Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-11
DOI: *10.15244/pjoes/191603* ONLINE PUBLICATION DATE:

Original Research

Impacts of Long-Term Positional Application of the Rice-Crab Model on the Field Environment

Mei Yang, Lingyun Shao, Yao Chi, Jin Chu, Hai Dong, Fengquan Yu*

Institute of Plant Protection, Liaoning Academy of Agricultural Sciences, Shenyang 110161, China

Received: 19 May 2024
Accepted: 24 July 2024

Abstract

The study entailed the continuous monitoring of rice-crab ecological farming systems over a span of 16 years to scrutinize the influence of distinct cultivation methodologies on the fundamental physicochemical attributes of paddy soils and the economic advantages of the ecosystem. The treatments encompassed the rice-crab farming system (CR) and the conventional single-crop paddy field (FP). The findings underscored that, relative to the conventional single-crop rice farming system, the rice-crab ecological farming system markedly ameliorated the physicochemical attributes of the soil, particularly within the initial 3 to 4 years, with comparatively negligible alterations in the subsequent 13 years, eventually attaining a relatively stable state. In synopsis, the soil bulk density witnessed a reduction of 0.05 $g\cdot cm^{-3}$, while soil porosity exhibited an augmentation of 2.1%. The content of soil organic matter escalated from 25.5 $g\cdot kg^{-1}$ to 28.4 $g\cdot kg^{-1}$, reflecting an increase of 2.90 $g\cdot kg^{-1}$. Additionally, the soil's total nitrogen content experienced a rise of 0.19 $g\cdot kg^{-1}$, whereas the levels of available nitrogen, phosphorus, and potassium surged by 21.2 $mg\cdot kg^{-1}$, 2.23 $mg\cdot kg^{-1}$, and 29.0 $mg\cdot kg^{-1}$, respectively. With regard to nitrogen fertilizer utilization, the CR treatment demonstrated a notable enhancement of 10.3% over the FP treatment. Concerning the economic benefits derived from rice and crabs, no significant discrepancy was observed in rice yield. Nonetheless, the enhanced quality of rice precipitated a 13.8% escalation in rice prices. Furthermore, the crab production within the CR treatment yielded a net economic advantage of approximately 18,269 RMB per hectare, thereby accomplishing the objective of dual benefits stemming from rice and crabs.

Keywords: long-term positional application, rice-crab model, soil physicochemical properties, economic benefit

Introduction

In the early 1990s, researchers initiated pilot studies on the integrated rice-crab farming system in Panjin City, Liaoning Province, thereby accumulating nearly three decades of experiential data [1-3]. Currently, this integrated farming system covers approximately 10% of the total rice field area in Liaoning Province, with primary concentrations in regions such as Panjin and Yingkou in the Liaohe River Delta and Dandong in the Yellow Sea rice-producing area [4]. By 2010, over 10,000 farmers nationwide had

*e-mail: yfq2023@aliyun.com

adopted the rice-crab farming model, leading to the establishment of a "company + farmers + base" business framework, which facilitated the rapid expansion of the rice-crab industry. This innovative ecologically integrated farming model, characterized by "one water serving two purposes, dual benefits from one place, and coexistence of rice and crabs," optimizes the utilization of agricultural resources. Remarkably, it not only yields significant economic value from crab production but also markedly enhances the quality of rice, thereby resulting in a substantial increase in income for rice farmers [5, 6].

Ensuring the long-term and sustainable development of the rice-crab farming model, as well as safeguarding the production capacity of the system, requires comprehensive research into the interaction mechanisms within the rice-crab symbiotic system. Previous studies have indicated that various fertilization methods significantly influence the growth and reproduction of Chinese mitten crabs [7]. Excessive application of ammonium-nitrogen fertilizer can induce crab toxicity, thereby impeding their growth and development [8, 9]. Following ammonium-nitrogen toxicity, crabs exhibit noticeable disruptions in their physiological and biochemical processes, leading to metabolic disorders in organs such as the liver and pancreas, as well as a reduction in immune system functionality [9]. To ensure safe fertilization for crabs without compromising rice yield and quality, research suggests that the optimal nitrogen fertilizer application should not exceed 270 kg per hectare [10]. Furthermore, adopting a judicious fertilization approach can significantly mitigate nitrogen leaching losses in rice-crab farming fields and augment nitrogen utilization efficiency [11].

As the rice-crab model continues to mature, various ecological farming models have emerged across different regions of southern China, including rice-fish, rice-duck, and rice-shrimp farming, gaining popularity among local farmers [12, 13]. Compared to single rice cultivation, these multi-species models exhibit notable efficiency in resource utilization and have demonstrated robust developmental trends [12, 14, 15]. It has been reported that the rice-crab farming model contributes to increased soil organic matter, beneficial soil biota populations, and soil nutrient levels, ultimately enhancing soil fertility. However, despite its significant economic benefits, research on the impact of the rice-crab farming model on soil ecosystems remains limited, particularly regarding the long-term evolution of soil fertility under multi-year rice-crab farming systems. A comprehensive understanding of the long-term evolution of soil fertility within the rice-crab farming system holds paramount significance for its sustainable development [5, 16]. To address this research gap, this study focuses on the following scientific questions: First, the long-term application of the rice-crab ecological farming system can significantly improve the physical structure of the soil, such as by reducing soil bulk density and increasing soil porosity, thereby enhancing soil aeration and water infiltration. Second, whether this model can significantly increase the content of soil organic matter and total nitrogen and improve soil nutrient status, including the levels of available nitrogen, phosphorus, and potassium, thus providing more sufficient nutrients for crops. Additionally, this study evaluates whether the long-term application of the rice-crab farming model can enhance the quality and market price of rice and provide additional economic benefits through crab production, achieving both economic and ecological benefits.

