Cleaner Production Technologies Increased Economic Benefits and Greenhouse Gas Intensity in an Eco-Rice System in China

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Abstract: The sustainability of intensification of rice production is a prime concern for China. Application of organic amendments, changes in crop rotation system, ducklings’ introduction, and construction of vegetated drainage ditches are some of the original management strategies to mitigate environmental pollution from paddy fields. Although these practices affect the rice culturing system through different mechanisms, there is limited investigation on their effectiveness on nutrient pollution alleviation. Therefore, a field study was carried out with the assessment of soil physico-chemical properties, greenhouse gas emissions, nitrogen removal efficiency, grain yield, and economic benefits by comparing the eco-rice culturing system (ER) to the local single rice cultivation system (CK).

Results showed that the ER system can significantly improve soil fertility by increasing the pH in acidic soil, organic matter, total nitrogen (TN), and available potassium (K) content by 5.2%, 25.7%, 19.1%, and 19.4% in relation to CK, respectively. Meanwhile, about 10% of the total fertilizer N was removed from the harvesting of the plant species (Myriophyllum elatinoides and Pennisetum purpureum) in the vegetated drainage ditches. However, the ER system decreased the plant height (1.1%) and the number of tillers (9.6%), resulting in a reduction of the total grain yield (6.0%). Moreover, compared with the CK system, the ER system increased CH4 cumulative emission, global warming potential (GWP), and greenhouse gas intensity (GHGI) by 11.1%, 8.1%, and 14.3%, respectively, and decreased N2O by 27.2%, but not statistically significantly (p < 0.05). Even so, by taking the costs of farm operations and carbon costs of greenhouse gas emissions, the net economic benefits by applying the ER system were higher relative to the CK system. Thus, our study provides further understanding of the technology which has the potential to transform sustainable rice production to a more profitable, income generating, and environmentally friendly industry in China.

Keywords: eco-rice; vegetated drainage ditch; organic amendment; greenhouse gas emissions; nitrogen use efficiency

1. Introduction

China is now the world’s largest producer, consumer, and importer of fertilizers, who’s overall yearly utilization has augmented from 15.1 Mt in 1982 to 58.4 Mt in 2012 [1]. Intensive use of chemical fertilizers has largely contributed to the increase of China’s agricultural production in the last 30 years. However, nutrients are not used very efficiently in Chinese agriculture, especially the efficiency of N use, which is just about 30%–35% [2], and is much lower than that in European countries and the
US [3], which is mostly because of undeveloped nutrient management [4]. Meanwhile, the excessive use of chemical fertilizers has serious negative impacts on the environment, such as breakdown of soil structure, increased greenhouse gas emissions, and decline of soil fertility [5–7]. Therefore, optimal agricultural practice should be carried out to ensure food and environment safety, as well as the maintenance of sustainable agrarian production in China [8,9].

Rice is the principal staple cereal crop in China, which accounts for 35% of the entire food agriculture [10], and the cultivated area allocated for its cultivation comprises 27% of the whole national area assigned for food generation [11]. However, as a non-point pollution source, pollution from paddy fields due to the excessive use of chemical fertilization in Southeast China has become very serious nowadays. Facing this situation, China’s ecologists and agronomists have begun to develop policies, patterns, and technologies associated with cleaner rice production. In effect, a new concept in Chinese rice production has been proposed, which is called ecological-rice (ER) agriculture [12]. At its essence, this agricultural system contains a series of practices, such as the development of nutrient management plans [13], rice–livestock integrations [14], field drainage installations [15], and application of no-till agriculture [16], to achieve a balance between economic and environmental benefits. The most popular of all the practices is rice-livestock integration, comprising rice–duck [17], rice–fish [18], and rice–crayfish [19] co-culturing systems. Results from these composite agricultural ecosystems have demonstrated that rice-livestock integrations can enhance nutrient use efficiency and reduce nutrient loss to the environment because of the complementary use of livestock and rice [20–22]. Rice–livestock integrations can also provide a potentially new approach to increase the food safety of rice production [18]. After several years of practice and development, ecological-rice agriculture in China has achieved substantial progress, as it has established a theoretical system and obtained useful acknowledge [23] and also has demonstrated its effectiveness in county-level pilot studies [24].

