Effects of Rice-Crayfish Co-Culture Model on Soil Physicochemical Properties in Waterlogged Paddy Fields: Postprint

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Abstract

The rice-crayfish co-culture system is a composite ecosystem based on waterlogged paddy fields, centered on rice cultivation, and characterized by straw return to the field for crayfish farming. Through a 10-year (2005-2015) location-fixed experiment, with the mid-season rice monoculture system as the control, this study investigated the effects of the rice-crayfish co-culture system on soil physicochemical properties in the 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm soil layers, as well as on rice yield; using the input-output method, the economic benefits of the rice-crayfish co-culture system were evaluated. The results showed that the long-term rice-crayfish co-culture system significantly reduced soil compaction in the 15-30 cm soil layer, with soil compaction at depths of 15 cm, 20 cm, 25 cm, and 30 cm decreasing by 20.9%, 29.9%, 24.8%, and 14.7%, respectively, compared with the mid-season rice monoculture system. The long-term rice-crayfish co-culture system increased the content of >0.25 mm water-stable aggregates, mean weight diameter, and geometric mean diameter in the 0-40 cm soil layer, but decreased the fractal dimension of aggregates in the 0-20 cm soil layer. Compared with the mid-season rice monoculture system, the long-term rice-crayfish co-culture system significantly increased the contents of organic carbon, total potassium, and alkali-hydrolyzable nitrogen in the 0-40 cm soil layer, total nitrogen content in the 0-30 cm soil layer, total phosphorus and available phosphorus contents in the 0-10 cm soil layer, and available potassium content in the 20-40 cm soil layer. The rice-crayfish co-culture system significantly decreased the total reducing substances in the 0-10 cm soil layer, but increased the total reducing substances in the 20-30 cm soil layer. The rice yield under the rice-crayfish co-culture system was significantly higher than that under the mid-season rice monoculture system, with an increase of 9.5%; its total output value, profit, and output/input ratio increased by 46,818.0 yuan · hm^{-2}, 40,188.0 yuan · hm^{-2}, and 100.0%, respectively, compared with the mid-season rice monoculture system. Thus, the rice-crayfish co-culture system improved soil structure, increased soil nutrients, enhanced rice yield and economic benefits, but also increased the risk of gleyization in soil layers below 10 cm.

Full Text

Preamble

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Effect of integrated rice-crayfish farming system on soil physico-chemical properties in waterlogged paddy soils

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Abstract: Integrated rice-crayfish system is a complex ecological system based on waterlogged paddy field cultivation characterized by crayfish feeding on rice straw. Using the rice monoculture system as the control, a 10-year (2005–2015) field experiment was conducted to study the effects of integrated rice-crayfish system on rice yield and soil physico-chemical properties at soil depths of 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm. The economic benefit of integrated rice-crayfish system was evaluated using the input-output method. The results indicated that long-term integrated rice-crayfish system significantly reduced soil compaction at the 15–30 cm layer. The soil compaction at 15 cm, 20 cm, 25 cm and 30 cm depths was lower in integrated rice-crayfish system than in rice monoculture system by 20.9%, 29.9%, 24.8% and 14.7%, respectively. Long-term integrated rice-crayfish system increased soil water-stable aggregates ($>$ 0.25 mm) content, aggregate mean weight diameter (MWD) and geometric mean diameter (GMD) in the 0–40 cm layer, but decreased aggregate fractal dimension (D) in the 0–20 cm layer. Compared with rice monoculture system, long-term integrated rice-crayfish system significantly increased the contents of soil organic carbon, total K and available N in the 0–40 cm layer, and total N in the 0–30 cm layer, total P and available P in the 0–10 cm layer and available K in the 20–40 cm layer. The total amount of reducing matter in the 0–10 cm soil layer of the long-term integrated rice-crayfish system was lower than that in the monoculture rice system, but it was higher in the 20–30 cm soil layer. Rice yield in integrated rice-crayfish system significantly increased by 9.5% compared to the monoculture rice system. The output, profit and ratio of output to input in integrated rice-crayfish system were higher than those in the monoculture rice system by 46,818.0 yuan · hm^{-2}, 40,188.0 yuan · hm^{-2} and 100.0%, respectively. It was therefore clear that integrated rice-crayfish system improved soil structure, enhanced soil nutrient and increased rice yield and economic benefit. However, it also increased the risk of soil gleying in the 10 cm depth.

