

The “Double-Edged Sword” Nature of Rice-Crayfish Co-Culture and Sustainable Development Strategies: Postprint

Authors: Cao Cougui, Yang Jiang, Wang Jinping, Yuan Pengli, Songwen Chen

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Abstract

In recent years, the rice-crayfish [rice-*Procambarus clarkii* (crayfish)] co-culture model has been vigorously developed across China due to its high comprehensive benefits. Among these, Hubei Province has experienced the most rapid development of rice-crayfish co-culture, characterized by large cultivation areas, relatively mature technology, and the formation of the “Qianjiang Model”. This paper introduces the characteristics and development status of the rice-crayfish co-culture model, taking the rice-crayfish co-culture model in Hubei Province as the research object. Through industrial surveys, combined with experimental demonstrations and fixed-location experiments, this study investigates the production and ecological effects of the rice-crayfish co-culture model, with particular emphasis on analyzing its “double-edged nature”. The “double-edged nature” of the rice-crayfish co-culture model is mainly manifested in: (1) stabilizing grain production and increasing efficiency, while simultaneously exhibiting a phenomenon of prioritizing crayfish over rice: compared with the traditional rice monoculture system, the rice-crayfish co-culture model can increase yield by 4.63%~14.01% and improve rice quality, yet in some instances, rice management is neglected, resulting in relatively low rice yields; (2) enhancing soil fertility while concurrently aggravating soil secondary gleyization: the contents of readily oxidizable organic carbon (ROC), total nitrogen, total phosphorus, and total potassium in soils under the rice-crayfish co-culture model are higher than those under the traditional rice monoculture system, but soils in this model exhibit darker coloration, more compact structure, and pronounced gleyization; (3) conserving water resources while potentially increasing water consumption: paddy fields with high groundwater levels in the rice-crayfish co-culture system demonstrate improved water use efficiency and enhanced water storage capacity, whereas those with low groundwater levels may increase water consumption by 50%~80%; (4) reducing fertilizer and pesticide application while

increasing water nutrient content, yet simultaneously elevating the risk of water eutrophication: fertilizer and pesticide costs in the rice-crayfish co-culture model are reduced by 79.5% and 50.0%, respectively, while the concentrations of total nitrogen, total phosphorus, nitrate nitrogen, and ammonium nitrogen in surface water are all higher than in rice monoculture; (5) mitigating pest damage while exacerbating certain diseases, accompanied by changes in biodiversity: stem borer infestation is reduced in the rice-crayfish co-culture model, but basal rot disease is aggravated, and biodiversity first decreases and then increases with the duration of co-culture. Based on the aforementioned status and issues, this study proposes optimizations and recommendations for the rice-crayfish co-culture model, including: adapting measures to local conditions to avoid blind expansion; establishing research standards for standardized development; optimizing the model through scientific water and fertilizer management; and leveraging favorable conditions to prevent and control diseases, pests, and weeds, thereby providing a foundation for the sustainable development of the rice-crayfish co-culture model.

Full Text

The “Dual Character” of Rice-Crayfish Culture and Strategies for Its Sustainable Development

CAO Cougui^{1,2}, JIANG Yang¹, WANG Jinping^{1,2}, YUAN Pengli¹, CHEN Songwen¹

¹Key Laboratory of Crop Physiology, Ecology and Cultivation (The Middle Reaches of Yangtze River), Ministry of Agriculture, Huazhong Agricultural University, Wuhan 430070, China

²Hubei Collaborative Innovation Center for Grain Industry, Yangtze University, Jingzhou 434025, China

Abstract: In recent years, rice-crayfish culture has been vigorously developed nationwide due to its high comprehensive benefits. Hubei Province has experienced the most rapid development, with large cultivation areas and relatively mature technology, forming the “Qianjiang Model.” This paper introduces the characteristics and development of rice-crayfish culture, focusing on Hubei Province as a case study. Through industrial surveys, combined with experimental demonstrations and long-term field experiments, we examined the production and ecological effects of rice-crayfish culture, with particular emphasis on analyzing its “dual character.” The dual character is mainly manifested in five aspects: (1) **Stabilizing grain production while increasing efficiency, yet showing a tendency to prioritize crayfish over rice:** Rice-crayfish culture can increase yields by 4.63%-14.01% compared with conventional rice monoculture and improve rice quality, but some operations neglect rice management, resulting in low yields. (2) **Improving soil fertility while aggravating secondary gleyization:** Soils in rice-crayfish fields show higher contents of readily oxidizable organic carbon (ROC), total nitrogen, total phosphorus, and