Our study presents several innovations: Firstly, unlike previous short-term studies, this research involves 16 years of continuous monitoring of the rice-crab ecological farming model, systematically analyzing its long-term effects on soil physical and chemical properties, filling the gap in long-term dynamic studies. Secondly, this research not only focuses on changes in soil physical and chemical properties but also systematically evaluates soil biological properties, such as enzyme activity, and the impact of these changes on crop growth and yield, providing a comprehensive soil health assessment. Additionally, through detailed economic benefit analysis, the study assesses the economic feasibility and advantages of the rice-crab farming model in improving rice quality, market price, and crab production, offering theoretical support for its promotion. Lastly, the research delves into the specific mechanisms of soil improvement under the rice-crab farming model, such as the impact of crab activities on soil structure and the application of organic-inorganic fertilizers on soil nutrient accumulation, providing scientific explanations for the ecological effects of the rice-crab farming model. Through these innovative studies, this paper not only validates the environmental and economic benefits of the rice-crab ecological farming model but also provides a scientific basis and practical guidance for its broader application. These findings are of significant importance for promoting sustainable agricultural development.

Experimental Procedures

Overview of the Test Area

The experiment was conducted within the rice field area situated in Jiangjia Village, Bawangzi Town, Panshan County, Panjin City, Liaoning Province, China (latitude N 40°45' to 41°27', longitude E 121°27' to 122°29'). This locale is typified by a single-season rice cultivation zone prevalent in Northern China, characterized by a warm temperate continental semi-humid monsoonal climate. It registers an annual average temperature of 8.3ºC, an annual average precipitation of 623.6 mm, and an annual average sunshine duration of 2787 h. Irrigation for the experiment was facilitated utilizing water sourced from the Liao River, conforming

Table 1. Physical-chemical characteristics of tested soil (2006).

pH	Bulk density/ ($g\cdot cm^{-3}$)	Porosity/%	Organic matter/%	Total N/%	Total P/%	Total K/%	Hydrolysable N/ ($mg\cdot kg^{-1}$)	Ava. P/ ($mg\cdot kg^{-1}$)	Ava. K/ ($mg\cdot kg^{-1}$)
7.9	1.36	48.87	2.54	0.14	0.05	0.18	95.1	10.0	198

to the stipulated criteria for irrigation in green food production and freshwater aquaculture.

The experimental site is situated within the core trial and demonstration area designated for rice-crab ecologically integrated farming. Historically, prior to 2006, the area was conventionally utilized for rice cultivation. Subsequently, in 2006, the experimental setup commenced. The treatment plots allocated for rice-crab ecologically integrated farming spanned an area of 667 m^2, with three replications implemented. Correspondingly, adjacent plots of equivalent size, where crab farming was absent and conventional rice farming prevailed, served as control plots (referred to as FP treatment), and also replicated thrice. The soil composition in the vicinity is categorized as saline-alkali paddy soil, and the fundamental physical and chemical attributes of the topsoil (0~20 cm) are detailed in Table 1.

Experimental Design

Between 2007 and 2022, a continuous monitoring and tracking study was undertaken, comparing conventional rice fields (referred to as the FP treatment) with rice-crab ecologically integrated farming fields (designated as the CR treatment). Throughout the 16-year duration, the experimental treatments and locations remained consistent, with fixed monitoring sites established each year. The rice variety selected for the experiments was 'Yanfeng 47'.

In the FP treatment, conventional fertilization practices indigenous to the locality were adhered to, comprising a basal application of 750 $kg\cdot hm^{-2}$ of a ternary compound fertilizer (composed of N-P_2O_5-K_2O at percentages of 26%-15%-18%), along with 150 $kg\cdot hm^{-2}$ of urea for tillering and 75 $kg\cdot hm^{-2}$ of urea for panicle development. This corresponded to a total nutrient application of N 298.5 $kg\cdot hm^{-2}$, P_2O_5 112.5 $kg\cdot hm^{-2}$, and K_2O 135 $kg\cdot hm^{-2}$. Field management procedures followed traditional rice cultivation practices typical of the area.

In the context of the Controlled Release (CR) treatment, a singular application of organic-inorganic fertilizer tailored specifically for rice-crab cultivation was uniformly administered prior to the transplantation of rice seedlings. This application was executed at a rate of 1200 $kg\cdot hm^{-2}$, comprising nutrients with a composition of N-P_2O_5-K_2O at 22.5%-8.75%-7.5%, maintaining an inorganic-to-organic nitrogen ratio of 7:3. Consequently, the total nutrient dosage amounted to N 270 $kg\cdot hm^{-2}$, P_2O_5 105 $kg\cdot hm^{-2}$, and K_2O 90 $kg\cdot hm^{-2}$. The cultivation methodology employed in these fields adhered to the "Panshan rice-crab integrated farming" model, characterized by the implementation of parallel ditches and ridges, interspersed planting of rice and fallow spaces, cultivation of beans on the ridges, and the early introduction of crab juveniles. Chinese mitten crabs were introduced into the fields precisely one week following the transplantation of rice seedlings, with a stocking density of 9000 $crabs\cdot hm^{-2}$. Additionally, 1050 $kg\cdot hm^{-2}$ of crab feed was supplied concurrently. Notably, no supplementary fertilizer was administered throughout the subsequent growth stages of the rice plants.

Indicator Measurements

Annually, spanning from mid to late May, soil samples were systematically collected prior to land preparation utilizing the S-shaped five-point sampling technique. These samples, sourced from the surface layer spanning 0-20 cm depth, underwent meticulous mixing, air-drying at ambient temperature, and subsequent analysis through diverse methodologies.