Keywords: Integrated rice-crayfish system; Waterlogged paddy field; Soil structure; Organic carbon; Soil nutrient; Economic benefit

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Introduction

Integrated rice-aquaculture systems represent a major farming model in southern China’ s rice-growing regions with a long historical tradition. This model artificially combines rice (*Oryza sativa*) cultivation with aquaculture within the same ecosystem, utilizing the three-dimensional space of paddy fields to maximize the use of light, heat, water, and biological resources, thereby achieving high material productivity and economic benefits [1]. Simultaneously, it prevents soil fertility degradation, reduces environmental pollution, maintains ecological balance, and keeps the agricultural ecosystem in a virtuous cycle [2]. In recent years, the integrated rice-crayfish system has emerged as a novel rice-aquaculture model in the middle and lower reaches of the Yangtze River, characterized by waterlogged paddy field conditions, rice cultivation as the central activity, and crayfish feeding on returned rice straw. This model has developed rapidly in the region, with nearly 140,000 hectares currently under cultivation in Hubei Province alone. Surveys indicate that this model generates approximately 45,000 $\text{yuan} \cdot \text{hm}^{-2}$ more income than traditional “rice-rapeseed rotation” or “rice-wheat rotation” systems, demonstrating excellent economic and social benefits.

In the integrated rice-crayfish system, rice and red swamp crayfish (*Procambarus clarkii*) maintain a mutually beneficial relationship. On one hand, crayfish eliminate weeds and pests in the paddy fields, while their excreta and residual feed can be utilized for rice growth. On the other hand, the paddy field water maintains relatively high dissolved oxygen levels and provides abundant animal and plant food sources, creating an excellent habitat for crayfish [3]. Compared with rice monoculture systems, crayfish-integrated paddy ecosystems not only significantly improve the utilization efficiency of energy, water, and nutrients, enhancing system stability and resistance to external shocks [4], but also promote local material cycling, prevent energy flow loss from the paddy fields, and achieve rational improvement and utilization of the paddy field ecosystem in both structure and function.

Current research on the effects of integrated rice-fishery systems on paddy soil physicochemical properties has primarily focused on rice-fish and rice-crab systems [5-7], with few reports on the integrated rice-crayfish system. This study investigates the physical and chemical properties of soil under the integrated rice-crayfish system, aiming to provide data support for evaluating soil quality changes under this model and to offer a theoretical basis for further promoting the integrated rice-crayfish system.

1.1 Study Site Description

The experimental site was located at Guanshan Branch of Bailihu Farm in Qianjiang City, Hubei Province (30°11 36.07 N, 112°43 22.68 E), situated in the low-lying lake region of the Jianghan Plain. The area experiences a north subtropical monsoon humid climate with a mean annual temperature of 16.1°C, a frost-free period of 246 days, and mean annual precipitation of 1,100 mm. The winter static groundwater level ranges from 40–60 cm. The soil type is alluvial soil developed from lacustrine deposits.

1.2 Experimental Design

The field experiment was initiated in 2005, with two treatments: integrated rice-crayfish system (CR) and rice monoculture system (MR), each replicated three times. Each plot covered an area of 300 m^2, surrounded by ridges 60 cm wide and 40 cm high, wrapped with plastic film. To prevent water and crayfish movement between treatments, a ditch 0.4 m wide and 1.0 m deep was established between plots. In the CR treatment plots, a crayfish ditch 3.0–4.0 m wide and 0.8–1.0 m deep was excavated along one side of each plot, with nylon crayfish barrier nets installed around the perimeter. The nets were buried approximately 1.0 m underground and extended about 0.3 m above ground, supported by small bamboo sticks. The CR system involved flooding the fields after mid-season rice harvest for crayfish cultivation, with full rice straw return to the field. The MR system involved winter drying after rice harvest without crayfish cultivation, but also with full rice straw return. The rice variety used was mid-season 'Jianzhen 2' , and the crayfish species was red swamp crayfish (*Procambarus clarkii*).