total potassium than conventional rice fields, but exhibit darker color, tighter structure, and obvious gleyization. (3) **Conserving water resources while potentially increasing water consumption:** Fields with high groundwater levels show improved water use efficiency and enhanced water storage capacity, but fields with low groundwater levels may increase water consumption by 50%-80%. (4) **Reducing fertilizer and pesticide use while increasing water nutrient concentrations, but also raising eutrophication risks:** Fertilizer and pesticide costs are reduced by 79.5% and 50.0%, respectively, while total nitrogen, total phosphorus, nitrate nitrogen, and ammonium nitrogen concentrations in surface water are higher than in rice monoculture. (5) **Reducing some pests while aggravating certain diseases and altering biodiversity:** Lepidopteran pests decrease, but basal rot disease intensifies, and biodiversity initially declines then increases with cultivation years. Based on these findings, we propose optimization strategies and recommendations for rice-crayfish culture, including: adapting measures to local conditions to avoid blind expansion; establishing research standards for standardized development; optimizing the model through scientific water and fertilizer management; and implementing guided prevention and control of diseases, pests, and weeds. These recommendations provide a basis for the sustainable development of rice-crayfish culture.

Keywords: Rice-crayfish culture; Rice yield; Soil fertility; Water quality; Diseases, weeds and pests; Biodiversity

Currently, China's agriculture faces numerous challenges, including decreasing per capita arable land, intensifying resource and environmental constraints, and increasing difficulty in ensuring both food security and farmers' income. In recent years, Qianjiang City in Hubei Province has innovatively developed the "rice-crayfish co-culture" ecological model, integrating rice (*Oryza sativa*) cultivation with red swamp crayfish (*Procambarus clarkii*) farming. This model has been praised by the Ministry of Agriculture as "a successful exemplar of modern agricultural development and a revolution in modern agriculture" [?]. The comprehensive benefits are primarily reflected in increased agricultural efficiency, achieving "dual use of water, double harvest from one field, stable grain production with increased income, and multiple wins." This approach effectively improves farmland resource utilization and output benefits, expands development space, and promotes the transformation and upgrading of traditional agriculture. However, *Procambarus clarkii* is also the most widely distributed invasive crustacean species, and large-scale changes in cultivation systems inevitably generate certain environmental effects. To scientifically advance the development and application of rice-crayfish culture, this study combines industrial surveys with experimental demonstrations and long-term field experiments to analyze the "dual character" of this model, providing a basis for its rational, standardized application and sustainable development.

1. Characteristics of the Rice-Crayfish Culture Model

Rice-crayfish culture represents an ecological agriculture model integrating aquaculture with rice cultivation, where crayfish and rice coexist symbiotically in paddy fields during the rice growing season. In 2001, farmers in Qianjiang City, Hubei Province, pioneered the “rice-crayfish rotation” model by excavating simple perimeter trenches in rice fields to raise crayfish, enabling annual harvests of “one rice crop and one crayfish crop.” After nearly a decade of development and research, scientists and farmers improved this model to address limitations such as harvesting only one crayfish crop per year, conflicts between rice planting and crayfish rearing periods, and suboptimal crayfish growth during transplanting season. This led to the development of the “rice-crayfish co-culture” model.

The rice-crayfish co-culture model involves planting one mid-season rice crop annually while raising two crayfish crops. The original narrow trenches (1 m wide and 0.8 m deep) were expanded into broader aquaculture trenches (4 m wide and 1.5 m deep) [Figure 1: see original paper]. During rice growth, field water connects with trench water, allowing rice and crayfish to coexist. During certain periods (tillage and harvest), the rice field is drained while crayfish retreat to the aquaculture trenches. Broodstock crayfish are released in August–September before rice harvest, or juvenile crayfish are stocked in September–October after harvest. Marketable crayfish are harvested from mid-April to late May of the following year, while additional juveniles are restocked. Field preparation and rice transplanting occur in late May to early June, with broodstock or marketable crayfish harvested again in August–September, creating a continuous cycle [Figure 2: see original paper]. This model effectively improves comprehensive paddy field utilization, producing approximately $750 \text{ kg} \cdot \text{hm}^{-2}$ more marketable crayfish, solving the problem of no autumn crayfish production, and ensuring product quality.