The Huaihe River Basin is the main single rice crop region of China, significantly contributing to the total national grain production [25]. Tongcheng is a typical traditional agricultural county in this area. Farmers in Tongcheng County plant two types of crops per year, the method they applied is known as rice–winter wheat rotation system. However, this traditional tillage practice limits the time for plant growth and the supply of soil nutrients available for plant production [14]. Thus, local growers frequently use extra chemical fertilizers, which exceed the lowest amount that is necessary for optimum plant development in order to increase grain production [26], without paying attention to the effective utilization and protection of land resources. Furthermore, cultivators commonly speculate that replacing long-established agricultural methods with suggested eco-cultivation strategies may intensify the input necessities, augment the risks related with unconfirmed procedures, and jeopardize the sale of their crops, and hence reduce their wages [27]. Therefore, they are often cautious to implement eco-cultivation and they use the wait-and-see approach. Consequently, China now has to confront the increasing threats of agricultural non-point source pollution that have accumulated over the last decade [28].

According to the reported research achievements in ecological-rice agriculture, we chose Tongcheng County as the main study area in order to gradually integrate newly developed environmental technologies into the farm-wide program. The objectives of our study were as follows: (1) to establish a modern cleaner rice production system, which could deliver higher economic profits, ecological and social benefits in local farming; (2) to analyze the existing limitation factors, in order to put forward related countermeasures and suggestions for the development of ecological-rice agriculture; and (3) to further optimize and improve the industrialization mode, based on the local characteristics, to lead to eco-agricultural development. We hypothesize the ER system can provide the basic requirements and holistic insight of the ecological-rice agricultural system for sustainable crop production in the Huaihe River Basin region.
2. Materials and Methods

2.1. Investigation Area Characteristics

Our research was carried out at the Kongcheng village (30°59′ N, 116°64′ E), which is situated in the center of the Tongcheng County in the east region of China and has a humid northern subtropical climate. The long-term average precipitation of Tongcheng County is 1409 mm, of which 70% falls from April to October, and the mean annual temperature is 15.6 °C. At this site, the major type of rice variety planted was “Zhendao 16”. We chose a representative and well-managed field with an area of 0.7 ha to contrast the eco-management strategies and an adjacent rice field was chosen as control with an area of 0.5 ha. The soil of the paddy field was silty clay loam in texture with an average pH of 5.5, and the topsoil (0–20 cm) had a salt content of <0.3 g kg\(^{-1}\), categorized as non-saline soil [29]. The two field systems had the same irrigation water source and management. Since the village is located at the Dabie-mountain Hilly Area and is still a less-developed area, there are no obvious sources of industrial pollution nearby.

Eco-management strategies with agricultural diversification were applied on 21 May, 2015, in the experimental area for this study and these included: (1) application of the residue of rapeseed oil extract (rapeseed cake) as an organic fertilizer to enrich the soil microbiome and enhance the ability of the soil to sequester nitrogen and carbon [30]; (2) replacement of the local rice production system with a rice–duck complex ecosystem to improve soil fertility and soil structure [31]; (3) application of the rice–Chinese milk vetch (Astragalus sinicus L.) instead of the rice–wheat rotation system to reduce the amount of chemical fertilizers [32]; and (4) construction of vegetated drainage ditches to prevent the loss of nutrients into the water surrounding the experimental field [33].

2.2. Field Experimental Treatments

2.2.1. Rice–Duck Complex Ecosystem

Twenty-day-old native ducklings (Sheldrake) were allocated into the ER region at a ratio of 225 ducklings per hectare, 17 days following plant transplantation. The ER areas were enclosed with 1 m tall nylon nets to prevent the ducklings from fleeing. One duck shelter was placed in each plot for the ducklings to rest and feed, and these ducks were retrieved and transferred into the vegetated drainage ditch on 25 August to continue growing.

