

## Article

# Evaluation and Screening of Co-Culture Farming Models in Rice Field Based on Food Productivity

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**Abstract:** Traditional farming practice of rice field co-culture is a time-tested example of sustainable agriculture, which increases food productivity of arable land with few adverse environmental impacts. However, the small-scale farming practice needs to be adjusted for modern agricultural production. Screening of rice field co-culture farming models is important in deciding the suitable model for industry-wide promotion. In this study, we aim to find the optimal rice field co-culture farming models for large-scale application, based on the notion of food productivity. We used experimental data from the Jiangsu Province of China and applied food-equivalent unit and arable-land-equivalent unit methods to examine applicable protocols for large-scale promotion of rice field co-culture farming models. Results indicate that the rice-loach and rice-catfish models achieve the highest food productivity; the rice-duck model increases the rice yield, while the rice-turtle and rice-crayfish models generate extra economic profits. Simultaneously considering economic benefits, staple food security, and regional food output, we recommend the rice-duck, rice-crayfish, and rice-catfish models. Simulating provincial promotion of the above three models, we conclude that food output increases from all three recommended models, as well as the land production capacity. The rice-catfish co-culture model has the most substantial food productivity. None of the three models threatens staple food security, as they do not compete for land resources with rice cultivation.

**Keywords:** rice field co-culture farming; integrated benefits; model screening; model promotion; food-equivalent unit; arable-land-equivalent unit

## 1. Introduction

Although China's agricultural development has gained great achievements, the problem of unsustainability is increasingly prominent. Because of strengthened constraints of water and land resources, as well as notable ecological issues, the agricultural development in China is about to reach the bottleneck. Both the total area and the per capita area of arable land in China continue to decline [1,2]. Furthermore, the total shortage of fresh water in China is around  $3.6 \times 10^{10} \text{ m}^3$ , including  $3 \times 10^{10} \text{ m}^3$  of water shortage for agriculture [3,4]. In addition, the high consumption of agro-chemicals leads to widespread environmental pollution [5,6]. Usage of fertilizer and pesticide per unit area in China is twice as high as that in the US and EU [7], making China the biggest market for fertilizer, pesticide, and agricultural film. The low efficiency of fertilizer and pesticides also raises concerns over agro-chemical runoff and groundwater contamination, which disturb the balance of the ecosystem [8–10]. Over-exploitation of agricultural resources, overuse of agricultural inputs and the

superposition of internal and external pollution in agriculture have resulted in a series of problems that pose challenges on sustainable agricultural development [11–14]. Therefore, the development of sustainable agriculture should give priority to improving the efficiency in agricultural practices under severe constraints in resources and environment.

With a humid climate and limited arable land, as well as a large population, the East Asian agricultural region has developed a sustainable food production scheme, rice field co-culture farming (RFCF), which cyclically utilizes land, water, and biological resources in rice paddy fields [15], and plays an important role in the food and nutrition supply in densely populated areas. Compared to traditional RFCF models, the modern RFCF models adopt the principals of modern ecology as well as advanced ecological technology, to make better use of the water and land resources in the paddy ecosystem. When raising aquatic animals in the rice paddy fields, rice and aquatic animals mutually benefit from each other and form a compound circular ecology mode [16,17]. Currently in China, major RFCF models include the rice-duck, rice-fishery, rice-crayfish, and rice-crab models. RFCF brings several benefits in the following aspects [18–22]: 1. Stabilizing the rice yield as well as improving quality, as aquatic animals help weeding the paddy field; 2. Improving soil quality through increasing soil fertility and enhancing soil permeability; and 3. Improving the production efficiency through green production. As the RFCF procedure requires fewer inputs in fertilizers and pesticides, the chemical residues in rice could decrease, thus increasing the rice price because of higher safety. Reduced inputs of fertilizers and pesticides could also save production costs. Besides, the RFCF increases agriculture efficiency through combining crop planting and aquaculture, as well as forming a more vigorous experience in leisure- and sightseeing-agriculture [23]. Thus, the Chinese government advocates the promotion of the RFCF models in a wide area in China. The No. 1 documents of the Central Committee from 2016 to 2018, as well as relevant development plans, all clearly state support for the development of RFCF. By 2017, the total RFCF area reached 1.87 million hectares (ha), spreading in 27 provinces in China [24].

The evaluation and screening of premium RFCF models are crucial to the large-scale promotions. Previous studies looked at different aspects of RFCF, but there were some limitations. Some scholars evaluated the effects of different RFCF models on soil and product quality [25–28], concluding that RFCF models improve the water quality and soil fertility, as well as enhance the qualities of land outputs. The literature also evaluated the effect of applying RFCF to the region-scale value of ecological service function [29], as well as stakeholders' economic benefits from applying RFCF in rural areas [30,31]. To the best of our knowledge, despite several studies evaluating how RFCF models affect the food productivity [17,32], little research has been done to compare different RFCF models. In this study, we fill this gap by comparing several RFCF models in the perspectives of food productivity and economics.

