water

Review

Advances in Ecology Research on Integrated Rice Field Aquaculture in China

Jing Yuan [1], Chuansong Liao [1,*], Tanglin Zhang [1,2], Chuanbo Guo [1,2] and Jiashou Liu [1,2]

1 State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China; yuanj@ihb.ac.cn (J.Y.); tlzhang@ihb.ac.cn (T.Z.); guocb@ihb.ac.cn (C.G.); jsliu@ihb.ac.cn (J.L.)
2 University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: liaocs@ihb.ac.cn

Abstract: Integrated rice field aquaculture, a practice normally used by rural small-scale farmers, is not only supporting farms and livelihoods but is also reducing poverty and is playing a more and more important role in China. It is also becoming one of the main freshwater aquaculture systems, in addition to ponds, lakes, reservoirs, streams, and other aquaculture systems. During the past 40 years, both the production and areas of integrated rice field aquaculture in China have significantly increased from 0.13 million t and 0.74 million ha in 1990 to 3.25 million t and 2.56 million ha in 2020, respectively. Advances in ecology research on integrated rice–fish aquaculture were one of the main contributors to this achievement. In this paper, we systematically reviewed the advances in ecology research on three major integrated rice field aquaculture systems in China, namely rice–fish, rice–crab, and rice–crayfish coculture systems, the contribution of the research, and future prospects. We found that progress in ecology research on theories, biological studies, models, and eco-engineering techniques, coupled with policy support promoted the development of the rice field aquaculture industries. This review could assist individual small-scale farmers to make better use of rice field space to produce safer aquatic and rice products at a lower cost and help aquaculture scientists to further study the ecology of integrated rice field aquaculture systems.

Keywords: rice field; integrated aquaculture; ecology; review; prospects; coupling degree; eco-certification

check for updates

Citation: Yuan, J.; Liao, C.; Zhang, T.; Guo, C.; Liu, J. Advances in Ecology Research on Integrated Rice Field Aquaculture in China. *Water* **2022**, *14*, 2333. https://doi.org/10.3390/w14152333

Academic Editors: Xiangli Tian and Li Li

Received: 26 May 2022
Accepted: 24 July 2022
Published: 28 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Integrated rice field aquaculture evolved from rice–fish coculture, and is playing a more and more important role in China, as the largest aquaculture producer in the world. It is also becoming one of the main freshwater aquaculture systems, in addition to ponds, lakes, reservoirs, streams, and other aquaculture systems, amounting to 10.52% of China's freshwater aquaculture production and 33.71% of the aquaculture area in 2020 [1] (Figure 1). China, the most populous country, is short of land resources and is also the biggest consumer of rice; therefore, food security is a priority of the Chinese government. The development of aquaculture by digging more ponds is strictly controlled by law. Therefore, integrated rice fields are getting more and more attention as a resource for increasing aquaculture production because of their properties of water conservation and using less land. This practice is normally adopted by individual small-scale farmers as an ideal use of land and an easy source of cheap, fresh, and convenient animal protein. It not only promotes sustainable agricultural and aquaculture development and farms and livelihoods, but also reduces poverty [2–4]. Consequently, during the past 40 years, both the production and area of integrated rice field aquaculture in China have significantly increased from 0.02 million t and 0.35 million ha in 1982 to 3.25 million t and 2.56 million ha in 2020, respectively [1,5] (Figure 2). Advances in ecology research, policy support, and aquaculture techniques for integrated rice–fish aquaculture are probably the main contributors to this achievement.

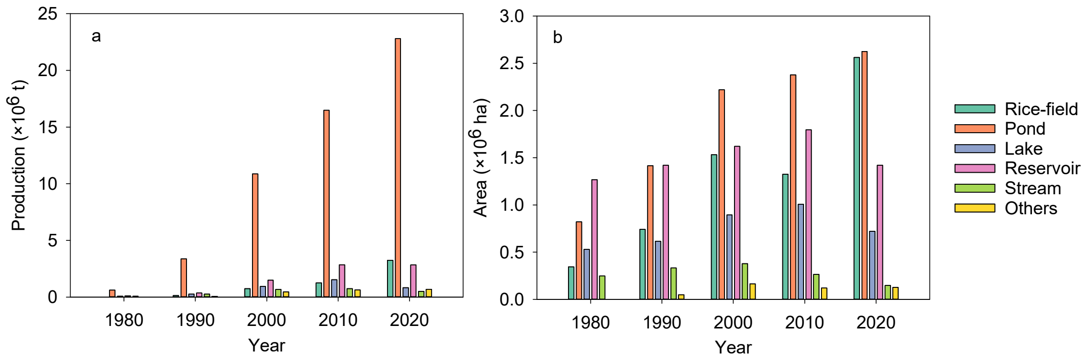

Figure 1. Comparison of freshwater aquaculture production (**a**) and area (**b**) between rice fields and other main water bodies in China [1].

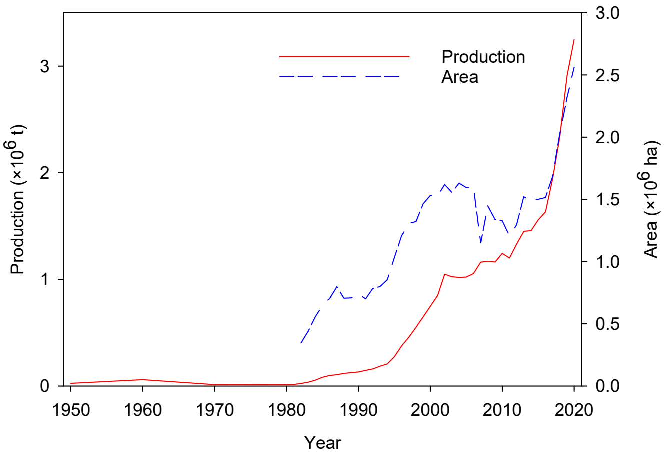

Figure 2. Changes in the aquaculture production and area in rice fields in China from 1950 to 2020 [1,5].

