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Review

Rice-crayfish coculture system and related developments at the age of climate-smart agriculture

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Abstract: Agriculture affects and is affected by climate change. The development of climate-smart agriculture (CSA) is an effective way for agricultural production to cope with climate change. The rice-crayfish coculture system is a combination of the concept of climate-smart agriculture with the experience of traditional Chinese mixed crop-fish systems. This paper reviews the advantages and potential risks of rice-crayfish coculture with respect to climate, ecological environment and economic benefits, and summarises the successful management strategies and operation experiences during the implementation of this CSA practice in Qianjiang City. We also introduce various mixed crop-fish systems in China and suggest the potential of using wetland resources to develop mixed crop-fish systems and CSA.

Keywords: climate-smart agriculture, crayfish-rice coculture, mixed crop-fish system

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INTRODUCTION

Despite tremendous efforts made by the international community to solve food problems, the issue of food security is still very prominent and has become increasingly urgent. According to the Global Report on Food Crisis 2019 released by the UN Food and Agriculture Organization (FAO), in 2018 approximately 29 million people were affected by acute food insecurity due to climate change [1]. This causes annual production losses of 3 million tons of rice, 9 million tons of wheat and 2 million tons of soya bean, which accounts for 32-39% of the fluctuations in global food production [2, 3]. However, at least one-fifth of the world's greenhouse gases comes from agriculture including forestry, fisheries and livestock production [4]. Therefore, agriculture has become an important area for coping with, mitigating and adapting to climate change.

The mixed crop-fish system is a traditional agricultural system that is similar to the mixed crop-livestock system. The rice-fish farming model in the mixed crop-fish system has a long history and is distributed all over the world [4]. The traditional rice-fish culture system in Longxian Village (Zhejiang province, China), is among the first major agricultural heritage in the world and was established more than 1,200 years ago [5]. In recent years the rice-crayfish coculture system, which fits the practice of climate-smart agriculture (CSA), promoted the formation of a ¥100-billion industrial chain [6]. This system is growing fastest in terms of cultivation area and has exhibited the most significant increase in economic benefits to the modern agricultural production model among China's agricultural industries. According to statistics, the total economic output value of crayfish was approximately ¥369 billion in 2018 and over 8.4×10^5 hm^2 of rice fields developed rice-crayfish coculture [6]. It can be said that the success of the rice-crayfish coculture model represents a successful practice of CSA in China. Moreover, this system can be used as a model for the development of modern agriculture in China and shows the development potential of traditional mixed crop-fish systems in the era of CSA.

MODES OF RICE-CRAYFISH COCULTURE SYSTEM

Crayfish are native to north-eastern Mexico and south-central USA, and are currently widely distributed in Asia and Europe. Crayfish have become an invasive organism that causes a series of ecological problems in many countries [7]. Crayfish farming began in the US mainly in Louisiana and mainly by pond farming with an area of approximately 4.3×10^4 hm^2 and an annual production of approximately 10,000 - 27000 tons [8]. Crayfish farming in rice paddy fields began in the US in the 1960s when the rice-crayfish rotational strategy was adopted [8, 9]. At present, only a few countries in the west such as the US, Portugal and Spain still carry out the rice-crayfish coculture, but the crayfish production and farming areas in these countries have not been widely developed [10].

Crayfish were introduced to China in the 1920s and then expanded rapidly to almost all of China's freshwater areas [11], bringing great trouble to agricultural production. During the 1990s, the Chinese began eating crayfish and the catching of wild crayfish did not come close to satisfying consumer needs. Inspired by the breeding of fish in rice fields, in 2001 the first breeding of crayfish in rice fields began in Qianjiang City, Hubei province, China. At the early stage, the rice-crayfish coculture in China was based on a rice-crayfish rotation mode (one rice and one crayfish): rice is cultured during the rice season and crayfish is farmed during the non-rice season in the same rice field, which happens to be similar to the rotation strategy adopted in the US. Later, this system gradually developed into a China-specific rice-crayfish rotation plus cocropping mode (one rice and two crayfish), which adds a rice and crayfish cocropping system during the rice season. The purpose of the specific operation process is to release the parental crayfish before the rice harvest in August-September of each year, release the young crayfish after the rice harvest in September-October, and harvest the commercial crayfish between the middle of April and end of May in the second year. Between the end of May and early June, the fields will be transplanted, and the parental crayfish or commercial crayfish will be harvested before rice harvesting in August and September [12]. In general, 1500 kg/hm^2 of crayfish are produced in the rice-crayfish rotation mode and 2250 kg/hm^2 of crayfish are produced in the rice-crayfish rotation plus cocropping mode [12], which exceeds the average yields of crayfish monocropping in ponds in the US (225-1120 kg/hm^2) [8]. China's rice-crayfish rotation plus cocropping mode has effectively improved the comprehensive utilisation of rice fields, increased crayfish production, solved the problem of unproductive crayfish production in autumn, and ensured the quality and specifications of commercial crayfish. This mode is generally welcome by Chinese farmers and customers.