Soil Physical Properties

The physical properties of the soil were mainly determined by the bulk density and porosity, which were determined by the ring knife method [17, 18]. The volume of 200 mL ring knife with a bottom cover was selected, and the mass of the ring knife was weighed and recorded as M_0; fresh soil samples were uniformly loaded into the ring knife, and the mass of the ring knife and soil was weighed and recorded as M_1; the ring knife and soil were dried at 105°C for 4 h, and then naturally cooled in the desiccator for 4 h, and the mass of the ring knife and soil was weighed and recorded as M_2, and then the calculation of the bulk density was carried out by the following Equations:

$$Relative\ water\ content\ \ (W)\ = \frac{M_1 - M_2}{M_1 - M_0}$$

$$Bulk\ denisty = \frac{(M_1 - M_0) \times (1 - W)}{200}$$

Soil samples were loaded into the ring cutter in a field-tight condition, fastened to the perforated top cover, and weighed as M_3; the ring cutter was soaked in water for 24 h and weighed as M_4. The Equation for the determination of soil porosity is given below:

$$Porosity = \frac{M_4 - M_3}{200}$$

Soil Chemical Properties

The determination of soil organic matter content utilized the potassium dichromate-sulfuric acid oxidation method [19]. pH levels were assessed employing a potentiometric technique. Total nitrogen content was quantified employing the Kjeldahl nitrogen determination method [20]. Total phosphorus concentration was determined via the molybdenum antimony anti-colorimetric method [21]. Total potassium content was measured through a mixed acid digestion method followed by atomic absorption spectroscopy [22]. Water-soluble nitrogen was assessed utilizing sodium hydroxide alkali diffusion [23]. Available phosphorus was quantified employing the molybdenum antimony anti-colorimetric method [24], while available potassium levels were determined through ammonium acetate extraction followed by atomic absorption spectroscopy as per NY/T 889-2004 standard protocol [25]. Soil redox potential was determined using an automatic redox potential meter (FJA-6) with undisturbed 0-20 cm topsoil samples collected from the rice fields within 3 h of extraction. Measurements were taken each year on May 20th for 16 consecutive years. In addition, in 2022, the exchangeable base ion content was determined with ammonium acetate and analyzed using ICP.

Soil Enzyme Activities

Soil phosphatase activity was measured using the disodium phenyl phosphate method [26]. Urease content was determined using the indophenol blue colorimetric method [27].

Crab and Rice Yields

The mass of Chinese mitten crabs was weighed using an electronic balance. The crab survival rate was calculated as the number of crabs recaptured divided by the number released, multiplied by 100% [28]. Rice yield was determined based on actual field measurements, but data for yield measurements were only available for 2021-2022.

Nitrogen Fertilizer Utilization Efficiency

The Equation for the nitrogen fertilizer utilization efficiency (%) is given below:

$$Nitrogen\ fertilizer\ utilization\ efficiency = \frac{nitrogen\ uptake\ in\ the\ fertilized\ area - nitrogen\ uptake\ in\ the\ unfertilized\ area}{amount\ of\ nitrogen\ applied}$$

Data Statistics and Analysis

Using DPS 18.1 software [29], the trial's raw data were submitted to a one-way ANOVA after being tallied using Excel 2019.

Results

Soil Physical Properties

Continuous monitoring of soil physical properties from 2007 to 2022 revealed that the rice-crab ecological farming system (CR) significantly improved soil bulk density and porosity compared to the conventional single-crop paddy field (FP). In 2007, there were no significant differences between the two systems in terms of soil bulk density and porosity. However, starting in 2011, the CR treatment showed a notable decrease in soil bulk density and a significant increase in soil porosity, a trend that continued in subsequent years and stabilized after 2013. Specifically, the soil bulk density under the CR system gradually decreased to approximately 1.28 g·cm^{-3}, while soil porosity increased to 52.64%. Compared to the FP treatment, the soil bulk density in the CR treatment decreased by 4.41% in 2011, 5.19% in 2013, and 5.88% in 2022. Concurrently, soil porosity in the CR treatment increased by 3.06% in 2011, 5.28% in 2013, and 6.55% in 2022. These results indicate that the rice-crab ecological farming system significantly enhances soil structure, improving aeration and water infiltration, thereby creating a more favorable environment for crop growth (Table 2).

General Chemical Properties of Soil

Throughout the study period, there were no significant differences in soil pH and redox potential (Eh) between the two treatments. However, the rice-crab ecological farming system (CR) showed significant advantages in terms of organic matter content and total nitrogen content. Specifically, during the early years of the study (2007-2008), there were no significant differences in organic matter and total nitrogen content between the CR and FP treatments. However, from 2009 onwards, the CR treatment significantly outperformed the FP treatment in both parameters ($p<0.05$). For instance, in 2009, the organic matter content in the CR treatment reached 28.2 g·kg^{-1}, which was 12.8% higher than in the FP treatment. The total nitrogen content in the CR treatment was 1.55 g·kg^{-1}, 8.4% higher than in the FP treatment. This trend continued and further strengthened in subsequent years. By 2022, the organic matter content in the CR treatment increased to 29.1 g·kg^{-1}, a 14.9% increase compared to the FP treatment. Similarly, the total nitrogen content in the CR treatment increased to 1.63 g·kg^{-1}, a 14.5% increase compared to the FP treatment (Table 3).

Table 2. Physical properties of soil.

Year	Bulk density/(g·cm^{-3})		Porosity/%	
	FP	CR	FP	CR
2007	1.36a	1.36a	48.92a	49.02a
2008	1.34a	1.33a	49.74a	50.06a
2009	1.36a	1.32a	49.07a	50.39a
2010	1.35a	1.32a	49.45a	51.00a
2011	1.36a	1.30b	49.40a	50.91a
2012	1.36a	1.30b	49.10a	51.41b
2013	1.35a	1.28b	49.40a	52.00b
2014	1.34a	1.29b	49.40a	52.41b
2015	1.35a	1.28b	49.40a	52.41b
2016	1.36a	1.27b	49.40a	52.00b
2017	1.36a	1.28b	49.40a	52.41b
2018	1.35a	1.29b	49.40a	52.41b
2019	1.36a	1.28b	49.40a	52.64b
2020	1.35a	1.29b	49.40a	52.41b
2021	1.36a	1.27b	49.40a	52.64b
2022	1.36a	1.28b	49.40a	52.64b

Note: Significant differences between treatments are indicated in the same column by different letters ($p<0.05$).

Table 3. Effect of perennial rice-crab system on soil general chemical properties.