We use data collected in an experimental site in the Jiangsu Province of China, and evaluate six RFCF models using the food-equivalent unit (FEU) method and arable-land-equivalent unit (ALEU) method. The six RFCF models considered include the rice-duck model, rice-catfish model, rice-crayfish model, rice-turtle model, rice-loach model, and rice-carp model. Results indicate that the rice-loach and rice-catfish models perform well in increasing overall food productivity, while the rice-duck model improves rice output. From an economic point of view, the rice-turtle model and the rice-crayfish model are superior to others. The rice-carp model is preferred neither from the perspective of comprehensive productivity, nor from the perspective of economic profits. We contribute to the existing literature in the following aspects: first, instead of focusing on one specific RFCF model as previous studies did, we make comparisons among multiple models; second, based on different RFCF models, we analyze not only the economic benefits of RFCF models, but also the food productivity. Last but not least, we estimate the potential effects of the large-scale promotion of the premium models on food production (including rice) in Jiangsu Province.

## 2. Materials and Methods

### 2.1. Study Region and Location of Experiment

Located in the downstream area of the Yangtze River and the Huai River, Jiangsu Province benefits from the dense water-network in the flat terrain and a high land-reclamation rate, and thus is known for rich rice and fish products. With a large population and limited arable land areas, Jiangsu mainly increases food productivity by increasing unit area yield and multiple cropping. Thus, the unit area rice yield in Jiangsu always ranks the first among major rice-producing provinces in China. In 2017, the multiple-cropping index of arable land in Jiangsu surpassed 165%, higher than other provinces from similar climate zones. To further increase food productivity in Jiangsu, new approaches combining planting and aquaculture need to be adopted. In 2017, the area of RFCF in Jiangsu accounted for nearly 1/5 of the province-wide inland aquaculture area including lakes, ponds, reservoirs, rivers, and ditches. Hence, fully utilizing rice field aquaculture spaces and increasing output efficiency to pursue high yield of high-quality food products plays an important role in the transformation and upgrading of agricultural development in Jiangsu Province.

The test site of this study is located in the Jiangyan district of Taizhou, central area of Jiangsu Province, as shown in Figure 1. In recent years, RFCF in this area has developed rapidly because of the provincial government's financial support and economic incentives for operating co-culture farming, with an area of 111.67 hectares (ha) and 266.67 ha in 2017 and 2018, respectively. There are several RFCF models in this district, but they yield little benefits. The project team conducted a pre-survey in the above area in 2017 through on-site visits and telephone interviews, aiming to understand the basic production and operation situation of typical symbiotic farm owners. On this basis, the Jiangyan Agricultural Commission asked related agro-technical stations to pick a total of six RFCF models that are expected to perform well on a large scale for experimental purposes. The experimental base was located at the Hantu Agricultural Rice and Wheat Production Base in Heheng village, town of Shengao. The Hantu base in Jiangyan District is the promoting and demonstrating base of the Technical System of Modern Agricultural Industry in Jiangsu Province, with a total area of 75.33 ha.

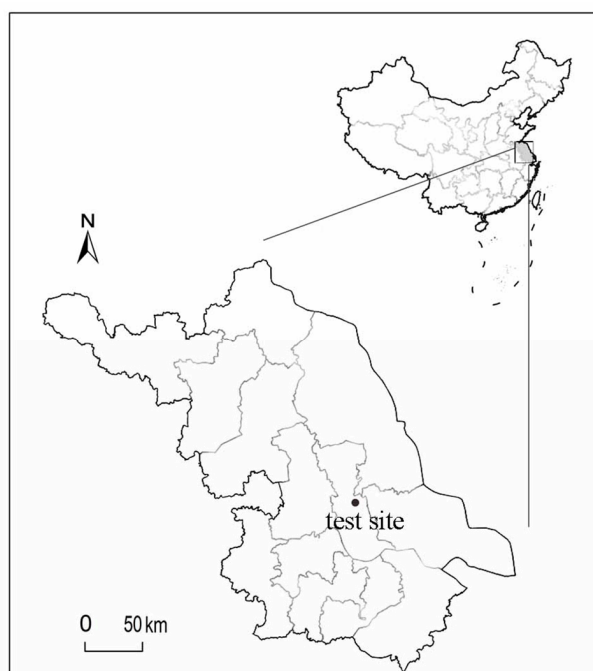


Figure 1. Location of the experiment site.