2.2.2. Rice–Chinese Milk Vetch Rotation System

Chinese milk vetch was sown in the rice gathering period in late autumn, and then mechanically plowed 15 cm deep into the soil of the surface soil as in situ green fertilizer, prior to the following rice transplantation. Afterward, the fields were flooded with 5–7 cm depth of water. Considering that excessive addition of biomass can prolong the vegetative developmental time of rice and cause grain deterioration [34], the Chinese milk vetch was introduced at a density of 6 tons per hectare.

2.2.3. Construction of Vegetated Drainage Ditches

The vegetated drainage ditches (800 m long and approximately 1.0 m deep, with an average 4.0 m width at the top and 2.8 m at the base) were introduced at the ecological-rice study site as the major water conduits to prevent nutrients from escaping from the paddy grounds. The vegetated drainage ditches were constructed by sequential dams in order to control water movement and obtain optimum water flow. Two aquatic plant species, namely, Myriophyllum elatinoides and Pennisetum purpureum were grown in the vegetated drainage ditches, and coated about 60% of the aquatic surface, and 90% of the ditch ridges.
2.3. Agrotechnology Applied

Indigenous traditions were implemented in the current study for agrarian procedures, such as cultivation, irrigation, and fertilization. Rice seedlings were raised in mid-May, transplanted manually in late-June in 25 cm × 15 cm rows between ridges, and finally harvested in early November. Water ditches with approximately 5 cm depth were created four days before transplanting and kept flooded for the duration of duck nursing for approximately 70 days, which were later drenched up to the time of rice harvesting. Next, Chinese milk vetch was sown in late-November and then collected in mid-May, 2016. No field irrigation was performed throughout the duration of Chinese milk vetch development. The Chinese milk vetch used as fertilizer in this study was obtained from the harvested cropping season before this field experiment.

Ecological-rice agriculture (ER), and local traditional rice agriculture system (CK) were used as the two experimental treatments in this study. The regional traditional fertilization practice was implemented for research (Table 1).

2.4. Sample Collection and Chemical Analysis

The sketch of the main sampling points of water, soil, rice and GHGs can be seen in Figure A1. Water quality samples for testing were collected from the sampling sites located at 0, 400, and 800 m from the vegetated drainage ditch with three replications, which was regularly carried out during the middle of the morning once a week and every two days for approximately one week after the application of fertilizer. All water quality samples were collected in acid-washed polythene bottles (200 mL) and kept at 4 °C till further testing. Prior to laboratory analysis, the samples were thawed, and then the suspended particles were removed by passing the solution through 0.5 µm pore filter membranes. The concentration of total nitrogen (TN) was determined by injecting the samples into an AA3 continuous segmented flow analyzer (AA3 HR Auto Analyzer, SEAL Analytical, Germany). For each water sample, the physicochemical properties such as pH, dissolved organic material, and TN levels were calculated as described by Burt [35].

In the two experiment fields, five soil samples were collected as replication along an “S” pattern line using a soil auger from the top 20 cm of the soil profile both at the start and after the harvest of rice. After removing the fine roots and stones, the samples were air-dried and analyzed for soil physico-chemical properties (pH, soil organic matter, soil TN, available P, and available K) according to the standard methods recommended by the Chinese Society of Soil Science [36].

Plant height and the number of tillers (produced by the outgrowth of axillary buds to form shoot branches) are crucial factors determining rice plant architecture and influencing rice grain production [37]. Rice plant height and number of tillers were measured at the harvest stage of rice, and also using the method of S shape sampling with five points in the two experiment fields respectively. The fresh weight of the plants in the ditch was monitored by reaping all the above-ground biomass above the water surface in the experimental field. Rice grain yield was determined individually for each experimental field by harvesting the whole area.