Year	pH		Eh/mv		Organic matter/(g·kg^{-1})		Total N/(g·kg^{-1})	
	FP	CR	FP	CR	FP	CR	FP	CR
2007	7.9a	7.9a	247a	247a	24.6a	25.2a	1.38a	1.39a
2008	7.9a	7.8a	247a	245a	25.3a	26.5a	1.41a	1.45a
2009	7.8a	7.8a	248a	243a	25.0a	28.2b	1.43a	1.55b
2010	7.8a	7.5a	246a	243a	26.5a	28.5b	1.42a	1.61b
2011	7.8a	7.8a	246a	243a	25.0a	28.7b	1.42a	1.60b
2012	8.0a	7.7a	247a	242a	26.1a	29.2b	1.40a	1.63b
2013	8.0a	7.7a	248a	241a	25.8a	28.9b	1.39a	1.65b
2014	8.1a	7.5a	248a	241a	25.5a	28.6b	1.40a	1.62b
2015	8.0a	7.8a	246a	242a	26.3a	29.0b	1.38a	1.60b
2016	7.9a	7.7a	247a	241a	25.6a	29.0b	1.39a	1.60b
2017	7.8a	7.7a	248a	241a	25.2a	29.3b	1.41a	1.63b
2018	8.0a	7.5a	246a	240a	25.1a	28.8b	1.40a	1.65b
2019	8.1a	7.6a	247a	242a	25.3a	29.1b	1.42a	1.63b
2020	7.9a	7.8a	248a	245a	25.6a	29.2b	1.41a	1.64b
2021	8.0a	7.9a	246a	241a	25.1a	29.1b	1.40a	1.65b
2022	8.1a	7.6a	247a	242a	25.3a	29.1b	1.42a	1.63b

Note: Different lower-case letters in the same row represent significant differences ($P<0.05$).

Soil Available Nutrient Contents

The soil in the experimental area demonstrated an abundance of hydrolysable nitrogen, an excess of available potassium, and a moderately lower level of available phosphorus. Available nutrient indicators serve as metrics for the soil's capacity to provide nutrients readily accessible to plants during the growing season. As illustrated in Fig. 1, over the 16-year period, all available nutrient indicators for the FP treatment exhibited non-significant variations, with mean values of 99.3 mg·kg^{-1} for hydrolysable nitrogen, 10.11 mg·kg^{-1} for available phosphorus, and 198 mg·kg^{-1} for available potassium. In contrast to FP, the CR treatment demonstrated significant alterations in all indicators from 2007 to 2010, but insignificant changes from 2011 to 2022. Notably, the hydrolysable nitrogen, available phosphorus, and available potassium indicators for the CR treatment experienced substantial changes from 2007 to 2010, increasing from 102 mg·kg^{-1} to 123 mg·kg^{-1}, 10.8 mg·kg^{-1} to 13.0 mg·kg^{-1}, and 209 mg·kg^{-1} to 228 mg·kg^{-1}, respectively. Subsequent to 2010, the interannual variations in these indicators for the CR treatment were statistically non-significant, maintaining mean values of 122 mg·kg^{-1} for hydrolysable nitrogen, 12.6 mg·kg^{-1} for available phosphorus, and 230 mg·kg^{-1} for available potassium. Throughout the 16-year duration, the CR treatment witnessed a notable increase in all available nutrient indicators, with percentage increments as follows: 20.1% for hydrolysable nitrogen, 22.2% for available phosphorus, and 14.7% for available potassium, in comparison to the FP treatment.

Soil Exchangeable Base Ions Contents

As additional testing for soil exchangeable salt base ion content was conducted only in 2022, our study presents the results for that specific year. From Table 4, it is evident that, in comparison to the FP treatment, the CR mode demonstrates a consistent trend of decreasing ion content. Notably, the levels of exchangeable Na^+ and Ca^{2+} ions exhibit a significant reduction. Given that the experimental area is characterized by coastal saline-alkali soil, the exchangeable Na^+ ion content in the soil is considerably higher than that found in conventional soils. Through the field practices implemented under the rice-crab farming model, there is a significant decrease in the levels of Na^+ and Ca^{2+} ions within the plots.

Table 4. Soil exchangeable base cation contents in different cropping systems.

Exchangeable cation variety	FP/(mg·kg^{-1})	CR/(mg·kg^{-1})
Na^+	528a	478b
K^+	330a	323a
Mg^{2+}	965a	910a
Ca^{2+}	781a	564b

Note: Different lower-case letters in the same row represent significant differences (P<0.05).

Enzyme Activities in Soils

As depicted in Fig. 2, the URE activity in the CR treatment significantly lags behind that of the FP treatment, suggesting diminished urease activity within the rice-crab farming system compared to conventional rice cultivation. Typically, urease activity shows a significant positive correlation with soil organic matter content, total nitrogen, available nitrogen content, and total porosity. However, in this study, all indicators of the CR treatment surpass those of the FP treatment, except for urease content, which displays an inverse trend. This deviation may stem from the FP treatment incorporating a higher amount of inorganic ammonium nitrogen in the base fertilizer, totaling 300 kg·hm^{-2}. This heightened urease activity induced by the substrate promotes the conversion of ammonium nitrogen to nitrate nitrogen, facilitating rice growth

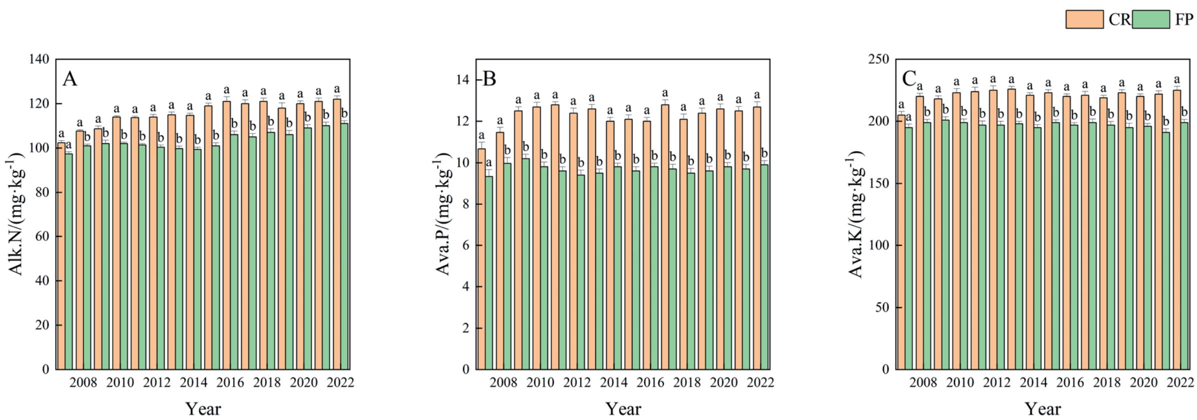

Fig. 1. Soil available nutrient contents in different cropping systems.
Note: Significant differences between treatments are indicated by different letters (p<0.05).