## 2.2. Experimental RFCF Models

The six RFCF models presented in this study—the rice-duck model, the rice-crayfish model, the rice-catfish model, the rice-loach model, the rice-turtle model, and the rice-carp model—have a total experimental area of 8 ha; details are shown in Table 1. In addition, there are 14.67 ha of conventional rice field performing as the control group. A medium-maturing Japonica rice cultivar with superior taste, Nanjing 2728, was used for the rice-crayfish model. For other models, Nanjing 9108, a late-maturing Japonica rice cultivar with superior taste cultivated widely in the Jiangyan district was used. According to "Integrated Rice-Fish Co-culture Farming Technical Specifications (2017)" published by the Chinese Ministry of Agriculture, the main technical norms of the RFCF are: 1. The percentage of the areas of ditch and puddle should not exceed 10% to make sure of the sufficient planting area of rice and to protect the plough layer; 2. Straw application to advance soil fertility; 3. Prohibit the use of antibiotics and pesticides in fishery; 4. Control the use of disinfectant and water-improving fishery drugs; and 5. Prioritize the use of organic fertilizers and restrict the use of chemical fertilizers. Field engineering, rice planting dimensions, fertilizer transportation, and pest- and weed-control in this experiment strictly complied with the requirements of agricultural eco-cycling technical standards. Rice in the rice-crayfish model was planted using a potted-tray seedling machine, with an in-row and inter-row spacing at 12.4 cm × 28.0 cm. Rice in the other five RFCF models were planted using a carpet seedling machine, with an in-row and inter-row spacing at 11.0 cm × 30.0 cm. Regarding aquatic animals, the densities of duck, catfish, turtle, and carp were 18, 300, 80, and 80 per Chinese mu (1 Chinese mu = 0.0667 ha), respectively, while for crayfish and loach they were 30.0 and 36.0 kilograms per Chinese mu, respectively.

**Table 1.** Brief introduction of the experimental rice field co-culture farming (RFCF) models.

RFCF Model	Area (ha)	Symbiote	Source of model
Rice-duck	2.67	Gaoyou Duck	Major model used in the Jiangyan district
Rice-catfish	2.00	African Sharptooth Catfish	Introduced from Jiangxi Province; with six years' history and good results
Rice-crayfish	1.33	Louisiana Crayfish	Started in Qianjiang, Hubei Province; with the largest scale in China
Rice-turtle	0.67	Local Turtle	Started in Deqing County, Zhejiang Province
Rice-loach	0.67	Taiwan Loach	Applied in many provinces; with a small-scale demonstration in our experimental base
Rice-carp	0.67	Amur Carp	Typically applied in Yangzhou, Jiangsu Province; mainly aimed at increasing visits to tourist sites

## 2.3. Estimation of Food Productivity

### 2.3.1. Food-Equivalent Unit Method

The team of Jizhou Ren, who is an expert in grassland agriculture, proposed the concept of the food-equivalent unit (FEU) [33–35]. The FEU is a comprehensive measurement based on calories and protein content, which adds up the multiplications of corrected coefficients ( $C_H$  and  $C_P$ ), calorie content ( $H$ ), and protein content ( $P$ ) in food, i.e.,  $FEU = HC_H + PC_P$ .

In general, there are plant-based food and animal-based food, each of which has different nutritional functions. The FEU calculation of the plant-based food uses Japonica rice as the standard food, while that of the animal-based food uses mutton as the standard food. Plant-based foods are generally caloric food; thus, the FEU ( $FEU_p$ ) calculation sets  $HC_H$  and  $PC_P$  at 0.9 and 0.1, respectively [33,34]. Animal-based foods are protein-orient foods, thus setting  $HC_H$  and  $PC_P$  at 0.1 and 0.9, respectively, in the FEU calculation ( $FEU_a$ ). By setting the FEU of standard foods (Japonica rice and mutton) at one, we obtain the  $H$  and  $P$  values for Japonica rice and mutton from the Table of Food Nutrients [33] and

calculate the coefficient of  $C_H$  and  $C_P$  following equations (1) and (2). We then further calculate the  $FEU$  of all food products involved in our experiment.

$$FEU_p = \frac{H}{1585} + \frac{P}{77}, \quad (1)$$

$$FEU_a = \frac{H}{6676} + \frac{P}{21.6}, \quad (2)$$

$$FEU' = FEU[E(100 - W)] / [E_s(100 - W_s)]. \quad (3)$$

Equation (3) is a correction of the  $FEU$  calculation based on the proportions of water content and edible parts, where  $E$  is the actual edible part,  $E_s$  is the standard edible part,  $W$  is the actual water content, and  $W_s$  is the standard water content.