1.3 Field Management

Land preparation and rice transplanting were conducted in mid-to-late June each year, following the principle of wide rows with narrow spacing and dense planting near ditches, with a plant spacing of 16.7 cm × 26.6 cm. Rice was harvested at the end of September. Fertilizer application rates were generally 120 kg $N \cdot hm^{-2}$, 36.0 kg $P_2O_5 \cdot hm^{-2}$, and 60.0 kg $K_2O \cdot hm^{-2}$ annually. In the CR treatment, juvenile crayfish were stocked in October 2005 at a density of 150,000–225,000 individuals $\cdot hm^{-2}$. The crayfish reproduced naturally in the paddy fields, with supplementary broodstock added annually as needed. Crayfish feed was applied from March to May each year, with an average input of 1,800 kg $\cdot hm^{-2}$. The feed contained total nitrogen, phosphorus, and potassium at 46.6 $g \cdot kg^{-1}$, 11.0 $g \cdot kg^{-1}$, and 10.5 $g \cdot kg^{-1}$, respectively. Adult crayfish were harvested by early June each year, while immature juveniles migrated to the crayfish ditches with the water. These juveniles re-entered the paddy fields after land preparation, transplanting, tillering control through sun-drying, and reflooding. A second season of mature crayfish was harvested before mid-season rice harvest. After rice harvest at the end of October, fields were reflooded to begin the next crayfish cultivation cycle.

1.4 Soil Sampling

Soil samples were collected in mid-October 2015 after rice harvest using an S-shaped five-point sampling method. In each plot, soil samples were collected from layers at 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm depths. During collection and transport, soil disturbance was minimized. Collected samples were cleared of plant roots and stones, mixed thoroughly, and air-dried. A portion of the air-dried soil was passed through 20-mesh and 100-mesh sieves for relevant indicator determination, while another portion was reserved for soil aggregate analysis.

1.5 Soil Analysis Methods

Soil compaction was measured using a soil compaction meter [8]. In mid-October 2015, a CP40-II digital soil compaction meter was used for direct in-situ field measurements across a soil depth range of 0–40 cm, with data recorded every 1 cm and 18 replicate measurements per plot. Soil pH, organic carbon, total nitrogen, total phosphorus, total potassium, alkali-hydrolyzable nitrogen, available phosphorus, and available potassium were determined following the methods described in Reference [9]. Specifically, soil pH was measured using a 1:5 soil-to-water ratio with a pH meter; soil organic carbon was determined by the potassium dichromate volumetric method; total nitrogen by the semi-micro Kjeldahl method; total phosphorus by H_2SO_4-$HClO_4$ digestion with molybdenum-antimony anti-colorimetry; total potassium by NaOH fusion-flame photometry; alkali-hydrolyzable nitrogen by the alkaline hydrolysis diffusion method; available phosphorus by the Olsen method; and available potassium by neutral NH_4Ac extraction-flame photometry. Total reducing substances were measured by $Al_2(SO_4)_3$ extraction-potassium dichromate volumetric method, while Fe^{2+} and Mn^{2+} were determined by $Al_2(SO_4)_3$ extraction-volumetric method [10].

Water-stable aggregates were fractionated using the wet sieving method provided by Elliott [11]. A DM2000-III soil aggregate analyzer was used to sequentially pass soil samples through 2 mm, 1 mm, 0.25 mm, and 0.053 mm sieves, separating five size classes of water-stable aggregates: >2 mm, 1–2 mm, 0.25–1 mm, 0.053–0.25 mm, and <0.053 mm. The separated aggregates of different sizes were oven-dried at 60°C and weighed.

1.6 Data Analysis

Experimental data were analyzed using SPSS 11.0 software for ANOVA, with other statistical analyses performed using Microsoft Excel 2007. The mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimension (D) of aggregates were calculated using the following formulas:

$$\mathrm{MWD} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

$$\mathrm{GMD} = \exp\left(\frac{\sum_{i=1}^{n} w_i \ln x_i}{\sum_{i=1}^{n} w_i}\right)$$

$$\frac{W(r < R_i)}{W_T} = \left(\frac{R_i}{R_{\max}}\right)^{3-D}$$

Where: R_i is the mean diameter of aggregates in a particular size class; $R_{\max}$ is the maximum aggregate diameter; w_i is the weight of aggregates in that size class; n is the number of sieves; $W(r < R_i)$ is the weight of aggregates with diameter smaller than R_i; W_T is the total weight of all aggregate size classes; and $(3 - D)$ is the slope of the linear relationship between $\log[W(r < R_i)/W_T]$ and $\log(R_i/R_{\max})$.