and development. Conversely, in the CR treatment, the total nitrogen application in the soil is 270 kg·hm^{-2}, significantly lower than that in the FP treatment, with 30% of the nitrogen being organic nitrogen, resulting in relatively low urease activity. Furthermore, urease activity correlates with the timing of exogenous nitrogen application in the soil.

Alkaline phosphatase (AKP) plays a crucial role in converting organic phosphorus in the soil into inorganic phosphorus, thus enhancing its availability for crops. The activity of alkaline phosphatase exhibits a significant negative correlation with soil phosphorus levels. In the context of AKP, the FP treatment demonstrates markedly higher activity compared to the CR treatment, indicating lower effective phosphorus content in the FP treatment soil than in the CR treatment soil. This observation aligns with the available phosphorus content values in this study. Specifically, the FP treatment soil exhibits moderately low available phosphorus levels, averaging 10.0 mg·kg^{-1} over 16 years, while the CR treatment soil presents moderately higher available phosphorus levels, averaging 12.3 mg·kg^{-1} over the same period (Fig. 1). This discrepancy could be attributed to the enhanced AKP activity in the FP treatment, facilitating the release of organic phosphorus and its subsequent absorption by rice. Conversely, the significant increase in available phosphorus content in the CR treatment adequately meets the requirements for rice growth, resulting in reduced alkaline phosphatase activity.

Economic Benefits

The findings, as summarized in Table 5, reveal that during the years 2021 and 2022, the CR treatment exhibited a marginal increase in rice yield compared to the FP treatment, albeit without achieving statistical significance. Notably, the CR treatment, characterized by distinct fertilization patterns, featured a reduced proportion of inorganic nitrogen coupled with a higher proportion of organic nitrogen. Consequently, the rice quality within the CR treatment surpassed that of the FP treatment, precipitating a 13.8% escalation in the price of CR-treated rice. Additionally, the CR treatment demonstrated elevated crab output, averaging approximately 20,000 RMB per hectare. When scrutinizing the net income implications, it becomes apparent that the CR treatment yielded a noteworthy average increment of 18,269 RMB per hectare in economic benefits across 2021 and 2022.

Moreover, the nitrogen utilization efficiency within paddy fields operating under the rice-crab farming system witnessed a commendable rise of 10.3%. This enhancement in efficiency is particularly notable when juxtaposed against the FP treatment's nitrogen fertilizer application, which amounted to 300 kg N·hm^{-2} in contrast to the CR treatment's lower total nitrogen application of 270 kg N·hm^{-2}, with 30% being organic nitrogen. The discernible improvement in nitrogen utilization efficiency within the rice-crab farming system in comparison to the FP treatment signifies a substantial boon.

Discussion

Changes in soil physical properties generally occur at a much slower pace compared to changes in chemical properties [30]. Experimental monitoring conducted over a span of 16 years in rice-crab farming fields reveals a decrease in soil bulk density and an increase in total porosity, indicative of improved soil structure.

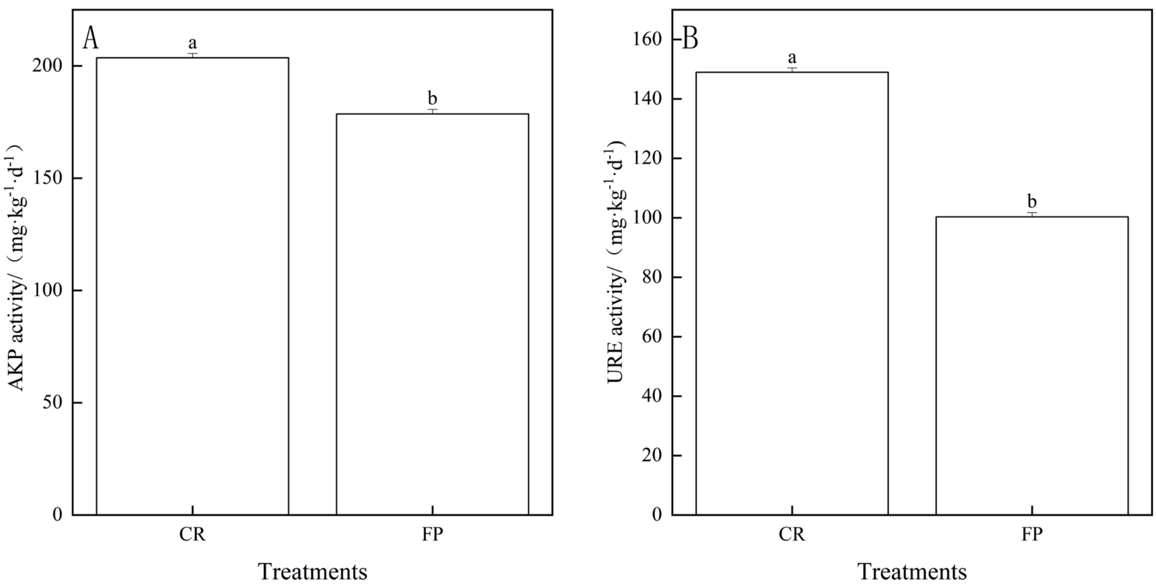

Fig. 2. Enzyme activities in soils with different cropping systems (in 2022).
Note: Significant differences between treatments are indicated by different letters (p<0.05).

Table 5. Economic benefits of different cropping systems.