$FEU_a$  and  $FEU_p$  can be mutually converted. Generally, 1:10 is a reasonable conversion rate between food nutritional grades, i.e., ten units of plant-based foods can produce one unit of animal-based foods in a food chain [33], as  $FEU_a = 10 \times FEU_p$ . Let  $FEU_p = FEU$ , then  $10 \times FEU = FEU_a$ . In this study, we obtain the  $E_s$  and  $W_s$  of relative animal products from the "Table of Food Nutrients in China" to correct the  $FEU_a$  value. Taking Japonica rice in the control group as a reference with setting its  $FEU$  at one, we calculate the  $FEU$  of animal products accordingly, as shown in Table 2.

**Table 2.** Food-equivalent unit of rice field symbiote <sup>1</sup>.

	Duck	Catfish	Crayfish	Turtle	Loach	Carp
$FEU_a$	0.74	0.90	0.93	0.85	0.87	0.95
Corrected $FEU_a$	0.74	0.83	0.93	0.86	0.81	1.21
Converted $FEU$	7.43	8.28	9.33	8.63	8.08	12.09

<sup>1</sup> To get results in this table, the  $FEU$  of Japonica rice = 1.0.  $FEU$ : food-equivalent unit.

### 2.3.2. Arable-Land-Equivalent Unit Method

Arable-land-equivalent unit ( $ALEU$ ) refers to land with productivity equivalent to that from standard farmland. It is in use to normalize food production potentials of agricultural resources such as farmlands, forests, grasslands, and aquaculture ponds [34–36]. In this study, we take the unit area food output from Japonica rice cultivation as the reference value and use  $ALEU$  to measure the food productivity from different types of land use (or operation) models.  $ALEU$  is expressed as:

$$ALEU = F(m, \sum_i f_i) / F_0(m_0, f_0). \quad (4)$$

In Equation (4),  $F$  is the final food output, which is a function of the operational model  $m$  and the yield,  $f_i$ , of variety  $i$ ;  $F_0$  is the food output of rice per unit area, which is affected by the present conventional rice paddy management,  $m_0$ , and the unit area yield of rice,  $f_0$ , under conventional management. All food outputs herein are estimated with  $FEU$ . We only consider one season of rice harvest in this study.

## 3. Results

### 3.1. Comparison of Food Productivity

Table 3 summarizes the measurements of food productivity from different farming models using  $FEU$  and  $ALEU$  calculation models. Models co-cultured with duck, crayfish, and catfish have higher unit area rice yield than conventional planting without animal raising. Subtracting the actual rice yield from ditch areas in rice-fishery co-culture, we observe losses in rice production for most of the models, compared with conventional rice fields. Rice productions from the rice-turtle and rice-carp models are reduced the most, which are almost 20% less than that from conventional rice fields. In addition, the rice

yield of the rice-loach model decreases by 15.8%. The rice-duck co-culture model is an exception, in which the rice yield is 18.1% higher than that in the control group. Even after subtracting rice outputs from the ditch area, rice yield from the rice-duck co-culture system is still higher than that in the control group.

**Table 3.** Food output per hectare from the six rice field co-culture farming models <sup>1</sup>.

Model	Rice (kg)	Symbiote (kg)	Actual Rice (FEU)	Symbiote (FEU)	Integrated Rice Field (FEU)	Integrated Rice Field (ALEU)	Rice Grain (ALEU)	Symbiote (ALEU)
Rice-duck	9870	405	8883.0	4895.7	13,778.7	1.65	1.06	0.59
Rice-catfish	8775	4050	7897.5	34,947.3	42,844.8	5.13	0.95	4.18
Rice-crayfish	8730	1950	7857.0	14,488.5	22,345.5	2.67	0.94	1.73
Rice-turtle	7419	720	6677.1	5965.0	12,642.1	1.51	0.80	0.71
Rice-loach	7815	4200	7033.5	39,190.6	46,224.1	5.53	0.84	4.69
Rice-carp	7440	750	6696.0	6061.0	12,757.0	1.53	0.80	0.73
Control	8355	—	—	—	—	1.00	1.00	—

<sup>1</sup> The area used for ditches is not considered for the calculation of the yields of rice and aquatic products. The actual rice yield in the RFCF model is calculated by subtracting 10% of ditch area. FEU: food-equivalent unit; ALEU: arable-land-equivalent unit.

From the perspective of integrated food output, all six models show significant increases in food output, compared with conventional rice fields. Because of the high unit area output of aquatic products in rice-loach and rice-catfish co-culture models, the total food outputs are approximately five times the food output of conventional rice fields, which demonstrates the pattern of “low rice production, high fishery production”. The total food output from the rice-crayfish co-culture model is more than twice the food output of conventional rice fields, with higher food output from the symbiotic products than that from rice. The total food outputs from rice-duck, rice-carp, and rice-turtle models are approximately 1–2 times the food output in conventional rice fields. The unit area outputs of duck, carp, and turtle are relatively low. Converting the outputs to FEU or ALEU, rice output is slightly higher than the above symbiotic products output.