Integrated rice field aquaculture in China includes 25 different models [4]. In this paper, we systematically reviewed the advances in ecology research for the three most important systems in China, namely the rice–fish, rice–crab, and rice–crayfish coculture systems [6]. We also introduced the prospects for ecology research on integrated rice field aquaculture. This information could assist individual small-scale farmers to make better use of rice field space to produce safer aquatic and rice products at a lower cost and help aquaculture scientists to further study the ecology of this industry.

For this review, we searched for Chinese articles in the China National Knowledge Infrastructure database and English articles in the Web of Science database in 2022. We collected as many relevant pieces of literature as possible, and we only selected and referred to important published articles and books. Most of the information that was extracted included productive data (such as density, area, yield, survival rate, feed, and pesticide usage), aquaculture models, and advances in ecological research.

2. Advances in Ecology Research on the Rice–Fish Coculture System

The rice–fish coculture system is the most ancient integrated rice field aquaculture system in the world [2], and many fish species have been chosen for coculture, such as grass carp (*Ctenopharyngodon idella*), common carp (*Cyprinus carpio*) and its diverse strains, goldfish (*Carassius auratus*) and its diverse strains, swamp loach (*Misgurnus anguillicaudatus*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), and tilapias (*Oreochromis* sp.) [7,8]. Furthermore, ecology research in this system not only accelerates the development of the rice–fish aquaculture industry, but also lays the foundation for the formulation and development of other rice field integrated aquaculture systems.

2.1. Establishment of the Rice–Fish Symbiosis Theory

Ni [9] studied the population interactions between rice and fish in the coculture system based on biological and ecological traits in the late 1970s and early 1980s and put forward the Rice–Fish Symbiosis Theory in 1981. Ni and Wang suggested that rice is the main body in the rice field ecosystem and is also the dominant population, which absorbs solar energy, carbon dioxide, water, and other nutrients, and produces organic materials by photosynthesis and rice and straw for stakeholders. Moreover, plenty of weeds, phytoplankton, and photosynthetic bacteria in the field also conduct similar energy conversion, transportation, and storage as rice, but they also compete with rice for fertilizers, water, space, and solar energy without providing useful products for people [10]. Thus, the clearance of weeds in rice fields, which results in the loss of fertility and solar energy for rice, is imperative. Furthermore, plankton, bacteria, and other microorganisms are usually flushed away by irrigation, directly or indirectly causing the loss of fertility and solar energy [10]. Fish culture in rice fields can partially compensate for this loss. Fish in rice fields can directly or indirectly utilize weeds, zoobenthos, plankton, and detritus, decreasing competition with weeds for fertilizers, and utilizing the food and energy that cannot be utilized by rice [10]. In addition, nutrient loadings from fish can also provide nutrients for rice and plankton, and the CO_2 released by fish can also be utilized by rice, weeds, and algae. Additionally, the fish may loosen the surface soil and improve the oxygen condition of the soil to promote the mineralization of organic matter and the release of nutrients [9]. In this ecosystem, rice and fish complement each other and both play an active role, promoting the cycle of materials inside the field, directing beneficial energy flow to both the rice and fish, and efficiently recycling the materials and energy in this coculture ecosystem [10].

The Rice–Fish Symbiosis Theory, although a qualitative description in theory, provides a theoretical base for the Chinese government to adopt specific extension policies for the development of this traditional practice with a long history. In 1983, the Health Commission of China listed fish culture in rice fields as an important measure for killing mosquitoes, and the Ministry of Agriculture, Husbandry, and Fisheries held the first nationwide "On Site Experience Exchange Conference on Fish Culture in Rice Fields" in Wenjiang County, Sichuan Province. Additionally, in 1984, the National Economic Commission of China listed fish culture in rice fields as a national technical development project and extended this technique to 18 provinces; and in 1987, the technical extension of fish culture in rice fields was accepted into the National Harvest Project and State Key Agricultural Extension Project. Then, in 1990, the Ministry of Agriculture held the second nationwide "On Site Experience Exchange Conference on Fish Culture in Rice Fields" in Chongqing [2]. Thus, the breakthrough of ecological theories for integrated rice field aquaculture won national policy support and accelerated the development of fish culture in rice fields in the 1980s (Figure 2).

2.2. Quantitative Determination of Material Cycling and Energy Flow in the Rice–Fish System

2.2.1. Rice–Fish Coculture Remains Rice Production

With the rapid development of integrated rice field aquaculture in the 1980s and 1990s, one of the biggest concerns for agricultural administration officers was whether this system would affect rice production since China has the largest population in the world and food security is a priority for the government. A systematic large-scale in situ experiment, including 155 rice–fish coculture fields and 93 rice monoculture fields in 31 villages in Qingtian County, Zhejiang Province (where its rice–fish culture system was designated by the FAO-GEF as one of the five first Globally Important Agricultural Heritage System (GIAHS) pilot sites in the world), was conducted to compare the difference between rice–fish coculture and rice monoculture from 2006 to 2010. Studies showed that there was no significant difference in rice production between the rice–fish coculture system and the rice monoculture system ($p > 0.05$). The average rice production over five years in the rice–fish coculture system was 6190 ± 150 kg/ha/crop, while that for the monoculture was

6520 ± 390 kg/ha/crop [11]. This result eliminated the concerns about a decrease in rice production due to fish culture in rice fields.