Cropping system	Year	Yield of rice/ (kg·hm^{-2})	Value of rice/ (RMB·hm^{-2})	Yield of crab/ (kg·hm^{-2})	Value of crab/ (RMB·hm^{-2})	Cost of rice production/ (RMB·hm^{-2})	Cost of crab production/ (RMB·hm^{-2})	Net income/ (RMB·hm^{-2})	N use efficiency/%
FP	2021	10187	29542	-	-	20250	-	9292	31.5
	2022	9960	28884	-	-	20250	-	8634	31.6
CR	2021	10648	35140	372	21576	20700	7800	28216	41.8
	2022	10583	34924	354	19824	20700	7800	26248	42.0

The bulk density of the soil under the CR system gradually decreased to approximately 1.28 g·cm^{-3}, while soil porosity increased to 52.64% by 2022. These changes are primarily attributed to the field activities of river crabs, which disrupt the soil plow layer, enhancing soil aeration and improving soil pore structure [31]. Additionally, enhancements in fertilizer composition and residual river crab bait significantly elevate soil organic matter content, consequently reducing soil bulk density and enhancing soil structure [32]. Throughout the study period, soil pH and redox potential (Eh) showed no significant differences between the two treatments. However, the CR system exhibited significant advantages in terms of organic matter content and total nitrogen content. From 2009 onwards, the organic matter content in the CR treatment significantly surpassed that in the FP treatment, reaching 29.1 g·kg^{-1} by 2022, a 14.9% increase compared to the FP treatment. Similarly, the total nitrogen content in the CR treatment increased to 1.63 g·kg^{-1}, a 14.5% increase compared to the FP treatment. This trend may be ascribed to the disturbance of water and soil by river crabs, leading to heightened dissolved oxygen content in water and improved soil redox conditions [33].

The augmentation in nutrient and organic matter content within rice-crab farming fields is partially attributed to the annual application of organic-inorganic compound fertilizers, containing 30% organic nitrogen. This organic nitrogen, not entirely decomposed and utilized within the same year, accumulates over time, thereby augmenting the soil's nutrient reservoir capacity [34-36]. Additionally, to foster high-quality river crabs, bait is continuously introduced into rice fields during their growth [37]. With an annual input of 1050 kg·hm^{-2}, a portion of the crab feed remains unconsumed in the rice fields, consequently increasing soil organic matter, total nitrogen, and total potassium content. Furthermore, weeds and aquatic organisms within the fields are consumed by river crabs and subsequently converted into feces, contributing to an increase in organic fertilizer within the rice fields [38]. Our study denotes that while the change in soil total phosphorus content in the rice-crab farming system is insignificant, available phosphorus content has markedly increased. This phenomenon may be attributed to the increased exogenous phosphorus being readily absorbed and utilized by plants, consequently resulting in a significant rise in active phosphorus content. Additionally, river crab excreta harbors abundant microorganisms and undigested protein from feed [39]. Partially digested feed components undergo breakdown and oxidation in water, elevating the available nutrient content and total microbial population within the rice fields [2]. Moreover, the foraging behavior of river crabs, wherein they consume weeds and floating organisms in field water, diminishes the absorption of available nutrients in the soil by other organisms, thereby furnishing adequate nutrients for rice growth [40]. The CR system also demonstrated notable improvements in soil enzyme activities, particularly alkaline phosphatase (AKP), which plays a crucial role in converting organic phosphorus into inorganic phosphorus, enhancing its availability for crops. The activity of AKP was significantly higher in the CR system, reflecting the increased available phosphorus content and meeting the nutrient requirements for rice growth. Economically, the CR system provided substantial benefits over the FP system. While rice yield differences between the two systems were not statistically significant, the quality of rice in the CR system was superior, resulting in a 13.8% increase in rice prices. Moreover, crab production within the CR system yielded a net economic advantage of approximately 18,269 RMB per hectare, demonstrating the dual benefits of rice and crab production. The nitrogen utilization efficiency in the CR system also witnessed a commendable rise of 10.3%, indicating a more efficient use of nitrogen fertilizers.

In the rice-crab farming ecological system, rice and crabs coexist synergistically, with rice fields serving as a conducive habitat and a source of feed for river crabs. The crabs, in turn, consume weeds and supplementary feed, the remnants of which return to the fields as organic manure. Organic nutrients supplant some of the roles of chemical nutrients, thereby reducing the overall input of chemical nutrients and curbing excessive fertilizer usage, consequently enhancing nutrient utilization efficiency and mitigating chemical fertilizer emissions into the environment. The foraging behavior of river crabs, characterized by their consumption of weeds, aquatic plants, and waterborne insects, optimizes the growth environment for rice, creating conditions unfavorable for the proliferation of diseases and pests. Consequently, this diminishes the frequency and quantity of chemical pesticide applications, fostering the sustainable advancement of rice cultivation. Furthermore, the ecological farming model substantially bolsters rice growth and quality, coupled with the production of high-value aquatic products, thereby augmenting farmers' income and fortifying their resilience to market vicissitudes. Additionally, it enriches market supply. Therefore, the rice-crab ecological farming model epitomizes a win-win scenario, ensuring both economic prosperity and ecological sustainability in rice cultivation.

Conclusions

The results of a 16-year field experiment in the rice-crab farming plots demonstrate that the long-term rice-crab farming model significantly improves soil physical, chemical, and biological properties. Especially in the initial 3 to 4 years, the soil bulk density significantly decreases, while soil porosity markedly increases. Soil organic matter, total nitrogen content, and available nitrogen, phosphorus, and potassium contents all show significant increases. Over the subsequent 13 years, these indicators exhibit no significant changes and reach a stable state. In terms of economic performance, the improvement in rice quality and the output of river crabs in the rice-crab farming system significantly boost farmers' income, with an increase in income exceeding 18,000 RMB per hectare. In conclusion, the rice-crab farming model is highly recommendable for widespread adoption, both from an economic and ecological perspective.

Acknowledgments

This study was supported by the following grants: Liaoning Province Panshan County Rice and Crab Scientific and Technological Farming Mission Fund (2023JH5/10400098).