2. Development of Rice-Crayfish Culture in China

Crayfish aquaculture is concentrated in the middle and lower reaches of the Yangtze River, primarily in Hubei, Jiangsu, and Anhui provinces. Hubei predominantly employs the rice-crayfish co-culture model, while Jiangsu focuses on mixed crab-fish and fish-shrimp culture systems. In rice-crayfish culture, farmers use non-polluting pesticides less frequently than in conventional rice farming, producing near-natural ecological rice. During rice growth, microorganisms and pests provide abundant feed for crayfish, while crayfish excrement supplies biological fertilizer for rice, forming a complementary biological chain that improves the ecological environment and creates ecological value. This model enhances land and water resource utilization, increases crayfish yield and size, and improves rice quality [?]. Crayfish yield reaches approximately $1,500 \text{ kg} \cdot \text{hm}^{-2}$, with purchase prices of $7.5\text{--}15 \text{ ¥} \cdot \text{kg}^{-1}$ depending on size, generating $4.5 \times 10^4 \text{--} 9.0 \times 10^4 \text{ ¥} \cdot \text{hm}^{-2}$ in revenue. Rice yields $9 \text{ t} \cdot \text{hm}^{-2}$ at $3.8 \text{ ¥} \cdot \text{kg}^{-1}$, producing $3.42 \times 10^4 \text{ ¥} \cdot \text{hm}^{-2}$. Total annual output value reaches $7.5 \times 10^4 \text{--} 1.2 \times 10^5 \text{ ¥} \cdot \text{hm}^{-2}$.

The high profitability has driven rapid nationwide expansion of rice-crayfish culture. According to the 2016 China Crayfish Industry Development Report by the National Aquaculture Technology Diffusion Terminus of China [?], national crayfish cultivation area exceeds 6×10^5 hm², with integrated rice-crayfish systems accounting for 70% (approximately 4.2×10^5 hm²), and this area continues to grow rapidly. Qianjiang City in Hubei, the origin of integrated rice-crayfish culture in the middle and lower Yangtze region, had only 667 hm² of rice-crayfish culture in 2010, which increased tenfold by 2013 and reached 2.11×10^4 hm² by the end of 2016. In Jianli County, Hubei, the integrated cultivation area exceeded 1.0×10^4 hm² in 2016 and reached 3.3×10^4 hm² in 2017, with an estimated potential area of over 6.7×10^4 hm² suitable for crayfish farming [Figure 3: see original paper].

Nationwide, approximately 15% of existing paddy fields are suitable for integrated rice-crayfish culture. According to 2016 data from the National Bureau of Statistics of China [?], national rice planting area reached 3.02×10^7 hm², suggesting that up to 4.5×10^6 hm² could be suitable for integrated cultivation.

3.1 Stable Grain Production and Efficiency vs. Emphasis on Crayfish Over Rice

The increased economic benefits of integrated rice-crayfish culture have enhanced farmers' enthusiasm for rice cultivation. In Qianjiang, total paddy field area has reached new highs annually, with integrated cultivation area increasing approximately 45-fold from 2010 to 2017 [Figure 3: see original paper]. As shown in Table 1, although rice planting area is reduced in rice-crayfish systems (with aquaculture trenches occupying 8% of the field), total paddy area and per-unit yields have not decreased. Rice-crayfish culture increased yields by 4.63%-14.01% compared with conventional rice cultivation.

The model also significantly reduced chalky grain percentage and chalkiness degree, improving rice appearance quality. Additionally, crayfish excrement and residual feed increase soil fertility, while crayfish feeding on weeds and insects provides partial weed and pest control, reducing chemical fertilizer and pesticide use and associated residue risks, thereby significantly enhancing market value.