2.2.2. Rice–Fish Coculture Decreases the Application of Chemical Fertilizers and Agricultural Pesticides

Fertilizers and agricultural pesticides are the main inputs of rice fields, affecting economic income and food safety. Experiments from 31 villages in Qingtian County indicated that the application amount of agricultural pesticides in the rice monoculture system was significantly higher than that in the rice–fish coculture system ($p < 0.05$) [11]. The application amount of chemical fertilizers was 158.39 ± 16.97 kg/ha/growing season in the rice–fish coculture system, which was much lower than 266.28 ± 18.15 kg/ha/growing season in the rice monoculture system. In addition, the application amount of agricultural pesticides was 1.81 ± 0.15 kg/ha/growing season in the rice–fish coculture system, which was also much lower than the 4.22 ± 0.16 kg/ha/growing season in the rice monoculture system [12]. During the five-year experiments, no herbicides were used in the rice–fish coculture system [12]. These results support that fish can control weeds and thus reduce the need for chemical fertilizers and decrease the application of agricultural pesticides. No application or much lower application of agricultural pesticides provides security for rice quality safety; thus, many rice products from integrated rice field aquaculture can be certificated and labeled as green and organic food [13]. Consequently, they have become famous brands that can be sold at a much higher price than rice from rice monoculture systems [5].

Further studies on the reason for the maintenance of rice production with low or zero pesticide application showed that rice planthoppers (including *Nilaparvata lugen*, *Sogatella furcifera*, and *Laodelphax striatellus*) were more abundant during their outbreak period (from late August to early September in each year, $p < 0.05$), the incidence of rice sheath blight caused by *Thanatephorus cucumeris* was higher ($p < 0.01$), and the weed biomass was significantly higher ($p < 0.01$) in the rice monoculture system than those in the rice–fish coculture system [14]. In addition, a lower cost and better price are the drivers for farmers to extend rice fish coculture, and better food safety increases consumers′ confidence.

2.2.3. Rice–Fish Coculture Increases Nitrogen Use Efficiency

In the rice monoculture system, nitrogen in chemical fertilizers can only be used by rice, while nitrogen in feeds can be used only by fish in the fish monoculture system. However, nitrogen in chemical fertilizers and feeds can be mutually used in the coculture system. Xie et al. [14] confirmed that the rice–fish coculture system increases nitrogen use efficiency when compared to the rice and fish monoculture systems, and Hu et al. [15] and Zhang et al. [16] confirmed that it decreases the nutrient loadings to the water environment. Experiments showed that 41.02% of the food source of fish in the rice–fish coculture system was from natural food produced in the rice fields [11]. Nitrogen intake from feed was 37.6 kg/ha and that from natural food sources in the rice fields was 42.2 kg/ha [15]. Among them, 17.99% (14.36kg/ha) of nitrogen was assimilated and 82.01% (65.44 kg/ha) was released by the fish, while 84.38% (55.22 kg/ha) of the released nitrogen was dissolved into the water in the form of ammonia excreted by the fish, which can be directly absorbed by the rice. The remaining nitrogen, 15.62% (10.22 kg/ha), was released in the form of feces, which returns to the soil [15]. Thus, fish can provide nutrients through feeding, excretion, and fecal production, compensating for the nitrogen needed for rice growth, and feces added to the soil can also provide nitrogen for the rice.

Quantitative studies on material cycling and energy flow in the rice–fish coculture system, together with other ecological research achievements in the rice–crab, rice–crayfish, and rice–turtle coculture systems led to the leapfrog development of the integrated rice field aquaculture industry both in terms of the amount produced and the area used (Figure 2).

3. Advances in Ecology Research on the Rice–Crab Coculture System

The Chinese mitten crab (*Eriocheir sinensis*) is used for traditional seafood in China and its aquaculture production reached 775,887 t in 2020 [1]. Fish–crab coculture systems started in the late 1980s [17] but developed very fast with a coculture area of 13,869 ha and a production of 61,800 t in 2019 [18]. As a young aquaculture sector, ecology research on rice–crab coculture received attention from the start of the industry [19–21]. Promoted by the Rice–Fish Symbiosis Theory, symbiosis was also studied in the rice–crab coculture and it was found that crabs can utilize the weeds in rice fields, loosen the soil, prey on pests, and provide fertilization through excretion and fecal production, while rice can purify water and protect crabs from their natural enemies [22]. Modern studies on rice–crab coculture ecology have focused on two aspects. One is the crab stocking density in relation to growth, yield, and environmental improvements including the larvae and juvenile crabs. The other is the progress in ecological engineering research.

For megalopa, a stocking density of 15 ind./m^2 can produce the highest crab yield and profit [23], while a stocking density of 120 ind./m^2 with an average weight of 0.005 g/ind. can promote nitrogen use efficiency [24]. For juveniles, a stocking density of 0.75 ind./m^2 with an average weight of 7.04 g/ind. has the highest profit without affecting the soil chemical indexes [25], and weeds can be effectively controlled at a stocking density of 0.50 ind./m^2 with an average weight of 12 g/ind. [26]. This quantitative determination of different stocking densities for different sizes under different ecological conditions lays the foundation for rice–crab coculture development [27–29].