BENEFITS OF RICE-CRAYFISH COCULTURE SYSTEM

The current mode of the rice-crayfish coculture system, which is widely promoted in China, is a typical CSA practice. It integrates the latest environmental protection concepts and agricultural technologies and methods, and achieves many benefits such as reducing the emissions of greenhouse gases, reducing the use of fertilisers and pesticides, increasing production yield, improving production quality, enhancing the resilience of fields, and greatly increasing farmers' income.

Rice fields are an important artificial source of atmospheric methane (CH_4) and nitrous oxide (N_2O), especially CH_4 emissions. The average annual CH_4 emissions from paddy fields are 33-40×10^9 tons, accounting for approximately 17% of the total global CH_4 emissions [13]. Straw returning is a popular method of utilising straw in China, but at the same time this method can stimulate CH_4 emissions [14, 15]. Waterlogging in the off-rice season with straw return is the main way to return rice straw to the field. According to a previous report [16], when crayfish are released in the above process, the cumulative CH_4 emissions were reduced by 41.2% compared with those without crayfish, and this reduction was equivalent to that of simple waterlogging in the off-rice season. Breeding crayfish with straw return had no significant effect on cumulative CO_2 and N_2O emissions, nor on soil dissolved organic carbon, acetic acid or ammonium nitrogen [16]. Breeding crayfish with straw return can therefore reduce CH_4 emissions, thereby significantly reducing the greenhouse effect caused by straw returning.

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Land is the foundation of agriculture. The use of chemical fertilisers and pesticides is an important means to ensure agricultural production and income. Excessive use of pesticides and fertilisers has increased many environmental problems such as soil acidification and groundwater pollution [17]. In rice fields with rice-crayfish coculture, there are abundant sources of organic substances including feed residue, straw and crayfish excrement, which directly reduces the amount of chemical fertilisers. Compared with rice monoculture mode, the rice yield of long-term integrated rice-crayfish mode increases by 16.3% and the nitrogen fertiliser for direct-seeding rice decreases by 26.6% [18]. Because crayfish are very sensitive to most of the pesticides used in conventional rice fields [19], pesticides are not used or their use is controlled as much as possible to ensure the safety of crayfish farming, thus reducing the pesticide residue and contributing to food safety. The cost in pesticides for rice-crayfish coculture also reduces up to 50.0% compared to that for rice monocropping [12].

Paddy fields with rice-crayfish coculture are transformed into a specific structure which improves the resistance of the field to natural disasters such as drought and floods and ensures the safety of rice and crayfish production. The traditional paddy field is a field-ridge structure; the water cycle is open and the utilisation rate is low. The paddy field with rice-crayfish coculture is a structure consisting of field, internal bank, ditch and external bank (Figure 1). During the growth of rice, crayfish can move around the field; during field draining or rice harvest, crayfish live in the ditches. A transformed rice field with an external bank approximately 2.5 metres high combines water drainage and storage with closed water circulation. With this system, water storage per hectare in the paddy fields can be increased by 3000 m^3 [20].