The greenhouse gas (GHG) (CH$_4$ and N$_2$O) fluxes were determined by using a static closed chamber method with a PVC chamber (50 × 50 × 110 cm) with five replications randomly placed in each ecosystem [38]. Gas samples were collected using a 20 mL syringe at 0, 10, 20, and 30 min after closure. The air temperature inside the chamber was monitored during gas collection. Mixing ratios of CH$_4$ and N$_2$O were simultaneously analyzed within 24 h with a gas chromatograph (Agilent 7890A) equipped with ECD (electron capture detector) and FID (flame ionization detector).

The global warming potential (CO$_2$ equivalents) of each treatment was calculated by multiplying the total cumulative CH$_4$ and N$_2$O emissions by 28 and 265, respectively [39]:

$$\text{Total global warming potential (GWP) (gCO}_2\text{ equivalents kg}^{-1}) = 28 \times \text{cumulative(CH}_4\text{)} + 265 \times \text{cumulative(N}_2\text{O)}.$$  

Greenhouse gas intensity (GHGI) was calculated as the ratio between GWP and rice yield [40].

$$\text{GHGI } \text{= net GWP/yield.}$$
Table 1. Fertilizer application rates for the experimental treatments at different growth stages of rice (kg ha\(^{-1}\)).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Application Date</th>
<th>Growth Stage</th>
<th>Applied Fertilization Rates (kg ha(^{-1}))</th>
<th>Fertilizer Form</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>CK</td>
<td>21 June</td>
<td>Pre-sowing</td>
<td>83.6</td>
<td>83.6</td>
</tr>
<tr>
<td></td>
<td>16 July</td>
<td>Tillering</td>
<td>103.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>25 August</td>
<td>Grain-filling</td>
<td>37.3</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total fertilizer amounts</td>
<td>224.8</td>
</tr>
<tr>
<td>ER</td>
<td>21 June</td>
<td>Pre-sowing</td>
<td>59.7  + 18.6 + 23.5</td>
<td>59.7 + 11.6 + 2.3</td>
</tr>
<tr>
<td></td>
<td>16 July (urea)</td>
<td>Tillering</td>
<td>69.3  + 16.0</td>
<td>0 + 8.6</td>
</tr>
<tr>
<td></td>
<td>25 August</td>
<td>Grain-filling</td>
<td>37.3</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total fertilizer amounts</td>
<td>224.4</td>
</tr>
</tbody>
</table>

CK—local single rice cultivation system; ER—ecological rice cultivation. \(^a\) Compound fertilizer I (N:P:K = 16:16:16) was applied at 522 kg ha\(^{-1}\) in the CK treatment; \(^b\) urea [CO(NH\(_2\))\(_2\), N = 46.4\%] was applied at 224 kg ha\(^{-1}\) in the CK treatment; \(^c\) compound fertilizer II (N:P:K = 25:5:20) was applied at 223.9 kg ha\(^{-1}\) in the CK treatment; \(^d\) Compound fertilizer I (N:P:K = 16:16:16) was applied at 373 kg ha\(^{-1}\) in the ER treatment; \(^e\) rapeseed cake fertilizer was applied at 597 kg ha\(^{-1}\) and consisted of 3.12% kg N ha\(^{-1}\), 1.95% kg P ha\(^{-1}\), and 1.3% kg K ha\(^{-1}\) in the ER treatment; \(^f\) Chinese milk vetch was applied at 6 t ha\(^{-1}\) and consisted of 3.92 g N kg\(^{-1}\), 0.39 g P kg\(^{-1}\), and 3.61 g K kg\(^{-1}\) in the ER treatment; \(^g\) urea [CO(NH\(_2\))\(_2\), N = 46.4\%] was applied at 149 kg ha\(^{-1}\) in the ER treatment; \(^h\) duck feces (about 10 kg feces per duck) was applied during the total duck activity period, and consisted of 0.071 g N per duck, 0.038 g P per duck, and 0.05 g K per duck in the ER treatment; \(^i\) compound fertilizer III (N:P:K = 25:5:10) was applied at 149 kg ha\(^{-1}\) in the ER treatment.
2.5. Statistical Analysis