### 3.2. Comparison of Economic Performances

Table 4 summarizes the estimated economic benefits of different models according to the sale of RFCF products and market price of the previous year. According to Table 4, profits of co-culture fields are higher than that of conventional rice fields. The rice-duck co-culture model generates the highest profits, followed by the rice-crayfish and rice-catfish models. Conventional rice production depends highly on inputs of agro-chemicals, which have lower cost of scale-operation; however, the output and benefits of conventional rice production are low as well. Although RFCF requires cost-raising inputs in field engineering, manual weed-control, biotic pesticides, and organic fertilizers, farmers obtain price premiums from improved rice quality.

Currently, the market benefits of turtles and crayfish are the best, even higher than profits of respective co-cultured organic rice. Considering market benefits, the rice-turtle model, which shows the most significant trend of “weak-rice, strong-fishery”, generates more than twice the profits of its co-cultured rice. The rice-crayfish model also generates higher profits from the crayfish than that from the rice. The economic benefits of other co-culture models are still mainly from organic rice. Although the costs of culturing catfish and duck are low, the output values are relatively low as well. By contrast, culturing loach brings a high output value, but is also at high production costs. Culturing carp has the lowest economic production–investment ratio.

Regarding the combined economic benefits of the RFCF outputs, the rice-turtle and rice-crayfish models are the best models, reaching more than six times the profits of conventional rice fields. The integrated economic benefits of the rice-duck and rice-catfish models are four to five times that of the conventional rice fields, and three to four times that of the conventional rice fields for the rice-loach



co-culture model. The integrated economic benefits of the rice-carp model are less than three times that of conventional rice fields.

We have to mention that the benefits of RFCF highly depend on selling prices of rice and aquatic products. Market prices vary based on locations and times. The presented results may only stand for this experiment. Moreover, the estimated benefits in this study are based on farmers' sale modes at the time of experiments. The actual unit area benefits of rice fields may be lower than the estimated benefits if rice or aquatic products are not sold off.

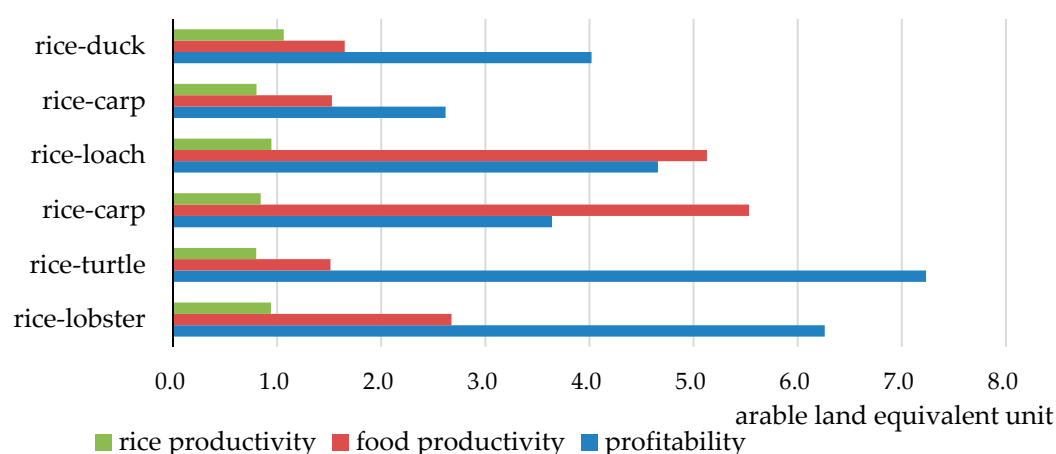
**Table 4.** Economic benefits of the six rice field co-culture farming models <sup>1</sup>.

Model	Rice			Symbiote			Actual Gain from Rice	Integrated Gain	ALEU from Net Gain
	Cost	Profits	Net Gain	Cost	Profits	Net Gain			
Rice-duck	14.2	68.9	54.6	6.8	18.9	12.2	49.2	61.3	4.02
Rice-cattfish	14.2	63.2	48.9	13.5	40.5	27.0	44.0	71.0	4.66
Rice-crayfish	14.6	62.9	48.2	26.0	78.0	52.1	43.4	95.5	6.26
Rice-turtle	14.2	53.6	39.4	40.4	115.2	74.9	35.5	110.3	7.23
Rice-loach	14.2	56.3	42.0	66.3	84.0	17.7	37.8	55.5	3.64
Rice-carp	14.2	55.3	41.0	19.5	22.5	3.0	36.9	39.9	2.62
Control	10.7	25.9	15.3	—	—	—	—	—	1.00

<sup>1</sup> Estimation from the sale of RFCF products and market price of the previous year, and the price of rice in the RFCF model was calculated as 10 RMB/kg. The cost of aquatic products includes field engineering, facilities, feed, manual management fees, and seedlings. Unit: 10<sup>3</sup> RMB/ha. ALEU: arable-land-equivalent unit.