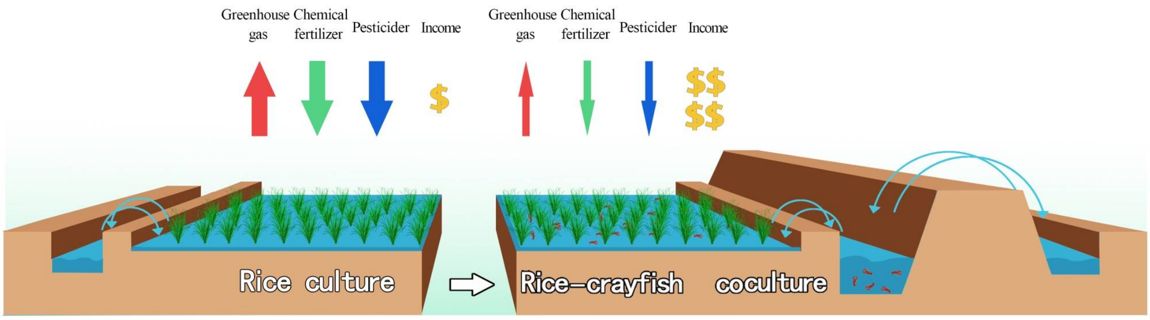

Figure 1. Comparison between rice culture and rice-crayfish coculture

The rice-crayfish coculture system not only increases the rice yield, but also improves the appearance and quality of rice. The rice-crayfish coculture system also increases rice yield by 4.6-14.0% compared with that from the traditional rice planting system. At the same time, the chalkiness degree and chalk grain rate of rice decrease by 10% and 2% respectively [12]. Consequently, the income of farmers that conduct rice-crayfish coculture significantly increases. For example, in Qianjiang City the net income from rice mono-cropping system is 15000 yuan/hm^2 while that from rice-crayfish coculture system is over 60000 yuan/hm^2 in 2015, about 4 times more than that obtained from rice mono-cropping [20].

RISK OF RICE-CRAYFISH COCULTURE SYSTEM

As the rice-crayfish coculture system has been promoted in a large area, such massive changes in agricultural production patterns are likely to produce a regional environmental impact, which may last several years. This is worthy of attention and vigilance.

First, rice-crayfish coculture might have an impact on the regional hydrometeorology, which in turn might have an impact on the other agricultural production. After rice-crayfish coculture processing, the rice paddy farming pattern is changed, and the field maintains a certain amount of water storage throughout the year. This large-scale farming engineering system may affect the regional water cycle and water use. In the Qianjiang area where rice-crayfish coculture was first conducted, the average groundwater level of the monitoring well rose significantly [21]. It is therefore necessary to continuously monitor changes in the regional climate in areas where large-scale integrated cultivation of rice and crayfish is carried out and further evaluate whether such changes will affect other agricultural production.

Second, rice-crayfish coculture might have an impact on the regional rice yield and diversity. Anhui, Hubei, Hunan, Zhejiang, Jiangxi and other provinces have large rice-crayfish coculture areas and are the main producing areas for double-season rice in southern China. The continuous expansion of the planting area may result in the rice-crayfish coculture using single-season rice to adapt to crayfish farming and reduce the impact of rice operation on aquaculture. When double-season rice is converted into single-season rice, the rice yield per unit area is reduced, which leads to a decrease in total rice yield and consequently may affect food security. In addition, the rice varieties cultivated under this special mode must be conducive to crayfish farming, which may lead to the reduction in rice varieties in these areas. The relatively low diversity of rice varieties is not conducive to addressing climate change and pest and disease risks.

Third, rice-crayfish coculture breaks the ecological balance of rice field, which might have an impact on biodiversity. Upon the introduction of crayfish for cultivation, the food-nutrition relationship in the rice field changes, and changes in field gully structure and farming method will have an impact on the biodiversity in the rice field. Insects in the field are relatively less affected by rice-crayfish coculture [12], but weeds in the rice field are significantly affected. Short-term rice-crayfish co-culture improves the weed control effects while long-term one gradually forms a new weed community structure [22]. More importantly, crayfish are an invasive organism, and once they escape from the culture area, they pose a large ecological risk.

Although there are many benefits of the rice-crayfish coculture system, we have to pay more attention to the potential risk. In the core area of the rice-crayfish coculture, monitoring points should be established to collect climate, environmental and biological information in time. Big data analysis should be used to evaluate and predict the risk level, and corresponding prevention and control measures should be formulated to minimise agricultural and environmental risks.

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QIANJING MODEL FOR DEVELOPING RICE-CRAYFISH COCULTURE SYSTEM

The key to successfully promoting CSA is to determine how to let farmers accept and implement new technologies and farming models advocated by CSA so that farmers become the real beneficiaries. Like most developing countries, China faces many problems related to agriculture, such as a large population, low per capita land area, scattered resources, weak economic position, lagging agricultural technology, decreased modern awareness, and news occlusion. The use of existing local government structures is perhaps the most convenient and effective way to promote climate-smart agricultural practices in developing countries.

