区10类稻田提供的生态系统服务。研究的服务包括稻田初级产品生产、气体调节、氮素转化、土壤有机质累积以及水调节和洪水控制等5项生态系统服务。研究结果显示，稻谷谷物产量为4.71–12.18 t ha\(^{-1}\) y\(^{-1}\)，稻草为4.65–9.79 t ha\(^{-1}\) y\(^{-1}\)；O\(_2\)调节量为8.27–19.69 t ha\(^{-1}\) y\(^{-1}\)，温室气体调节量为-2.13–19.24 t ha\(^{-1}\) y\(^{-1}\) (CO\(_2\)当量)；氮素输入量为209.70–513.93 kg N ha\(^{-1}\) y\(^{-1}\)，输出量为112.87–332.69 kg N ha\(^{-1}\) y\(^{-1}\)；土壤有机质库变化为0.69–4.88 t C ha\(^{-1}\) y\(^{-1}\)；水调节量为-19 875–6430 m\(^3\) ha\(^{-1}\) y\(^{-1}\)；洪水控制量为1500 m\(^3\) ha\(^{-1}\) y\(^{-1}\)。研究结果还显示，10类稻田的生态系统服务价值为8605–21 405美元 ha\(^{-1}\) y\(^{-1}\)，除了初级产品生产以外的其他生态系统服务价值仅占74%–89%。在施氮量为275–297 kg N ha\(^{-1}\)时，稻田生态系统服务价值相对较高。目前仅以农产品生产来计算稻田生态系统的价值显著低估了稻田生态系统对人类社会的重要性。随着越来越多的森林、草地等转变为城市和工业用途，农田特别是稻田生态系统将具有越来越高的生态重要性。农田生态系统农产品生产以外的生态系统服务将受到越来越多的关注。

关键词：稻田；生态系统服务；气体调节；土壤有机质累积；氮素转化