### 3.3. Comprehensive Comparison and Selection of RFCF Models

Combining rice productivity, food productivity, and market benefits, we compared all models comprehensively. Results are as shown in Figure 2.



**Figure 2.** Comparison of the six integrated rice field co-culture farming models.

Rice-duck co-culture model: Even though the total food output of the rice-duck co-culture system is not very high, the productions of rice and ducks as well as the total profits increased prominently. On-site surveys further prove that the rice-duck co-culture system is the most-adopted model with the largest application area in Jiangyan district at present. The techniques requirement for the rice-duck RFCF model is relatively mature. Moreover, applying the rice-duck model does not require much field engineering. In addition, ducks raised in the paddy fields have good weed- and pest-control effects. However, the main limitation of largely extending the rice-duck model exists in distribution channels of ducks. We suggest attracting investments in duck processing and by-product processing, such as marinated duck, frozen duck, duck down feather products, etc., to support large-scale promotion and application of the rice-duck model.

**Rice-crayfish co-culture model:** Overall, this model had a remarkable effect on increasing profits as well as stabilizing rice production, with a slight impact on rice yield and better food output. Owing to good market benefits of the rice-crayfish model, farmers in many regions have employed this model. Besides, crayfish is in high market demand in recent years, encouraging farmers to adjust the operating pattern of "one-season rice co-culturing with one-stubble crayfish" to that of "one-season rice with double- or triple-stubble crayfish". Raising more stubbles of crayfish not only helps farmers to take advantage of the low-lying fields that are idle in the winter season, but also improves their incomes. This model can be expanded, conditional on farmers' understanding of the operating techniques, as farmers need not to worry about selling the crayfish because of high demand.

**Rice-catfish co-culture model:** This model had similar effects on aquatic products and rice as the rice-crayfish model does, which stabilizes grain production and increases farmers' income. According to on-site interviews, the technique requirements for the rice-catfish model are relatively low. Besides, the application of the rice-catfish model requires a small amount of field engineering and low inputs. As the rice-catfish mode has been applied for a period, local farmers have already accumulated operating experience. However, similar to the rice-duck model, the market for catfish is unstable for enlarging the scale of this model. Currently, catfish produced are mostly sold to consumers in local markets. Once the problem of the monotony of the sales channel of catfish is solved, the rice-catfish model is good for large-scale promotion.

**Rice-loach co-culture model:** This model performed well in the integrated food productivity, but caused higher losses in rice yield, thus with fair market benefits. According to on-site surveys, the rice-loach model generates high input costs for farmers, and has high technology requirements for startup. Loaches are the prey of birds and hence bird-preventing measures are necessary during the early growth stage of the loach. Furthermore, loach drill holes after October, which causes problems for stocking them in paddy fields. Additionally, the markets for loach are unstable, which greatly affects the revenue. To promote this model, the local government or industrial organizations should establish regional breeding bases for loach seedlings, providing technical support, and improving cold-chain logistics, processing, and distribution channels.

**Rice-turtle co-culture model:** The rice-turtle model showed disadvantages in grain and food productivity, but had an economic advantage, according to Figure 2. However, according to local farmers with large-scale rice-turtle co-culture farming, it is difficult to sell out the turtles produced. The rice-turtle model further encounters the problems of high input costs and unstable prices of turtles. In the long term, it is risky to promote this model on a large scale because of the fluctuated market benefits and uncertain market prospects.

**Rice-carp co-culture model:** This model is mainly characterized by production of ornamental fish, instead of food. The experimental results confirm that this model not only resulted in low food output, but also caused obvious losses in rice. Additionally, carp is mainly sold for ornamental purposes in rural tourism attractions, with limited market outlets and relatively low economic benefits.