Progress in eco-engineering techniques was the other driver for the development of the rice–crab coculture. Enlightened by the edge effect of rice growth, the trench structure in rice fields has changed from line-shaped trenches to cross-shaped trenches, and then to circular-shaped trenches composed of peripheral and cross trenches (Figure 3). The compensation rates for rice yield loss because of trench building were 95.89%, 85.58%, and 58.02% for line-shaped, cross-shaped, and circular-shaped trenches, respectively [30]. Thus, the new trench shape helps to maintain rice yield without increasing the trench area. Normally, the total trench area accounts for approximately 10% of rice fields. Another reform is the building of new style ridges [13]. The most successful method of ecological ridge engineering is the Panshan model, which is applied in Liaoning Province. In this model, rice planting is based on large single ridges between double rows, i.e., one wide row and a narrow row, with narrow row spacing within the ridge and wider row spacing between the ridges [31]. Edge row densification reduces the plant spacing in the rice row on the field′s edge, where there is a marginal improvement in light, water, and fertilizer supply, which can improve rice yield [22]. Because of the improvements from this ecological engineering project, many provinces and autonomous regions in northern China have referenced the Panshan model when developing rice–crab coculture systems.

Fence building is another important eco-engineering project for rice–crab coculture. Vertical fences were designed in recent years for surrounding rice fields based on understanding the ecological traits of the mitten crab (Figure 4). Preventing the escape of the mitten crab ensures a better crab production. The fences are established using rigid plastics, metal leaves, bricks, or other materials, which are usually fixed into the soil and reached a 30 cm height above the soil.

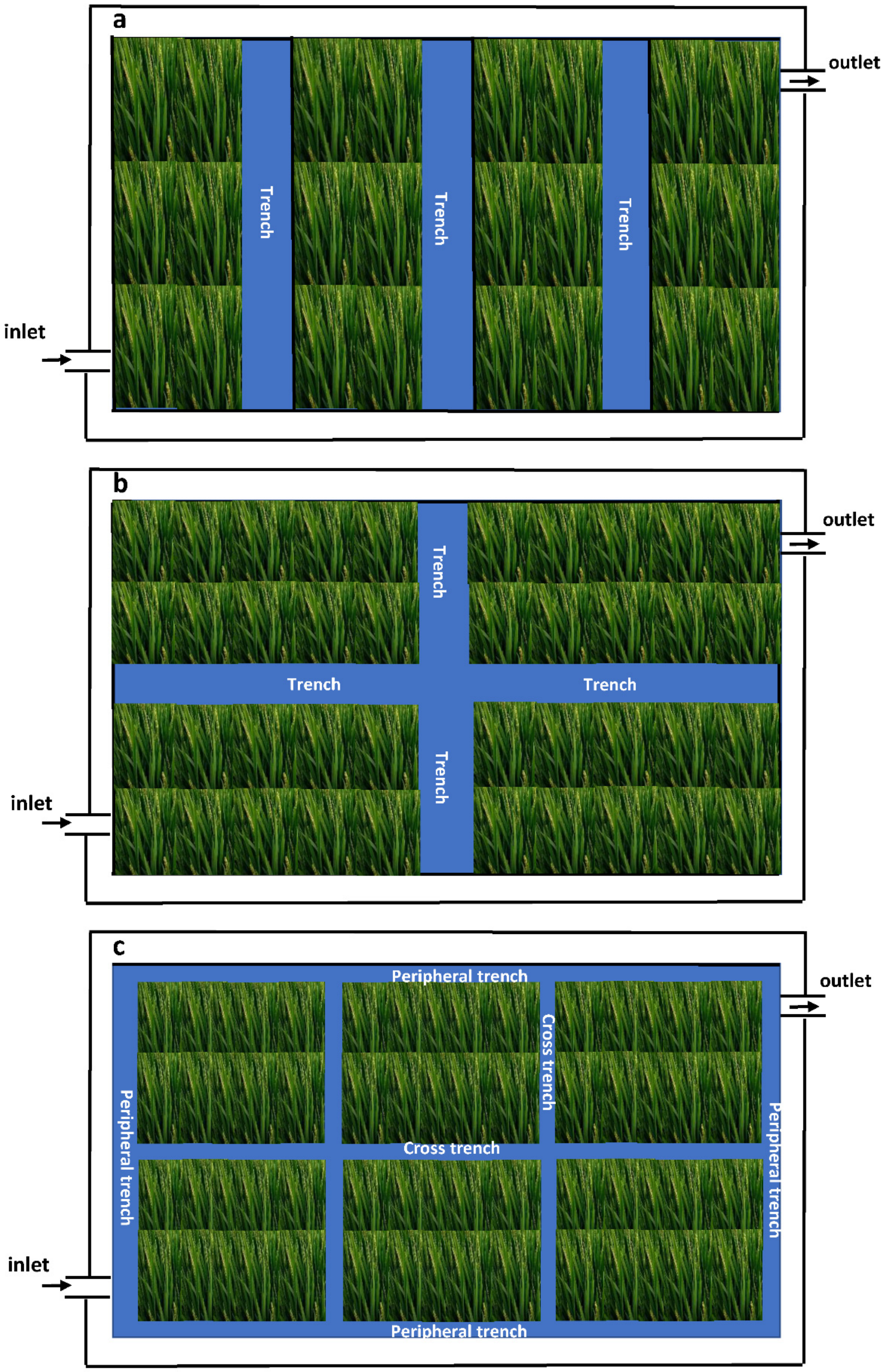

Figure 3. The evolution of trench designs in the rice–crab coculture system: (**a**) line-shaped trenches; (**b**) cross-shaped trenches; (**c**) and circular-shaped trenches.

Figure 4. A plastic fence for the prevention of escaping crabs in the rice–crab coculture system.