However, in practice, because crayfish generate 2-3 times the income of rice and rice management involves relatively complex operations (sowing, fertilization, irrigation, harvesting, storage, and transport) with lower comparative benefits, operators often become unwilling to cultivate rice. In Jianli County, Hubei, integrated rice-crayfish area increased approximately tenfold since 2014 [Figure 3: see original paper], while rice planting area actually declined, with many fields used for crayfish farming without rice cultivation. Since rice provides shelter and food for crayfish, some operators plant rice primarily to enhance crayfish production, paying little attention to rice management, resulting in declining rice yields and quality. Figure 4 [Figure 4: see original paper] shows 2016 yield

measurements from 20 demonstration sites in Hubei, with an average yield of $6.4 \text{ t} \cdot \text{hm}^{-2}$, far below the provincial average. While maximum yields reached $11.3 \text{ t} \cdot \text{hm}^{-2}$, 50% of sites yielded less than $6.0 \text{ t} \cdot \text{hm}^{-2}$, with the lowest only $2.3 \text{ t} \cdot \text{hm}^{-2}$. This phenomenon of prioritizing crayfish over rice undermines the symbiotic relationship and the model's significance for stabilizing grain production.

3.2 Soil Improvement vs. Secondary Gleyization

Rice-crayfish culture is suitable for low-lying paddy fields and river-adjacent fields with high groundwater levels, requiring perennial water in aquaculture trenches and abundant water resources. Low-lying and waterlogged fields often suffer from secondary gleyization due to year-round flooding and high groundwater, becoming cold-spring or muddy fields. Soil labile organic carbon content varies significantly with cultivation duration. Readily oxidizable organic carbon content is higher than in conventional rice fields, while dissolved organic carbon is lower. Rice-crayfish culture also increases soil nutrients, including total nitrogen, phosphorus, and potassium (Table 2), effectively improving soil fertility. These effects primarily result from crayfish activities (feeding, excretion, burrowing) and their impacts on soil microbial communities and functional diversity [?, ?].

However, rice-crayfish culture also negatively affects paddy soils, particularly in high-quality fields without high groundwater levels. Figure 5 [Figure 5: see original paper] shows impacts on soil profile structure and physicochemical properties. Rice-crayfish field soils appear darker, with higher root density, tighter structure, and obvious gleyization. Soil urease and hydrogen peroxidase activities are lower than in conventional rice fields (Figure 6 [Figure 6: see original paper]).

3.3 Water Conservation vs. Water Resource Consumption

Conventional paddy fields have an open water cycle, maintaining a water layer that is drained during tillering and maturity stages, with water added or removed as needed (Figure 7 [Figure 7: see original paper]), resulting in low water use efficiency. In rice-crayfish systems, aquaculture trenches store water year-round, communicating with field water to enhance overall water storage capacity. With connected trenches combining drainage and storage, the water cycle becomes closed, with rice production water primarily supplied from trenches. In low-lying fields with high groundwater, water use efficiency improves. However, in irrigated fields with low groundwater, hillside terraces, and mountain paddies, water consumption increases by 50%-80%. Some hilly areas using rice-crayfish culture can store an additional $3,000 \text{ m}^3$ per hectare, greatly enhancing drought resistance [?]. However, large-scale aquaculture engineering systems in fields with inadequate water sources or imperfect canal networks can affect regional hydrological cycles and water utilization, an impact that cannot be ignored [?].

3.4 Water Quality Purification vs. Eutrophication

Rice-crayfish culture requires water transparency of 30–40 cm; excessively fertile water can cause massive proliferation of ciliates, harming crayfish growth. Animal activity and metabolism affect dissolved oxygen and nutrient content. Rice-fish and rice-duck systems increase dissolved oxygen by 56.0% and 54.0%, respectively, compared with rice monoculture [?]. The ecological model also reduces pesticide and fertilizer application, decreasing agricultural environmental pollution. Figure 8 [Figure 8: see original paper] shows similar total production costs between rice-crayfish and conventional rice culture ($1.8 \times 10^4 - 2.1 \times 10^4$ ¥·hm⁻²). In rice-crayfish systems, crayfish seed and feed account for the highest cost proportion, while in conventional rice, fertilizer and pesticide costs dominate. Rice-crayfish culture reduces fertilizer costs by 79.5% and pesticide costs by 50.0%.

However, in practice, straw return and feed input increase total nitrogen, total phosphorus, nitrate nitrogen, and ammonium nitrogen concentrations in surface water compared with rice monoculture (Figure 9 [Figure 9: see original paper]). Farmers often prioritize crayfish yields and apply excessive feed, increasing eutrophication risks despite the model's potential for water quality improvement [?].