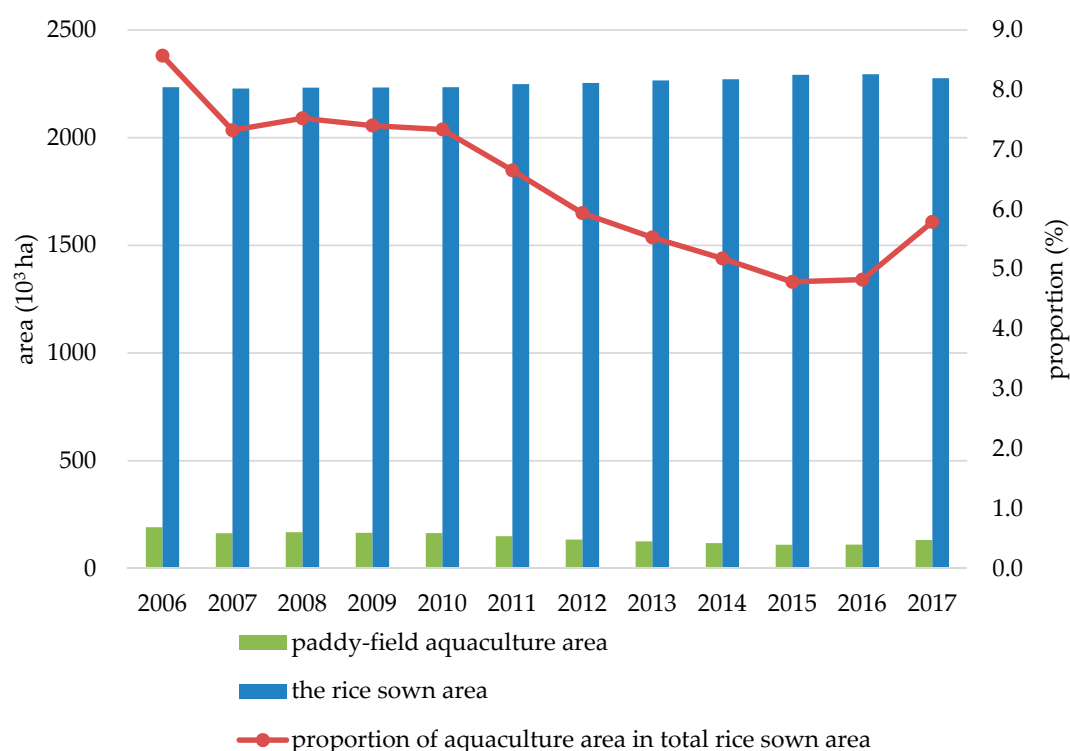
In summary, considering economic benefits for farmers and regional food security of grain ration, the rice-duck, rice-crayfish, and rice-catfish models could be priority options for large-scale promotion.

### 3.4. Potential Effects of Model Promotion on Regional Food Productivity

Jiangsu is the fourth-largest rice-producing province in China with plenty of paddy fields. There is still great potential for the expansion of rice field aquaculture. The production structure of rice field aquaculture complies with the trend of increasing demand for high-quality rice and animal food, and has a promising development potential. However, the RFCF area has decreased province-wide in Jiangsu, from 191,500 ha in 2006 (8.6% of total rice-sown area) to 110,800 ha (4.8% of total rice-sown area) in 2016. According to Figure 3, the area of RFCF has picked up from 2017 because of stimulating policies. However, we suggest that the RFCF should not expand recklessly in the near future. In Jiangsu, the total area of RFCF better not exceed 133,300 ha under present conditions, for two reasons: 1. RFCF is technology-intensive and labor-intensive. Jiangsu has developed into a non-agricultural economy,



which causes high opportunity costs for skilled labor force to engage in farming, which could be a constraint in labor resource; 2. Water and soil resource are also main constraints for integrated rice co-culture farming. According to agricultural statistics in China, per capita area of cultivated farmland in Jiangsu is just 58.6% of the national average, while water resources per capita are 27.6% of the national average. All along, Jiangsu has suffered from a tight resource environment.



**Figure 3.** Annual trends for the rice-sown area in Jiangsu Province.

Using 133,000 ha as the total constraint of the RFCF area and assuming the provincial rice-sown area to be stable at 2,276,000 ha as in 2017, we conducted simulating analyses of expanding the rice-duck, rice-crayfish, and rice-catfish models. We simulated the application of each of the three models in the existing RFCF area in Jiangsu, and calculated the total FEU and the corresponding ALEU. Table 5 summarizes the results. According to Table 5, applying all three models could increase food production and cropland area. The rice-catfish model has the most significant effect on improving the efficiency of provincial rice-sown resources. If the rice-catfish model is applied in all RFCF area in Jiangsu, the increased food productivity is equivalent to a 24% increase in the rice-sown area. As for the rice-duck and rice-crayfish models, the increased food productivity is equivalent to 3.8% and 9.8% increases in rice-sown area, respectively. In consideration of rice ration production in Jiangsu, none of the three models evidently cuts down the rice production. Therefore, none of the above three models is in contention for land with grain ration. The rice-duck model even has both grain- and land-increasing effects. Based on the five-year average unit area yield in Jiangsu, we estimated the impacts on total rice output of applying the above three models, which turn out to be between −0.34% and 0.37%. Thus, applying the three models does not significantly impair rice productivity. Under sufficient technical support, logistics, and marketing channels, the rice-crayfish model might be easier to promote at the current stage due to relatively high market benefits and high enthusiasm of operating entities.