The annual production of crayfish in Qianjiang, which is the birthplace of the rice-crayfish coculture system, reached 7.35×10^4 tons in 2017, accounting for approximately one-tenth of the national production, and crayfish product exports amounted to $190 million, making Qianjiang the country's largest crayfish export base [6]. The Qianjiang model is an example of a successful rice-crayfish coculture system in China. This model follows the management principles of 'government-led, enterprise-driven, farmer-participated market operation.' According to the characteristics of the project, the Qianjiang government has established a complete operational network of production, supply, sales and services in which the government, service organisations, companies and farmers participate, forming important interactions among the actively participating subjects. Information on the rice and crayfish industry can be collected and aggregated in a timely manner. The market circulation of rice and crayfish products is fast and stable, and supply and demand are balanced, which solves the most common problem of blind and disorderly development of planting and breeding in the agricultural industrial chain. This system reduces market risks and guarantee farmers' income.

In 2015 the area of rice-crayfish coculture in Qianjiang City reached 2.10×10^4 hm^2, which is approximately half the area of crayfish farming in Louisiana, USA [19, 20]. The active participation of research institutions provides technical support for the scientific development of rice-crayfish coculture. For example, Wuhan University, Huazhong Agricultural University, Hubei Institute of Fisheries Science, Institute of Hydrobiology of Chinese Academy of Sciences and other research institutes have rapidly developed and integrated new technologies related to rice-crayfish coculture.

The entry of financial and insurance institutions provides a wealth of financing channels and effective risk protection, enhancing the confidence and motivation of enterprises and individuals involved in the rice-crayfish coculture and related industries. Enterprises involved in consumer terminals actively participate in efforts to enrich product types and expand markets. Currently, crayfish are both simple edible food products and highly processed products such as chitin and its derivatives. The variety of products not only makes Qianjiang crayfish unique in the domestic market but also successfully occupies the international market. The Qianjiang Crayfish Festival, rice-crayfish rural tourism, e-commerce platforms and other means to promote the products to the community have stimulated the formation of a national crayfish consumer market. It was estimated that the gap between crayfish supply and demand is nearly 1 million tons in China and approximately 300,000 tons outside China [23].

FORMS OF MIXED CROP-FISH SYSTEM IN CHINA

Approximately two-thirds of the world's population today use mixed crop-livestock system production model, and the future population increases will also be concentrated in areas that utilise this production model [24]. According to the FAO report in 2006, livestock becomes the number one factor causing climate warming; it releases 18% of the world's greenhouse gases [25]. It seems that the increase of livestock might have to be limited to reduce emission. It is possible to alleviate this by developing and promoting a new complex agricultural system that guarantees both grain and meat supply.

Aquatic products including seafood and freshwater fish products are an important protein source of animal origin other than livestock. China plays a pivotal role in the development of freshwater aquaculture throughout the world, accounting for more than 60% of world production [26]. In 2016 China's freshwater aquaculture production reached 31,792,600 tons [27]. From the perspective of the farming model, all natural and artificial waters in China, such as ponds, lakes, reservoirs, rivers and rice fields, can be used for aquaculture [28]. The types of aquatic products cultivated in rice fields in China are varied, including fish such as crucian (*Carassius carassius*) and common carp (*Cyprinus carpio*), crustaceans such as shrimp (*Macrobrachium rosenbergii*) and crab (*Eriocheir sinensis*), amphibians such as frog (*Rana nigromaculata*) and bullfrog (*Rana catesbeiana*), and reptiles such as tortoise (*Chincmys reevesii*) and turtle (*Amyda sinensis*) [29]. These aquatic products can be cultured alone or combined with all types of aquatic crops to form a mixed crop-fish system. The system has the advantages of 'not competing with people for grain, not competing with grain for land' and 'one field, two harvests'. The great success in the rice-crayfish coculture indicates the great development potential for the mixed crop-fish system.