4. Advances in Ecology Research on the Rice–Crayfish Coculture System

The red swamp crayfish (*Procambarus clarkii*) is an alien crustacean that was introduced to China from Japan as early as 1929, although it is natively distributed in North America [32]. Since its introduction, the fighting against its invasion and effects on biodiversity and the environment, especially for the destruction of water conservation projects has never stopped until today [33–36]. However, it has also become the most successful exotic aquaculture species with a production increase from 0.05 million t in 2003 to 2.39 million t in 2020, and an area increase from 0.6 million ha in 2016 to 1.46 million ha in 2020 (Figure 5) [1]. Therefore, it is playing a more and more important role in China's aquaculture industry [37]. It has almost overtaken the production of 1.66 million t for tilapias and its production is 7.8 times the production of channel catfish (*Ictalurus punctatus*), which was 0.31 million t in 2020 [1]. Among all the crayfish aquaculture systems, the rice–crayfish coculture has become the most important model and it has developed very fast. The percentage of the rice–crayfish coculture area to the total crayfish aquaculture area increased from 70.83% in 2017 to 86.61% in 2020, while that of rice–crayfish coculture production to total crayfish aquaculture production increased from 72.40% in 2018 to 86.16% in 2020 [1] (Figure 6).

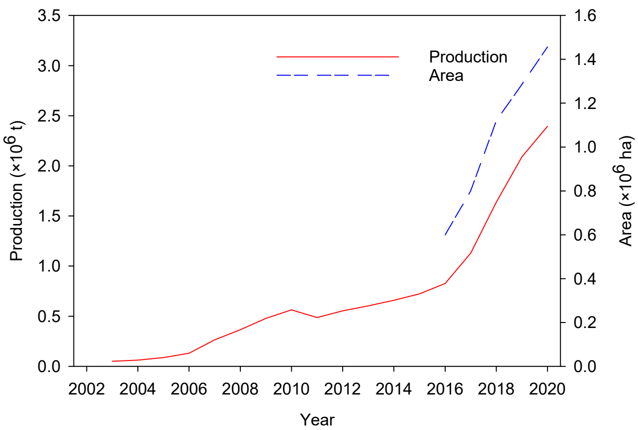

Figure 5. The red swamp crayfish aquaculture area and production from 2003 to 2020 in China [1].

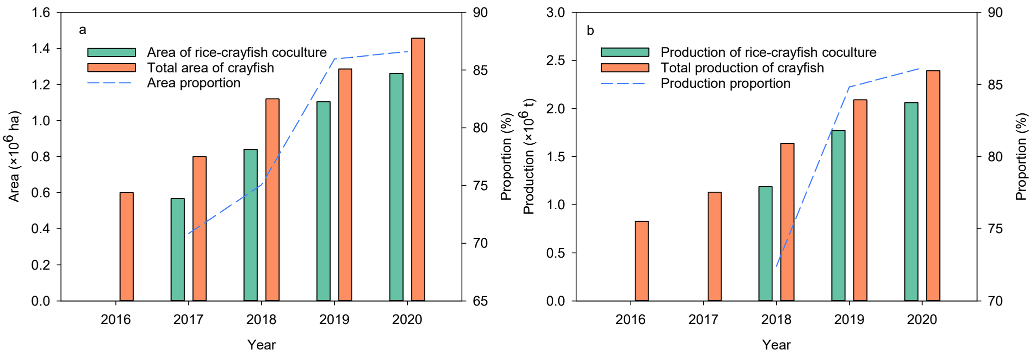

Figure 6. The red swamp crayfish area (**a**) and production (**b**) in the rice–crayfish coculture system and total crayfish aquaculture system in China [1].

Red swamp crayfish aquaculture in rice fields originated from fish farmers' practices and its aquaculture techniques were later summarized and extended by scientists and the government. The biggest barrier to developing this aquaculture is the concern for crayfish burrowing. However, this phenomenon is rarely observed in rice fields. The main reason is likely that the rice in the fields provides shelter for the crayfish. For instance, Cheng et al. confirmed that shadows can act as a solid shelter for red swamp crayfish, and more shadow partitioning, with a 60% shadow area, resulted in a decreased agonistic behavior, a lower mortality, and a higher body weight gain [38]. Yu et al. [39] also reported that an 80% artificial macrophyte coverage significantly increased the total biomass, the molting frequency, the total weight gain, the specific growth rate, and the daylight shelter occupancy when compared to those of a 20% coverage. Rice fields have more shadow areas and even partitioning conditions, which could be the ideal environment for red swamp crayfish growth. Moreover, an increased structural complexity could decrease the predation of native fishes by red swamp crayfish [38]. Additionally, dense rice and circular trenches in rice fields are beneficial for biodiversity protection from red swamp crayfish.

Red swamp crayfish have a small fecundity of about 500 eggs per female and normally reproduce in autumn when the water temperature is low and the hatching time is long [40], which affects the large-scale supply of juveniles. Research on the reproductive biology of red swamp crayfish is focused on solving this problem. For example, Jin et al. [41] systematically studied the spawning traits of red swamp crayfish and found that its spawning activities mainly took place from September to November with a mean fecundity of 429 $\pm$ 9 eggs per female, and there were two recruitments yearly, a major one from October to November and a minor one from March to May. They inferred that some eggs, prevented from hatching by a lower water temperature in winter, were more likely to hatch in the next spring, suggesting that reducing the fishing intensity on immature crayfish and avoiding sex selection during the reproductive period could improve the overall sustainability. Jin et al. [42] further indicated that the optimal temperature is 21–25 °C for adult reproduction and 25 °C for the embryonic development of red swamp crayfish. Consequently, this study provides evidence that manipulating the water temperature is an effective alternative for the mass production of juvenile red swamp crayfish.

The determination of the optimal stocking density for red swamp crayfish is very important since they have agonistic behaviors and fight for shelter. Many experimental and in situ studies have been conducted on this topic [39,43–45]. In summary, the optimal stocking densities were 90,000–120,000 juvenile crayfish at 3–4 cm in length per hectare and 75,000–90,000 juvenile crayfish at 4–5 cm in length per hectare [30].