Results

2.1.1 Effects on Soil Compaction

Soil compaction, composed of soil shear strength, compressive force, and friction, is a composite indicator of soil strength that can predict soil bearing capacity, tillage performance, and root penetration resistance [12]. As shown in Table 1 , soil compaction gradually increased with soil depth across all treatments. Analysis of soil compaction at depths of 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 35 cm, and 40 cm revealed that the integrated rice-crayfish system exhibited significantly lower soil compaction at 15 cm, 20 cm, 25 cm, and 30 cm depths compared with the rice monoculture system, with reductions of 20.9%, 29.9%, 24.8%, and 14.7%, respectively.

2.1.2 Effects on Water-Stable Aggregate Stability

The quantity and stability of soil aggregates are important indicators of soil structural stability, with higher content of >0.25 mm aggregates (R0.25) indicating greater stability. The mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimension (D) of soil aggregates can all characterize aggregate stability. MWD and GMD reflect the size distribution of soil aggregates, with larger values indicating higher mean aggregate diameter, greater aggregation, and stronger stability [13]. D characterizes soil structural composition and uniformity, with smaller D values indicating better soil structure [14]. As shown in Table 2 , R0.25, MWD, and GMD of water-stable aggregates gradually decreased with increasing soil depth. Across the 0–40 cm soil layer, R0.25, MWD, and GMD values showed increasing trends in the integrated rice-crayfish system compared with the rice monoculture system, while D values showed a decreasing trend in the 0–20 cm layer, though none of these differences reached statistical significance. The MWD and GMD values of the integrated rice-crayfish system were significantly higher than those of the rice monoculture system in the 0–10 cm and 30–40 cm layers, with MWD increasing by 26.3% and 34.3%, and GMD increasing by 40.5% and 47.5%, respectively.

2.2.1 Effects on Total Soil Nutrients

As shown in Table 3 , soil organic carbon, total nitrogen, and total phosphorus contents gradually decreased with increasing soil depth, while total potassium content in the integrated rice-crayfish system showed a gradual increasing trend. Soil organic carbon and total potassium contents in the 0–40 cm layer were significantly higher in the integrated rice-crayfish system than in the rice monoculture system, with organic carbon increasing by 33.5%, 22.6%, 36.7%, and 31.6% in the 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm layers, respectively, and total potassium increasing by 5.1%, 5.0%, 8.4%, and 10.1%, respectively. Soil total nitrogen content in the 0–30 cm layer was significantly higher in the integrated rice-crayfish system, increasing by 29.9%, 23.0%, and 28.7% in the 0–10 cm, 10–20 cm, and 20–30 cm layers, respectively. Soil total phosphorus content was significantly higher only in the 0–10 cm layer of the integrated rice-crayfish system, showing a 9.8% increase compared with the rice monoculture system, with no significant differences observed in the 10–40 cm layers. The soil C/N ratio in the integrated rice-crayfish system increased with soil depth, showing an increasing trend compared with the rice monoculture system, though the difference was not statistically significant. These results demonstrate that long-term integrated rice-crayfish system significantly increased soil organic carbon and total potassium contents in the 0–40 cm layer, total nitrogen content in the 0–30 cm layer, and total phosphorus content in the 0–10 cm layer.