In this paper, the checked data were all normally distributed, and the primary data were analyzed without any transformation. Differences in pH, soil organic matter (SOM), TN levels, and GHG cumulative emissions between treatments were determined with the JMP 11.0 statistical software (SAS Institute NC, USA) by applying the Student’s multiple range tests, which was used for comparisons among groups, and figures were plotted in the Microsoft Excel 2013 (WA, USA). We report least-squared means and standard errors with an n of 5. Differences with P values less than 0.05 were considered statistically significant.

3. Results

3.1. Soil Physico-Chemical Properties

Results showed that organic fertilization and duck integration significantly increased the SOM, TN, available K content, and pH in rice fields by 39.7%, 44.8%, 40.1%, and 7.5%, respectively, when compared to the initial field soil (P < 0.05; Table 2). However, the ER treatment decreased the available P concentration by about 3.4% (respective to initial soil) and 14.9% (respective to CK) (Table 2), although with no statistically differences. Meanwhile, increases in soil physico-chemical properties tested were observed in samples from the CK field, relative to those of the initial soil. However, none of them had statistical difference except TN and available K content. Comparing the ER treatment to the CK treatment, ER significantly increased pH, SOM, TN, and available K by about 5.2%, 25.7%, 19.1%, and 19.4%, respectively (Table 2).

Table 2. Physical and chemical properties of the soil in the two investigated agriculture ecosystem at different period.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Treatment</th>
<th>pH (H₂O)</th>
<th>SOM (g kg⁻¹)</th>
<th>TN (g kg⁻¹)</th>
<th>Available P (mg kg⁻¹)</th>
<th>Available K (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>Initial</td>
<td>5.5 ± 0.1b</td>
<td>22.4 ± 2.0b</td>
<td>1.3 ± 0.1c</td>
<td>12.4 ± 1.5a</td>
<td>71.4 ± 8.4c</td>
</tr>
<tr>
<td>After</td>
<td>ER</td>
<td>5.9 ± 0.1a</td>
<td>31.3 ± 1.9a</td>
<td>1.8 ± 0.1a</td>
<td>12.0 ± 1.3a</td>
<td>100.1 ± 8.7a</td>
</tr>
<tr>
<td>harvest</td>
<td>CK</td>
<td>5.6 ± 0.1b</td>
<td>24.9 ± 2.7b</td>
<td>1.5 ± 0.2b</td>
<td>14.1 ± 1.8a</td>
<td>83.8 ± 7.8b</td>
</tr>
</tbody>
</table>

Mean ± SD; lowercase letters within the same column indicate significant differences among the two aquatic plants (p < 0.05).