Overall, progress in the ecology research on rice–fish coculture systems contributes to increased economic benefits, decreased chemical fertilizer and agricultural pesticides usage [4], and improved environmental conditions [44,46,47]. Using Hubei Province as an example, with the largest amount of rice–fish coculture in China, the average production was 1.80 t/ha of crayfish with a benefit of about 7000 USD and the use of chemical fertilizers and agricultural pesticides decreased by more than 30% when compared to the rice monoculture system [4].

5. Future Prospects

During the past two decades, integrated rice field aquaculture has become the fastest developing sector of all the aquaculture systems in China, partially because of the progress in ecology research, policy support, and aquaculture techniques in this field. The basic principle of integrated rice field aquaculture is the coupling of aquatic animals, including fishes, crustaceans, and turtles, with rice production similar to that of the aquaponics to some degree from the viewpoint of coupling [48]. The present study systematically reviewed the advances in ecology research for three major integrated rice field aquaculture systems, the development process of each system, and the contribution of the ecology research. Moreover, we discussed new trends that have appeared in the integrated rice field aquaculture systems and industry, and we have introduced some prospects below.

Some qualitative and quantitative ecological theories of symbiosis, material cycling, and energy flow have been established for the aquaculture systems that were discussed above. However, there are as many as 25 types of integrated rice field aquaculture systems and more than 30 aquatic animals have been included in the industry [4]. Therefore, it is necessary to establish a standard coupling degree comprising a set of parameters to quantitatively determine the coupling efficiency of the nutrient flow in the different coculture systems. This will maximize nutrient use and minimize the input of feeds, fertilizers, and agricultural pesticides, contributing to the extension of specific coculture techniques and the sustainability of integrated rice field aquaculture. Currently, the trench area is forbidden to exceed 10% of the total area of the rice fields [30]; therefore, establishing a standard coupling degree that is suitable for different integrated rice field aquaculture systems will increase the efficiency of land use and reduce environmental impacts.

Although a green aquatic food and organic aquatic food certification system, and an aquatic products quality and safety traceability system have been established for food safety in China [13,49], it is necessary to build an eco-certification system for integrated rice field aquaculture in China since this industry is related with both agriculture and aquaculture. Eco-certification in integrated rice field aquaculture should be based on producing positive sustainability outcomes through the process of certification and a market for certified sustainable products from this system. This would rely on producer compliance with eco-certification criteria that effectively addresses sustainability issues and the acceptance of eco-certification amongst the stakeholders including the consumers, producers, and harvesters [50].

The development of integrated rice field aquaculture is also closely related to brand building, which relies on eco-culture development. Because of the success of eco-culture building in Qianjiang (a medium-sized city in Hubei Province), in this city, red swamp crayfish produced through the rice–crayfish coculture system has promoted the development of the tourism and catering industry, and it has become a model city for red swamp crayfish aquaculture and trade [51]. Similar cases have also been reported in Qingtian, a GIAHS pilot site [11], and many other places [30]. Additionally, aquaculture products from eco-culture-famous sites normally demand much higher prices than those from normal producing areas. Thus, eco-culture can ensure a much better income for stakeholders.