2.2.2 Effects on Soil pH and Available Nutrients

As shown in Table 4 , alkali-hydrolyzable nitrogen, available phosphorus, and available potassium contents decreased with increasing soil depth, while soil pH showed an increasing trend. Across the 0–40 cm soil layer, soil pH in the integrated rice-crayfish system showed an increasing trend compared with the rice monoculture system, though the difference was not statistically significant. Soil alkali-hydrolyzable nitrogen content in the 0–40 cm layer was significantly higher in the integrated rice-crayfish system, with increases of 33.8%, 28.3%, 43.6%, and 35.9% in the 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm layers, respectively, compared with the rice monoculture system. Soil available phosphorus content was significantly higher only in the 0–10 cm layer of the integrated rice-crayfish system, with no significant differences in the 10–40 cm layers, consistent with the trend observed for total phosphorus content. Soil available potassium content in the integrated rice-crayfish system showed no significant differences compared with the rice monoculture system in the 0–20 cm layer, but was significantly higher in the 20–40 cm layer, with increases of 15.2% and 22.9% in the 20–30 cm and 30–40 cm layers, respectively. These results indicate that the integrated rice-crayfish system significantly increased alkali-hydrolyzable nitrogen content in the 0–40 cm layer, available phosphorus content in the 0–10 cm layer, and available potassium content in the 20–40 cm layer.

2.2.3 Effects on Soil Reducing Substances

Active reducing substances in paddy soils (such as Fe^{2+} and Mn^{2+}) involve both chemical and biochemical changes, and their levels reflect the degree of soil gleying and quality degradation [15]. As shown in Table 5 , soil Fe^{2+}, Mn^{2+}, and total reducing substances in the rice monoculture system ranged from 0.048–0.084 $cmol \cdot kg^{-1}$, 0.017–0.028 $cmol \cdot kg^{-1}$, and 0.094–0.214 $cmol \cdot kg^{-1}$, respectively, while those in the integrated rice-crayfish system ranged from 0.073–0.100 $cmol \cdot kg^{-1}$, 0.018–0.025 $cmol \cdot kg^{-1}$, and 0.184–0.286 $cmol \cdot kg^{-1}$, respectively. According to the criteria established by Pan [16], soils under both rice cultivation systems were classified as lightly gleyed paddy soils.

With increasing soil depth, Fe^{2+} and Mn^{2+} contents showed a trend of initial increase followed by decrease, with the highest contents observed in the 20–30 cm layer. Total reducing substances in the rice monoculture system gradually decreased with increasing soil depth, whereas those in the integrated rice-crayfish system showed a trend of initial increase followed by decrease, with the highest content in the 20–30 cm layer. Soil Fe^{2+} content in the integrated rice-crayfish system was significantly higher than in the rice monoculture system in the 0–10 cm, 10–20 cm, and 30–40 cm layers, with no significant difference in the 20–30 cm layer. Soil Mn^{2+} content showed no significant differences between the two systems across the 0–40 cm layer. Total reducing substances showed no significant differences between the two systems in the 10–20 cm and 30–40 cm layers; however, in the 0–10 cm layer, total reducing substances were significantly lower in the integrated rice-crayfish system, while in the 20–30 cm layer, they were significantly higher. These results suggest that long-term integrated rice-crayfish system may increase the risk of soil gleying in layers below 10 cm.

2.3 Effects on Rice Yield and Economic Benefit

As shown in Table 6 , rice yield in the integrated rice-crayfish system was significantly higher than in the rice monoculture system, with a 9.5% increase. Excluding land rent and labor costs, the total output value and profit of the integrated rice-crayfish system were 65,858.4 $yuan \cdot hm^{-2}$ and 50,153.4 $yuan \cdot hm^{-2}$, respectively, representing increases of 46,818.0 $yuan \cdot hm^{-2}$ and 40,188.0

yuan $\cdot$ hm^{-2} compared with the rice monoculture system, with growth rates of 245.9% and 403.3%, respectively. In terms of output-input ratio, the integrated rice-crayfish system achieved a ratio of 4.2, a 100.0% improvement over the rice monoculture system. These results demonstrate that the integrated rice-crayfish system not only increases rice yield but also substantially improves farmers' income.

Discussion

Soil physical properties are factors affecting crop production, and stable, well-structured soil benefits plant growth. This study demonstrated that long-term integrated rice-crayfish system significantly reduced soil compaction in the 15–30 cm layer. Red swamp crayfish possess strong burrowing abilities and live in burrows during winter and summer, providing suitable temperatures to resist extreme external conditions and maintain a humid air environment [17]. Since paddy field rotary tillage and other measures make surface soil relatively uniform but have minimal impact on deeper soil layers, the presence of crayfish burrows in the integrated rice-crayfish system significantly reduced soil compaction in deeper layers while having little effect on surface soil compaction.