Conflict of Interest

The authors declare no conflict of interest.

References

1. YANG M., SHAO L., CHU J., LI Z., TIAN C., SUN F., YU F. Comparative Analyses of Carbon Footprints and Economic Benefits: Rice-Shrimp Co-Cropping, Rice-Crab Co-Cropping and Rice Monoculture Models. Polish Journal of Environmental Studies. **33** (2), 1413, **2024**.
2. LIANG X., YU Y., MEI J., FENG J., LI P., BAI Y., MA M., LIU F., QU Y., LANG Y., LI X. Effects of feed protein levels on Chinese mitten crabs (Eriocheir sinensis) under the rice-crab co-culture model: Performance, nutrient composition, antioxidant capacity and immunity. Aquaculture Reports. **35**, 101963, **2024**.
3. SUN N., YANG A.-P., WANG S.-M., ZHU G.-L., LIU J., WANG T.-Y., WANG Z.-J., QI B.-W., LIU X.-Y., LV S.-X., LI M.-H., FU Q. Mechanism of synergistic remediation of soil phenanthrene contamination in paddy fields by rice-crab coculture and bioaugmentation with Pseudomonas sp. Environment International. **182**, 108315, **2023**.
4. XU Q., WANG X., XIAO B., HU K. Rice-crab coculture to sustain cleaner food production in Liaohe River Basin, China: An economic and environmental assessment. Journal of Cleaner Production. **208**, 188, **2019**.
5. N'SOUVI K., SUN C., CHE B. Aquaculture technology adoption and profitability of the polyculture system practiced by prawn and crab farmers: Case study of Anhui province in China. Aquaculture Reports. **21**, 100896, **2021**.
6. WANG X., ZHENG R.-X., ZHANG D.-M., LEI X.-Y., WANG S., WAN J.-W., LIU H.-J., CHEN Y.-K., ZHAO Y.-L., WANG G.-Q., WANG Q.-J., GUO Z.-X. Effects of different stocking densities on growth performance, nutritional quality and economic benefit of juvenile female Chinese mitten crab (Eriocheir sinensis) in rice-crab culture systems. Aquaculture. **553**, 738111, **2022**.
7. CHEN B., GUO L., TANG J., LI Y., LI C. Comprehensive impacts of different integrated rice-animal co-culture systems on rice yield, nitrogen fertilizer partial factor productivity and nitrogen losses: A global meta-analysis. Science of The Total Environment. **915**, 169994, **2024**.