3.2. Plant Growth and Nutrient Removal in the Vegetated Drainage Ditch

As shown in Figure 1, the TN concentration of the wastewater was greatly influenced by fertilization. The TN peak values were detected in the summer period and were much higher than 2.0 mg N L⁻¹ (Grade V) in the surrounded water according to the China National Water Quality Standards’ definition. That means that the water influent from the CK or the ER system were both seriously polluted. However, the improvement of the quality of the wastewater under ER conditions was obvious (Figure 1). Although the water effluent was still under eutrophic conditions (Grade IV–V), or even worse (>Grade V) in some parts of the surrounded water, the TN removal capacities of the constructed vegetated drainage ditches ranged from 12.1% to 61.6% in the current study. Overall, the vegetated drainage ditch system was able to improve the retention of N nutrients, but its performance was still far from satisfactory.
During the increased water supply in the ER system, the growth of the rice tillers and yield was 6865.7 kg ha$^{-1}$ in the ER system and 7304.7 kg ha$^{-1}$ in the CK system. The grain yield was 6.0% lower in the ER system relative to the CK system. Since our experimental field had mechanized harvesting, the yields of both the systems are the actual total yield, rather than the yields from the field plots. This indicated that the plant development demands are still fulfilled better by the application of chemical fertilizers. Among the different yield components assessed, rice had higher tiller numbers m$^{-2}$ and plant height in the CK system, which probably caused the greater grain yield observed (Table 4). During the increased water supply in the ER system, the growth of the rice tillers and their shoots was inhibited by the activity of the ducks in the rice field, as the underwater tillers were regularly consumed by the ducks, and this may have also contributed to the lower yield in the ER system. However, the plant height, number of tillers, and rice yield all had no statistical difference between the two agricultural systems.
The CH4 production costs for fertilizers, employment, and other inputs comprised the most substantial expenses for ER treatment, accounting for more than half of the total cost during the rice season. The total fertilization (23.4%) expenses, respectively. In contrast, in the CK treatment, fertilization costs were the major input contributors, accounting for 32.9% of the total production costs in the ER treatment, which were followed by labor (23.7%) and other input costs (14.3%), respectively, while it decreased N2O by 27.2% (Table 5), but not significantly (p < 0.05).

3.4. GHG Emissions

Figure 2 shows the CH4 and N2O flux pattern from paddy soil throughout the rice growth period. The CH4 flux peaked at about 30 days after rice seedlings were transplanted in the two rice systems (Figure 2a), while the N2O fluxes were consistently low while flux peaks were observed mostly after N fertilization, and ER treatment had the exception of some peaks (Figure 2b). Compared with the CK system, the ER system increased the cumulative CH4 emission, GWP, and GHGI by 11.1%, 8.1%, and 14.3%, respectively, while it decreased N2O by 27.2% (Table 5), but not significantly (p < 0.05).

Figure 2. Seasonal variations in (a) CH4 fluxes and (b) N2O fluxes during the rice season. The arrow indicates N fertilization.

Table 5. Seasonal CH4 and N2O emissions, global warming potential (GWP), and greenhouse gas intensity (GHGI) during the rice growing season.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>CH4 (kg ha⁻¹)</th>
<th>N2O (kg N ha⁻¹)</th>
<th>GWP (kg CO2-eq ha⁻¹)</th>
<th>GHGI (kg CO2-eq kg⁻¹ grain yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER</td>
<td>97.1 ± 17.1a</td>
<td>0.7 ± 0.2a</td>
<td>2897.2 ± 510.3a</td>
<td>0.42 ± 0.1a</td>
</tr>
<tr>
<td>CK</td>
<td>86.4 ± 15.3a</td>
<td>0.9 ± 0.2a</td>
<td>2616.1 ± 465.7a</td>
<td>0.36 ± 0.1a</td>
</tr>
</tbody>
</table>

Mean ± SD; lowercase letters within the same column indicate significant differences among the two agricultural system (p < 0.05).

3.5. Economic, Social, and Ecological Benefits Analysis

Total input, total output, and net income were compared between the ecological-rice agriculture system (ER) and the local traditional rice agriculture system (CK) to assess their economic feasibility in agriculture. Table 6 shows the overall expenses for the input resources, the output profits, and the net revenue for the different agriculture management systems in a complete rice growing season. The production costs for fertilizers, employment, and other inputs comprised the most substantial expenses for ER treatment. For the whole season, other input costs were the main input contributors, accounting for 32.9% of the total production costs in the ER treatment, which were followed by labor (23.7%) and fertilization (23.4%) expenses, respectively. In contrast, in the CK treatment, fertilization costs were the major input expenditure, accounting for more than half of the total cost during the rice season. The total cost of ER was 1982.8 US $ per hectare higher than that of CK. On the whole, ER treatment field was
more difficult to work, especially during the duck stocking period, which required the employment of more seasonal staff. In the ER farming system, fence and duck shed construction, as well as feeding were the prevalent contributors to labor expenses. However, ER treatment application provided a substantially higher farm net profit in comparison to the CK treatment, and the difference was approximately one thousand US $ per hectare. This was mainly due to the better rice market price, which was about 1.4 times higher for ecologically grown rice than for CK grown rice.