**Table 5.** Effects of model promotion on rice cropland resources <sup>1</sup>.

Model	ALEU	Food Productivity		Rice Productivity	
		Estimated Increment of ALEU	% of Estimated Increment	Estimated Changes in Rice Cropland	% of Cropland Change
Rice-duck	219.3	86.3	3.8	8.4	0.37
Rice-catfish	355.7	222.7	9.8	−7.9	−0.35
Rice-crayfish	682.0	549.0	24.1	−7.3	−0.32

<sup>1</sup> The percentage (%) is the proportion of the estimated change in total rice-sown area; unit: 10<sup>3</sup> ha.

## 4. Conclusions and Discussion

### 4.1. Conclusions

This paper examines suitable schemes for large-scale promotion of different RFCF models in Jiangsu Province based on a diversity of (aquatic) animals combined with rice production. Using economic profits and food productivity as the primary evaluation criteria along with the FEU and ALEU methods, we analyzed data obtained from an experimental site in Jiangsu. Our study found that food productivity is higher for the rice-loach and rice-catfish models, followed by the rice-crayfish model, while the rice-duck, rice-turtle and rice-carp models are low in food productivity. Rice yield increases in the rice-duck model, while it decreases in the rice-turtle and rice-carp models. From the economic point of view, all six RFCF models generate higher market benefits from price premiums of improved quality compared with traditional rice production. However, the production costs are also higher due to ditch construction in paddy fields. The rice-turtle and rice-crayfish co-culture models have better performances in improving market profits, while the rice-carp co-culture model has the poorest performance. Based on market benefits, staple food security, and food productivity, we selected the rice-duck, rice-crayfish, and rice-catfish models for simulation analysis of provincial promotion. The three models generate significantly different effects on increasing land production capacity. The rice-catfish co-culture model works the best in increasing food production and hence potentially improving land productivity. Regarding the effects on staple food security, almost none of the three models compete with rice cultivation for land resource. The rice-duck co-culture model further increases rice yield.

### 4.2. Policy Implications

Jiangsu Province is densely populated and economically developed, and there is great pressure to support a larger population with less agricultural resources. Hence the promotion of RFCF in Jiangsu Province should aim at sustainable intensification of rice paddy fields, enhancing food productivity and economic viability on the limited land/water resources in an environmentally sound way [37]:

1. Integrated intensification of rice paddy fields. The co-culture of rice and aquatic animals in rice fields increases food production via efficient utilization of land and water resources [38]. Beyond the RFCF models mentioned in this study, more intensive and innovative models such as "double-stubble duck with one-season rice" and "double- and triple-stubble crayfish with one-season rice" are also promoted in actual practice, conforming to the trend towards sustainable intensive agriculture in densely populated areas. In view of the dual limitations of labor force and land/water resources in Jiangsu, RFCF should focus on judicious utilization of the existing resources ecologically and intensively rather than the expansion of the rice paddy aquaculture area. Moreover, the operation standards of RFCF should be further regulated, while the area scale and space scope of RFCF should be clearly stated.
2. Promoting industrialization according to local conditions. The three models proposed in the conclusions may not represent the premium schemes for application in Jiangsu Province. As new RFCF models continuously emerge, it is hardly possible to select one unified province-scale

model. Industrial clusters of aquatic product processing can provide possibilities for spillover effects on RFCF practice. In different regions, the RFCF promotion should rely on local production experience and industrial foundations, and follow the strategy of "one region, one (aquatic) product, one industry" to guide clustered agriculture development.

3. Consolidation of producers' bottom line awareness in ecology and assurance of high-quality food production. In actual operation, farmers may pursue high aquaculture production and therefore use too much feed, fertilizer, and fishery drugs, which may weaken the rice as well as cause stresses to the environment. To prevent pollution from agro-chemicals, on one side, the government should raise farmers' awareness of the "bottom-line" in the ecology and provide technical training to farmers. On the other side, the government and industry organizations should specify the regulations and standards of crucial techniques in developing RFCF, including high-quality rice variety standards, field engineering guidance, rice field water regulation, fertilizer application standards, aquaculture requirements, pollution-free methods of weed- and pest-control in rice fields, etc., to ensure the production of high-quality output.

#### 4.3. Limitations and Further Directions

The RFCF models included in this study are limited to one experimental site. In addition, the size of the experimental base for each model is relatively small. Thus, the results and conclusions might not be consistent with scaled-up cases. Furthermore, our study does not consider all existing RFCF models. Further experiments on larger scales should be conducted for future research and include additional RFCF models. Another potential improvement for further research is to consider wheat–rice double cropping, which is the primary cultivation system in Jiangsu Province. In this study, we only considered one season of the rice growth period and ignored the effects of different models on wheat productivity, which may not fully reflect the impacts on staple food security in Jiangsu.

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