8. QIN F., SHEN T., YANG H., QIAN J., ZOU D., LI J., LIU H., ZHANG Y., SONG X. Dietary nano ceriucrab (Eriom oxide promotes growth, relieves ammonia nitrogen stress, and improves immunity in cheir sinensis). Fish & Shellfish Immunology. **92**, 367, **2019**.
9. LIU Z., SHI A., ZHAO M., ZHENG C., CHEN J., NIU C., SONG Y., MA X., PANG Y., SHI X., CHENG Y., YANG X. Dietary N-carbamylglutamate (NCG) supplementation improves the survival, digestive and immunological parameters by promoting ammonia excretion in Chinese mitten crab (Eriocheir sinensis), under ammonia nitrogen stress. Aquaculture and Fisheries. **2024**.
10. LYU Y., YANG X., PAN H., ZHANG X., CAO H., ULGIATI S., WU J., ZHANG Y., WANG G., XIAO Y. Impact of fertilization schemes with different ratios of urea to controlled release nitrogen fertilizer on environmental sustainability, nitrogen use efficiency and economic benefit of rice production: A study case from Southwest China. Journal of Cleaner Production. **293**, 126198, **2021**.
11. ZHAO W., LIANG H., FU Y., LIU Y., YANG C., ZHANG T., WANG T., RONG L., ZHANG S., WU Z., SUN W. Effects of different fertilization modes on rice yield and quality under a rice-crab culture system. PLoS One. **15** (3), e0230600, **2020**.
12. GE L., SUN Y., LI Y., WANG L., GUO G., SONG L., WANG C., WU G., ZANG X., CAI X., LI S., LI P. Ecosystem sustainability of rice and aquatic animal co-culture systems and a synthesis of its underlying mechanisms. Science of The Total Environment. **880**, 163314, **2023**.
13. LI W., HE Z., WU L., LIU S., LUO L., YE X., GAO H., MA C. Impacts of co-culture of rice and aquatic animals on rice yield and quality: A meta-analysis of field trials. Field Crops Research. **280**, 108468, **2022**.
14. MA N., LIU X., WANG L., LIU G. A meta-analysis on the mitigation measures of methane emissions in Chinese rice paddy. Resources, Conservation and Recycling. **202**, 107379, **2024**.
15. BASHIR M.A., WANG H., SUN W., ZHAI L., ZHANG X., WANG N., REHIM A., RAZA Q.-U.-A., LIU H. The implementation of rice-crab co-culture system to ensure cleaner rice and farm production. Journal of Cleaner Production. **316**, 128284, **2021**.
16. YANG X., DENG X., ZHANG A. Does conservation tillage adoption improve farmers' agricultural income? A case study of the rice and fish co-cultivation system in Jianghan Plain, China. Journal of Rural Studies. **103**, 103108, **2023**.
17. LARSBO M., KOESTEL J., KRAB E.J., KLAMINDER J. Quantifying earthworm soil ingestion from changes in vertical bulk density profiles. European Journal of Soil Biology. **120**, 103574, **2024**.
18. WANG C., CHEN R., LU J., CHI H., TANG Y., ZHU X., LIU X. Impact of Exogenous Addition of Sulphur Powder on the Effectiveness of Kitchen Waste Compost Seedling Substrates. Polish Journal of Environmental Studies. **2024**.
19. BIAN Q., ZHAO L., CHENG K., JIANG Y., LI D., XIE Z., SUN B., WANG X. Divergent accumulation of microbe- and plant-derived carbon in different soil organic matter fractions in paddy soils under long-term organic amendments. Agriculture, Ecosystems & Environment. **366**, 108934, **2024**.
20. MAZZONCINI M., SAPKOTA T.B., BàRBERI P., ANTICHI D., RISALITI R. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil and Tillage Research. **114** (2), 165, **2011**.
21. TURNER B.L., BIELNICKA A. W., KIM P.J. Stable soil phosphorus transformations following long-term litter manipulation in a lowland tropical forest. Soil Advances. **1**, 100002, **2024**.
22. XIONG Z., ZHU D., LU Y., LU J., LIAO Y., REN T., LI X. Continuous potassium fertilization combined with straw return increased soil potassium availability and risk of potassium loss in rice-upland rotation systems. Chemosphere. **344**, 140390, **2023**.
23. CHEN S., ZHANG S., LI H., HU T., SUN G., CUI X., LIU J. Optimizing irrigation and nitrogen management improves soil soluble nitrogen pools and reduces nitrate residues in a drip-fertigated apple orchard on the Loess Plateau. Agricultural Water Management. **295**, 108770, **2024**.
24. ZHANG Y., YANG L., SUN W., RUAN Y., DOU H., SONG M., LONG H., ZHANG Y., WANG Y., GUO J., SHAO R., WANG H., YANG Q. An effective method of magnetic field treatment in increasing soil phosphorus availability in wheat rhizosphere. Rhizosphere. **27**, 100760, **2023**.
25. LIU Z., GE L., LI S., PAN R., LIU X. Kitchen Waste Compost's Impact on Rice Quality, Yield, and Soil Environment. Polish Journal of Environmental Studies. **32** (4), 3225, **2023**.
26. WEI K., WANG J., YUAN C., TANG J., ZHU B. Relationships of bacterial-feeding nematodes, phosphatase-producing bacteria, phosphatase activity and their effects on soil organic phosphorus mineralization under straw return. Applied Soil Ecology. **196**, 105280, **2024**.
27. MORENO J.L., GARCíA C., LANDI L., FALCHINI L., PIETRAMELLARA G., NANNIPIERI P. The ecological dose value (ED50) for assessing Cd toxicity on ATP content and dehydrogenase and urease activities of soil. Soil Biology and Biochemistry. **33** (4), 483, **2001**.
28. YANG M., LI Z., SHAO L., ZHAO X., CHU J., YU F. Impact of Different Modes of Comprehensive Rice Field Planting and Aquaculture Systems in Paddy Fields on Rice Yield, Quality, and Economic Benefits. Polish Journal of Environmental Studies. **2024**.
29. TANG Q.-Y., ZHANG C.-X. Data Processing System (DPS) software with experimental design, statistical analysis and data mining developed for use in entomological research. Insect Science. **20** (2), 254, **2013**.
30. VILLAFUERTE A. B., SORIA R., RODRíGUEZ-BERBEL N., ZEMA D. A., LUCAS-BORJA M. E., ORTEGA R., MIRALLES I. Short-term evaluation of soil physical, chemical and biochemical properties in an abandoned cropland treated with different soil organic amendments under semiarid conditions. Journal of Environmental Management. **349**, 119372, **2024**.
31. FU T., ZHANG Y., GUO X., XING C., XIAO X., LEI B., SUN Z., LI M. Salt transport dynamics across the sediment-underground brine interface driven by tidal hydrology and benthic crab burrowing in muddy tidal flats. Estuarine, Coastal and Shelf Science. **296**, 108586, **2024**.
32. FANG H., LIU K., LI D., PENG X., ZHANG W., ZHOU H. Long-term effects of inorganic fertilizers and organic manures on the structure of a paddy soil. Soil and Tillage Research. **213**, 105137, **2021**.
33. YIN L., FU L., WU H., XIA Q., JIANG Y., TAN J., GUO Y. Modeling dissolved oxygen in a crab pond. Ecological Modelling. **440**, 109385, **2021**.

34. BRAR B.S., SINGH K., DHERI G.S., BALWINDER K. Carbon sequestration and soil carbon pools in a rice–wheat cropping system: Effect of long-term use of inorganic fertilizers and organic manure. Soil and Tillage Research. **128**, 30, **2013**.
35. HAYATU N.G., LIU Y.-R., HAN T.-F., DABA N.A., ZHANG L., SHEN Z., LI J.-W., MUAZU H., LAMLOM S.F., ZHANG H.-M. Carbon sequestration rate, nitrogen use efficiency and rice yield responses to long-term substitution of chemical fertilizer by organic manure in a rice–rice cropping system. Journal of Integrative Agriculture. **22** (9), 2848, **2023**.
36. GAO P., ZHANG T., LEI X.-Y., CUI X.-W., LU Y.-X., FAN P.-F., LONG S.-P., HUANG J., GAO J.-S., ZHANG Z.-H., ZHANG H.-M. Improvement of soil fertility and rice yield after long-term application of cow manure combined with inorganic fertilizers. Journal of Integrative Agriculture. **22** (7), 2221, **2023**.
37. ZHANG Z., DU L., XIAO Z., LI C., WANG Z., ZHOU P., SUN G., YE Y., HU T., WANG H. Rice-crayfish farming increases soil organic carbon. Agriculture, Ecosystems & Environment. **329**, 107857, **2022**.
38. XU G., HAN W., SUN Y., LU Z., LONG Q., CHENG Y. Impacts of three feeding modes on the diet composition and contribution ratios for juvenile Chinese mitten crab Eriocheir sinensis. Aquaculture Reports. **29**, 101516, **2023**.
39. LI W., ZHANG Y., WANG H., FAN B., BASHIR M.A., JIN K., LIU H. Legacy effect of long-term rice–crab co-culture on N2O emissions in paddy soils. Applied Soil Ecology. **196**, 105251, **2024**.
40. WANG X., TJALE P.M., YAO Q., ZHANG D.-M., ZHANG B.-Y., CHEN Y.-K., ZHAO Y.-L., LIU H.-J., WANG Q.-J., GUO Z.-X. Comparison of the growth performance and nutritional qualities of Chinese mitten crab (Eriocheir sinensis) with different stocking densities in rice-crab culture systems. Aquaculture Reports. **20**, 100761, **2021**.