Table 6. Comparison of economic benefits of ecological-rice agriculture system and local traditional rice agriculture system based on money.

<table>
<thead>
<tr>
<th></th>
<th>Ecological-Rice Agriculture System (ER)</th>
<th>Local Traditional Rice Agriculture System (CK)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input (US $ ha(^{-1}))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed</td>
<td>87.4</td>
<td>67.4</td>
</tr>
<tr>
<td>Duckling</td>
<td>203.2</td>
<td>0</td>
</tr>
<tr>
<td>Feed</td>
<td>108.4</td>
<td>0</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>718.7</td>
<td>589.4</td>
</tr>
<tr>
<td>Machine</td>
<td>212.4</td>
<td>137.1</td>
</tr>
<tr>
<td>Labor</td>
<td>726.9</td>
<td>290.6</td>
</tr>
<tr>
<td>Others</td>
<td>1010.3</td>
<td>0</td>
</tr>
<tr>
<td>Total expenses</td>
<td>3067.3</td>
<td>1084.5</td>
</tr>
<tr>
<td><strong>Output (US $ ha(^{-1}))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>7028.7</td>
<td>5058.7</td>
</tr>
<tr>
<td>Duck</td>
<td>1126.1</td>
<td>0</td>
</tr>
<tr>
<td>Total revenue</td>
<td>8154.8</td>
<td>5058.7</td>
</tr>
<tr>
<td><strong>Net income (US $ ha(^{-1}))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5087.5</td>
<td>3974.2</td>
</tr>
</tbody>
</table>

The average exchange rate of RMB against US dollar in 2016 was 6.64. Each duck was bought for 0.90 dollars and sold for 6.02 dollars, while in the rice season 38 ducks died. The price of rice seed was 67.43 US $ ha\(^{-1}\). The price of fertilizer was 0.75 US $ ha\(^{-1}\) for compound fertilizer, 0.45 US $ ha\(^{-1}\) for rapeseed cake fertilizer, and 0.38 US $ ha\(^{-1}\) for urea, respectively. The grain yield in the ER system was 6865.7 kg ha\(^{-1}\) with a price of 1.02 US $ kg\(^{-1}\). The grain yield in the CK system was 7304.7 kg ha\(^{-1}\) with a price of 0.54 US $ kg\(^{-1}\).

4. Discussion

4.1. Chemical Fertilizer Substitution Effect on Paddy Soil and Rice Yields

In our study, the application of organic materials (rapeseed cake, Chinese milk vetch, and duck feces) significantly affected SOM and pH in the soil as compared to the CK treatment (Table 2). This is consistent with previously reported findings [41,42]. The increased soil fertility may be attributed to the increased decay of organic matter and the mixing of the soil due to the ducklings’ activities in the ER cultured fields, which could promote the oxidative–reductive capacity of the earth and enhance the effective processing of nutrients [43]. The increased soil pH might be attributed to the prolonged high levels of irrigation [44]. Other integrated rice–duck farming studies have confirmed that ducks’ activities promote the uptake and utilization of P by rice plants, resulting in a decreased availability P in the soil [17]. Yang et al. [38] also have shown that application of organic fertilizers can be a better option for maintenance of the environment.