Author Contributions: Conceptualization, J.Y., C.L. and J.L.; validation, J.Y., C.L., T.Z., C.G. and J.L.; data curation, C.L., J.Y. and J.L.; writing—original draft preparation, C.L. and J.Y.; writing—review and editing C.G., and J.L.; visualization, C.L. and J.L.; funding acquisition, C.L. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China: 2020YFD0900304, 2019YFD0900304; the Key Research and Development Program of Hubei Province: 2020BBB077.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FDMARA (Fisheries Department of Ministry of Agriculture Rural Affairs). *China Fisheries Year Book, 1983–2021*; China Agriculture Press: Beijing, China, 2021.
2. Liu, J.; Wang, Q.; Yuan, J.; Zhang, T.; Ye, S.; Li, W.; Li, Z.; Gui, J. Integrated rice-field aquaculture in China: A long-standing practice with recent leapfrog developments. In *Aquaculture in China: Success Stories and Modern Trends*; Gui, J., Tang, Q., Li, Z., Liu, J., De Silva, S.S., Eds.; John Wiley & Sons Ltd.: Canberra, Australia, 2018; pp. 174–183.
3. Prein, M. Integration of aquaculture into crop-animal systems in Asia. *Agric. Syst.* **2002**, *71*, 127–146. [CrossRef]
4. Tang, J.; Li, W.; Lu, X.; Wang, Y.; Ding, X.; Jiang, J.; Tang, Y.; Li, J.; Zhang, J.; Du, J.; et al. Development status and rethinking of the integrated rice-fish system in China. *China Rice* **2020**, *26*, 1–10. (In Chinese with English Abstract) [CrossRef]
5. Hu, L.; Tang, J.; Zhang, J.; Ren, W.; Guo, L.; Halwart, M.; Li, K.; Zhu, Z.; Qian, Y.; Wu, M.; et al. Development of rice-fish system: Today and tomorrow. *Chin. J. Eco-Agric.* **2015**, *23*, 268–275. (In Chinese with English Abstract) [CrossRef]
6. Luo, S. *Agroecological Rice Production in China: Restoring Biological Interactions*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2018; pp. 1–115.
7. Cai, R. *Fish Culture in Rice Fields*; Science Press: Beijing, China, 1982; pp. 22–23. (In Chinese)
8. Ni, D.; Wang, J. Recent development of fish culture in the rice field in China. *Acta Hydrobiol. Sin.* **1988**, *12*, 364–375. (In Chinese)
9. Ni, D. Rice-fish mutualism theory. *Sci. Hum. Being* **1984**, *1*, 10–11. (In Chinese)
10. Ni, D.; Wang, J. *Theories and Practices of Fish Culture in Rice Fields*; China Agriculture Press: Beijing, China, 1990; pp. 1–291. (In Chinese)
11. Chen, X.; Tang, J.; Hu, L.; Wu, M.; Ren, W. *Rice-Fish System in Qingtian: Ecology, Conservation and Utilization*; Science Press: Beijing, China, 2021; pp. 1–232.
12. Chen, X.; Wu, X.; Li, N.; Ren, W.; Hu, L.; Xie, J.; Wang, H.; Tang, J. Globally important agricultural heritage system (GIHAS) rice-fish system in China: An ecological and economic analysis. In *Advances in Ecological Research*; Li, P.P., Ed.; Zhejiang University Press: Hangzhou, China, 2011; pp. 126–137.
13. Miao, W. Recent developments in rice-fish culture in China: A holistic approach for livelihood improvement in rural areas. In *Success Stories in Asian Aquaculture*; De Silva, S.S., Davy, F.B., Eds.; Springer: Ottawa, ON, Canada, 2010; pp. 15–40.
14. Xie, J.; Hu, L.; Tang, J.; Wu, X.; Li, N.; Yuan, Y.; Yang, H.; Zhang, J.; Luo, S.; Chen, X. Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish system. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 1381–1387. [CrossRef]
15. Hu, L.; Ren, W.; Tang, J.; Li, N.; Zhang, J.; Chen, X. The productivity of traditional rice-fish co-culture can be increased without increasing nitrogen loss to the environment. *Agric. Ecosyst. Environ.* **2013**, *177*, 28–34. [CrossRef]
16. Zhang, J.; Hu, L.; Ren, W.; Guo, L.; Wu, M.; Tang, J.; Chen, X. Effects of fish on field resource utilization and rice growth in rice-fish coculture. *Chin. J. Appl. Ecol.* **2017**, *28*, 299–307. (In Chinese with English Abstract) [CrossRef]
17. Xue, Y.; Yang, H.; Ge, X. Rice crab symbiosis technology. *Shanghai Agric. Sci. Technol.* **1991**, *6*, 32–33. (In Chinese)
18. Ministry of Agriculture and Rural Affairs of China. Development report of China's rice and fishery comprehensive planting and breeding industry. *China Fish.* **2020**, *10*, 12–19. (In Chinese)
19. Cheng, Y.; Wu, X.; Li, J. Chinese mitten crab culture: Current status and recent progress towards sustainable development. In *Aquaculture in China: Success Stories and Modern Trends*; Gui, J.-F., Tang, Q., Li, Z., Liu, J., De Silva, S.S., Eds.; John Wiley & Sons Ltd.: Canberra, Australia, 2018; pp. 197–217.
20. Chen, F.; Zhang, Z. Ecological economic analysis of a rice-crab model. *Chin. J. Appl. Ecol.* **2002**, *13*, 323–326. (In Chinese with English Abstract) [CrossRef]
21. Xu, Q.; Wang, X.; Xiao, B.; Hu, K. Rice-crab coculture to sustain cleaner food production in Liaohe River basin. *J. Clean. Prod.* **2019**, *208*, 188–198. [CrossRef]
22. Bao, J.; Jiang, H.; Li, X. Thirty years of rice-crab coculture in China—Research progress and prospects. *Rev. Aquac.* **2022**, *14*, 1597–1612. [CrossRef]
23. Wang, W.; Wang, C.; Ma, X. *Mitten Crab Eco-Culture*, 2nd ed.; China Agriculture Press: Beijing, China, 2013; pp. 1–357. (In Chinese)
24. Wang, A.; Ma, X.; Xu, J.; Lu, W. Methane and nitrous oxide emissions in rice-crab culture systems of northern China. *Aquac. Fish.* **2019**, *4*, 134–141. [CrossRef]
25. Lv, D.; Wang, W.; Ma, X.; Chen, Z.; Yu, Y.; Li, C.; Yan, B. The effect of stocking density of Chinese mitten crab on yields of rice and crab in rice-crab culture system. *Hubei Agric. Sci.* **2010**, *49*, 1677–1680. (In Chinese with English Abstract)
26. Lv, D.; Wang, W.; Ma, X.; Wang, Q.; Wang, A.; Chen, Z.; Tang, S. Ecological prevention and control of weeds in rice-crab polyculture field. *Hubei Agric. Sci.* **2011**, *50*, 1574–1578. (In Chinese with English Abstract)
27. Xu, M.; Wang, W.; Ma, X. Regularity of different cultivation patterns on the soil physical and chemical properties, nutrition changes in rice-carb culture system. *Guangdong Agric. Sci.* **2013**, *9*, 53–57. (In Chinese with English Abstract) [CrossRef]
28. Sun, W.; Zhang, Q.; Ma, X.; Wang, W.; Wang, A. A study on effects of different crab stocking density on water environment and rice yield. *J. Shanghai Ocean Univ.* **2014**, *23*, 366–373.