Rice is one of the most important foods in China. The rice cultivation area in China accounts for approximately 1/4 of the world's total, and it is stable at 3×10^7 hm^2 each year [30]. In 2017 China's paddy field farming area was approximately 1.52×10^6 hm^2 and China was the largest rice-fish farming country in the world [27]. In China there is also the traditional habit of growing and eating aquatic vegetables, which include lotus, taro (*Colocasia esculenta*), water chestnut (*Eleocharis trilateralis*), *Zizania latifolia*, arrowhead (*Sagittaria sagittfolia*) and *Trapa bispinosa*. The planting area for aquatic vegetables can cover up to 7.33×10^5 hm^2, with the lotus planting area being the largest at approximately 5×10^5 hm^2 [31].

The vegetable-fish coculture system has existed in China for thousands of years. Fish or other freshwater aquaculture is directly farmed in aquatic vegetable fields in this system. Both vegetables and fish can be harvested in the same field. This model is very popular among Chinese farmers because of its simple management, small investment and good efficiency. The lotus-crayfish and lotus-fish coculture systems are the two most important production modes. For example, the area of lotus-crayfish coculture has reached 2×10^4 hm^2 in Anhui province [32]. Studies have shown that aquatic vegetables have the ability to purify water [33] and the vegetable-fish coculture system is environmentally friendly, popularising aquatic vegetable cultivation areas.

In addition, in the Yangtze River Delta region and Pearl River Delta region there is a long-established 'Mulberry-dyke and Fish-pond' agricultural production system, which originated in the Spring and Autumn Period and the Warring States Period. This system is approximately 2,500 years old and has 4,000 hm^2 of mulberry land and 10,000 hm^2 of fish ponds, which is the most concentrated, largest and most intact traditional Chinese mulberry fish pond system [34]. This system has formed a mulberry-silk-fish ecological cycle production model. In June 2004 Shezhong Village at Linghu Town became the teaching base for the Linghu mulberry-dyke and fish-pond system with the creation of FAO Asia-Pacific Integrated Fish Culture Training Center [34]. In 2018 the Huzhou Mulberry-dyke and Fish-pond System was officially selected as an important global agricultural and cultural heritage site. The planting of mulberry trees at the base of a pond can not only effectively strengthen the pond foundation but also improve the ability to withstand floods and disasters while effectively fixing carbon (9.47t/ hm^2.y) [35]. In addition, according to the actual market situation, farmers in various places have diversified their income by planting fruit trees, flowers and vegetables at the bases of ponds to form 'fruit-fish ponds', 'flower-fish ponds' and 'vegetable-fish ponds.'

PERSPECTIVE

The mixed crop-fish system makes full use of the space of a field, i.e. field surface, field ridge and water body. Fields and ridges are used to plant crops and water bodies are used for aquaculture farms. Cultivated crops and farmed aquaculture can be combined flexibly according to the actual situation so that the production patterns are rich and diverse with strong adaptability.

In China rice-crayfish coculture still has huge potential space to develop. At present, the rice-crayfish coculture area accounts for 1.9% of the country's rice fields. The area of rice fields suitable for rice-crayfish coculture accounts for approximately 15% of the area of rice fields in the country. Qianjiang City proposed the 'four-products agriculture' model: rice is planted in high-standard farmland, aquatic vegetables (such as *Zizania latifolia*, water parsnip and gorgon) are planted in the ditch, and fruit trees are planted on the ridge of the field while an aquaculture system is installed. This mode integrates the patterns of rice-crayfish, vegetable-fish and mulberry-fish pond systems to form an interaction between water and land. In addition, the active development of rural tourism based on such agricultural systems not only increases farmers' income but also promotes the concept and production methods of CSA. Outside China, some South-east Asian countries try to develop their own rice-shrimp systems [36, 37].

As a traditional agricultural system, the mixed crop-fish system coincides with the idea of CSA, which is worthy of further exploration and development. The traditional model of the mixed crop-fish system follows the laws of nature and advocates ecological harmony, taking into account the protection of agricultural production and the natural environment. Nowadays various production systems based on the mixed crop-fish system being promoted and implemented in China have been innovated on the basis of traditional production practice, which not only greatly improves the utilisation efficiency of agricultural land, yield and quality of agricultural products and ensures food safety, but also maintains the agro-ecological balance. Moreover, the successful experience from the management and operation of a complete industry chain that has been accumulated during the implementation of rice-crayfish coculture in China is valuable for large-scale promotion of climate-smart agricultural production practices worldwide. It also not only has important reference significance of promoting the crop-fish system, but also has reference value in promoting other forms of climate-smart agricultural practice.

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