Although the organic material input in the ER agriculture system cannot completely counterbalance the current utilization rate of N fertilizers, the N nutrient resources in organic matters can replace approximately 25.9% of the total N, 24.6% of the total P, and 35.9% of the total K consumption by the field. Even though similar amounts of total N were applied to rice fields during both treatment conditions (Table 1), CK treatment promoted greater rice yield than ER (Table 4). However, according to our economic analysis, rice produced by the ER system had higher market price, which can compensate for the economic losses due to the reduced yield. Therefore, the official promotion (subsidies, dissemination, and other incentives) of clean rice production requires further encouragement in China.
4.2. Effect of Vegetated Drainage Ditch on Water Purification

In the current study, the average TN concentrations decreased from 2.7 to 1.7 mg L$^{-1}$ (Figure 2) resulting in 39.1% removal efficiency. This removal efficiency rate is consistent with that observed by Flora and Kröger [45] and Vymazal and Březinová [46] but is lower relative to the reported 92% removal in agricultural ditches in Mississippi [47]. N sequestering is promoted in the presence of aquatic plants as they slowed the water flow and consequently enhanced particulate sedimentation rate [34]. As reported, aquatic plant varieties in the ditches have a key role in the effective processing of agrarian pollutants [48]. Accurate selection of plants species by assessing and comparing their nutrient elimination capacity is necessary to ensure the effectiveness of the drainage channels. In our study, about 10% of the total N was removed from the plants in the vegetated agricultural drainage ditch. Wang et al. [49] indicated that plant species which produce higher biomass can store greater amounts of N in their tissues. Therefore, M. elatinoides and P. purpureum are suitable plant species to sequester sufficient N from the drained water in our study. To improve performance of the ER system, the vegetated drainage ditch needs to be redesigned to prolong the water residence time.

4.3. Effect of Eco-Management on GHG Intensity

Generally, organic matters can certainly enhance GHG emissions compared with inorganic fertilizers [50,51], which is in agreement with our study. Rapeseed cake fertilizer, Chinese milk vetch, and duck feces were used as fertilizer in the ER system, and the relatively higher available C source in soil, which resulted in higher CH$_4$ emissions [52]. However, lower N$_2$O emissions were observed due to the relatively lower chemical N fertilizer application rate under anaerobic soil condition in the ER system (Table 4) [53]. In addition, our result showed that the ER system increased GWP as compared to the CK system, but not significantly. However, we did not calculate the soil carbon sequestration ($\delta$SOC) into GWP. As we all know, the organic matter retained in the soil can also increase soil carbon sequestration and the higher C sequestration potential neutralizes the negative impact of organic matter application on GHG emissions and results in an overall mitigation of GWP [38,54,55]. Moreover, the production of N fertilizer is also a large GHG emission source [56]. Yodkhum et al. [57] using the life cycle assessment methods to compare the organic and conventional rice production, and the comparative results showed that the GHG emissions of organic paddy rice were considerably lower than that of conventional rice production by accounting all GHG emissions including upstream and downstream ones. Otherwise, the carbon trade price was US $17 ton$^{-1}$ of CO$_2$ equivalent [58] and the carbon costs were 49.3 and 45.2 US $ ha$^{-1} for the ER and CK system, respectively. In our study, we ignored the economic benefits since these values were similar and farmers do not care about this issue.

5. Conclusions

Our results indicate that the ecological-rice (ER) agriculture system can increase soil pH and SOM contents, but decreased grain yield during the rice growing season. The vegetated drainage ditch implementation in the ER system prevented the release of excessive N concentrations of nutrient pollutants from the paddy grounds into the surrounding environment, and thus it is recommended to be applied locally in comparable soil regions. Moreover, in terms of net income, the ER system appeared to be almost 1.5 times more profitable than the conventional farming system, mainly due to the new awareness of consumers who are willing to pay higher prices for ecologically grown rice. However, in the future, a more dynamic organization of this scheme is necessary to sustain eco-rice production performance. Although the ER system would increase GHG emissions, no statistic differences were found compared to the CK system. Overall, the ER complex system brings positive economic and environmental changes, which means it could be extended to the aquatic environment of this area as a significant maintainable agricultural system with positive impact on the local ecosystem.
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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

**Figure A1.** Sketch of the main sampling points. The light-green squares mean the sampling plots of rice and greenhouse gas in the two fields; the brown triangles mean the sampling sites of soil; the blue circles mean the sampling points of water; and the dark-green squares mean the sampling positions of aquatic plants.

### References


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