29. Shou, L.; Zhang, Z.; Chen, S.; Wu, W. Analysis of economic benefit of organic rice and rice-crab cropping patterns in rice planting area of northeast China. *Shaanxi J. Agric. Sci.* **2021**, *67*, 1–8. (In Chinese with English Abstract) [CrossRef]
30. National Fisheries Technology Extension Center. *Technical Modes for Integrated Rice-Field Aquaculture*; China Agriculture Press: Beijing, China, 2021; pp. 86–127. (In Chinese)
31. Dong, Y.; Jiang, H.; Yu, Y.; Sun, B. Water-temperature characteristics of rice-field-crab "Panshan mode". *J. Anhui Agri. Sci.* **2010**, *38*, 12483–12485. (In Chinese with English Abstract) [CrossRef]
32. Wu, T.; Gao, P. Status and development prospects of the freshwater red swamp crayfish. *Inland Fish.* **2008**, *2*, 15–17. (In Chinese)
33. Li, Z.; Xie, Y. *Invasive Alien Species in China*; China Forestry Publishing House: Beijing, China, 2002. (In Chinese)
34. Gong, S.; Li, L.; Lu, J.; Zhang, X.; He, X.; Xiong, C. A study on burrowing behavior of *Procambarus clarkii*. *Freshwater Fish.* **2007**, *37*, 3–7. (In Chinese with English Abstract) [CrossRef]
35. Wu, Z.; Cai, J.; Jia, Y.; Lu, J.; Jiang, Y.; Huang, C. Predation impact of *Procambarus clarkii* on *Rana limnocharis* tadpoles in Guilin area. *Biodivers. Sci.* **2008**, *16*, 150–155. (In Chinese with English Abstract) [CrossRef]
36. Cai, F.; Wu, Z.; He, N.; Ning, L.; Huang, C. Research progress in invasion ecology of *Procambarus clarkii*. *Chin. J. Ecol.* **2020**, *29*, 124–132. (In Chinese with English Abstract) [CrossRef]
37. Liu, J.; Li, Z. The role of exotics in Chinese inland aquaculture. In *Success Stories in Asian Aquaculture*; De Silva, S.S., Davy, F.B., Eds.; Springer: Ottawa, ON, Canada, 2010; pp. 173–186.
38. Huang, C.; Xiong, Q.; Tang, J.; Wu, M. Shadow area and partitioning influencing mortality, healthiness and growth of juvenile red swamp crayfish *Procambarus clarkii* (Decapoda). *Aquac. Res.* **2012**, *43*, 1677–1686. [CrossRef]
39. Yu, J.; Xiong, M.; Ye, S.; Li, W.; Xiong, F.; Liu, J.; Zhang, T. Effects of stocking density and artificial macrophyte shelter on survival, growth and molting of juvenile red swamp crayfish (*Procambarus clarkii*) under experimental conditions. *Aquaculture* **2020**, *521*, 735001. [CrossRef]
40. Xia, A. *Aquaculture of Red Swamp Aquaculture*; China Agriculture University Press: Beijing, China, 2007. (In Chinese)
41. Jin, S.; Jacquin, L.; Xiong, M.; Li, R.; Li, W.; Lek, S.; Tang, Z. Reproductive pattern and population dynamics of commercial red swamp crayfish (*Procambarus clarkii*) from China: Implications for sustainable aquaculture management. *PeerJ* **2019**, *7*, e6214. [CrossRef]
42. Jin, S.; Jacquin, L.; Huang, F.; Xiong, M.; Li, R.; Lek, S.; Li, W.; Liu, J.; Zhang, T. Optimizing reproductive performance and embryonic development of red swamp crayfish *Procambarus clarkii* by manipulating water temperature. *Aquaculture* **2019**, *510*, 32–42. [CrossRef]
43. Ren, Z. Technology for culture red swamp crayfish in rice fields. *Chin. Aquac.* **2012**, *3*, 22–25. (In Chinese) [CrossRef]
44. Yu, J.; Ren, Y.; Xu, T.; Li, W.; Xiong, M.; Zhang, T.; Li, Z.; Liu, J. Physicochemical water quality parameters in typical rice-crayfish integrated systems (RCIS) in China. *Int. J. Agric. Biol.* **2018**, *11*, 54–60. [CrossRef]
45. Huang, F.; Feng, Y.; Li, H.; Li, W.; Zhang, T. Effects of stocking of different sizes on growth performance and production of red swamp crayfish in rice fields. *Biol. Resour.* **2020**, *42*, 421–427. (In Chinese with English Abstract) [CrossRef]
46. Huang, J.; Zheng, X.; Wu, Z.; Liu, H.; Deng, F. Can increased structural complexity decrease the predation of an alien crayfish on a native fish? *Hydrobiologia* **2016**, *781*, 191–197. [CrossRef]
47. Ma, D.; Qian, J.; Liu, J.; Gui, J. Development strategy for integrated rice field aquaculture. *Strateg. Study CAE* **2016**, *18*, 96–100. (In Chinese with English Abstract) [CrossRef]
48. Baganz, G.F.M.; Junge, R.; Portella, M.C.; Goddek, S.; Keesman, K.J.; Baganz, D.; Staaks, G.; Shaw, C.; Lohrberg, F.; Kloas, W. The aquaponic principle—It is all about coupling. *Rev. Aquac.* **2021**, *14*, 252–264. [CrossRef]
49. Huang, L.; Song, Z.; Feng, Z.; Meng, T. The application of traceability system of aquatic products quality and safety in building the market access system. *Chin. Fish. Qual. Stand.* **2011**, *2*, 26–33. (In Chinese with English Abstract)
50. Amundsen, V.S.; Osmundsen, T.C. Virtually the reality: Negotiating the distance between standards and local realities when certifying sustainable aquaculture. *Sustainability* **2019**, *11*, 2603. [CrossRef]
51. Qin, Z. Propel the innovation of system and mechanism with "crayfish-rice cooperation" model—Observation and reflection of comprehensive reform in Qiangjiang as a nationwide small-medium. *Chin. Devel.* **2016**, *16*, 51–56.