3.5 Disease, Pest, and Weed Control: Suppression and Promotion

Rice-crayfish culture significantly affects paddy field pests, diseases, and weeds. Table 3 shows that with extended cultivation duration, insect pests such as brown planthopper (*Nilaparvata lugens*), striped stem borer (*Chilo suppressalis*), and rice leaf folder (*Cnaphalocrocis medinalis*) are effectively controlled, particularly stem borer, as rice-crayfish fields remain flooded in winter, resulting in zero overwintering larvae (Table 4). However, rice basal rot disease significantly worsens with cultivation duration, and other studies indicate increased severity of sheath blight and rice blast [?].

Weed control effects should not be overestimated. While total weed quantity decreases initially (Figure 10 [Figure 10: see original paper]), certain species rebound rapidly with extended cultivation, including *Euphorbia lathyris*, *Echinochloa crusgalli*, and *Cyperus rotundus*. Rice-crayfish culture provides partial control of *Mazus japonicus*, *Alternanthera philoxeroides*, and *Eclipta prostrata*.

3.6 Biodiversity: Increases and Decreases

The rice-crayfish model introduces the invasive crayfish species, altering trophic relationships, field structure, cultivation systems, and management practices, thereby affecting paddy field biodiversity. Research shows that conventional rice monoculture maintains relatively high biodiversity. After implementing rice-crayfish culture, biodiversity declines due to field engineering but gradually recovers after four years (Figure 11 [Figure 11: see original paper]). Insect

populations are less affected by cultivation patterns, beginning recovery after one year (Table 5). Total insect numbers initially decrease then increase with cultivation duration, with neutral insects being most abundant, followed by herbivorous insects, and parasitic insects being least common. Rice-crayfish culture maintains high natural enemy populations after several years, such as spiders (Table 3), but weeds also rebound quickly (Figure 10), particularly under direct-seeding conditions where some aggressive weeds become dominant species.

4. Model Optimization and Recommendations

In summary, rice-crayfish culture is developing rapidly nationwide, with enormous potential suitable area reaching 4.5×10^6 hm². Research demonstrates that properly implemented rice-crayfish culture is significant for stabilizing grain production, increasing farmer income, and promoting green development. However, blind expansion and non-standardized management can cause negative impacts. To promote sustainable development, the following optimization strategies are proposed:

- 1. Adapt to local conditions and avoid blind expansion.** Research and define optimal conditions for rice-crayfish culture, establishing standardized development criteria including groundwater level, soil type, water resource availability, and water quality. Suitable sites should have abundant sunlight, good ecological conditions, sufficient clean water, and convenient irrigation/drainage. Fields with low groundwater, sandy soils, poor water retention, or inadequate water resources are unsuitable.
- 2. Establish research standards for standardized development.** Standardize and normalize key technologies across six aspects: quality rice variety standards, paddy field engineering construction, year-round water management, integrated crayfish feeding and rice organic fertilization, healthy ecological crayfish culture, and green pest control technologies to produce high-quality, safe ecological rice and crayfish products.
- 3. Optimize the model through scientific water and fertilizer management.** Investigate the rice-crayfish symbiotic relationship, clarify nutrient cycling patterns (especially nitrogen and phosphorus), and avoid excessive feed and fertilizer inputs to maximize mutualistic benefits and ensure material cycling. Implement full straw return to reduce autumn-winter feed input, plant appropriate vegetation in early spring, apply moderate feed in spring-summer to reduce chemical fertilizer use, and practice scientific water management to regulate fertilizer through water-fertilizer coupling, ensuring good water quality and healthy crayfish.
- 4. Implement guided prevention and control of diseases, pests, and weeds.** Study biodiversity in rice-crayfish fields to maintain ecological balance and mutualistic relationships, clarifying pest, disease, and weed occurrence patterns. Biodiversity forms the foundation for system balance and pest control. Plant beneficial vegetation in trenches and ridges in early

spring to maintain dominant populations (*Vallisneria natans*, *Hydrilla verticillata*, *Ceratophyllum demersum*) and conduct field weeding before rice planting. Additionally, utilize biodiversity, agronomic measures, and physical methods for integrated pest management.

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