Soil aggregates are the fundamental units of soil structure and, as important components of soil structure, play crucial roles in coordinating water, nutrients, air, and heat in soil, as well as maintaining and stabilizing soil looseness and maturity [18]. Aggregate stability largely depends on the cementing capacity of organic and inorganic binding substances on soil particles [19], while the formation of water-stable aggregates primarily relies on the cementing action of organic matter [20]. This study showed that under long-term integrated rice-crayfish system, the content of >0.25 mm aggregates, MWD, and GMD all increased to varying degrees compared with the rice monoculture system, with MWD and GMD values being significantly higher in the 0–10 cm and 30–40 cm layers. This may be attributed to the significantly higher accumulation of soil organic carbon in the 0–40 cm layer under long-term integrated rice-crayfish system, thereby increasing organic cementing substances and their role in aggregation. Research by Oades et al. [21] demonstrated that polysaccharide substances also contribute to soil aggregate formation. Crayfish molting shells are rich in chitosan, which can increase the content of >0.25 mm water-stable aggregates [22], thereby improving water-stable aggregate stability to some extent. Fractal dimension of soil aggregates is closely related to soil structure and stability; that is, a smaller fractal dimension of aggregate size distribution indicates better soil structure and stability, as well as stronger erosion resistance [23]. This study found that fractal dimension in the integrated rice-crayfish system showed a decreasing trend in the 0–20 cm layer compared with the rice monoculture system, indicating that long-term integrated rice-crayfish system improved soil structure and stability in the 0–20 cm layer and enhanced aggregate erosion resistance, likely due to the significant increase in large-sized water-stable aggregates with stronger erosion resistance.

Soil organic carbon accumulation is primarily determined by the balance between organic matter input and mineralization rates of different carbon types [24]. This study showed that total soil organic carbon content in the integrated rice-crayfish system was significantly higher than in the rice monoculture system across the 0–40 cm layer. On one hand, the integrated rice-crayfish system maintains flooded conditions during winter for crayfish cultivation, leaving paddy fields in a waterlogged state during the fallow season with poor soil aeration, which reduces aerobic microbial activity and slows organic matter decomposition. On the other hand, uneaten crayfish feed, molting shells, and excreta during crayfish growth provide additional organic inputs, making the integrated rice-crayfish system more conducive to soil organic carbon sequestration compared with the winter-dried rice monoculture system. The soil C/N ratio is both an indicator of soil carbon and nitrogen nutritional balance [25] and an important marker of soil nitrogen mineralization capacity and whether soil organic matter decomposition is nitrogen-limited [26]. This study showed that the soil C/N ratio in the integrated rice-crayfish system increased with soil depth and was higher than in the rice monoculture system, though not significantly. This suggests that newly input organic matter or fertilizer-derived organic matter in the surface layer of the integrated rice-crayfish system tends to migrate downward, and that nitrogen mineralization is lower than in the rice monoculture system, favoring soil organic carbon storage. This study also demonstrated that long-term integrated rice-crayfish system significantly increased total potassium content in the 0–40 cm layer, total nitrogen content in the 0–30 cm layer, and total phosphorus and available phosphorus contents in the 0–10 cm layer compared with the rice monoculture system. This may be due to increased nutrient inputs from uneaten crayfish feed, molting shells, and excreta, as well as crayfish burrowing activities that reduce soil bulk density, increase soil porosity, and enhance soil permeability [27], allowing long-term water leaching to transport nitrogen and potassium downward. For soil phosphorus, except for small amounts of organic phosphorus in plant residues, most phosphorus exists in inorganic forms, with externally added phosphorus primarily adsorbed in the surface layer due to its low mobility and minimal leaching, resulting in little variation in deeper soil layers [28]. Consequently, the integrated rice-crayfish system significantly increased total phosphorus and available phosphorus contents only in the 0–10 cm layer, consistent with the findings of Wu et al. [29].

Vertical movement of soil available nutrients in the profile is primarily influenced by surface vegetation uptake, temperature, precipitation, and soil water movement. This study showed that alkali-hydrolyzable nitrogen, available phosphorus, and available potassium contents decreased with increasing soil depth, reflecting the obvious biological enrichment and surface accumulation of available nutrients. This distribution pattern may be related to the amount of aboveground litter and vertical root distribution, as plant roots absorb nutrients from deeper soil layers and return some nutrients to the surface through litter, providing a rich nutrient source while gradually depleting nutrients in deeper layers [30]. Generally, alkali-hydrolyzable nitrogen is highly correlated with total nitrogen, and available potassium is highly correlated with total potassium. This study demonstrated that long-term integrated rice-crayfish system significantly increased alkali-hydrolyzable nitrogen content in the 0–40 cm layer and available potassium content in the 20–40 cm layer. Available nutrient levels are related to soil properties and affected by fertilization practices [31]. Since 50% of potassium fertilizer was top-dressed during the rice booting stage, residual available potassium remained in the soil at maturity, resulting in no significant difference in available potassium content in the 0–20 cm layer between the integrated rice-crayfish system and rice monoculture system.

Reducing substances include inorganic and organic systems, with the former primarily comprising ferrous iron, manganous manganese, and sulfides, and the latter being much more complex organic reducing substances [32]. This study showed that soil Fe^{2+} content in the integrated rice-crayfish system was significantly higher than in the rice monoculture system in the 0–10 cm layer, while total reducing substances were significantly lower, possibly due to higher organic reducing substances in the 0–10 cm layer of the rice monoculture system. In the integrated rice-crayfish system, crayfish bottom-dwelling activities, including crawling, foraging, and burrowing, disturb paddy soil and function as inter-tillage, increasing soil dissolved oxygen content. Additionally, crayfish consume weeds and underwater plants, increasing light penetration and raising water and soil temperatures. Increased soil oxygen and temperature promote oxidation of active organic reducing substances, thereby reducing organic reducing substances. This study also found that while soil Fe^{2+} content in the integrated rice-crayfish system showed no significant difference from the rice monoculture system in the 20–30 cm layer, total reducing substances were significantly higher in this layer. This may be because the integrated rice-crayfish system increased organic carbon content in the 20–30 cm layer, while bioturbation by crayfish had limited effect on increasing dissolved oxygen in this layer. Under flooded conditions, abundant organic matter generated organic reducing substances under anaerobic conditions, promoting accumulation of reducing substances.

Conclusions

1. Long-term integrated rice-crayfish system significantly reduced soil compaction in the 15–30 cm layer, with reductions of 20.9%, 29.9%, 24.8%, and 14.7% at depths of 15 cm, 20 cm, 25 cm, and 30 cm, respectively, compared with the rice monoculture system.
2. Long-term integrated rice-crayfish system increased the content of >0.25 mm aggregates, MWD, and GMD in the 0–40 cm layer to varying degrees compared with the rice monoculture system, with MWD and GMD values being significantly higher in the 0–10 cm and 30–40 cm layers. The aggregate fractal dimension in the integrated rice-crayfish system was lower than in the rice monoculture system in the 0–20 cm layer.
3. Total potassium content and soil C/N ratio in the integrated rice-

crayfish system showed increasing trends with soil depth. Compared with the rice monoculture system, long-term integrated rice-crayfish system significantly increased soil organic carbon, total potassium, and alkali-hydrolyzable nitrogen contents in the 0–40 cm layer, total nitrogen content in the 0–30 cm layer, total phosphorus and available phosphorus contents in the 0–10 cm layer, and available potassium content in the 20–40 cm layer.

4. The integrated rice-crayfish system significantly increased soil Fe^{2+} content in the 0–10 cm, 10–20 cm, and 30–40 cm layers. The system significantly increased total reducing substances in the 20–30 cm layer but decreased total reducing substances in the 0–10 cm layer.
5. Compared with the rice monoculture system, the integrated rice-crayfish system significantly increased rice yield by 9.5%. The total output value, profit, and output-input ratio of the integrated rice-crayfish system increased by 46,818.0 $\text{yuan} \cdot \text{hm}^{-2}$, 40,188.0 $\text{yuan} \cdot \text{hm}^{-2}$, and 100.0%, respectively.

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Note: Figure translations are in progress. See original paper for figures.